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Lifts and stops in proficient and dysgraphic handwriting

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ABSTRACT

In this study, the handwriting performances of dysgraphic children were compared to those of proficient children and adults. The task consisted in writing a single word at normal and fast speeds. A distinction was made between two kinds of pauses, which are often confounded: pen lifts, when the pen is above the paper, and pen stops, when it is immobile on the paper. The number and duration of lifts and stops were analyzed, together with the mean velocity. No difference in the number of lifts was observed between the three groups of writers, but the lift durations were shorter for adults. While dysgraphic children were able to write as fast as proficient children, their stops were more numerous and longer than those of proficient children who, themselves, made more stops than adults. A distinction was made between short, normal, and long, abnormal, stops. The results of this study suggest that pen stops are more appropriate than pen lifts in differentiating the handwriting fluency of dysgraphic and proficient children.

1. Introduction

The main goal of handwriting is to leave a written trace on paper. For a long time, all analyses devoted to handwriting production were based on, and carried out with respect to, the written trace. The handwriting movement, the process, was thus deduced *a posteriori* from the static trace, the final result. In this context, handwriting was considered as a continuous movement interrupted by 'pauses' or 'breaks' i.e. temporary halts in the flow of the written trace (Olive, 2010; Sumner, Connelly, & Barnett, 2012). These pauses were visible under the form of trace interruptions. Many of these pauses

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are 'normal' in the sense that they are simply imposed by the text to be written. This is the case for the between-word and between-letter spaces, and for the between-stroke spaces within some letters. It is worth noting that, in principle, these pauses correspond to jumps from one point to another, for instance, from the end of a letter to the start of the following letter. Therefore, the term 'pause' deserves to be questioned; the term 'lift' may prove more appropriate.

In the last thirty years, with the development of digitizer-based technology, it has become possible to record and analyze the motion of the pen during handwriting with a good temporal and spatial resolution. The interest in handwriting movement has increased, particularly as regards the temporal and kinematic characteristics of normal and pathologic handwriting performance. Simultaneously, it has become possible to determine precisely how many lifts occurred and how long they lasted. Several studies were devoted to a comparison of these aspects of handwriting for dysgraphic children and proficient children. Most of them observed that dysgraphic children showed a lack of continuity and fluency, longer lift duration or extended lift intervals between strokes (Kosterman, Westzaan, & Van Wieringen, 1994; Rosenblum, Parush, & Weiss, 2003b; Rosenblum, Weiss, & Parush, 2001; Rosenblum, Weiss, & Parush, 2003a; Schoemaker, Shellekens, Kalverboer, & Kooistra, 1994; Schoemaker & Smits-Engelsman, 1997; Smits-Engelsman, Van Galen, & Portier, 1994; Sovik, Arntzen, & Thygesen, 1987; Wann & Jones, 1986). It should be remembered that, with the first digitizers, the pen coordinates were not available when the pen was not in contact with a surface and thus, it remained impossible to follow the pen displacement during the lifts; lifts were still, therefore, defined as 'pauses' or temporary halts while writing. It is for this reason, also that many studies of handwriting have used sequences of cursive letters not involving pen lifts. Nevertheless, changes in the lift number and duration have been considered as reflecting either low-level (motor) or high-level (cognitive) writing processes. Low-level process lifts were related to the dynamics of handwriting motor execution and, as such, could serve to give the child the opportunity to program sequences of movements for character or word formation, and to select the optimal size, speed, and angle, as well as to adjust wrist and finger positions (Meulenbroek & Van Galen, 1984). Raising the pen could also be justified by the need to visually control the written trace. High-level lifts are those generated by the cognitive processes of writing, such as language formulation, which involves working memory (Kellogg, 1996; McCutchen, 1996, 2000; Peverly 2003). By and large, during a copying and/or reproduction task (Peverly, 2003), or during text composition, in which conceptual and linguistic processes are involved (Olive & Piolat, 2002), lifts shorter than 250 milliseconds were assumed to reflect transcription, whereas longer lifts were assumed to reflect planning, translating or reviewing (Peverly, 2003).

