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Numerical abilities of school-age children with Developmental Coordination Disorder (DCD): A behavioral and eye-tracking study

Alice Gomez, Manuela Piazza, Antoinette Jobert, Ghislaine Dehaene-Lambertz, Caroline Huron *

Cognitive Neuroimaging Unit, CEA DRF/I2BM, INSERM, Université Paris-Sud, Université Paris-Saclay, NeuroSpin center, 91191 Gif/Yvette, France

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A B S T R A C T

Developmental Coordination Disorder (DCD) is a disorder of motor coordination which interferes with academic achievement. Difficulties in mathematics have been reported. Performance in the number line task is very sensitive to atypical development of numerical cognition. We used a position-to-number task in which twenty 7-to-10 years old children with DCD and 20 age-matched typically developing (TD) children had to estimate the number that corresponded to a hatch mark placed on a 0–100 number line. Eye movements were recorded. Children with DCD were less accurate and slower to respond than their peers. However, they were able to map numbers onto space linearly and used anchoring strategies as control. We suggest that the shift to a linear trend reflects the ability of DCD children to use efficient strategies to solve the task despite a possibly more imprecise underlying numerical acuity.

Developmental Coordination Disorder (DCD) is defined as an impairment in motor coordination which interferes with academic achievement and daily life activities (DSM-IV-TR, American Psychiatric Association., 2000). Current prevalence estimates range from 1.8% (Lingam, Hunt, Golding, Jongmans, & Emond, 2009). At a sensory perceptual level, DCD impairs basic visual form detection, motion detection, visuo-spatial processing and tactile perception (meta-analysis in Wilson, Ruddock, Smits-Engelsman, Polatajko, and Blank (2013)). Executive dysfunction (Rahimi-Golkhandan, Steenbergen, Piek, Caeyenberghs, & Wilson, 2016; Rahimi-Golkhandan, Steenbergen, Piek, & Wilson, 2015) has been consistently reported with impairments of working memory, inhibitory control and executive attention. In contrast, language and reasoning skills seem to be relatively spared (Alloway, 2007; Cheng, Chen, Tsai, Shen, & Cherng, 2011).

At an academic level, DCD has a significant negative impact on handwriting skills (Jolly, Huron, Albaret, & Gentaz, 2010; Missiuna, Rivard, & Pollock, 2004; Rosenblum & Livneh-Zirinski, 2008), reading, spelling and literacy learning (Alloway & Temple, 2007; Cheng et al., 2011; Dewey, Kaplan, Crawford, & Wilson, 2002; Kadesjö & Gillberg, 1999). Difficulties in learning mathematics have also been reported (Alloway, 2007; Alloway & Archibald, 2008). In a study involving 43 children with DCD, Vaivre-Douret et al. (2011) observed that 88% of the children have school failure in mathematics whereas 12% have no problems in mathematics. Pieters, Desoete, Van Waelvelde, Vanderswalmen, and Roeyers (2012) used a task in which children had to solve as many additions and subtractions as possible within 2 min to test mental computation and number sys-

* Corresponding author at: Cognitive Neuroimaging Unit, CEA DRF/I2BM, INSERM, Université Paris-Sud, Université Paris-Saclay, NeuroSpin Center, 91191 Gif/Yvette, France.

E-mail address: caroline.huron.unicog@gmail.com (C. Huron).

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tem knowledge; they showed that children with DCD performed significantly worse in these tasks than age-matched controls. Alloway (2007) reported poor performance in numeracy measures assessed by the Wechsler Objective Numerical Dimensions that involves both a numerical operations subtest (addition, subtraction, division, multiplication, fractions, and algebra) and a mathematical reasoning subtest. Although these studies provide evidence for substantial difficulties in mathematical abilities in children with DCD, they do not provide sufficient insights into the nature of the impaired functional mechanisms.

The number line task, in which children are presented with numbers and then asked to locate their position on a number line, has yield substantive understanding into the normal development of numerical abilities (Opfer & Siegler, 2007; Siegler & Booth, 2004; Siegler & Opfer, 2003) as well as in the atypical development (Geary, 2007; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Hoard, Geary, Byrd-Craven, & Nugent, 2008; Opfer & Martens, 2012; O'Hearn & Luna, 2009). Kindergarten children use a logarithmic representation of numbers, in which more space is devoted to small numbers and the distances between magnitudes at the middle and upper ends of the line are compressed. A shift to a linear representation, in which the intervals between consecutive numbers are the same whatever the values of the numbers, occurs later in development with increasing formal schooling. Typically developing children transition to a linear representation of the 0-to-100 number line between kindergarten and second grade (Siegler & Booth, 2004) and between second and sixth grade for the 0-to-1000 number line (Siegler & Opfer, 2003). Moreover, accuracy of estimation on the number line task predicts achievement in numerical abilities (Schneider, Grabner, & Paetsch, 2009; Siegler & Booth, 2004). More specifically, increasing reliance on linear representations has been related to higher math achievement test scores (Booth & Siegler, 2006; Siegler & Booth, 2004) and to a better learning of novel arithmetic problems (Booth & Siegler, 2008).

Different strategies have already been identified to solve the number line task. Newman and Berger (1984) were the first to show that, since kindergarten, children were able to count forward from the beginning point when they have to estimate positions along the line near this point. Since the first grade, children were able to count backward from the large endpoint to estimate positions corresponding to large numbers. Children of third grade used their knowledge of proportionality to count either forward or backward from the midpoint when the position along the line was too far from both endpoints (see also, Petitto (1990)). Recently, Rouder and Geary (2014) confirmed that first grade children used endpoints to make their placements on the number line. Moreover, they reported that between the first and the second grade, children used the midpoint as an additional anchor to partition the line (see also, Barth, Slusser, Cohen, and Paladino (2011), Karolis, Iuculano, and Butterworth (2011)). Eye tracking studies have provided further insights into the strategies used to solve number line problems (Heine et al., 2010; Schneider et al., 2008; Sullivan, Juhasz, Slattery, & Barth, 2011; Van Viersen, Slot, Kroesbergen, Van't Noordende, & Leseman, 2013). For instance, eye movements data of children from 7, 8 and 9 year-old (Schneider et al., 2008) showed that they used midpoint strategies and counting up strategies when solving number line estimation tasks. Analyses of eye fixations in adults (Sullivan et al., 2011) revealed the use of the line's endpoints and midpoint to solve the task and that pattern of errors were consistent with proportional estimation strategies. Therefore, in the present study, we recorded eye movements of children, when they performed the number line task, to see whether children with DCD would use a similar or different strategy from that used by typically developing children.

