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Action representation deficits in adolescents with developmental dyslexia

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Abstract

Developmental dyslexia (DD), a severe and frequent disorder of reading acquisition, is characterised by a diversity of cognitive and motor deficits whose interactions still remain misunderstood. Although deficits in the automatization of sensorimotor control have been highlighted, the cognitive prerequisite of sensorimotor control, or internal action representation allowing prediction, have never before been investigated. In this study, we considered action representation of 18 adolescents with pure DD and 18 age matched typical readers. Participants actually and mentally performed a visually guided pointing task involving strong spatiotemporal constraints (speed/accuracy trade-off paradigm). While actual and mental movement times of typical readers were isochronous and both conformed to Fitts' law, the movement times of dyslexics differed between conditions, and only the actual movement times conformed to Fitts' law. Furthermore, the quality of motor imagery correlated with word reading and phonological awareness abilities. This suggests that the process of action representation is impaired in pure DD and supports the sensorimotor perspective of DD. Theoretical implications are discussed.

Keywords: developmental dyslexia, adolescence, internal forward models, motor imagery.

1. Introduction

Developmental dyslexia (DD) is a specific, severe and persistent disorder of word identification and reading automatization, appearing independently of mental, neurological, visual, hearing, intellectual or educational deficits (W.H.O., 1994). This developmental disorder is frequently observed in the general population, with at least one dyslexic child in each class of pupils (Barrouillet et al., 2007). It significantly interferes with school learning and daily living activities requiring reading. The different etiopathogenic theories of DD describe a diversity of cognitive and motor deficits, whose interactions remain misunderstood, and have been progressively generalised in two divergent perspectives (Ramus, 2003).

The *phonological* perspective suggests that a phonological deficit is directly responsible of reading disorders (Liberman, 1973; Snowling, 2001). This deficit arises from a dysfunction of the neural circuitry involved in the representation and processing of speech sounds (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Paulesu et al., 2001; Temple et al., 2001) with genetic predisposition (for a review: Giraud & Ramus, 2013). However, the exclusivity of a phonological deficit has been challenged by several theories describing deficits in auditory (Tallal, 1980), visual (Eden, VanMeter, Rumsey, & Zeffiro, 1996; Lovegrove, Bowling, Badcock, & Blackwood, 1980), and motor (Nicolson, Fawcett, & Dean, 2001) processing, at both behavioural and neurological levels.

These additional deficits led to a *sensorimotor* perspective (Stein, 2001), suggesting that the phonological deficit is part of a multi-modal sensorimotor syndrome. Notably, the theory of an automatization deficit (Nicolson et al., 2001) has been largely supported by studies that have highlighted impairments in DD for balance control, motor coordination, eye movement control and motor learning (Fawcett & Nicolson, 1999; Iversen, Berg, Ellertsen, & Tønnessen, 2005; Kapoula & Bucci, 2007; Poblano et al., 2002; Pozzo et al., 2006; Stoodley & Stein, 2013; Velay, Daffaure, Giraud, & Habib, 2002; Vieira, Quercia, Michel, Pozzo, & Bonnetblanc, 2009; Viholainen et al., 2006). However, the specificity (i.e., the link with reading disorders) and the nature (i.e., the underlying mechanisms) of these sensorimotor deficits are yet under debate. Their frequency varies across studies (Fawcett & Nicolson, 1999; Fawcett, Nicolson, & Dean, 1996; Moe-Nilssen, Helbostad, Talcott, & Toennessen, 2003; Nicolson & Fawcett, 1999; Quercia et al., 2005; Ramus, Rosen, et al., 2003) and, given the high degree of co-morbidity between DD, attention deficit with hyperactivity disorder (ADHD), and developmental coordination disorder (DCD), it has been suggested that sensorimotor deficits do not have a direct causal link with reading disorders (Chaix et al., 2007; Kaplan, Wilson, Dewey, & Crawford, 1998; Ramus, Pidgeon, et al., 2003; Rochelle & Talcott, 2006; Van Daal & Van der Leij, 1999; Wimmer, Mayringer, & Raberger, 1999).

Although numerous studies have suggested deficits in the automatization of sensorimotor control in DD, the involvement of crucial cognitive mechanisms, like mental action representation has never been investigated up to date. The ability to mentally represent or mentally simulate motor actions constitutes an important feature of motor behaviour. Evidence support the hypothesis that mental simulation of movement is generated by internal forward models, which are neural networks that mimic the causal flow of the physical process by predicting the future sensorimotor state (e.g., position, velocity) given the efferent copy of the motor command and the current state (Miall & Wolpert, 1996; Wolpert & Flanagan, 2001). Motor prediction through forward models is useful in production of quick and accurate movements, in anticipation and cancellation of the sensory consequences of movement, as well as in mental practice (Gueugneau, Schweighofer, & Papaxanthis, 2015; Wolpert & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 1995). Neuroimaging, behavioural, and clinical studies identified the cerebellum as an important neural site of learning forward models and of adaptive prediction in movement and cognition (Shadmehr & Krakauer, 2008; Sokolov, Miall, & Ivry, 2017). The cerebellum interconnects with the parietal lobule. It may be that sensorimotor prediction generated in the cerebellum updates a state estimate in the parietal cortex, which maintains forward models (Wolpert, Goodbody, & Husain, 1998).

