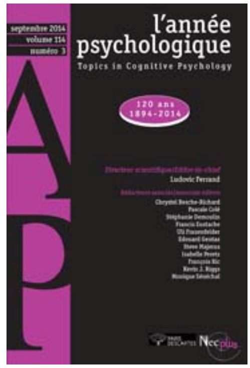

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A one-year survey of cursive letter handwriting in a French second-grade child with developmental coordination disorder

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ABSTRACT

We examined the evolution of cursive letter handwriting in a French girl with Developmental Coordination Disorder (DCD) throughout the second-grade, and compared it to that of typically developing (TD) pre-schoolers (5-6 years old; N = 98), first-graders (6-7 years old; N = 85) and second-graders (7-8 years old; N = 88). Children were asked to write cursively 20 randomly-dictated letters. Each letter track was digitized, and eight kinematic parameters were measured to evaluate writing fluency. Results showed that even with remediation, the DCD child's handwriting productions evolve much less over the year than those of TD children, and remained more similar to those of pre-schoolers than to those of first- or second-graders at all stages. Moreover, the number of parameters which differed significantly between the DCD child and TD children increased over time. The most discriminative parameters were letters size and mean speed. These results again raise the question of the need for handwriting remediation in DCD children once the delay with TD children becomes too important.

Suivi sur un an de l'évolution de l'écriture manuscrite des lettres cursives chez une enfant atteinte d'un trouble d'acquisition de la coordination

RÉSUMÉ

Nous avons analysé l'évolution de l'écriture des lettres cursives au cours de l'année de Cours élémentaire 1 (CE1/7-8ans) chez une enfant présentant un Trouble d'acquisition

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de la coordination (TAC), en comparaison avec celle d'enfants typiques de grande section de maternelle (GS/5-6ans; N = 98), Cours préparatoire (CP/6-7 ans, N = 85), et CE1 (N = 88). Vingt lettres de l'alphabet ont été dictées aux enfants dans un ordre aléatoire. Pour chaque lettre, huit paramètres cinématiques ont été mesurés pour évaluer la fluidité des tracés. Nos résultats montrent que les tracés des lettres de l'enfant TAC évoluent beaucoup moins au cours de l'année de CE1 que celles d'enfants typiques, et demeurent similaires à celles d'enfants de GS. En outre, le nombre de paramètres différents entre l'enfant TAC et les enfants typiques augmente avec le temps, les plus discriminatifs étant la taille des lettres et la vitesse d'écriture. Ces observations questionnent une nouvelle fois sur l'utilité d'une remédiation de l'écriture chez les enfants TAC lorsque le retard par rapport aux enfants typiques devient trop important.

1. INTRODUCTION

Poor handwriting is a core deficit in Developmental Coordination Disorder (DCD) (Bo, Bastian, Kagerer, Contreras-Vidal, & Clark, 2008; Cheng, Chen, Tsai, Shen, & Cherng, 2011; Dewey, Kaplan, Crawford, & Wilson, 2002; Miller, Missiuna, Macnab, Malloy-Miller, & Polatajko, 2001; Rosenblum & Livneh-Zirinski, 2008; Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003). In recent years, increasing attention has been devoted to the study of handwriting in DCD children (Chang & Yu, 2010; Cheng et al., 2011; Rosemblum & Livneh-Zirinski, 2008). However, the evolution of their handwriting productions over time has been poorly investigated. In this context, we present here a detailed analysis of the evolution of cursive letter handwriting in a DCD girl throughout her second-grade school year, and compare it to that of pre-school, first-grade and second-grade typically developing (TD) children.

Handwriting is a complex activity involving perceptivo-motor, cognitive and linguistic skills, which requires years of practice before it is mastered completely (Blöte & Hamstra-Bletz, 1991; Chartrel & Vinter, 2004; Vinter & Zesiger, 2007; Viviani, 1994). Handwriting acquisition, which starts in pre-school at the age of five, is slow and difficult (Bara & Gentaz, 2007, 2010; Zesiger, 1995). In the initial steps, children build visual representations of letters which subsequently serve as a guide for motor production. The first training exercises consist in copying letters from models, a task which is very similar to drawing. As learning progresses, writing becomes more automatic, thus requiring less attentional resources. At this stage, the differentiation between writing and drawing appears progressively and children's written productions evolve, on both qualitative (general form of letters, letter recognition) and quantitative (speed of production) levels (Bara & Gentaz, 2010; Brenneman, Massey, Machado, & Gelman, 1996; Adi-Japha & Freeman, 2001; Levine & Bus, 2003; Yamagata, 2007). From a cognitive point of view, handwriting acquisition is characterized by a progressive shift from a retro-active control of movement (based on sensorial, visual and kinesthetic feedbacks) to a proactive control (based on an internal representation of motor acts) (Meulenbroek & van Galen, 1988; Palluel-Germain, Bara, Hillairet de Boisferon, Hennion, Gouagout, & Gentaz, 2007; Zesiger, 1995). In France, the necessity of learning three different typographies for each same letter (firstly capital, then script and cursive forms) at an early stage adds a further level of complexity to the acquisition of handwriting (Bara, Morin, Montésinos-Gelet & Lavoie, 2011). Indeed, while most books use script form, French children aged 5 have to learn to write cursive letters.

Even with an appropriate training, some children fail to attain standard handwriting abilities. Children are considered as dysgraphic if the characteristics of their handwriting are significantly different from those of their peers in standardized tests such as BHK (Hamstra-Bletz & Blöte, 1993; Karlsdottir & Stefansson, 2002; Overvelde & Hulstijn, 2011). Dysgraphia then appears as a generic term for children with handwriting difficulties of various origins. For instance, dysgraphia can be found in children with developmental disorders such as DCD (Chang & Yu, 2010; Geuze, 2005, 2007; Huron, 2011; Miller et al., 2001; Plumb, Wilson, Mulroe, Brockman, Rosenblum & Livneh-Zirinski, 2008), dyslexia (Nicolson & Fawcett, 2011), or attention deficit hyperactivitiy disorder (Adi-Japha, Landau, Frenkel, Teicher, Gross-Tsur, & Shalev, 2007), or even in children without any other developmental specificity.