Performance in the number line task is very sensitive to atypical development of numerical cognition as observed in children with mathematical learning difficulties and in participants with Williams's syndrome (Ashkenazi, Mark-Zigdon, & Henik, 2009; Geary, 2007; Geary et al., 2008; Hoard et al., 2008; Opfer & Martens, 2012; O'Hearn & Luna, 2009). Individuals with William's syndrome continue to use a logarithmic representation of numbers into adulthood even after extensive training (Opfer & Martens, 2012; O'Hearn & Luna, 2009). Seven-years-old children with mathematical learning difficulties are significantly less precise in their estimation of the number position on the number line: they make fewer placements consistent with a linear representation than their peers (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Geary et al., 2008). An eye tracking study (van't Noordende, van Hoogmoed, Schot, & Kroesbergen, 2016) showed different line estimation strategies between children with mathematical learning difficulties and children with typical mathematical development: a lower linear fit and a lower accuracy were associated with a less efficiently use of reference points to solve number line problems (Van Viersen et al., 2013).

To study the mechanisms of mathematical difficulties reported in DCD, we used an alternate version of the number line task (position-to-number) in which the hatch mark is already placed on the line and the children are asked to indicate the number that corresponds to it. We made this choice to prevent children with DCD from having poor performance in the task not because of numerical estimation inaccuracy, but because of their motor disorder that would prevent them from placing the hatch mark at the right position on the line.

Given mathematical difficulties in DCD, we expected differences in numerical estimation between children with DCD and typically developing children. Two specific hypotheses could account for a greater inaccuracy of magnitude estimates in DCD: first, children with DCD might fail to transition from logarithmic to linear representations of magnitudes, like individuals with Williams' syndrome. An alternative hypothesis is that children with DCD might be able to map numbers onto space linearly but their estimates might be less accurate than those of typically developed children. Eye movements were recorded to investigate differences in strategies that children employ when solving number line estimation tasks (Heine et al., 2010; Schneider et al., 2008).

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1. Methods

1.1. Recruitment and selection procedure

Children were recruited through advertisements in local newspapers and on the internet. For both children with DCD and typically developing children, the inclusion criteria stipulated that the participants were 7–10 of age, had no current or past history of organic disease, neurological or psychiatric disorders, reading disorders, oral language disorders, AD-HD, mental retardation or prematurity (<39 weeks of gestation), and did not take any medication. Moreover, in the DCD group, children were included only if they were already diagnosed with DCD by a medical doctor specializing in movement disorders and if they met the DSM-IV-TR criteria for DCD (American Psychiatric Association, 2000). In the control group, children were not included if parents reported any coordination difficulties.

The first step in the selection procedure was a telephone interview with AJ, which was followed by a questionnaire to complete by the parents for each child who appeared to fulfill the inclusion criteria. For children with DCD, we also asked parents to send the medical reports including psychometric assessments and all the information used for the diagnosis of DCD. CH, a medical doctor who specializes in DCD, screened the medical information of each child in order to check its status as a child with DCD according to the four criteria of the DSM-IV-TR and to eliminate unwanted comorbid disorders (dyslexia, ADHD, oral language disorders, autism for instance).

At the end of this process, 24 children with DCD and 30 control children were invited to come at the laboratory. In order to check the presence of coordination disorders in children with DCD and the absence of coordination difficulties in control children, they were all tested with the Movement Assessment Battery for Children (M-ABC, Sudgen & Henderson, 1992; French version: Soppelsa & Albaret, 2004). Children with DCD were considered for inclusion in the study when they scored below the 15th percentile. Therefore, we did not include one child (among 24) who scored above the 15th percentile in the M-ABC. Control children were considered for inclusion in the study if they scored above the 20th percentile on the M-ABC: nine children (among 30) were not included because they scored below the 15th percentile in the M-ABC.

In order to further check the absence of intellectual deficit in both groups, all children were tested with a sub-test of the WISC-IV (Similarities, Wechsler, 2003). As explained in the WISC-IV Technical and Interpretive Manual, the similarities subtest is considered as a one of the most correlated score with a general intellectual score (Range of Pearson correlation coefficient between Similarities score and General Intellectual Quotient score in 7–10 year-old population: 0.57–0.68). In the DCD group, we did not include in the study two children who scored at 6 and 3 for the similarities subtest.

At the same time, CH conducted medical interviews with the parents that revealed information that they did not mention before: one child with DCD had suffered from a cerebral neonatal cytomegalovirus infection and one control child had a genetic disease with hearing loss. We did not include them in the study.

1.2. Participants

The study involved twenty children with DCD and twenty healthy children from 7 to 10 years old (for a total of 54 children met). All these children also participated into a recently published experiment (Gomez et al., 2015). The experiment was approved by the Ethical Committee of the Medical Faculty of Kremlin Bicêtre (Paris, no 100027). In accordance with the Declaration of Helsinki, a written informed consent was obtained from all participants and their parents before the experiment.

The DCD group comprised 5 girls and 15 boys, with a mean age of 8.4 years ($SD = 0.27$). Their mean score was 17.2 (2.4th pc, $SD = 5.43$) at the M-ABC, 13.95 ($SD = 0.72$) at the similarities subtest of the WISC-IV. Eighteen children were known by the French Departmental Office for People with Disabilities (MDPH) because of the negative effects of their motor coordination impairments on their daily life and/or their academic performance. For the other two children, teachers received official recommendations of the school doctor to adjust the academic work to their handwriting difficulties. Interviews with parents and the grades from school revealed that 11 children with DCD had difficulties in mathematics.