Today, with the arrival of new graphic tablets, it is possible to record the (x,y) pen coordinates even when it is not in contact with the tablet (up to one and half centimeters above its surface). Thanks to this, it has been confirmed that the pen was far from 'pausing' during the lifts and that the 'in air' movements formed a considerable part of the handwriting movements, the rate and duration of which is significantly greater for dysgraphic children, for instance (Rosenblum et al., 2001; Rosenblum et al., 2003a,b).

The use of a pen tablet also allows us to identify possible real pauses of the pen occurring during the writing trace, when the pen is in contact with the paper. In other words, during such pauses the writer does not lift the pen but, yet, stops it. Therefore, for the sake of clarity, we will simply refer to these pauses as 'stops'. A stop is a time period during which the pen is immobile. Contrary to lifts, which are unequivocally characterized by the fact that the pen is no longer in contact with the paper, there are several ways of defining a stop. In theory, two successive points presenting the same pen coordinates can delimit a stop. According to this definition, the minimal detectable stop depends on the sampling rate of the graphic tablet: the greater the sampling rate, the shorter the minimal detectable stop duration and, thus, the greater the number of potentially observable stops. For example, for a 100 Hz sampling rate, the shortest potentially detectable stop is 20 ms, which falls to 10 ms for a 200 Hz sampling rate (see Methods). Of course, occurrences of 10 ms stops are more probable than 20 ms stops. In addition, the spatial resolution of the pen tablet is also crucial for delimiting the stops. The shorter the distance between two adjacent points, the harder it is to attain exactly the same coordinates and, as a result, the lower the possibility of detecting a stop. Practically, with a spatial resolution of 2080 dpi, a displacement of 0.005 mm is observable. Therefore, although temporal and spatial resolutions act in opposite ways, it has become easier to detect stops in handwriting. Another way of defining stops is to consider them as corresponding to moments when the instantaneous velocity is zero or close to zero (Reinders-Messelink et al., 2001). However, since the position data given by the tablet is, in most cases, filtered before analysis, velocity is rarely null. Moreover, the use of various filtering methods can induce different thresholds for quantifying accurately a movement onset, and serious problems have been demonstrated when the dynamics of the movements vary across conditions (Teasdale, Bard, Fleury, & Proteau, 1993). Stops are, therefore, those time points when the velocity reaches a value below a given level, for instance below 7.5 mm/s (Wann & Jones, 1986), or below 1/5 of the mean handwriting velocity (Kosterman et al., 1994). In another study (Van Gemmert, Teulings, & Stelmach, 1998), stops were defined as time points when the pen is in contact with the paper and no movement is detected for more than 25 ms; however, the exact method used to define these stops was not described. Regardless of the methods used for their detection, it is not until now that an extensive study of handwriting stops has been carried out. Some results regarding the number of stops and their total within letter and/or word durations are available (Kosterman et al., 1994; Reinders-Messelink et al., 2001; Van Gemmert et al., 1998; Wann & Jones, 1986). However, the question of how long a relevant stop should be still remains unknown.

Stops can be observed because they are imposed by the shape of the letters to be written, in particular when letters contain sharp angles requiring trajectory inversions ('w' or 'g' for example). It is important to remember that handwriting is a complex motor skill involving a sequence of discrete and continuous movements, and ending these movements or changing their direction can give rise to a short period of time during which the velocity is null, or close to zero. These 'normal' stops were not those which were of interest in this study. Obviously, the occurrence of stops also depends on the global speed of the movement: the greater the speed, the fewer the stops. Stops that are either too numerous or too long may be an indicator of dysfluency or poor handwriting. Put another way, could stops allow us to differentiate good and poor handwriters? As a matter of fact, stops in handwriting may be more effective than lifts in revealing low level motor difficulties as lifts may depend more on high level linguistic processes (spelling, syntax, semantics). Stops occurring while the pen stays in contact with the paper may reflect difficulties in the mechanics of writing, such as those described in the case of dysgraphic children (Hamstra-Bletz & Blöte, 1993).