DCDs are diagnosed when children fail to develop normal motor coordination (Barnhart, Davenport, Epps, & Nordquist, 2003; Dewey & Wilson, 2001; Huron, 2011; Polatajko & Cantin, 2005; Visser, 2003; Willoughby & Polatajko, 1995). These disorders are estimated to affect 5 to 8% of all school-age children, with a higher incidence in boys than in girls (2:1) (American Psychiatric Association, 2000; Dewey & Wilson, 2001; Mæland, 1992; Sugden & Chambers, 1998; Wright & Sugden, 1996). The underlying neuroanatomical bases of DCDs are still in debate (for reviews, see Ahonen, Kooistra, Viholainen, & Cantel, 2004; Huron, 2011; Zwicker, Missiuna, & Boyd, 2009). Like most developmental disorders, DCDs may have multiple causes. In DCDs, the development and learning of motor skills are altered, and the main stages of psychomotor development are therefore delayed, resulting in clumsiness in everyday life and sporting activities (American Psychiatric Association, 2000). Moreover, DCD children rapidly experience difficulties at school. The acquisition of handwriting is, in particular, very difficult for DCD children, for whom poor handwriting is a common deficit (Chang & Yu, 2010; Geuze, 2005, 2007; Huron, 2011; Miller et al., 2001; Plumb et al., 2008). As they might have disorders in automatizing motor movements, each letter is produced by a succession of sequential movements (Mazeau, 1995). Since these movements are under voluntary control, this is extremely costly for the children in terms of attention, and it prevents them from performing higher order academic tasks such as composing or paying attention to the spelling or grammar.

In recent years, few studies have been devoted to characterizing handwriting difficulties in children with DCD (Chang & Yu, 2010; Cheng et al., 2011; Rosemblum & Livneh-Zirinski, 2008). They showed that, when compared to typically developing (TD) children of the same age, written productions of DCD children are characterized by slow speed at initiation, an excessive number of unnecessary pen movements, irregular pressure of the pen on the paper, poorer quality (readability), erroneous spatial organization (in particular a higher incidence of mirror letters), and greater variability in time taken and in the form of the letters (e.g. Jolly, Huron, Albaret, & Gentaz, 2010; Rosenblum & Livneh-Zirinski, 2008).

Clinical research efforts of the past 30 years have offered numerous descriptions of DCD children, both at the level of group of children and at the level of individuals. A critical point highlighted by these studies is the strong variability of results between children of the DCD population (e.g. Bo et al., 2008). Few studies, however, really concentrate on the longitudinal development of DCD children (for a review see Geuze, Jongmans, Schoemaker, & Smits-Engelman, 2001). Exceptions are the studies by Cantell (1998), Roussounis, Gaussen, & Stratton (1987), Visser, Geuze, & Kalverbeer (1998) and Visser (1998). While a few longitudinal studies on handwriting in dysgraphic children are available (Hamstra-Bletz & Blöte, 1993; Karldottir & Stefansson, 2002; Overvelde & Hulstijn, 2011), to our knowledge, no such study on the development of handwriting in children with DCD along time has been performed. Single case studies, such as a special case of longitudinal research, are rare (e.g. Henderson, Knight, Losse, & Jongmans, 1991). Research interest in the developmental trajectories of individual DCD children, which is essential in order to understand the aetiology and development of these spatial and visuo-motor problems, seems, however, to be lacking. In a preliminary study, we analyzed the characteristics of 6 cursive (la, b, i, p, r, t) letters produced by a first-grader with DCD, in two distinct tasks, a copying task and a dictation task, and compared her productions to those of TD pre-schoolers (N = 55) and first-graders (N = 60) (Jolly et al., 2010). In both tasks, we found that the DCD child's letters, like those of pre-schoolers, were characterized by slower movements alternating with velocity peaks. Moreover, her handwritten productions were more similar to those of pre-schoolers than to those of first-graders, and the discriminative parameters which differentiated the most between the DCD child and TD children were total length of tracks and mean speed. Interestingly, the lag between the DCD child and TD children of the same age was greater in the dictation task, suggesting that the mobilization of the mental representation of letters and of the motor movements required to produce them was deficient in the DCD child.

In this general context, we became interested in conducting a longitudinal study of the evolution of cursive letter handwriting in this DCD child, for whom the medical data and the access to written productions was easy. The DCD child handwriting was analyzed throughout her second-grade school year, and compared to that of pre-school, first-grade and second-grade (TD) children. The task consisted in a random dictation of 20 alphabet letters, which the children were asked to write cursively. Each letter track was monitored using a graphic tablet, and several kinematic parameters, such as track length and writing speed, were measured to evaluate writing fluency. Our main hypothesis was that the lag between the handwriting skills of DCD and TD children would increase with time despite remediation. More specifically, we hypothesized that the number of parameters which differ significantly between the DCD child and TD children would increase over time. In order to investigate these hypotheses, we analyzed the evolution of the eight kinematic parameters of the DCD child's handwriting productions throughout the second-grade and compared it to that of pre-school ($N = 98$), first-grade ($N = 85$) and second-grade ($N = 88$) TD children.

2. METHOD

2.1. Participants

The present study was conducted in accordance with the Declaration of Helsinki. It was approved by the laboratory LPNC ethics committee. It was conducted with the understanding and written consent of each child's parent and in accordance with the ethics convention between the academic organization (LPNC-CNRS) and educational organizations. Concerning the DCD child, her parents have given written informed consent to publish this case details.

2.1.1. Control groups

Ninety-eight pre-school children (44 girls) (mean age 5 years and 11 months), eighty-five first-grade children (34 girls) (mean age 6 years and 4 months at mid-year, 6 years and 10 months at the end of school year), and eighty-eight second-grade children (43 girls) (mean age 7 years and 5 months at mid-year, 7 years and 11 months at the end of school year) participated in the study. None of the children included in the study presented known learning problems or neuromotor disorders.

2.1.2. The DCD child

The DCD child (M.) is a little girl born in 2002, after a normal pregnancy and delivery. Early childhood was normal. Behavioural problems appeared at school at the age of 3, in particular in the form of integration problems and oppositional behaviour, associated with anxiety. Graphic and praxic difficulties appeared at the age of four. She was diagnosed with developmental dyspraxia (DSM-IV) at the age of five. The BHK test (Hamstra-Bletz, de Bie, & Brinker, 1987; French version by Charles, Soppelsa, & Albaret, 2003) was used to evaluate her dysgraphia at the age of 6 (first-grade). M. is right-handed and holds a pen incorrectly (her thumb under the index finger). Results of her BHK test were significantly different from those of TD first-grade children, and confirmed problems in spatial organization. Her total score was 31 and differed by 2 standard deviations from the mean score of TD first-grade children (13 +/− 6.8). Her mean writing speed (number of characters written in 5 minutes) was 25 and differed by one standard deviation from the mean speed of TD first-grade children (48.9 +/− 24.4). M. has been receiving systematic remediation for graphic activities since the age of 4 by an occupational therapist (two sessions a week during 36 weeks, and one session a week during 72 weeks). The remediation that she received used a combination of techniques, including visual-motor training, handwriting practice and also explicit and supplemental handwriting instruction (i.e. a task-oriented approach). A recent survey showed that 90% of pediatric occupational therapists used such an eclectic treatment approach (Feder, Majnemer, & Symnes, 2000).