The control group comprised 9 girls and 11 boys, with a mean age of 8.5 years ($SD = 0.26$). Their mean score was 2.38 ($SD = 2.35$) at the M-ABC, 14.35 ($SD = 0.72$) at the similarities subtest of the WISC-IV.

The two groups did not differ in age, $F(1,38) < 1$, $p = 0.89$, $MSE = 1.37$, neither in sex ratio, $\chi^2 = 1.76$, $p = 0.18$. There was a significant difference between the groups on the M-ABC score, $F(1,38) = 119.12$, $p < 0.0001$, partial $\eta^2 = 0.76$. For the WISC-IV subtests, the mean score of the similarities subtest was not different between the two groups, $F(1,38) < 1$, $p = 0.70$.

1.3. Procedure

1.3.1. Visuo-spatial processing measures

To assess visuo-spatial processing, we used the arrows subtest of the NEPSY (Korkman, Kirk, & Kemp, 2003) and the block design sub-test of the WISC-IV (Wechsler, 2003). In the arrows subtest, children were asked to look at an array of arrows arranged around a target and to indicate the arrow(s) that points to the center of the target. This subtest is designed to measure the ability to judge line orientation. In the Block design subtest, children were asked to reproduce a geometric pattern using red-and-white blocks. This subtest is designed to assess visuo-spatial skills.

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1.3.2. Number line task

We used a position-to-number (PN) task, in which children were shown a position on a number line and asked to estimate the number that corresponded to it. Each trial began with a fixation cross on the screen presented during 1500 ms and followed by a horizontal 45.5 cm number line, in the middle of the computer screen with 0 at the left end and 100 at the right end. The position to be estimated was indicated by a vertical hatch mark that intersected the number line. Target numbers were: 2, 3, 6, 7, 11, 14, 15, 19, 21, 23, 24, 28, 32, 36, 44, 47, 51, 58, 63, 69, 72, 76, 84, 87, 91, and 98. Following Siegler and Booth (2004), the numbers below 30 were over-sampled to maximize discriminability of logarithmic and linear functions.

Stimuli were displayed on the Tobii TX-300 23-inch monitor, with a 1280 × 1024 pixels resolution. Children were seated at a distance of approximately 60 cm from the screen. E-prime 2 software (www.pstnet.com) was used to control the presentation of stimuli and data collection. Experimental stimuli were presented in a random order for each child.

Instructions given at the beginning were "We're going to play a game with number lines. I want you to tell me what number corresponds to the mark on the number line." A number line that included the 0 and 100 endpoints and marked in the middle was presented on the screen. The experimenter said: "If this is 0 and this is 100, what is this number [pointing to the hatch mark]?" If the child did not give a correct answer, the experimenter said "You see the hatch mark is right in the middle of the line, the middle of 100 is 50, therefore this hatch mark corresponds to 50". This is the only time children could receive a feedback. No more instruction was given and no feedback was given during the task. For all trials, the number line remained on the screen until the experimenter had typed the child's response.

1.4. Measurements

1.4.1. Visuo-spatial subtests

Standard scores of the block design subtest (WISC-IV) and the arrows subtest (NEPSY) were reported for each child.

1.4.2. Number line task

Vocal responses were recorded to track children's estimates for each trial. The onset of each vocal response was recorded with E-prime 2. Then, trial-by-trial, vocal response times were manually computed using the CheckFiles software (Protopapas, 2007).

1.4.3. Eye movements

Eye movements were collected using a Tobii TX-300 eye tracker (Tobii Technology Inc., Stockholm, Sweden) that sampled at 300 Hz and analyzed with Tobii Studio software.

1.5. Data analysis

1.5.1. Visuo-spatial processing

Mean scores of the arrows subtest and the block design subtest were computed for each group of children. We conducted an ANOVA on each mean score with the group (DCD versus Control) as a between subject variable.

1.5.2. Number line task

To measure differences in accuracy of children's estimates, we calculated each child's percent absolute error for each number.

$$Percentage\,Absolute\,Error\,(PAE) = \left(\frac{|Estimated\,Number - presented\,position|}{Scale\,of\,Estimates}\right)$$

The percent of absolute error (PAE) can be defined as the absolute value of the difference between the presented position and the estimated number divided by the scale of the estimates considered (i.e. 0–100 in the present study). For example, if a child was asked to estimate the number that corresponded to the position of 14 on a 0–100 number line and answered 25, the percent absolute error would be 11%: (25–14)/100. Lower absolute error indicates more accurate estimates.

To determine if the error magnitude varied depending on the position of the hatch mark, we divided the number line into 5 categories: 0–20, 20–40, 40–60, 60–80 and 80–100. For instance, the category 0–20 included all the trials for which the number indicated by the position of the hatch mark was between 0 and 20. It has to be noted that the categories 0–20 and 80–100 corresponded to hatch marks near the two marked endpoints 0 and 100 and, the category 40–60 included the midpoint 50 (not marked on the line).

We performed ANOVAs on (1) mean PAE and (2) on reaction times with group as a between subjects factor and category of the hatch mark position as a within subject factor.

The next analyses examined whether children used a logarithmic or a linear representation of numbers. The fit of linear and exponential (Siegler & Opfer, 2003) functions to the median estimates of children for each presented position were computed separately for each group (DCD vs. control). To determine which model best predicted children's performance patterns, formal models were compared via Akaike information criterion, corrected for smaller sample size (AICc). AICc is a measure of the relative goodness of fit of a model. The lowest value indicates the preferred model. Finally, to test whether the group-level findings correctly reflected individual profiles, we assessed how each model explained the patterns of estimation biases observed for each child on each of the 26 number positions. An ANOVA was performed on each individual's goodness of fit (R2) for each model (linear and exponential).