Given this literature state, our intention here was to study whether action representation is altered in DD. To that aim, we used the 'motor imagery' paradigm. During motor imagery, individuals mentally perform movements, without actually execution (Demougeot & Papaxanthis, 2011; Michel, Gaveau, Pozzo, & Papaxanthis, 2013; Papaxanthis, Paizis, White, Pozzo, & Stucchi, 2012). Actual and mental movements engage similar brain areas, including the motor cortex, parietal cortex and cerebellum (Jeannerod, 2001), with forward models believed to be involved in mental movement simulation (Wolpert & Flanagan, 2001). It has been proposed that the temporal features of mental movements emerge from the predictions of the forward internal model (Papaxanthis et al., 2012; Sirigu et al., 1996). During mental movements, neural commands are prepared, but they do not reach the muscle level. However, the efference copy of these motor commands is still available to the forward models, which predicts the future states of the arm and thus provides temporal information that are very similar to that of actual movements. Data from healthy subjects (Cerritelli, Maruff, Wilson, & Currie, 2000; Courtine, Papaxanthis, Gentili, & Pozzo, 2004; Decety, Jeannerod, & Prablanc, 1989; Gueugneau, Crognier, & Papaxanthis, 2008), from patients (Bennabi et al., 2014; González, Rodríguez, Ramirez, & Sabaté, 2005; Sirigu et al., 1996), and developmental studies (Smits-Engelsman & Wilson, 2013; Spruijt, van der Kamp, & Steenbergen, 2015; Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Caeyenberghs, Wilson, Van Roon, Swinnen, & Smits-Engelsman, 2009; Choudhury, Charman, Bird, & Blakemore, 2007a, 2007b; Crognier, Skoura, Vinter, & Papaxanthis, 2013; Skoura, Vinter, & Papaxanthis, 2009) suggest that the close temporal relation between actual and mental movements is a hallmark of the normally developed sensorimotor and cognitive system, and constitute a solid set of evidence indicating that the timing of mental movements arises from forward models.

In the present study, adolescents with pure DD (no associated diagnosis of DCD, AD or ADHD) and age matched typical readers, actually and mentally accomplish a visually guided pointing task involving strong spatiotemporal constraints (speed-accuracy trade-off paradigm). Mental action representation process is estimated by the compliance to Fitts' law, which predicts that the time taken to perform a movement linearly increases with task difficulty (Fitts, 1954), and by the isochrony between actual movement time and mental movement time. Behavioural studies have shown that speed-accuracy trade-off in mental movements, as well as close temporal relation between actual and mental movements times, are acquired and consolidated at adolescence after a progressive improvement during childhood (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Choudhury et al., 2007a, 2007b; Crognier et al., 2013; Skoura et al., 2009). We expected that typical readers would modulate their movement times with task difficulty in both actual and mental conditions, while the dyslexic group would present a lack of modulation in the mental condition due to action representation deficits. In addition, the quality (or ability) of motor imagery was assessed through questionnaires. We predicted differences in auto-evaluation of motor imagery quality between typical readers and dyslexics.

2. Materials and Methods

2.1 Participants

Eighteen adolescents with DD (ten boys and eight girls; mean age: 14.10 ± 0.3 years) and eighteen age-matched typical readers (eight boys and ten girls; mean age: 14.10 ± 0.2 years) participated in the study. Each group was composed of 3 left-handers and 15 right-handers (Oldfield, 1971). All participants were native French speakers and recruited from ordinary secondary schools in Belgium on the basis of an anamnestic questionnaire, medical and/or paramedical files and standardized tests of praxis and reading performed individually prior to the study. Given the implication of phonological deficits in DD (see introduction), phonological awareness was also assessed in dyslexic participants (see Table 1). Participants were included if they had no bilingual context during reading acquisition, no diagnosis of attentional, motor, language or intellectual disorders (e.g., AD, ADHD, DCD, dysphasia) and no medical history (e.g., neurological disorders). Dyslexic participants were included into the study if: (i) they had received a formal diagnosis of developmental dyslexia, (ii) they were in possession of recent medical, neuropsychological, and speech therapist attestations showing persistence of their reading disorder and allowing them to benefit from education adjustments during their high school studies (e.g., extra time for examinations), and (iii) performed below the 10^{th} percentile compared to typically developing readers (matched for age or grade level) on standardized reading and phonological awareness tests. As documented in their personal medical and paramedical field, all the dyslexic participants had a diagnosis of associated dysorthographia and four of them had a diagnosis of associated dyscalculia. Control participants were included if they had normal reading development and performed greater or equal to the 16^{th} percentile on the same standardized reading tests. Table 2 shows that while dyslexic and control participants did not differ in age and in praxis test, they differed in reading tests. The study was approved by the Ethics Committee of Research Institute in Psychological Science at the Université Catholique de Louvain. Prior to the study, written informed consents were obtained from the parents of each participant. Parents and participants were naïve to the experiment hypotheses.

Table 1

Assessments used for the participants' inclusion in each group

Assessments	Dyslexic group N = 18	Control group N = 18
Anamnestic questionnaire	✓	✓
Medical and/or paramedical files	✓	
Praxis test (NEPSY-II)	✓	✓
Cubes (accuracy, speed)		
Reading tests (Phonolec)	✓	✓
Regular, irregular, pseudo words (accuracy, fluency)		
Phonological awareness tests (Phonolec)	✓	
Syllables deletion in first, median and final positions (accuracy, fluency)		
Phonemes deletion in first, median and final positions (accuracy, fluency)		

Table 2

Descriptive statistics of the sample

Variables	Dyslexic group (N=18)	Control group (N=18)	Group differences
	Mean (SD)	Mean (SD)	
Age (years)	14.10 (1.16)	14.10 (0.85)	ns (not significant)
Cubes (% CR in CT)[a]	80.36 (8.15)	83.73 (7.47)	ns
Words reading - accuracy			
Regular words (% CR)[b]	98.06 (2.44)	99.72 (0.64)	$P < 0.001$
Irregular words (% CR)	94.72 (6.52)	98.06 (2.51)	$P < 0.05$
Pseudo words (% CR)	72.22 (11.91)	90.83 (5.21)	$P < 0.001$
Words reading - fluency			
Regular words (s)[c]	43.00 (10.99)	31.11 (5.84)	$P < 0.05$
Irregular words (s)	16.34 (4.86)	11.91 (2.73)	$P < 0.05$
Pseudo words (s)	63.05 (15.88)	51.00 (10.60)	$P < 0.05$