M. was 6 years and 7 months old at the time of the first dictation (end of first-grade), 7 years and 1 month old at the time of the second dictation (mid second-grade year) and 7 years and 7 months old at the time of the last dictation (end of second-grade year).

2.2. Task and material for the analysis of written tracks

Children were asked to write the 26 dictated letters, with no time limit. The letters were dictated in four different random orders, and children were asked to write each letter once, in cursive. We checked that the dictation order had no effect on children performances (data not shown). Two dictations were performed for first- and second-graders, one at mid-year and one at the end of the year. For pre-schoolers, only one dictation at the end of the school year was performed. Dictations were performed on a sheet of paper placed on a Wacom© Intuos 3 A5 USB graphic tablet. All tracks were monitored using specific software (Bluteau, Paya, Coquillart,

& Gentaz, 2008; Bluteau, Hillairet de Boisferon, & Gentaz, 2010; Hennion, Gentaz, Gouagout, & Bara, 2005; Jolly et al., 2010), which extracts 8 different parameters for each track: (1) "nb strokes" corresponds to the number of pen strokes which constitute the letter; (2) "in-air time" corresponds to the total time (in seconds) during which the pen is not in contact with the tablet; (3) "length" corresponds to the total length of the track in cm; (4) "duration" corresponds to the total writing time in sec; (5) "speed" is the mean speed in cm/sec (length/time ratio); (6) "nb peaks" corresponds to the number of velocity peaks. The measure of this parameter requires prior filtration of raw data with an order 3 Butterworth filter at a seizure frequency of 8 Hz (Butterworth, 1930); (7) "nb static moments" corresponds to the number of static moments, i.e. periods during which the distance is null; (8) "nb slow mvts" corresponds to the number of slow movements, i.e. groups of static moments of under 150 ms, between which the distance is less than 0.1 cm.

2.3. Statistical analyses

Although included in the dictation (they are visible in the examples shown in Fig. 1), the letters k, q, w, x, y and z were not included in the statistical analyses because most pre-schoolers and part of the mid-year 1st-graders did not know how to trace them.

Mean values and standard deviations were calculated for each letter and each parameter for each control. Comparisons between groups were then performed using either an independent samples Student test (for the comparison of pre-school, 1st-grade and 2nd-grade groups) or a paired samples t-test (for the comparison of mid-year and end-of-year performances of 1st-graders and 2nd-graders). For mirror letters, the mean number and SD of mirror letters produced by children were calculated for each control group. To evaluate the progression of M's performances for each parameter, the differences between the mid-2nd grade and the end of 1st-grade values, and between the end of 2nd grade and the mid-2nd grade values were calculated for each letter. The mean difference and SD of the 20 letters were then calculated for each parameter. For the DCD child letters, the unique value of each parameter and the number of mirror letters were compared to the mean of each control group at matched time of the year using the Singlims software, which was developed by Pr John Crawford's group for the comparison of single case values to a normative group (Crawford & Garthwaite, 2002, 2007). In brief, the formula of the modified t-test comparing an individual's score with the mean score of a normative group is:

$$t = \frac{X1 - X2}{S2\text{v}\,\overline{(\text{N2} + 1)\,/\text{N2}}},$$

where *X*1 is the individual's score, *X*2 the mean score in the normative sample, *S*2 the standard deviation of scores in the normative sample, and *N*2 the number of persons in the normative sample (Crawford & Garthwaite, 2002; http://www.abdn.ac.uk/~psy086/dept/psychom.htm). In order to counteract the problem of multiple comparisons and to maintain the familywise error rate, a Bonferroni correction was applied: Since 20 comparisons (one per letter) were performed for each parameter, an alpha-correction level of .05/20 = .0025 was used.

3. RESULTS

3.1. Qualitative analysis of the cursive letters produced by the DCD child

Our investigation of the evolution of the DCD child's cursive letter handwriting was based on the random dictation of twenty letters. Three dictations were performed: One at the end of her first-grade year, one in the middle of her second-grade year, and one at the end of her second-grade year. They are presented in Figure 1 (A to C). The same task was also carried out by typically developing (TD) children of different ages and class levels, who were then used as control groups: Pre-school, first-grade, and second-grade. The task was performed once in the middle and once at the end of the year, except for pre-schoolers who only performed the dictation at the end of the year. An example of a typical dictation for each control group is presented in Figure 1 (D to H).

Initial observation of the DCD child's handwriting productions suggested that her letters were larger than those of all control groups, even the pre-schoolers. Moreover, the DCD child wrote her letters randomly on the paper, with no regard for lines. This problem in spatial organization is typical of DCD children (see introduction).

We also analyzed the number of mirror letters produced by the DCD child (Figure 2A). She wrote two mirror letters (d and g) in the dictation performed at the end of the first-grade year, one (g) in the middle of her second-grade year, and none at the end of the same year. Her first-grade result was significantly higher than that of pre-schoolers (mean = .013; $p = 0$) and first-graders (mean = .0006; $p = 0$). Her mid second-grade result was also significantly higher than that of pre-schoolers (mean = .013; $p = 0$), first-graders (mean = .0006; $p = 0$) and second-graders (mean = .0006; $p = 0$). Her end of second-grade result did not differ significantly