1.5.3. Eye movements

Tobii Studio Software (Tobii, Stockholm) was used to calculate the coordinates and duration of each fixation using the I-VT fixation filter. The I-VT fixation classifier applies an angular velocity threshold on each data point. Data points with angular velocity below 30°/s threshold are classified "fixation" and data points above are classified "saccade". General characteristics (fixation counts, total fixation duration, mean fixation duration and path length) were computed for each trial and each child.

The data were also analyzed with an Areas Of Interest (AOI) approach. Using eye movements tracking during a number line estimation task, Sullivan et al. (2011) showed a preference of participants for fixating on the midpoint and the two endpoints of the line. Therefore, three areas of interest (AOI) corresponding to the reference points were defined: the "0" AOI (defined as a square ranging from −15 to a 115 in X and from 360 to 660 in Y) around the beginning point of the number line, the "50" AOI (defined as a square ranging from 535 to a 665 in X and from 360 to 660 in Y) around the midpoint, and the "100" AOI (defined as a square ranging from 1085 to a 1215 in X and from 360 to 660 in Y) around the endpoint. AOIs were created using a tool for spatial segmentation.

The total duration of fixation was computed for each AOI and each of the 5 categories of the position of the hatch mark on the number line as defined above. An ANOVA was conducted on the total fixation duration with group (DCD or C) as a between subject variable, AOI (0, 50, 100) and category of the hatch mark (0–20, 20–40, 40–60, 60–80, 80–100) as within-subject variables.

Because some hatch marks fell within the AOI, it is possible that part of the fixation duration in the AOI may be due to fixation at the hatch mark rather than at the reference point. Therefore, supplementary analyses were conducted by excluding trials for which the hatch marks were in the AOI (hatch marks corresponding to 2 and 3 for the "0" AOI, to 44, 47, 51 for the "50" AOI, and 98 for the "100" AOI).

1.5.4. Correlations between number line performance and eye movements or visuo-spatial skills

To further assess whether eye-movements could be responsible for performance in the number line task, we correlated general eye-movement characteristics (number of fixations, mean fixation duration, total duration of fixation) to performance in the number line task (Lin R^2, PAE) while controlling for age and IQ (score in similarities).

To assess if visuo-spatial skills could account for the observed numerical performance on the number line task, we correlated general spatial abilities (mean score in NEPSY and Blocks) to performance in the number line task (Lin R^2, PAE) while controlling for age and IQ (score in similarities).

Finally, to test whether eye-movements characteristics were related to general movement disorders, we correlated the number of fixations to the score in the M-ABC.

2. Results

2.1. Visuo-spatial processing

The mean score of the arrows subtest was significantly lower in children with DCD, 13.1 ($SD = 0.46$) than in control children, 8.9 ($SD = 0.83$), $F(1,38) = 18.44$, $p = 0.0001$, partial $\eta^2 = 0.33$. The mean score of the block design subtest was significantly lower in children with DCD 7.53 ($SD = 0.68$) than in control children, 12.27 ($SD = 0.69$), $F(1,35) = 24$, $p < 0.0001$, partial $\eta^2 = 0.40$.

2.2. Number line

One child from the DCD group was excluded from these analyses because she might not have understood the task. Indeed, all her answers were either the number 50 or a digit. However, our results were not qualitatively modified by this exclusion.

2.2.1. Accuracy of estimates (see Fig. 1)

An ANOVA on mean PAE with group as a between subjects factor and category of the hatch mark position as a within subject factor showed a significant group effect, $F(1, 37) = 9.07$, $MSE = 30.55$, $p < 0.01$, partial $\eta^2 = 0.19$, a significant category effect, $F(4, 148) = 4.53$, $MSE = 17.32$, $p < 0.001$, partial $\eta^2 = 0.11$, and no interaction, $F(4, 148) = 1.70$, $MSE = 17.32$, $p = 0.15$. Because four DCD children made very surprising large errors (e.g., give the answer 5 instead of 95), a complimentary analysis was run to insure that the greater PAE observed in DCD children was not only led by these errors: once trials with error >50 were filtered out, we kept a significant effect of the group: $F(1, 37) = 5.99$, $MSE = 21.794$, $p < 0.05$, partial $\eta^2 = 0.14$, of the categories: $F(4, 148) = 6.68$, $MSE = 9.2$, $p < 0.01$, partial $\eta^2 = 0.15$, but no interaction: $F(4, 148) = 6.68$, $MSE = 9.2$, $p = 0.19$.

Mean PAE was greater in children with DCD ($M = 7.3\%$, $SD = 2.51\%$) than in control children ($M = 4.9\%$, $SD = 2.57\%$). Post-hoc analyses of the category effect showed that the mean error was lower when the hatch mark was near the midpoint of 50