Dysgraphic children show a deficit in motor programming and/or motor execution and are often unable to achieve a completely automated process, thus making their handwriting unclear. Two main parameters have been used to assess and define dysgraphia: legibility and performance time (Wann & Kardirkmanathan, 1991). In general, dysgraphic handwriting is slow, with long and frequent pen lifts, lacking in continuity and fluency, presenting significant variability at spatial, temporal and kinematics levels, and an increase in the use of visual feedback and retroactive control (Berninger et al., 1997; Rosenblum et al., 2003b; Sovik et al., 1987; Wann & Kardirkmanathan, 1991). Thus, the written production of dysgraphic children is characterized by instability and a lack of regularity in the shape of the letters and in the spaces between them, and, also, by a greater number of lifts than for proficient handwriters (Wann & Jones, 1986). Comparisons between the handwriting kinematics of proficient and dysgraphic children have, occasionally, revealed a tendency for the former group to write slower than the latter group (Feder, Majnemer, & Synnes, 2000; Kushki, Schwellnus, Ilyas, & Chau, 2011; Paz-Villagrán et al., 2011). This surprising finding suggests that, if dysgraphic children take more time to write the same text, it is not because of a slower movement, but due to the fact that they have more stops or longer stops than proficient children. Thus, stops could be used as a fluency index. Moreover, Chartrel and Vinter (2008) studied the effect of speed on cursive letter production in proficient 5-to-7 year-old children and they showed that the increase of speed led to a more fluent movement in older children. We assumed that handwriting may be more fluid at fast writing speed and, accordingly, that the number and duration of stops may decrease when writing speed increases. If this is the case, we propose that handwriting stops may constitute a relevant cue for evaluating handwriting fluency and, consequently, for differentiating between proficient and dysgraphic children. Since it is known that movement speed and fluency increase from children to adults, we also assume that the number and duration of stops should decrease in adults with respect to children. Proficient adults' performance may thus be considered as the standard of handwriting fluency. Therefore, we compared proficient adults, proficient children and dysgraphic children in the same writing task. Also, since we wanted to focus on the motor characteristics of handwriting, we chose a simple writing task, without linguistic or spelling difficulties. Subjects had to write a single familiar word several times, without any syntactic and semantic context. This task is easier than those of previous studies involving the writing of a long text. It was simple to carry out, even for dysgraphic children who often suffer from other learning difficulties, in particular dyslexia. Furthermore, we wanted to ascertain if asking the children to write faster than they would normally do lead to less stops and, thus, to more fluent handwriting. This is an important point since, firstly, the link between handwriting speed and the occurrence of stops needs to be clarified, and, secondly, dysgraphic children are known to be slower than age-matched proficient children. We thus examined stop occurrences in two conditions: normal writing speed, in which subjects wrote at their usual speed, and fast writing speed, in which they were asked to write as fast as possible while maintaining the legibility of the written trace.

2. Method

2.1. Participants

Data was obtained from 26 proficient adult handwriters (PA, 15 females and 11 males, 22 to 57 year-old), 39 proficient children (PC, 16 girls and 23 boys, 7 to 9 y-old) and 16 dysgraphic children (DC, 2 girls and 14 boys, 8 to 11 y-old). The PA group was recruited from among the lab staff. All children belonged to two mainstream primary schools located in Marseilles and all were attending grade 3. In these schools children were divided among normal and special classes. The latter classes receive children with reading difficulties. Dysgraphic children belonged to these special classes and all were also diagnosed as dyslexic. The children's handwriting was tested using the Concise Assessment Scale for Children's Handwriting (BHK; Hamstra-Bletz, De Bie, & Den Brinker, 1987; French adaptation: Charles, Soppelsa, & Albaret, 2003). This standardized norm-referenced test was designed to screen handwriting samples and to detect handwriting difficulties.