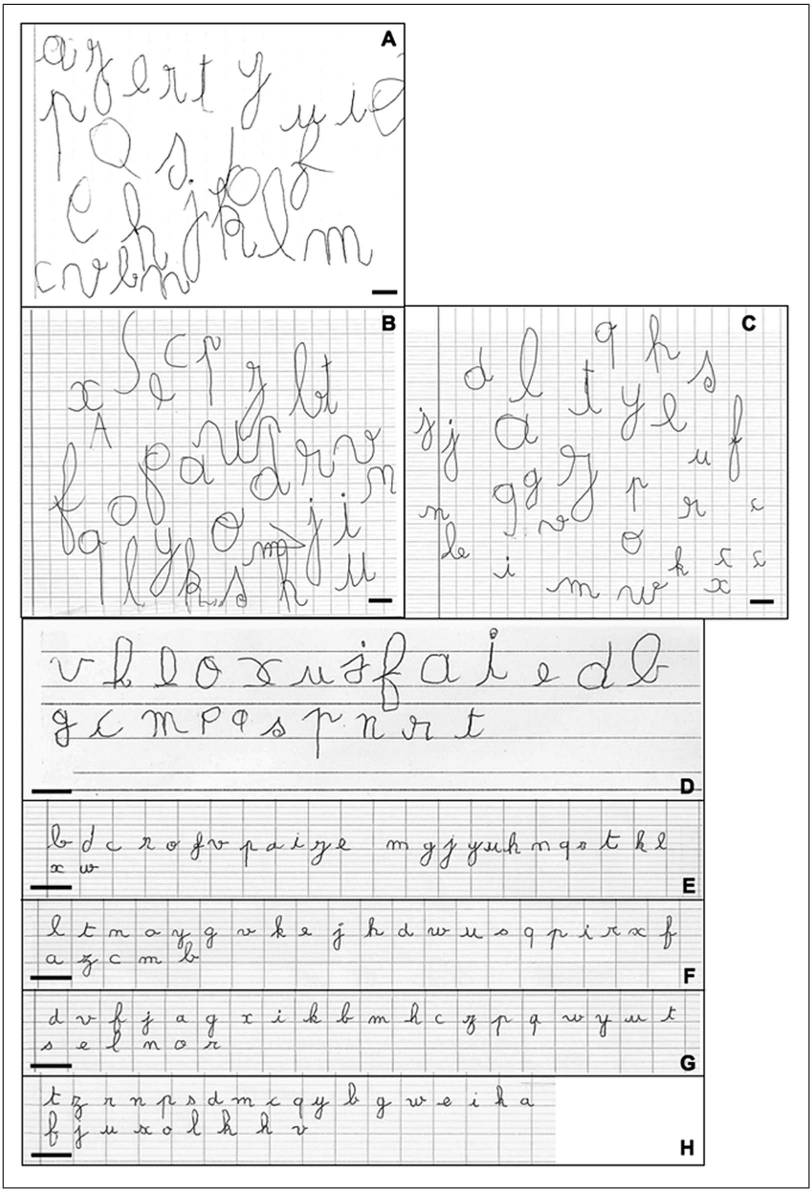


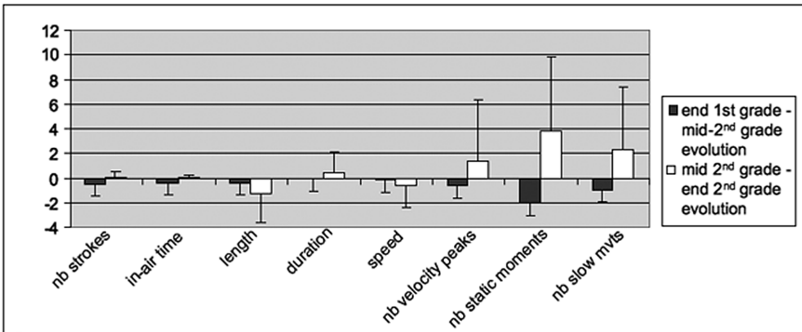
Figure 1. Samples of cursive letter handwriting by children. Dictations performed by the DCD child at the end of first-grade (A), in the middle and end of second-grade (B and C respectively), and examples of dictations performed by children at the end of pre-school (D), in the middle (E) and end (F) of first-grade, and at the middle (G) and end (H) of second-grade (note: The horizontal black bars correspond to 1 cm).

from that of pre-schoolers (mean = .013; p = 0.71), first-graders (mean = .0006; $p = 0.918$) and second-graders (mean = 0; $p = 1$).

We next observed the evolution of M's written performances for each kinematic parameter between the end of 1st-grade and the end of 2nd-grade (Figure 2B). To this hand, we calculated for each letter and each parameter the difference in the performances between two successive levels. The mean and SD deviations for all 20 letters was then calculated. Negative values attest for a progression, while positive values indicate

DCD child		end 1st grade	mid 2nd grade	end 2nd grade
		2	1	0
Pre-school	moy	0,013	0,013	0,013
	SD	0,0346	0,0346	0,0346
	n	81	81	81
	p	0 ***	0 ***	0,71
1st grade	moy	0,0006	0,0006	0,0006
	SD	0,0058	0,0057	0,0058
	n	84	86	84
	p	0 ***	0 ***	0,918
2nd grade	moy		0,0006	0
	SD		0,0055	0
	n		84	96
	p		0 ***	1

A



B

Figure 2. (A) Comparison of the number of mirror letters produced by the DCD child (first line) with those of the different control groups. Significant differences are indicated (*** p < .001). (B) Evolution of M's performances for each parameter between the end of 1st-grade and mid-2nd grade (grey boxes) and between mid-year and end-of-year 2nd grade (white boxes).

a decreased performance. Between end-of-1st grade and mid-2nd grade, a slight evolution is observed for the number of velocity peaks (mean $= -0.63$; $SD = 3.93$), the number of static moments (mean $= -2.05 \pm 5.37$), and the number of slow moves (mean $= -0.89 \pm 4.38$). However, these three parameters regress between mid-2nd grade and end of 2nd grade (mean $= 1.45 \pm 4.96$ for the number of velocity peaks, 3.85 ± 5.97 for the number of static moments, and 2.35 ± 4.99 for the number of slow moves), while a slight progression in length (mean $= -1.28 \pm 2.31$ cm) is observed during this period. These results thus show that M's handwriting only slightly evolves between 1st- and 2nd-grade, and that the main positive evolution is letters' size. This observation can be confirmed by a visual inspection of M's written productions (Figure 1 A to C).

3.2. Quantitative analysis of the cursive letters produced by TD children

We began to analyze the results of the different control groups, in order to quantify the progression between groups and to check that they all differed from each other. Mean values and standard deviations were calculated for each parameter of each letter. We then compared these values in adjacent control groups using a Student test. Tables presenting mean and SD values for each letter and each parameter for each group, as well as the results of all statistical tests, can be found online in the Supplementary Content. Due to the huge amount of data generated by our analysis, it was not possible to present a detailed analysis of each parameter, each letter and each group. In order to facilitate comprehension, we therefore chose to present the results as follows. Firstly, we present a parameter-by-parameter analysis: For each parameter, the number of letters for which this parameter was significantly different in two consecutive groups ($\alpha = .0025$) is scored. For example, a score of '0' means that no letter had a different mean for this parameter, i.e. there was no difference between the two groups for this parameter. In contrast, a score of '20' means that the mean for this parameter was significantly different in the two groups for all letters. The higher scores therefore reflect the biggest differences between the two groups. The scores for the eight parameters are presented altogether in a single graph. Secondly, we performed a letter-by-letter analysis by calculating, for each letter, the number of parameters out of eight which were significantly different in two consecutive groups ($\alpha = .0025$). For example, higher scores in the categories '0 or 1 different parameter' mean that there was little to no difference between the two groups. In contrast, higher scores in the categories '6 to 8 different parameters' reveal strong differences between groups. The overall distribution of these results for the 20 letters is presented in a second graph.