Note.
a = Percentage of Correct Responses in Correct Time
b = Percentage of Correct Responses
c = seconds

2.2. Measurement of motor imagery quality

Before the experiment, we measured the general motor imagery ability of participants using the French version of the Movement Imagery Questionnaire (MIQr) (Hall & Martin, 1997). The MIQr measures the difficulty level (from 1 = very difficult to 7 = very easy) of forming visual and kinaesthetic images of movements (involving a body limb or the whole body) with a 7-point-scale in 8 items (maximum score = 56; visual modality = 28; kinaesthetic modality = 28). During the experiment, we also measured the quality of motor imagery (QMI) by asking the participants to report after each mental trial the quality of their mental movement on a 7-point-scale (1 = very poor; 7 = excellent).

2.3. Material and Experimental procedure

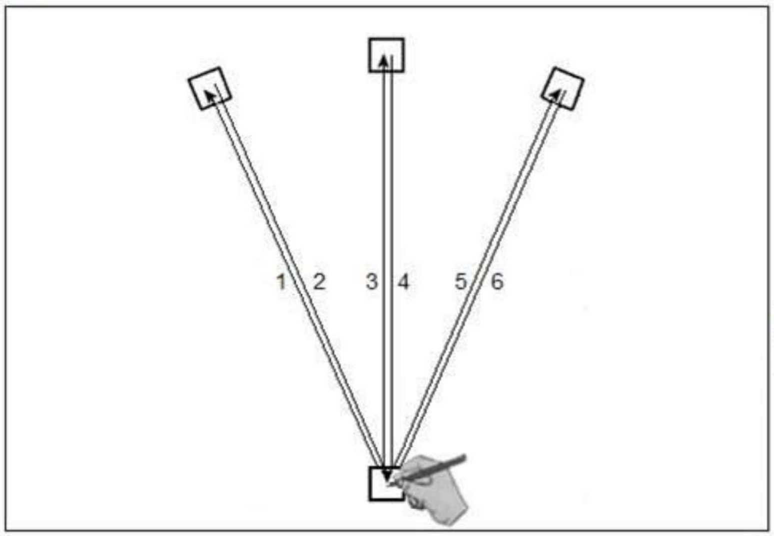
The experiment took place in a quiet room inside the participants' school. Participants were comfortably seated on a chair in front of a table whose edge was aligned with their chest at the level of the diaphragm. The experiment consisted in a visually guided pointing task involving strong spatiotemporal constraints (speed/accuracy trade-off paradigm). For each trial, a plain sheet of paper (A3 format) was presented to the participants at a distance of 10 cm from their chest. In each sheet, four targets (squares of same size) were printed (see Figure 1A). From trial-to-trial, the size of the targets changed (0.5 x 0.5; 1 x 1; 1.5 x 1.5; 2 x 2; 2.5 x 2.5 cm) with the aim to modulate the difficulty of the task according to the Fitts' Law (Fitts, 1954) :

$$ID = \log_2 (2*A/W),$$

where, ID is the index of difficulty, A is the amplitude of the movement (i.e., the inter-target distance between the starting target and the three others = 19 cm), and W is the width of the target. Figure 1B shows the five target's width, the constant movement amplitude, and the corresponding ID.

During the experiment, participants had to actually or mentally point the four targets as accurate and as fast as possible, while holding a pencil in their dominant hand. For the mental trials, participants were asked to feel themselves performing the task (internal motor imagery or first-person perspective; as in (Gueugneau et al., 2013; Michel et al., 2013; Skoura et al., 2009). As for actual trials, mental trials were performed with eyes open to avoid a multi-task effect engendered by mental reproduction of the targets' spatial arrangement, but also to avoid the use of an external perspective (e.g., to see themselves pointing). Given the coarse resolution of movement durations, long trials are necessary to obtain reliable measurements in motor imagery protocols (Demougeot & Papaxanthis, 2011; Gentili, Han, Schweighofer, & Papaxanthis, 2010; Sirigu et al., 1996). Therefore, one trial (actual or mental) consisted of three cyclical pointing movements between the targets, namely six arm movements (see Figure 1A). Before initiation of an actual or a mental trial, the participants placed the pencil in the center of the starting target. They were free to start the actual or mental movement when they felt ready; there were no reaction time constraints. For the mental trials, participants were asked to maintain the pencil immobile in the center of the starting target and to mentally move it through the targets, as if they would actually do it. For the actual trials, participants were informed that if they missed more than two targets during a trial, the trial would be cancelled and retaken. Very few trials were repeated in both groups (dyslexic group = 0.83%; control group = 1.33%).

A



B

Target Width	Amplitude	ID
0.5 x 0.5 cm	19 cm	6,3 bits
1 x 1 cm	19 cm	5,3 bits
1.5 x 1.5 cm	19 cm	4,7 bits
2 x 2 cm	19 cm	4,3 bits
2.5 x 2.5 cm	19 cm	4,0 bits

Figure 1. Experimental setup. **(A)** A sheet of paper (A3 format) was placed on a table and participants had to actually or mentally point the targets as accurate and as fast as possible. **(B)** Five different sizes of targets and one constant movement amplitude (inter-target distance) were used to modulate the difficulty of the task (ID).