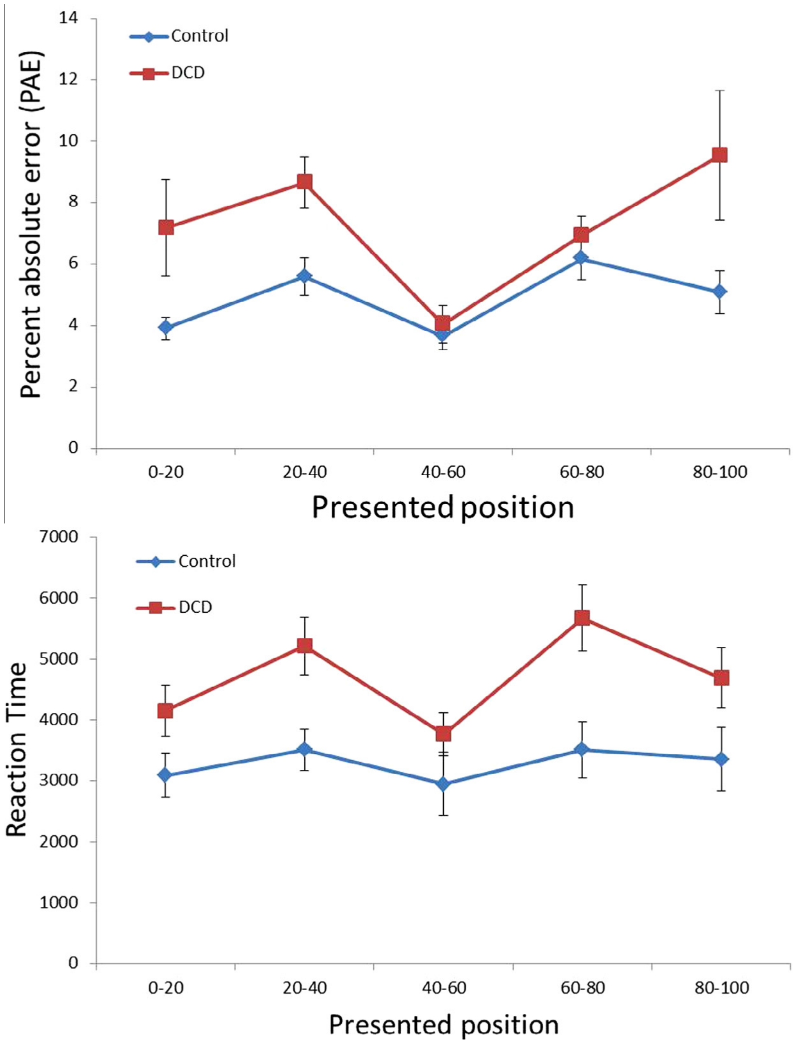

Fig. 1. Percent of absolute error (top), PAE (error bars are two Standard-Error-to-the-mean, SEMs), and reaction time in ms (bottom) of each group (DCD and Control) for each category of hatch mark position (0–20, 20–40, 40–60, 60–80, 80–100) on the number line task from 0 to 100.

(i.e., belonging to category 40–60, $M = 3.86\%$, $SD = 2.41\%$) than for hatch marks away from any anchor (i.e., belonging to categories 20–40 and 60–80, $ps < 0.005$).

2.2.2. Reaction times (see Fig. 1)

Vocal responses of a child with DCD were not fully recorded and thus his response times could not be included in the analyses. Therefore, the results of these analyses concerned 18 children with DCD and 20 control children. An ANOVA on reaction times (RT) with group as a between subjects factor and category of the hatch mark position as a within subject factor showed a significant group effect, $F(1, 36) = 6.57$, $MSE = 1.44 \cdot 10^7$, $p < 0.05$, partial $\eta^2 = 0.15$, a significant category effect, $F(4, 144) = 5.87$, $MSE = 1.67 \cdot 10^6$, $p < 0.001$, partial $\eta^2 = 0.14$, and no interaction, $F(4, 144) = 1.58$, $MSE = 1.67 \cdot 10^6$, $p = 0.18$. Children with DCD responded slower ($M = 4699$ ms, $SD = 2059$ ms) than control children ($M = 3282$ ms, $SD = 2006$ ms). Children of both groups were faster to answer for the hatch marks near the beginning point ($M = 3623$ ms, $SD = 1822$ ms) and the midpoint ($M = 3355$ ms, $SD = 2074$ ms) than for the hatch marks away from any anchor (i.e., belonging to categories 20–40 and 60–80, $ps < 0.05$).

2.2.3. Pattern of estimates

In both groups, the linear function (AICc = 74 and AICc = 14, in children with DCD and controls, respectively) fitted better than the exponential one (AICc = 253 and AICc = 246, in children with DCD and controls, respectively) as indicated by the lower value of AICc and the higher value of R^2 (R^2 DCD children = 0,99 and R^2 controls = 0,99 for the linear, and R^2 DCD children = 0,93 and R^2 controls = 0,94 for the exponential). Values of AICc were higher in the DCD group than in the control group for both models (linear model: 74 > 14; exponential model: 253 > 246). To test whether the group-level findings correctly reflected individual profiles, we assessed how each model explained the patterns of estimation biases observed for each child on each of the 26 number positions. Using an excel worksheet developed by Slusser and Barth (which can be retrieved from: https://wesfiles.wesleyan.edu/home/hbarth/web/PublicWebFiles/SlusserBarthExcelSheet.xls) we computed R^2 and AICc scores for each child and each model. The pattern of estimates of a child was considered as better fitted by a linear model if the AICc score of the linear model was the lowest, indicating that it was the preferred model. The results showed that all children were, at an individual level, best fitted by the linear model (except one child with DCD, who was equally poorly fitted both by the linear and exponential model; $AICc_{lin} = 403$ and $R^2_{lin} = 0.41$; $AICc_{exp} = 401$ and $R^2_{exp} = 0.42$).

An ANOVA was also performed on each individual's goodness of fit (R2) for each model (linear and exponential). The analyses confirmed that there is no interaction between the group and the model: $F(1, 37) < 1$, $p = 0.66$, both groups (DCD and Control) were best fit by a linear equation, $F(1, 37) = 256.76$, $MSE = 0.002$, $p < 0.001$, partial $\eta^2 = 0.87$. However, control group estimates always fitted the model far better than estimates from the DCD group $F(1, 37) = 5.89$, $MSE = 0.03$, $p < 0.05$, partial $\eta^2 = 0.14$. The linear equation accounted for only 86% in the DCD group and 96% of the variance in the control group, $p < 0.05$, and the best fitting exponential equation accounted for only 71% in the DCD group and 81% of the variance in the control group, $p < 0.05$ (see Fig. 2).