To illustrate the progression from pre-school to the end of second-grade, mean values for each parameter and each group are presented in Figure 3, for the letters ‘p’ and ‘u’. The acquisition of handwriting in children was associated with an overall decrease in the number of pen strokes, in-air time, track length, total duration, speed, number of velocity peaks, number

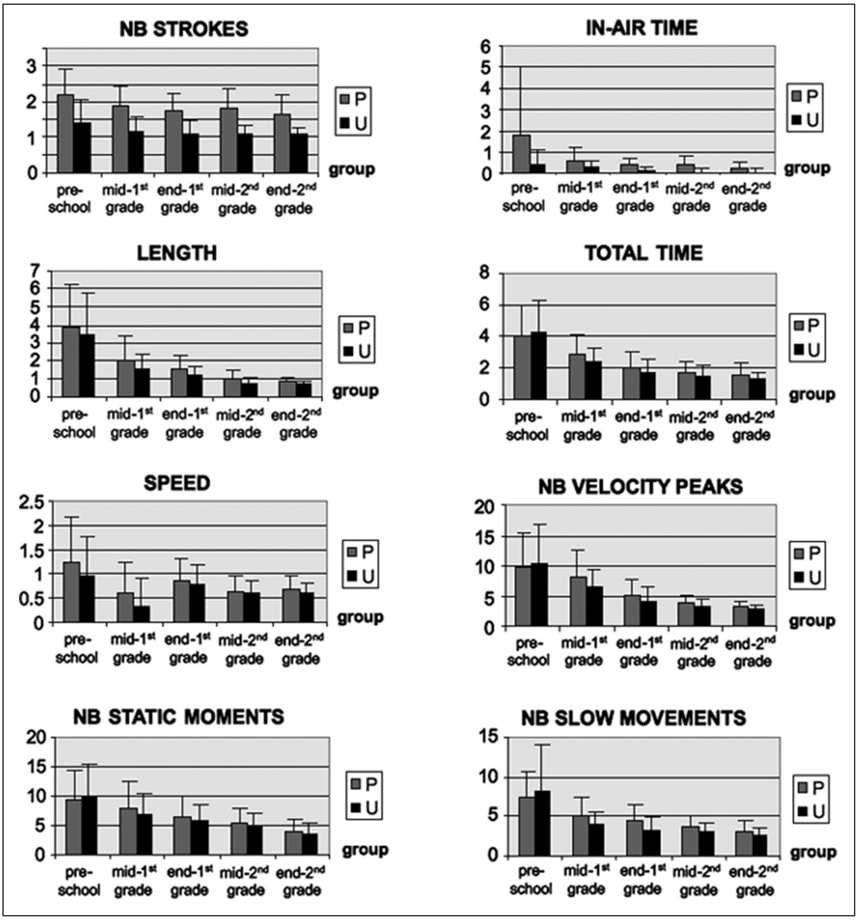


Figure 3. Examples of the evolution of the different kinematic parameters from pre-school to end of second-grade. Mean values and standard deviations of each parameter for each control group, for the letters “p” (grey bars) and “u” (black bars).

of static moments, and number of slow movements (see Supplementary Content).

Statistically significant results ($\alpha = .0025$) of the comparisons between control groups are presented in Figure 4. The results of the parameter-by-parameter analysis are presented in the left-hand graphs (Fig 4A, 4C, 4E, 4G), and those of the letter-by-letter analysis in the right-hand graphs (Fig. 4B, 4D, 4F, 4H). Our results revealed that the control groups significantly differed from one another. The comparison between pre-school and mid first-grade year revealed, for example, that five parameters out of eight were different for at least 15 letters out of 20 (length, duration, speed, number of velocity peaks, and number of slow movements) (Fig. 4A), and that 17 letters out of 20 had at least four parameters out of 8 which differed from one group to another (mean $= 5 \pm 1$ parameters significantly different) (Fig. 4B). On comparing first-graders' mid-year to end-of-year results, we found that four parameters out of eight were different for at least half of the letters (length, duration, speed, and number of velocity peaks) (Fig. 4C), and 15 letters out of 20 displayed at least four parameters which significantly differed between the two groups (mean $= 4 \pm 1$) (Fig. 4D). Slightly fewer differences were observed between end-of-year first-graders and mid-year second-graders. For instance, three parameters out of eight were different for at least half of the letters (length, speed, and number of velocity peaks) (Fig. 4E), and 17 out of 20 letters showed significant differences for at least three parameters (mean $= 3.35 \pm 0.99$) (Fig. 4F). Finally, for second-graders, five out of eight parameters differed for at least half of the letters between mid-year and end of year (length, duration, number of velocity peaks, number of static moments, and number of slow moves) (Fig. 4G), and differences in at least four parameters out of 8 emerged in 17 out of 20 letters (mean $= 4.3 \pm 1.17$) (Fig. 4H).

To sum up, our results showed that the normative groups were significantly different from one another, and demonstrated that the fluency of cursive letters handwriting clearly increased with age from pre-school to the end of second-grade.

3.3. Quantitative comparison of the DCD child's cursive letters with TD children's productions

For each letter and each parameter, we next compared the results of the DCD child to those of the different control groups. Tables presenting the values obtained by M. for each letter and each parameter, as well as the results of the statistical comparisons between M. and each control group, can be found online in the Supplementary Content. Significant results of these comparisons are presented as described above.