Before the experiment, the participants were familiarized with the experimental protocol. First, they were trained to generate kinaesthetic sensations through two imagery exercises: (i) draw successive circles (on average 5 trials for each participant) and (ii) throw an object along a table in various trajectories (on average 5 trials for each participant). Then, they were trained on the experimental task: after a demonstration given by the experimenter in both actual and mental conditions, the participants trained themselves (2 x 2 cm target width; one of the easiest thus most neutral target's size) until they have correctly applied the instructions (on average 5 trials for each participant). During the experiment, each participant performed ten actual and ten mental trials for each ID in a random order (i.e., 100 trials per participant). A break of 5-10 minutes was systematically proposed at the middle-test or before according to the participant request or his attention-concentration state.

2.4. Data recording and statistical analysis

For the MIQr, individual scores were calculated for the visual and kinaesthetic imagery modalities by summing points obtained on the 4 items. These scores were expressed as a percentage (%) of the maximum score; a score of 100 % (i.e., 28/28 in each imagery modality or 56/56 for the total score) indicated excellent imagery ability.

For the pointing task, we recorded the actual movement time, the mental movement time, and the QMI score (% of the maximum score; i.e., 7/7 in Likert Scale). Actual and mental movement times were recorded by means of an electronic stopwatch held by the participants in their non-dominant hand. They started the stopwatch when they actually or mentally initiated the movement and stopped it when they finished the movement. The participants were trained during the practice trials to perfectly coordinate the starting and stopping of the stopwatch with the starting and stopping of their actual or mental movements. Before being analysed, individual actual and mental movement times were filtered at a confidence interval of ± 2 SD by group and by condition. Statistical analyses were performed using the IBM SPSS Statistics 20 software (SPSS, 2011). Statistical effects were considered as significant at $P < 0.05$. Statistical analyses were performed in four steps:

(i) We investigated between-groups (Mann-Whitney test) and within-group (Wilcoxon tests) differences in the ability to form visual and kinaesthetic images of movements (MIQr; qualitative variables).

(ii) We made a general analysis to investigate whether groups differed (*t-tests* for independent samples; Shapiro-Wilk W test; $P > 0.05$) in their actual and mental movement times. In this analysis, we did not consider movement times for each ID separately, but we averaged the times of the five ID for each participant. We also run a non-parametric correlation analysis between mental movement times and QMI scores to assess whether good quality of motor imagery corresponded to faster movements. In this analysis, scores corresponding to mental movement times identified as out of confidence interval were excluded.

(iii) We investigated whether actual and mental movement times of the two groups were conformed to Fitts' Law. For each participant, we performed a linear regression analysis between the mean actual or mental movement times and the ID. We calculated the slope (the extent to which performance becomes slower as ID increases), the *y*-intercept (general index of the speed of task performance), and the correlation coefficient (R^2). These parameters were compared by means of Kruskal-Wallis ANOVA (Shapiro-Wilk W test: $P < 0.05$; Levene's test: $P < 0.05$) with *group* (dyslexic, control) as a between-subject factor and *movement* (actual, mental) as within-subject factors. In further analyses, actual and mental movement times were compared in an ANOVA with *group* (dyslexic, control) as a between-subject factor and *movement* (actual, mental) and *difficulty* (five ID) as within-subject factors. A Bonferroni correction for multiple comparisons was applied on difficulty factor. For all statistical analyses, power (1-error probability) was > 0.95.

(iv) We performed a non-parametric correlational analysis to assess the relationship between motor imagery ability (QMI scores obtained in the pointing task and in the MIQr) and reading ability (Phonolec scores). To further explore this analysis, we also performed a non-parametric correlational analysis to assess the relationship between motor imagery ability (QMI scores) and phonological awareness ability (Phonolec scores). For these analyses, combined scores of reading and phonological awareness were calculated for each participant by dividing the total fluency by the total accuracy (fluency/accuracy). These combined scores were calculated either by averaged subtests or by subtest, in order to consider the different types of processes involved in the reading test (i.e., analytic vs automated word recognition) and the different levels of complexity involved in the phonological awareness test (i.e., phoneme vs syllable, initial vs median vs final position).

3. Results

3.1. Lower visual and kinaesthetic imagery abilities for the dyslexic group

Figure 2 depicts the average scores (+SD) for both groups in the MIQr, which was administrated before the experiment. It is noticeable that the dyslexic group obtained significantly lower scores than the control group in both visual (U=41.50, P<0.001) and kinaesthetic (U=63.50, P<0.01) modalities of motor imagery. For each group, scores were equivalent between the two imagery modalities (dyslexics: Z=-0.39, P=0.70; typical readers: Z=-1.58, P=0.12).

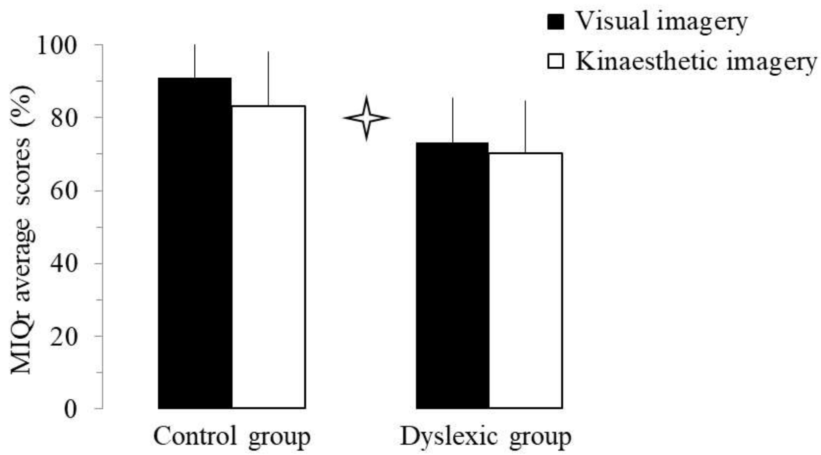


Figure 2. Movement Imagery Questionnaire (MIQr) average scores (+SD) in visual and kinaesthetic imagery modalities for both groups. Star indicates significant difference between the two groups for both modalities of motor imagery.