2.3. Eye movements

2.3.1. General characteristics

Fixation counts on the screen were higher in children with DCD ($M = 13.68$, $SD = 3.35$) than in controls ($M = 11.38$, $SD = 3.44$), $F(1, 37) = 4.27$, $MSE = 11.99$, $p < 0.05$, partial $\eta^2 = 0.10$, but the mean fixation duration was shorter ($M = 341.35$ ms, $SD = 99.57$ ms versus $M = 462.28$ ms, $SD = 102.28$ ms, $F(1, 37) = 13.62$, $MSE = 10464$, $p < 0.001$, partial $\eta^2 = 0.27$. As a result, the total fixation duration was not different between groups, ($M = 4499$ ms, $SD = 1387$ ms for children with DCD and $M = 4779$ ms, $SD = 1422$ ms for controls; $F(1, 37) = 0.38$, $MSE = 1016612$, $p = 0.54$). Children with DCD also exhibited a longer total path length ($M = 2156.65$ mm, $SD = 690.57$ mm) than controls ($M = 1602.45$ mm, $SD = 709.50$ mm), $F(1, 37) = 273.50$, $MSE = 503416$, $p < 0.05$, partial $\eta^2 = 0.14$, but the mean length of each saccade was not significantly different between groups ($M = 150.25$ mm, $SD = 26.09$ mm for children with DCD versus $M = 134.10$ mm, $SD = 26.79$ mm for controls; $F(1, 37) = 3.5$, $MSE = 53200$, $p = 0.068$).

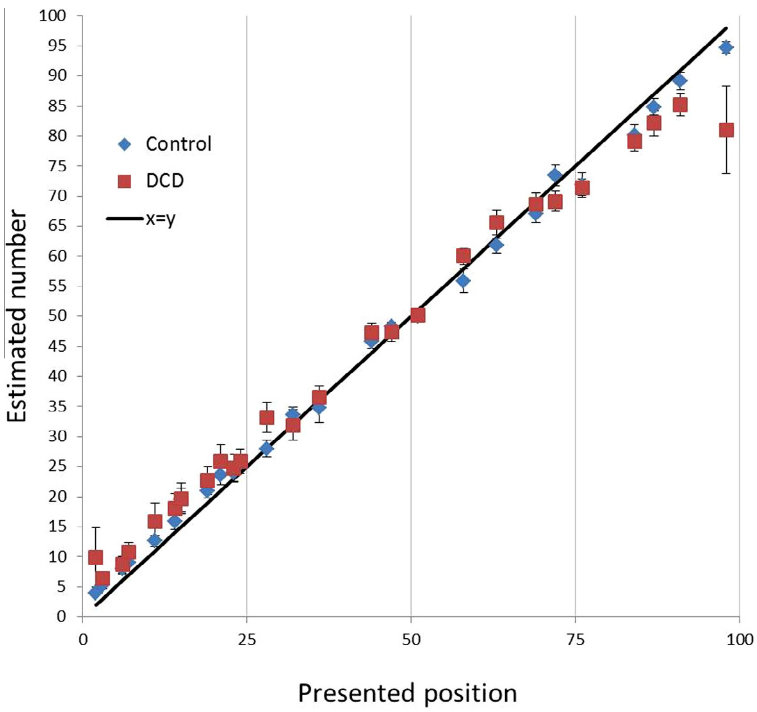

Fig. 2. Median responses (SEMs) of each group (DCD, and Control) for each presented position on the 0–100 number line task. The linear model (x = y) is plotted.

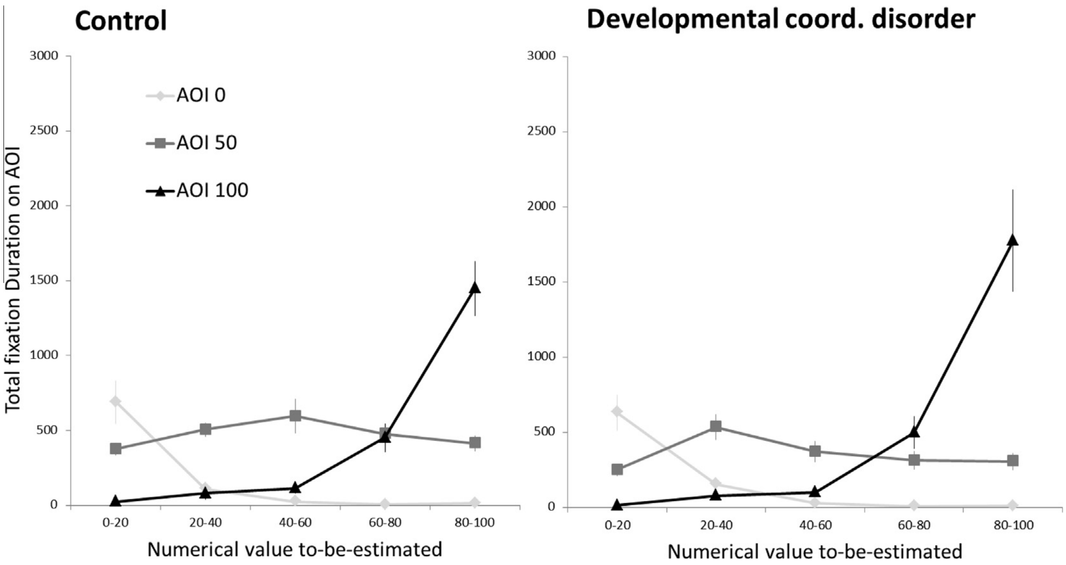

Fig. 3. Total fixation duration for each hatch mark position in the control group (left), and the DCD group, (right), for the AOI "0" (light grey), the AOI "50" (grey), and the AOI "100" (black), according to each numerical value to-be-estimated. Error bars are SEMs.

2.3.2. AOI analyses (Fig. 3)

Fig. 3 shows the total fixation duration for each category (0–20, 20–40, 40–60, 60–80, 80–100) and each AOI for the control group (top graph) and the DCD group (bottom graph).