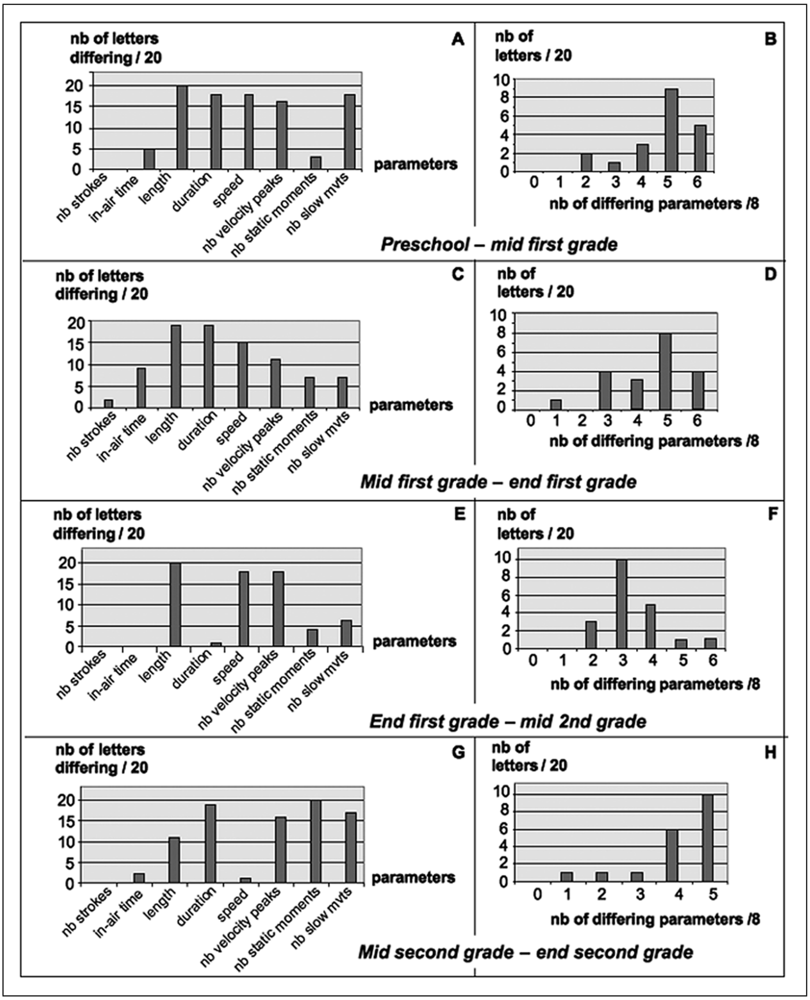


Figure 4. Results of the comparisons between control groups. Successive groups were compared two-by-two using a Student test. On the left (A, C, E, and G), the significant differences between successive groups ($\alpha = .0025$) are presented parameter-by-parameter. For each parameter, the bar indicates the number of letters out of 20 for which this parameter is significantly different ($\alpha = .0025$) in the two groups analyzed. On the right (B, D, F, and H), are presented the histograms of distribution of the differences between successive groups, i.e. the number of letters corresponding to each number of parameters significantly different ($\alpha = .0025$). (A and B) Comparison between pre-school and mid first-grade year. (C and D) Comparison between mid- and end of first-grade year. (E and F) Comparison between end of first-grade and mid second-grade year. (G and H) Comparison between mid- and end of second-grade year. The p-values of the comparisons between groups for each parameter and each letter can be found online in the Supplementary content.

We started by comparing the DCD child's end of year first-grade results with the end-of-year results of TD pre-schoolers and first-graders (Figure 5). For each parameter, the number of parameters which were significantly different between the DCD child's letters and the control

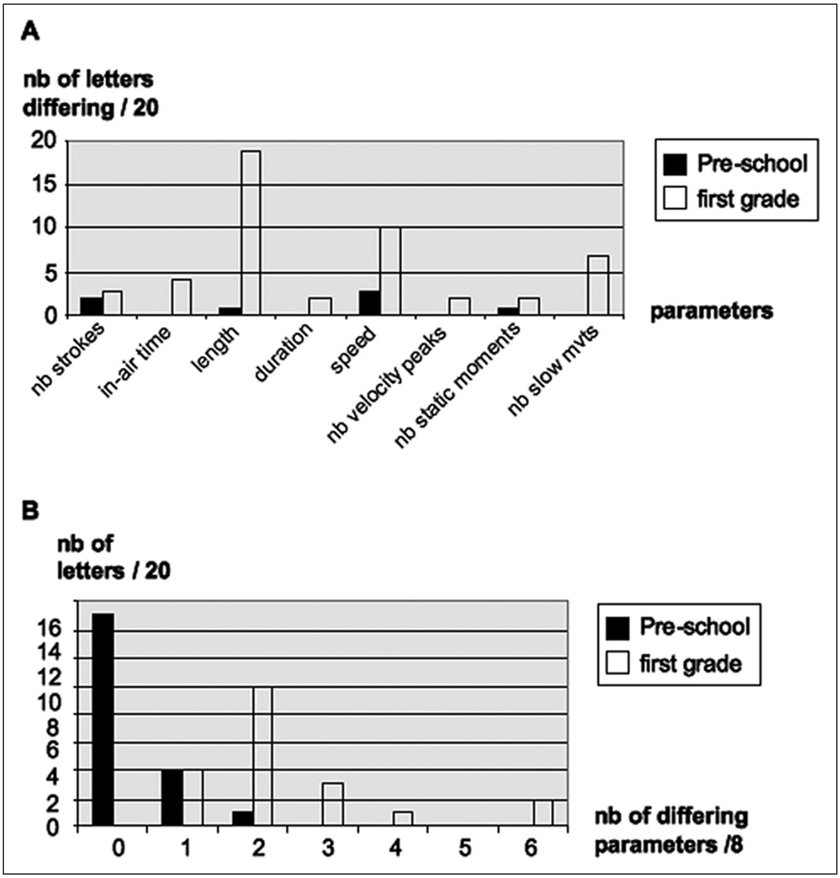


Figure 5. Comparison between the end of first-grade DCD child results and those of the normative groups. Results of the DCD child at the end of first-grade were compared to those of pre-schoolers (black bars) and to end-of-year first-graders (dotted bars). (A) For each parameter, the bars indicate the number of letters for which this parameter is significantly different ($\alpha = .0025$) in the DCD child and the control groups. In (B) is presented the histogram of distribution of the differences between the DCD child and the control groups, i.e. the number of letters corresponding to each number of parameters significantly different ($\alpha = .0025$). The p-values of the comparisons between M's performances and the different groups for each parameter and each letter can be found online in the Supplementary content.

groups was higher for first-graders than for pre-schoolers (Fig. 5A). The DCD child's letters displayed very little differences with those of pre-schoolers (mean = 0.3 ± 0.57 parameters different) (Fig. 5B). In contrast, the overall number of parameters which differed between the DCD child and the control groups was higher for the first-graders' group (mean = 2.45 ± 1.43 parameters different) (Fig. 5B). One important observation is that the parameters which were significantly different for the DCD child always displayed a higher value than the mean of the control group. The most discriminative parameters between the DCD child and first-graders were track length and speed: The DCD child produced larger letters, at a higher speed than TD children of the same age (Fig. 5A).

We next compared the results of the DCD child throughout her second-grade year with those of pre-schoolers, first-graders and second-graders. Two comparisons were performed: One in the middle of her second-grade year (Figure 6) and one at the end of her second-grade year (Figure 7).