Slower actual and mental movement times for the dyslexic group

Figure 3A illustrates the grand average (+ SD) of actual and mental movement times (all IDs mixed) for both groups. For the control group, grand averages were 3.21 ± 0.32 s for the actual movements and 3.45 ± 0.58 s for the mental movements. For the dyslexic group, the same values were 3.67 ± 0.44 s and 4.16 ± 0.83 s, respectively. The statistical analysis confirmed that the dyslexic group performed both actual (t_{34}=3.65, P<0.01) and mental (t_{34}= 2.97, P<0.01) movements significantly slower than the control group.

The analysis of the QMI scores (quality of motor imagery; see Figure 3B) showed that the dyslexic group (on average: 70.61±13.01) performed the mental trials with significantly lower scores (U = 81; P < 0.05) than the control group (on average: 79.60±19.54). It is of interest that while there was a significant correlation between the QMI scores and the time of mental movements in the control group (Spearman Rho = -0.67, P<0.01), indicating that for the control group, faster mental movements corresponded to higher QMI scores. Such a correlation was totally absent from the dyslexic group (Spearman Rho = -0.11, P>0.1).

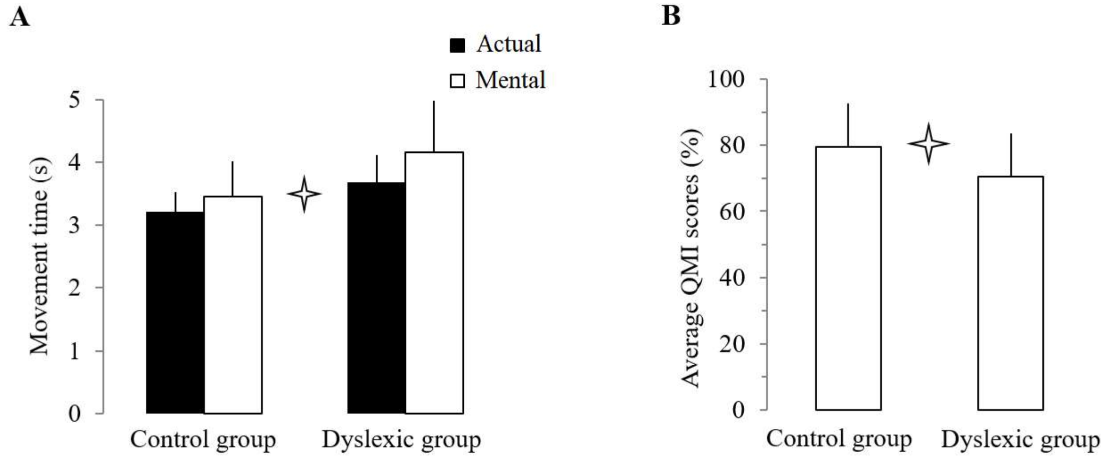


Figure 3. General analysis of groups' performances in the visually guided pointing task. **(A)** Average values (+ SD) of actual and mental movement times (all IDs mixed) for both groups. (**B)** Average values (+ SD) of QMI scores for both groups. Stars indicate significant differences between the two groups.

3.2 Lower conformity to Fitts' Law for the dyslexic group in the mental condition

In continuity with the previous results, a thorough investigation of movement times revealed that the dyslexic group did not follow Fitts' Law during mental trials (see white symbols of the Figure 4B, upper row). Indeed, mental times remained almost identical when the index of difficulty varied. On the contrary, actual movement times of both groups and mental movement times of control group (see Figure 4A) conformed to Fitts' Law. For each parameter of the linear function, ANOVA revealed a main effect of group for the mental condition, but not for the actual condition. In the mental condition, Mann-Whitney tests showed that the dyslexic group had significantly lower slope values (U = 62, $P < 0.01$), higher *y*-intercept values (U = 40, $P < 0.001$) and lower R^2 values (U = 48, $P < 0.001$) than the control group (see Table 3).

The analysis of all movement times further confirmed the previous results. ANOVA revealed a main effect of *movement* ($F_{1,34}=13.66$, $P<0.05$, $\eta^2=.29$), a main effect of *difficulty* ($F_{4,136}=243.42$, $P<0.001$, $\eta^2=.88$), and a main effect of *group* ($F_{1,34}=12.75$, $P<0.05$, $\eta^2=.27$). There were also interaction effects between *movement* and *difficulty* ($F_{4,136}=35.44$, $P<0.001$, $\eta^2=.51$), between *difficulty* and *group* ($F_{4,136}=5.6$, $P<0.05$, $\eta^2=.14$), as well as between *movement*, *difficulty* and *group* ($F_{4,136}=9.93$, $P < 0.001$, $\eta^2=.23$). *Post-hoc* analysis for the triple interaction effect revealed a significant gradual increase of both actual and mental movement times with the gradual increase of ID for the control group ($P<0.05$), while the dyslexic group presented this gradual increase only for the actual movement times ($P<0.05$). Indeed, the dyslexic group presented an increase of the mental movement times only between $ID_{5.3}$ and $ID_{4.7}$ ($P<0.05$). In addition, while actual and mental movement times did not differ for the control group (for all IDs, $P>0.1$), they significantly differed for the dyslexic group (for all comparisons $P<0.05$; but $ID_{6.3}$ and $ID_{5.3}$, $P>0.1$).