2.2. Handwriting procedure

We assessed the handwriting procedure by asking the participants to write the same word eight times at normal handwriting speed, and eight times at a fast speed. At fast speed, participants were required to write as fast as possible while maintaining legibility. They were allowed to position the tablet according to their usual handwriting posture. The cursive word 'lapin' (rabbit) was used because it is a very familiar word without any spelling difficulty. Participants wrote with an inking pen on a sheet of paper (A5 format: 21.0 cm $\times$ 14.8 cm) fixed to a digitizer tablet (Wacom, Intuos3 A5, sampling frequency 200 Hz). The word to be written was presented in cursive letters before the handwriting test. To begin with the participants were asked to write it three times without the tablet to ensure that they wrote it correctly in cursive letters and with the correct spelling. Then, the model was removed and they had to write on the experimental paper sheet fixed to the tablet. On the sheet of paper 16 rectangles (5.0 cm $\times$ 1.5 cm) were drawn and the participants had to write each word inside a rectangle.

2.3. Data acquisition and processing

For both data acquisition and processing, we used software developed in the laboratory which allows the discrimination and visualization of both drawn and 'in air' movements (between letters) during handwriting. Because the moment at which subjects put the dot on the letter 'i' varies greatly both within and between writers, we decided to remove this point and the two 'in air' movements preceding and following it.

Five spatiotemporal variables were used as dependent variables:

- Mean writing velocity (written length/written time),
- Number of lifts,
- Mean duration of lifts,

– Number of stops,
– Mean duration of stops.

We defined a ‘stop’ as a period in which the pen is in contact with the paper and does not vary its position for at least 15 milliseconds. We took 15 ms as the smallest possible stop duration because, since the spatial resolution of pen tablets is very high, it is possible to distinguish small variations of the pen position. In other words, micro-variations of the pen position can be measured even when the writer remains immobile. Theoretically, it is possible to have a stop when only two successive coordinates (1 coordinate interval) are identical. However, the risk of having two identical points simply by accident is high. For this reason, we considered that a stop had occurred when at least three successive coordinates (2 coordinate intervals $\times$ 5 ms) remained identical, and we also took into account the uncertainty measure (the exact moment in the interval when the coordinates change, which is half the sampling period: 2 $\times$ 2.5 ms). Note that we only processed the ‘on paper’ stops, those occurring when the pen was tracing the letters and not those possibly occurring during the ‘in air’ displacements. The main reason for this choice was that the vertical coordinate (z) of the ‘in air’ displacement is not available in pen tablets (they only supply the orthogonal projection of the 3rd dimension on the (x,y) surface). Furthermore, ‘in air’ stops are very rare with respect to ‘on paper’ stops.

To preserve correct stop detection we did not filter the tablet data. To remove the signal noise, we postulated that two successive stops separated by less than 30 ms should belong to the same longer stop. For instance, when a 25 ms stop (2.5 + 20 + 2.5) was separated from another stop lasting 15 ms (2.5 + 10 + 2.5) by an interval of 5 ms, we considered that both stops should be summed to form a single 40 ms stop (2.5 + 20 + 5 + 10 + 2.5, see Fig. 1). The 30 ms minimal between-stop interval was determined based on the fact that, in handwriting, the smallest stroke-duration is about 100 ms (Maarse, van Galen, & Thomassen, 1989; Teulings, 1996; Van Galen, 1991). We assumed that, if a between stops movement was 3 times shorter than 100 ms, it constituted too short a duration for an actual movement and should be considered as signal noise. A detailed examination of the data obtained in the four groups validated this assumption.