The ANOVA conducted on the total fixation duration showed no group effect, $F < 1$, and none of the interactions involving the group was significant, $F(4, 148) = 1.2$, $MSE = 157028$, $p = 0.30$ for the group × AOI interaction, $F(2, 74) = 2.18$, $MSE = 238654$, $p = 0.12$ for the group × category interaction and $F(8, 296) = 0.67$, $MSE = 196281$, $p = 0.71$ for the group × AOI × category interaction). Main effects of category, $F(4, 148) = 35.51$, $MSE = 157028$, $p < 0.001$, partial $\eta^2 = 0.49$, of AOI, $F(2, 74) = 36.47$, $MSE = 238654$, $p < 0.001$, partial $\eta^2 = 0.50$, and the interaction between category and AOI, $F(8, 296) = 106.83$, $MSE = 196281$, $p < 0.001$, partial $\eta^2 = 0.74$, were significant. Post-hoc analyses showed that in both groups, the total duration of fixation on the AOI 0 was the highest ($ps < 0.001$) when the hatch mark fell between 0 and 20 whereas the total duration of fixation on the ROI 50 and 100 was the highest when hatch marks fell between 40 and 60, and 80 and 100, respectively (all $ps < 0.001$). Analyses excluding trials for which the hatch marks were in the AOI (hatch marks corresponding to 2 and 3 for the "0" AOI, to 44, 47, 51 for the "50" AOI, and 98 for the "100" AOI) reported similar significant main effects and interactions. However, post hoc analyses showed similar effects for the "0" AOI ($ps < 0.001$) and "100" AOI ($ps < 0.001$) but no significant results for the "50″ AOI ($ps > 0.06$).

2.4. Numerical performance correlations with eye movement or visuo-spatial ability (Table 1)

The correlations between general eye-movement characteristics (number of fixations, mean fixation duration, total duration of fixation) and the performance in the number line task (Lin R^2, PAE) while controlling for age and the score at the similarities subtest were not significant neither in children with DCD nor in control children.

The correlation between general visuo-spatial skills (mean score in NEPSY and Blocks) and the performance in the number line task (Lin R^2, PAE) while controlling for age and the score at the similarities subtest were not significant neither in children with DCD nor in control children.

3. Discussion

The first finding of the present experiment shows that children with DCD, like typically developing children, use a linear scale to map spatial positions and numbers. The form of this intuitive mapping is initially logarithmic in typical children and becomes linear between first and fourth grade (Siegler & Opfer, 2003). The present results show that children with DCD can also shift to a more mature, linear representation of the number line. They suggest that they are able to conform to the linear math system in which the difference between two consecutive numbers is identical regardless of the position on the number line.

It has been proposed that the shift toward a linear representation resulted from knowledge acquired through formal education. Using a number line task in Amazonian children and adults who are native Munduruku speakers, a language with a very small lexicon of number, Dehaene, Izard, Spelke, and Pica (2008) provided evidence that the logarithmic mapping of

Table 1
Pearson correlation coefficient for each group controlled for age and the score at the similarities subtest between (A) eye movement measures (number of fixation, total fixation duration, mean fixation duration) and the number line performance (linear goodness of fit R^2, PAE) (top), and between (B) spatial tasks (Arrows score and Blocks design score) and the number line performance. In both groups, none of the correlations were significant.

A/ Control	Number fix.	Total fix. duration	Mean fix. duration
Number line Lin. R^2	$r = -0.18$, $p = 0.47$	$r = -0.01$, $p = 0.97$	$r = 0.22$, $p = 0.38$
Number line PAE	$r = 0.04$, $p = 0.87$	$r = -0.21$, $p = 0.41$	$r = -0.17$, $p = 0.49$
DCD			
Number line Lin. R^2	$r = 0.17$, $p = 0.52$	$r = 0.38$, $p = 0.14$	$r = -0.03$, $p = 0.90$
Number line PAE	$r = 0.15$, $p = 0.59$	$r = 0.39$, $p = 0.13$	$r = 0.08$, $p = 0.76$

B/ Control	Arrows (NEPSY)	Blocks (WISC)
Number line Lin. R^2	$r = 0.35$, $p = 0.19$	$r = 0.25$, $p = 0.36$
Number line PAE	$r = -0.38$, $p = 0.15$	$r = -0.19$, $p = 0.49$
DCD		
Number line Lin. R^2	$r = -0.02$, $p = 0.93$	$r = 0.19$, $p = 0.49$
Number line PAE	$r = 0.05$, $p = 0.85$	$r = -0.20$, $p = 0.46$

numbers onto space is a universal intuition. However, in the absence of a structured mathematical language and formal education, the shift toward a linear representation of numbers did not occur, even in adults. The persistence of the logarithmic mapping into adulthood suggests that maturational processes alone cannot account for the log-linear shift. Rather, the form of the mapping critically depends on the education that people receives. Consistently with previous reports (for a meta-analysis see Wilson et al. (2013)), children with DCD showed spared performance in the similarities task. These normal intellectual skills could explain why children with DCD can benefit from formal education and thus acquire the linear structure of the number line.

A mechanism that could account for the shift toward a linear representation with education is the use of particular strategies to solve the task. In the present study, eye tracking data showed that participants fixated longer on the middle and extremities of the number line: children in both groups stared at the beginning point (0) longer than at the middle and end points when the number to estimate was between 0 and 20, and stared longer at the anchors of 50 and 100 for numbers between 40 and 60, and 80–100 respectively. Our results, obtained in a position-to-number line task, are consistent with previous reports that children fixated on the endpoints and midpoint of the line to solve the classical number-to-position line problems (Schneider et al., 2008). The use of similar strategies in both groups was also supported by the change of performance (both in speed and accuracy) for magnitudes close to an anchor point: children of both groups were more precise and faster when the hatch marks were near the midpoint. This suggests that children of both groups used the line's two endpoints plus the midpoint as references to make their estimations. Overall, these results indicated that children with DCD used the anchors in the same way as controls.

Despite their ability to map numbers on space linearly, numerical estimation in the number line task was less accurate and slower in children with DCD. According to one theoretical proposal (e.g. Feigenson, Dehaene, and Spelke (2004), Opfer and Siegler (2007), Siegler and Ramani (2009)), placements on the physical number line reflect the precision of the approximate number representation. Under this view, impairments in the accuracy of placements can be explained by an imprecision of the numerical magnitude representation. Less precision in estimating numbers from placements on the line of children with DCD would reflect, at a behavioral level, the imprecision of their internal subjective scale. This hypothesis is consistent with the report of lower performance of children with DCD in non-symbolic and symbolic number comparison tasks (Gomez et al., 2015).