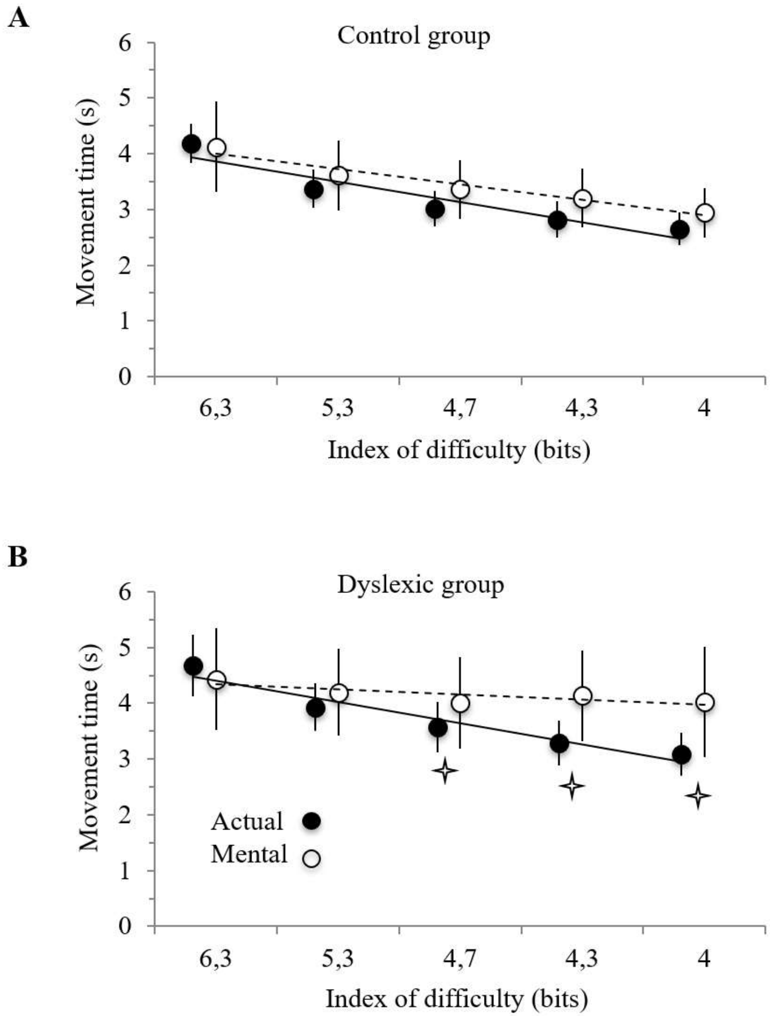


Figure 4. Fitts' Law analysis of groups' performances in the visually guided pointing task. Average values (±SD) of actual and mental movement times according to the index of difficulty (ID) for the control group **(A)** and the dyslexic group **(B)**. In the dyslexic group, stars indicate significant difference between actual and mental movement times.

Table 3

Descriptive statistics of both groups for the linear function parameters between actual or mental movement times with ID.

Conditions/Parameters	Dyslexic group N = 18	Control group N = 18	Group differences
	Mean (SD)	Mean (SD)	
Actual movements			
Slope	0.68 (0.14)	0.66 (0.11)	U = 141, *P* = 0.52
y-intercept	0.31 (0.66)	-0.06 (0.60)	U = 114, *P* = 0.13
R^2	0.98 (0.02)	0.98 (0.02)	U = 136, *P* = 0.42
Mental movements			
Slope	0.17 (0.30)	0.49 (0.25)	U = 62, *P* < 0.01
y-intercept	3.32 (1.78)	1.03 (0.99)	U = 40, *P* < 0.001
R^2	0.55 (0.33)	0.87 (0.22)	U = 48, *P* < 0.001

3.3. Link between motor imagery, reading, and phonological awareness abilities

For all participants, there was a significant correlation between the MIQr scores (averaged visual and kinaesthetic scores) and the combined scores of word reading averaged subtests (MIQr with averaged regular, irregular and pseudo words: Spearman Rho = -0.63, P<0.0001; Figure 5A). Note that this correlation was true for each word reading subtest (MIQr with regular words: Spearman Rho = -0.63, P<0.0001; MIQr with irregular words: Spearman Rho = -0.55, P<0.0001; MIQr with pseudo words: Spearman Rho = -0.65, P<0.0001) indicating that better ability in motor imagery corresponded to better ability in word reading. Similar results were found between the pointing task QMI scores and all the word reading subtests (QMI with averaged regular, irregular and pseudo words: Spearman Rho = -0.34, P<0.05; QMI with regular words: Spearman Rho = -0.47, P<0.005; QMI with irregular words: Spearman Rho = -0.31; P<0.05; QMI with pseudo words: Spearman Rho = -0.33; P<0.05).

In dyslexic participants, there was a significant correlation between the MIQr scores and the combined scores of phoneme deletion in median position only (Figure 5B; Spearman Rho = -0.44 , P<0.05); the correlations between the MIQr scores and the combined scores of phoneme deletion in first and final positions or the combined scores of syllables deletion in first, median and final positions were not significant (all P values >0.05). Similar results were found with the pointing task QMI scores: the correlation was significant with the combined scores of phoneme deletion in median position only (Spearman Rho = -0.57 , P<0.01), while other correlations were not significant (all P values >0.05).