M's second-grade results were again more similar to those of pre-schoolers than to those of first-graders and second-graders. For each parameter, the DCD child's letters were very similar to those of pre-schoolers (mean = 0.1 ± 0.31 parameters different both at mid-year, and at the end of the year) (Fig. 6B and 7B). In contrast, the DCD child's letters displayed more differences when compared to those of first- and second-graders (Fig. 6A and 7A respectively), and the overall number of parameters which differed between the DCD child and the various control groups increased with the scholar level of the group (Fig. 6B and 7B). In the middle of second grade for instance, the mean number of parameters differing between the DCD child's letters and the control groups was 1.7 ± 0.66 for first-graders, and 1.7 ± 1.03 for second graders. In the middle of her second-grade year, the most discriminative parameters between the DCD child and first-graders were length and speed, and the number of velocity peaks was also discriminative between the DCD child and second-graders (Fig. 6A). At the end of her second-grade year, the mean number of parameters differing between the DCD child's letters and the control groups increased: 2.7 ± 0.92 for first-graders, and 4.45 ± 1.39 for second graders (Fig. 7B). The parameters differing between the DCD child and first-graders were length, number of slow movements, and to a lesser extent speed (5 letters out of 20), while duration, speed, number of velocity peaks and number of static moments were also discriminative between the DCD child and second-graders (fig. 7A). As observed for the first-grade results, the values of the parameters which

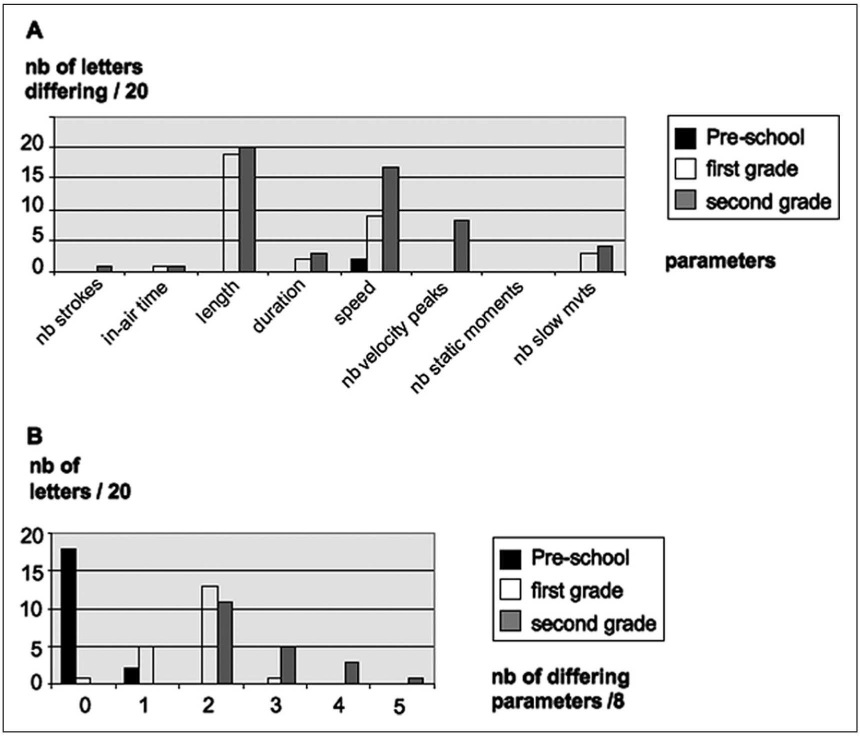


Figure 6. Comparison between the middle of second-grade DCD child results and those of the normative groups. Results of the DCD child in the middle of second-grade were compared to those of pre-schoolers (black bars), middle-year first-graders (dotted bars) and middle-year second-graders (grey bars). (A) For each parameter, the bars indicate the number of letters for which this parameter is significantly different ($\alpha = .0025$) between the DCD child and the control groups. In (B) is presented the histogram of distribution of the differences between the DCD child and the control groups, i.e. the number of letters corresponding to each number of parameters significantly different ($\alpha = .0025$). The p-values of the comparisons between groups for each parameter and each letter can be found online in the Supplementary content.

differed significantly for the DCD child were once again consistently higher than the control group mean.

Figure 8 summarizes the mean number of parameters which were significantly different between M. and the control groups at each time point.

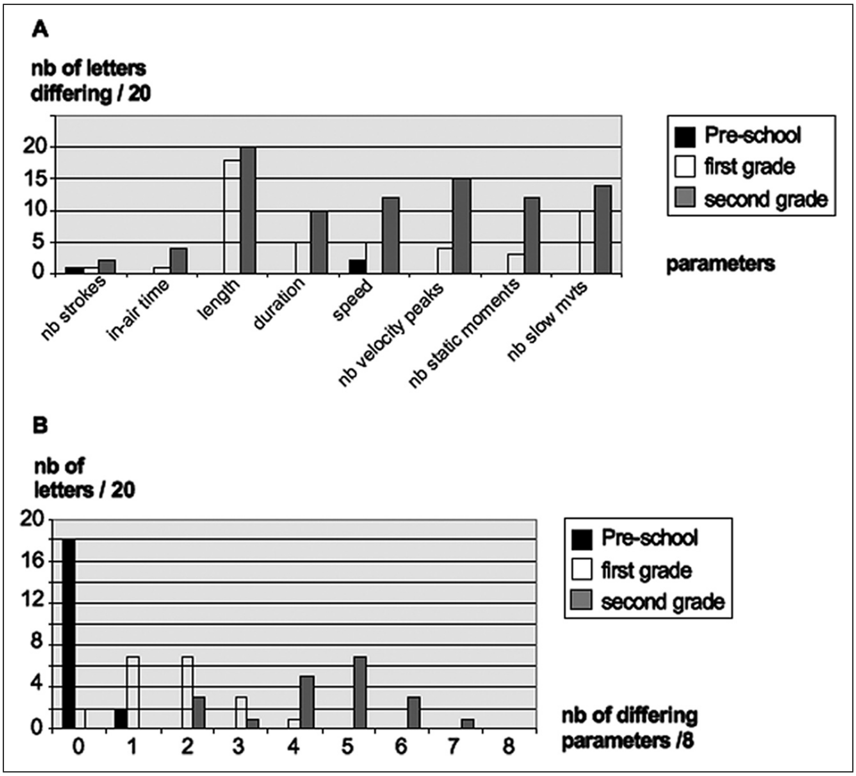


Figure 7. Comparison between the end of second-grade DCD child results and those of the normative groups. Results of the DCD at the end of second-grade were compared to those of pre-schoolers (black bars), end-of-year first-graders (dotted bars) and end-of-year second-graders (grey bars). (A) For each parameter, the bars indicate the number of letters for which this parameter is significantly different ($\alpha = .0025$) in the DCD child and the control groups. In (B) is presented the histogram of distribution of the differences between the DCD child and the control groups, i.e. the number of letters corresponding to each number of parameters significantly different ($\alpha = .0025$). The p-values of the comparisons between groups for each parameter and each letter can be found online in the Supplementary content.