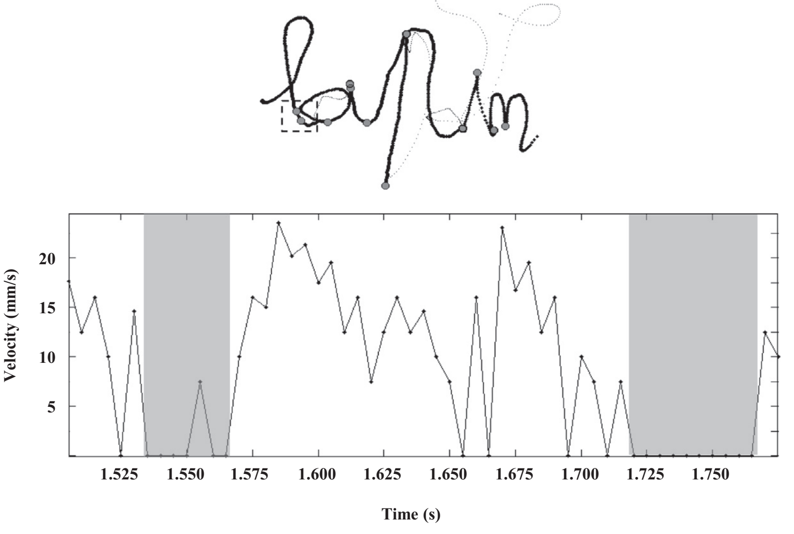

Fig. 1. Example of stop fusion. Upper part, the word ‘lapin’ written by a dysgraphic child who made 12 stops (grey points). The dotted lines correspond to (x,y) coordinates during pen lifts and the dotted window highlights the segment produced in the descendant stroke of the letter, ‘l’, in which two stops were present. Lower part, the raw (unfiltered) velocity corresponding to the segment produced in the dotted square. The two grey areas correspond to the two stops in the dotted window. As explained in the methods section, the first stop (40 ms long) results from the fusion of two stops (25 and 15 ms long) separated by a 5 ms interval. Note that the grey areas take into account the uncertainty of the measure (2.5 ms before and after the stops).

The five variables were averaged across the 8 repetitions of the word for both speed conditions and for each subject. The handwriting variables were submitted to an ANOVA with the condition, speed (Normal and Fast) as repeated measures and the condition, group (PA, PC and DC), as the between subjects factor. When necessary, Fisher's LSD post-hoc tests with Bonferroni's correction were applied. In addition to their statistical analysis, stops were also classified according to their duration and were localized on the written trace.

3. Results

Mean results are summarized in Table 1. Results of post-hoc tests for the groups' comparisons are presented in Table 2.

3.1. Velocity

No difference in the mean writing velocity between the three groups was observed ($F_{(2, 78)} = 1.0$, ns) at normal (PA: 32 mm/s; PC: 26 mm/s; DC: 25 mm/s) and at fast (PA: 39 mm/s; PC: 37 mm/s; DC: 42 mm/s)) writing speeds. As expected, velocity was greater when a speed constraint was imposed ($F_{(1, 78)} = 126.1$, $p < 0.001$), but the group by speed interaction was significant ($F_{(2,78)} = 7.3$, $p < 0.005$). Post-hoc tests revealed no difference between groups, neither at normal nor at fast speeds, and showed that the 3 groups increased their velocity, with DC showing the greatest increase. As a matter of fact, DC group was the slowest in the normal speed condition and became the fastest in fast speed condition (Table 1).

3.2. Lifts

3.2.1. Number of lifts

The group factor had a significant effect on the number of lifts ($F_{(2,78)} = 4.3$, $p < 0.05$). Adults exhibited a similar number of lifts to PC, and fewer lifts than DC ($p < 0.05$). No difference was observed between the two children groups (Fig. 2A; Table 1). In general, fast writing induced a reduction in lift

Table 1
Mean values of handwriting dependent variables studied for proficient adults (PA), proficient children (PC) and dysgraphic children (DC).

	PA (Mean ± SD)		PC (Mean ± SD)		DC (Mean ± SD)	
	Normal	Fast	Normal	Fast	Normal	Fast
'On paper' velocity (mm/s)	32 ± 8	39 ± 11	26 ± 8	37 ± 14	25 ± 9	42 ± 19
Number of lifts	1.7 ± 1.3	1.3 ± 1.2	2.1 ± 1	2.2 ± 1	2.5 ± 1	2.4 ± 1.1
Lifts duration (s)	0.177 ± 0.156	0.098 ± 0.103	0.775 ± 0.468	0.534 ± 0.351	1.095 ± 0.705	0.758 ± 0.626
Number of stops	3.9 ± 1.6	2.5 ± 1.4	7.6 ± 2.3	5.5 ± 1.9	10.7 ± 4.3	6.3 ± 3.2
Stops duration (ms)	23 ± 10	19 ± 8	45 ± 15	36 ± 15	60 ± 23	42 ± 19

SD = standard deviation.

Table 2
Handwriting performance comparison between groups. *P* values of dependent variables at normal and at fast speed of writing.