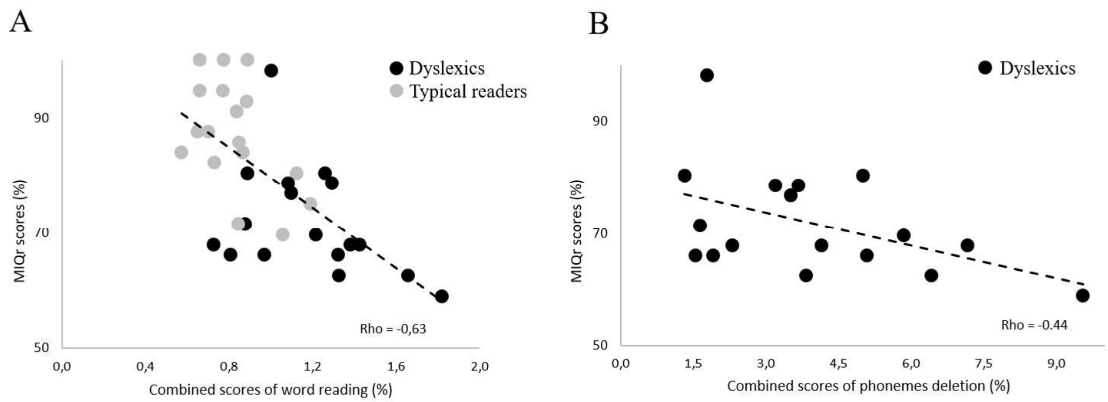


Figure 5. Correlation analysis between motor imagery, reading, and phonological awareness abilities. **(A)** For all participants, correlation between the MIQr (averaged visual and kinaesthetic) scores and the combined scores of word reading (Phonolec; averaged regular, irregular and pseudo words). Dyslexics in black and typical readers in grey. **(B)** For the dyslexic group, correlation between the MIQr scores and the combined scores of phoneme deletion (Phonolec; median position).

4. Discussion

Here, we investigated mental action representation in adolescents with pure DD and typical readers. We used the mental chronometry paradigm to quantitatively analyse the temporal features of actually and mentally performed arm movements requiring high spatiotemporal constraints. In addition, we qualitatively evaluated motor imagery by means of the MIQr questionnaire which measures the quality of mental images in several movements, and self-reported scores (QMI), which indicates the quality of mental movements during our specific pointing task. Our main results revealed that the dyslexic group in comparison to the control group: i) performed actual and mental movements significantly slower, ii) showed deficits in mental action representation, attested by the lack of compliance to Fitts' law in mental condition and the lack of isochrony between actual and mental movement times, and iii) their lower quality of motor imagery correlated with words reading and phonological awareness abilities.

4.1. Slowness of actual and mental movements in DD

We found that adolescents with DD executed arm movements significantly slower than typical readers. This observation could be anticipated from previous findings and is in accordance with the theory of an automatization deficit (Nicolson et al., 2001). Specifically, it has been largely supported by several studies that individuals with DD present impairments in balance control, motor coordination, eye movement control, and motor learning (Fawcett & Nicolson, 1999; Iversen et al., 2005; Kapoula & Bucci, 2007; Poblano et al., 2002; Pozzo et al., 2006; Stoodley & Stein, 2013; Velay et al., 2002; Vieira et al., 2009; Viholainen et al., 2006).

On the other hand, the general observation that mental movement durations were longer in the DD group constitutes a novel result. This result may suggest alterations in cognitive mechanisms responsible for the mental representation of motor actions in parallel to those observed in movement execution. This finding also relies on previous observations which suggest that DD influences the generation and manipulation of mental–visual images. A previous study reported that dyslexic children show both slower reaction times regarding the stimulus ‘‘letters’’ and ‘‘pseudo-letters’’ and increased overall reaction times compared to non-dyslexic children (Kaltner & Jansen, 2014).

4.2. Action representation deficits in DD

Several developmental studies, using a speed-accuracy trade-off task, suggest that compliance to Fitts’ law in both actual and mental conditions, as well as close temporal relation between the two conditions, is a hallmark of the normally developed cognitive and sensorimotor system (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Choudhury et al., 2007a, 2007b; Crognier et al., 2013; Skoura et al., 2009; Smits-Engelsman & Wilson, 2013; Spruijt et al., 2015). In our study, typical readers showed a modulation of both actual and mental movement times with task difficulty and an isochrony between actual and mental movement times, as has been previously demonstrated by similar studies in typically developed adolescents and adults (Caeyenberghs, Wilson, et al., 2009; Choudhury et al., 2007a; Crognier et al., 2013; Maruff, Wilson, De Fazio, et al., 1999 ; Cerritelli et al., 2000; Smits-Engelsman & Wilson, 2013). Thus, our findings also argue in turn that mental action representation process is definitely acquired at adolescence.

More interestingly, our results revealed that adolescents with DD did not show strong relationships between mental movement times and target size as typical readers did. Thereby, one could assume that when adolescents with DD mentally represent arm movements between visual targets, they did not fully integrate task constraints (i.e., target size and movement speed). More appealing, the fact that adolescents with DD showed poorer correlations and greater differences between actual and mental movements than typical readers, indicates a specific weakness of mental action representation in DD. This last conclusion is further supported by the observation that adolescents with DD did respect Fitts’s law for actual movements.

Concerning the quality of motor imagery, the dyslexic group performed mental trials with significantly lower QMI scores than the typical readers group. Furthermore, while QMI scores significantly correlated with mental movement times in the control group, such a correlation was not found in the dyslexic group. In agreement with these results, the dyslexic group also presented significantly lower MIQr scores than the control group. The fact that lower quality of motor imagery has been found in the dyslexic group for both the Fitts’ pointing task and the MIQr, whereas these tasks involve different types of movement (i.e., visually guided pointing versus involving a body limb or the whole body), argue that the obtained results are well specific to the processes involved in action representation and are not due to a simple task effect (e.g. ocular motricity deficits, general difficulty because of instructions/task complexity or task duration,…). Importantly, the quality of motor imagery assessed in both the Fitts’ pointing task and the MIQr significantly correlated with words reading ability and phonological awareness ability, which is known as a crucial prerequisite of reading acquisition (Puolakanaho et al., 2007; Ziegler et al., 2010).