To sum up, our results showed that, between the end of first-grade and the end of second-grade, the cursive letters produced by the DCD child remained more comparable to those of pre-schoolers. Interestingly, the lag between TD children and the DCD child affected all letters without distinction, even easy letters such as the "e", or familiar letters such as the "a" which is present in her name.

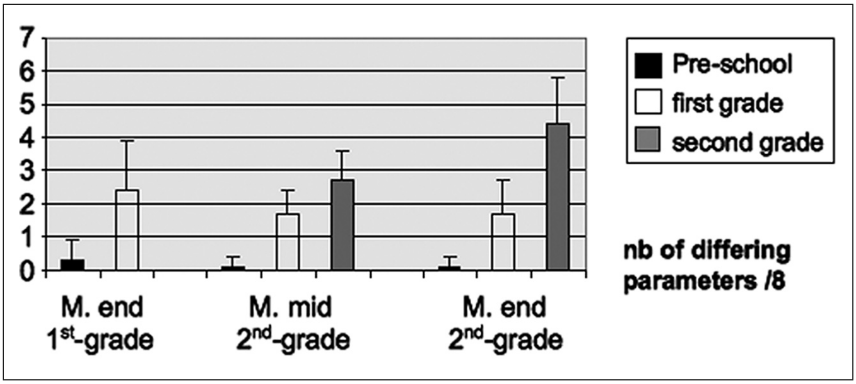


Figure 8. Mean number of parameters out of 8 which are significantly different ($\alpha = .0025$) between M. and the control groups. At each time point, M's productions present few differences with pre-schoolers (black bars), greater differences with end-of-year first-graders (dotted bars), and even more differences with end-of-year second-graders (grey bars).

4. DISCUSSION

In the present study, we provide a complete one-year survey of 20 cursive letters produced by a DCD child throughout her second-grade year, and compared them to those of typically developing children of the same age.

Our results on TD children were globally consistent with those observed in the literature (Blöte & Hamstra-Bletz, 1991; Charles et al., 2003; Hamstra-Bletz & Blöte, 1990; Karlsdottir, 1996; Maeland & Karlsdottir, 1991). We found a clear progression in cursive letter handwriting between the end of pre-school and the end of second-grade. In particular, the decrease in some parameters such as letter size, total writing time, number of velocity peaks and number of slow movements attests for writing fluency improvement. Importantly, due to the large number of children tested, and to the high frequency of testing (i.e. every 6 months), our study provides for the first time a very detailed analysis (8 kinematic parameters) of handwriting in TD children.

The analyses of the developmental trajectories of individual DCD children, such as the one reported here, seem particularly relevant for a better understanding of the aetiology of their neuro-motor problems. For instance, our analysis of the DCD child's handwritten productions revealed important differences with TD children of the same age. Firstly, we found that the acquisition of the correct orientation of letters in handwriting production was delayed in this DCD child compared to TD children of the same age. Secondly, we found that, in contrast to TD children, her handwritten productions evolved much less between the end of first-grade and the end of second-grade: In keeping with our preliminary observations (Jolly et al., 2010), the characteristics of her cursive letters remained more similar to those of pre-school children than to those of children of the same age, at all stages. The lag between the DCD child and TD children of the same age therefore increased with time. It is worth noting that the lag between TD children and the DCD child affected all letters, even letters which are present in her name such as the 'a', therefore reflecting a general lack in the automation of motor movements.

In keeping with our previous observations (Jolly et al., 2010), we found here that the most discriminative writing parameters between the DCD child and TD children of the same age were length and speed: The DCD child produced larger letters but at a higher speed. These results can be explained by the principle of isochrony, an invariant feature of handwriting in adults (Binet & Courtier, 1893; Lacquaniti, Terzuolo, & Viviani, 1983; Wright, 1993). It has been shown that motor programs are characterized by this principle: There is a proportional and direct relationship between the trajectory length and movement velocity (irrespective of letter size, the time taken to write it remains constant).

Other handwriting parameters which differentiate the DCD child from TD children include the number of slow movements, velocity peaks, and static moments. These parameters directly reflect the lesser fluency of the DCD child's handwriting. Indeed, as shown earlier, the cursive letters produced by the DCD child were characterized by the alternation of slow movements and velocity peaks, which resembled those of TD pre-schoolers (Jolly et al., 2010). This particular pattern reflects hesitations during handwriting, which may be due to a deficit in procedural memory (Nicolson & Fawcett, 2011). Similarly, the high number of static moments reveals hesitations during handwriting, most probably caused by a deficiency in the motor program associated with handwriting in DCD children.

The detailed analysis of the parameters of the DCD child's letters which evolve between the first- and the second-grade proved interesting and informative. Our results showed that mainly track length significantly improved between first- and second-grade, while other parameters such as the number of velocity peaks and the number of slow moves got worse with time (see Figure 2). Of course, it would be interesting to perform a similar analysis on a greater number of DCD children in order to identify the parameters, if any, which can evolve with time and those which cannot. These parameters could eventually be used in handwriting tests to help in the early detection of dysgraphic problems associated with developmental coordination disorders. Results of the present study were consistent with those of our previous study (Jolly et al., 2010), and showed that despite training and remediation, the automation of motor movements associated to handwriting does not develop correctly in DCD children. This is most likely due to a deficient proactive control in DCD children, as suggested by Wilson, Maruff, Ives, & Currie (2001).

The need for remediation of dysgraphic problems in DCD children is a key question. To what extent can intervention repair the handwriting deficit in DCD children, and what kind of intervention is efficient? Several different approaches have been tested so far, with varying degrees of success (Huron, 2011; Pless & Carlsson, 2000; Polatajko & Cantin, 2005; Sugden, 2007; Sugden & Chambers, 1998). Although remediation has proven to have some positive effects, no generalization or long-term maintenance has been observed, and despite remediation DCD children never reach the level of TD children. This gives rise to questions concerning the necessity of intervention. Our present results show that even with remediation, the handwritten productions of this DCD child evolve much less than those of TD children, and that the difference with TD children of the same age therefore increased with time. Since remediation is generally very costly for the DCD child, especially in terms of attention, our results again raise the question of the need for remediation for these children. In particular, the discontinuation of writing remediation once the delay with TD children becomes too important would free up precious attentional resources for the DCD child. Such an approach would be consistent with the proposal made by Cheryl Missiuna during the Leeds Consensus Conference (2006): "We need to be developing and researching models of intervention that do not presume to create change in the child but, instead, focus solely on changing the environment."

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