Estimates of children with mathematical learning difficulties are less accurate than those of typically developing children but they also have lower linear fit scores (e.g. Geary et al. (2007, 2008), van't Noordende et al. (2016)). Therefore, the patterns of results of children with DCD in the number line task are different from those reported in children with mathematical learning difficulties without DCD. Moreover, both behavioral and eye-tracking data show that children and adults with mathematical learning difficulties cannot rely on reference points to solve number line problems and use dysfunctional strategies (Huber, Sury, Moeller, Rubinsten, & Nuerk, 2015; Van Viersen et al., 2013; van't Noordende et al., 2016). This suggests that the mechanisms underlying mathematical learning difficulties could be different in children with DCD than in children without DCD. It has also to be noted that our sample of children with DCD was not representative of the whole population of children with DCD since we excluded children with reading disorders, oral language disorders, AD-HD.

The conformation of children with DCD to a linear representation despite the inaccuracy of their estimations seems at odd with the usual association between linearity and precision of placements in development. Indeed, when typically developing children shift to a linear representation, they also display an increase in the accuracy of their placements (Opfer & Siegler, 2007; Siegler & Booth, 2004; Siegler & Ramani, 2009). Uneducated Mundurukus who did not shift to a linear strategy also presented larger errors in their estimates (Dehaene et al., 2008). Moreover, in dyscalculic children, the inaccuracy of placement is associated with a delay in the shift to a logarithmic representation (Geary, 2007; Geary et al., 2007, 2008). However, this association between an increase in placement accuracy and the shift to a linear structure may not be as systematic as previously assumed. Indeed, Opfer and Martens (2012) have shown that Williams patients can increase their accuracy on their estimation (with age or training) but they do not shift to a linear representation (even after an extensive training). Rouder and Geary (2014) also showed that children improve drastically the accuracy of their placements from the first grade until the fifth grade whereas they had understood that the use of an additional anchor such as the midpoint would help them to make their placements more accurate (and thus more linear) since the second grade. Finally, in children with impaired visuo-spatial abilities, Crollen, Vanderclausen, Allaire, Pollaris, and Noel (2015) have observed a shift to a linear representation with persisting inaccuracy. Taken together, these results suggest that accuracy and linearity are two different measures that are not reducible one to the other. Therefore, repeated observations of an association between the linearity and accuracy of placements on the number line may simply reflect a common developmental trajectory of two independent processes that can be dissociated under certain circumstances. In the present case, it is possible that the three anchors strategy used by children with DCD imposed a roughly linear structure on the estimation of the positions on the line and that the lack of precision in estimation relied on difficulties in calibrating each position from the two closest reference points.

In this study, consistently with previous reports (Alloway, 2007, 2009; Alloway & Archibald, 2008; Tsai et al., 2012), children with DCD exhibited lower performance than control children in the block design task of the WISC and in the arrows task of the NEPSY, which both involved spatial processing. A recent study that compared children with high and low visuospatial abilities showed that children with low visuo-spatial abilities were less accurate in the number line task but were as able as children with high visuo-spatial abilities to map the numbers linearly (Crollen & Noël, 2015). This is consistent with previous reports of an association between impairments in the number line and spatial impairments reported in Williams patients, another developmental disorder affecting spatial abilities (e.g. Brown et al. (2003), Farran (2006), Farran and Jarrold (2005), O'Hearn and Luna (2009)). However, in this study we did not find any significant correlation between performance in spatial tasks and performance in the number line task. This could be explained by the lack of consistent results about the impact of visuo-spatial abilities on number line performance. Indeed, Geary et al. (2008) reported that higher visuo-spatial memory performance was associated with lower accuracy and more frequent use of the log strategy in typically developing children. Moreover, Geary and colleagues showed that these correlations between spatial skills and NL performance disappeared for children of the second grade. Further studies will have to be conducted to better understand the exact nature of the links between spatial skills and number line.

As in previous studies (Creavin, Lingam, Northstone, & Williams, 2014; Robert et al., 2014), eye-tracking records showed abnormal eye-movements in children with DCD: although the total fixation duration either on the whole screen or on regions of interest was not different between groups, the number of fixations was higher and the duration of each fixation was shorter in the children with DCD than in the control children. They also made more saccadic eye movements outside the 0–100 line and their total path length was longer. However, we did not find any association between the imprecision of ocular movements and the imprecision of the numerical estimate of children with DCD. Moreover, despite these impairments, children with DCD seem to be able to compensate their shorter duration of individual fixation by performing a greater number of fixations to fixate specific regions as long as controls.

Overall, our results show that despite an impaired ability to estimate a magnitude from a position on a number line, children with DCD were able to understand the concept of linearity (numbers are separated by the same interval) and to apply efficient strategy to roughly conform to the linear structure of the number line. We suggest that the preservation of the linear structure observed in children with DCD is due to their ability to benefit from formal education to understand the strategies that can be used to solve number line problems. These results imply that providing children with DCD with conceptual strategies to solve mathematical problems might be particularly relevant to allow them to achieve their academic goals in mathematics at school. However, further behavioral experiments have to be conducted to know whether children with DCD understand other concepts than the one of linearity that underlie mathematical reasoning.

Further behavioral experiments have to be conducted to study the weaknesses and the strengths of children with DCD in mathematical cognition. Several studies suggested that computer-based simulations used to train movement and cognitive skills in cerebral palsy and neurodisability (Duckworth et al., 2014, 2015; Mumford, Duckworth, & Wilson, 2015; Wilson, 2014; Wilson, Steenbergen, Caeyenberghs, Green, & Duckworth, 2016) might be adapted for children with DCD, targeting a range of cognitive functions. In the same line, an adaptative game software, "The number race", designed to address mathematical learning disabilities, (Wilson, Dehaene, Dubois, & Fayol, 2009; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006) could be adequately used to increase the acuity of numbers estimation in children with DCD.

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