Similar results have been reported by previous studies using a Fitts’ pointing task in DCD children. The dissociation between actual and mental performances has been interpreted as an impairment in the process of action representation (Ferguson, Wilson, & Smits-Engelsman, 2015; Maruff, Wilson, Trebilcock, & Currie, 1999; Wilson, Maruff, Ives, & Currie, 2001). Note that the lack of compliance to Fitts’ law in mental condition occurred in DCD children only, and not in children with ADHD or DCD+ADHD (Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Williams, Omizzolo, Galea, & Vance, 2013), underlining that impairments in action representation is not linked to a factor of comorbidity. Note, however, that sensorimotor processes, such as postural adjustments in voluntary unloading was impaired in DD+DCD children, but preserved in pure DCD and DD children (Cignetti et al., 2018), suggesting a possible difference between sensorimotor and cognitive mechanisms for action control in pure DD.

4.3. Internal models of action in DD

At the behavioural level, the concept of internal forward model may account for our findings (Miall & Wolpert, 1996; Wolpert & Flanagan, 2001). The forward model, relating the sensory signals of the actual state of the arm (e.g., position, time, and velocity) to the neural commands predicts the future states of the arm (e.g., position, velocity). Theoretically, timing information for the mentally represented movement is provided by the internal forward model, which predicts the sensory consequences of the movement on the basis of the prepared, but blocked neural commands. When the CNS has an accurate internal representation of limb and environmental dynamics, movement prediction is very close to movement production (in mental actions, this is attested by the well-known isochrony and the compliance to Fitts' law) and, theoretically, movement can be controlled in feed-forward without requiring on-line feedback regulation. If internal representations are biased or variable, a discrepancy between state estimation and actual state could emerge.

In our study, adolescents with DD did not completely preserve this ability as they exhibited temporal dissimilarities between actually and mentally performed arm movements. DD-related decline in mental actions may be associated to the fact that sensory information from the periphery is not available to the motor system during mental movement simulation as it is during movement execution. The lack of sensory information prevents individuals with DD from verifying whether the simulated movement is similar to its actual counterpart and therefore precludes the calibration of simulated actions on the basis of sensorimotor information provided from their actual execution.

Although forward models allow to supply the feedback motor control, their development requires obligatorily the processing and the integration of intermodal sensory feedback. Developmental studies suggested that forward models are acquired by learning during childhood through the repetition of motor experiences; i.e., the acquisition of a systematic relation between the motor commands, the environment, and their effects on the executed movement will progressively allow the formation of an accurate action representation or mental movement simulation (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009; Crognier et al., 2013; Guilbert, Molina, & Jouen, 2016; Molina, Tijus, & Jouen, 2008; Skoura et al., 2009). Therefore, the general proprioceptive dysfunction in DD (Martins da Cunhà, 1979; Martins da Cunha & Alves Da Silva, 1986; Quercia et al., 2007, 2005) could be one of the origins for action representation deficit in DD. Furthermore, the cerebellum has been identified as an important neural site of learning forward models and of adaptive prediction in movement and cognition (Shadmehr & Krakauer, 2008; Sokolov et al., 2017). However, both clinical and neuroimaging studies have highlighted functional and constitutional abnormalities of the cerebellum in DD (Brown et al., 2001; Eckert et al., 2003; Finch, Nicolson, & Fawcett, 2002; Leonard, 2001; Nicolson et al., 1999; Rae et al., 2002). Moreover, the parietal cortex has been identified as being dedicated to the storage and update of forward models (Wolpert et al., 1998) and the ability to process the predictive control with age is hypothesised to increase through its maturation (Choudhury et al., 2007a, 2007b; Giedd et al., 1999). It may be that through their connections, sensorimotor prediction generated in the cerebellum updates a state estimate in the parietal cortex (Wolpert et al., 1998). Finally, both the cerebellum and the lower parietal lobule (or supramarginal gyrus) are dedicated to the comparison between the motor command of a movement and its sensorial consequences (visual and proprioceptive) (Jeannerod, 2009). However, functional abnormalities of the left lower parietal lobule and the bilateral superior parietal lobules, which are involved in phonological and orthographic processing, have also been identified in DD (Peyrin et al., 2012; Ruff, Cardebat, Marie, & Démonet, 2002). In this view, the present study suggests that possible interactions between proprioceptive, cerebellar and parietal dysfunctions could be involved in the co-occurrence of cognitive and sensorimotor deficits in DD.

4.4. Limitations and Perspectives

The present study raises the importance to consider action representation in DD and support the sensorimotor perspective of DD (Stein, 2001). We are aware that the ideal design would have been to confirm the absence of co-morbid disorders by means of a complete standardized assessment of praxis and attention. However, neither the participant's individual anamnestic questionnaires nor their medical or paramedical fields mentioned an history or a diagnosis of DCD, AD or ADHD. The assessment of action representation across different subtypes of pure DD children (i.e., phonological vs. surface vs. mixt) will also be informative concerning the specificity of action representation deficits in DD. In addition, longitudinal follow up of both typically developed children and children at risk for specific learning disorders are needed to investigate the specific role of sensorimotor development (or intermodal sensorial integration) in reading acquisition mechanisms.

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Declarations of interest

None.

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