	PA vs PC P		PA vs DC P		PC vs DC P	
	Normal	Fast	Normal	Fast	Normal	Fast
'On paper' velocity (mm/s)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Number of lifts	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Lifts duration (s)	**0.001**	**0.05**	**0.001**	**0.005**	n.s.	n.s.
Number of stops	**0.001**	**0.005**	**0.001**	**0.005**	**0.01**	n.s.
Stops duration (ms)	**0.001**	**0.01**	**0.001**	**0.005**	0.07	n.s.

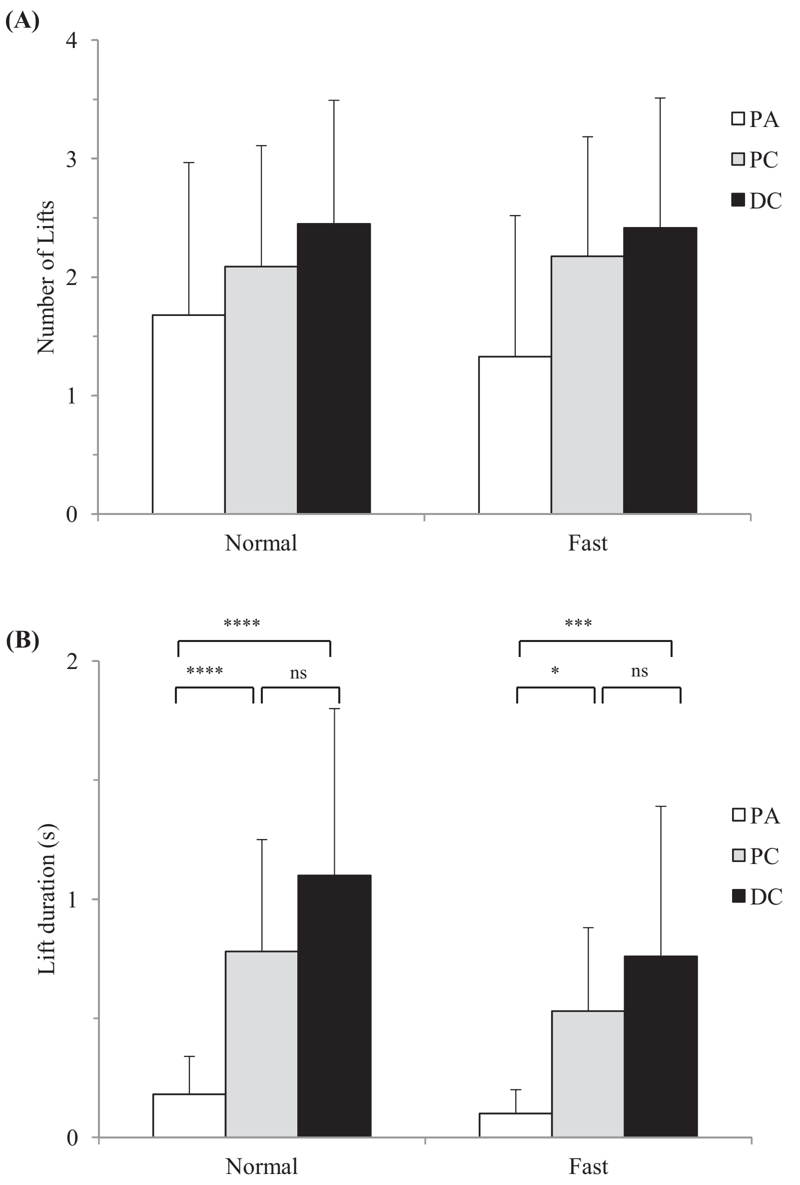

Fig. 2. (A) Number of lifts and (B) lift duration during handwriting performance realized by PA, PC and DC groups at normal and fast speeds. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.005$; $^{****}p < 0.001$.

number ($F_{(1,\ 78)} = 4.7$, $p < 0.05$). The group by speed interaction was significant ($F_{(2,78)} = 10.1$, $p < 0.001$), indicating that the reduction was not the same for all groups: the lift number decrease was significant for the adult group, but not for both groups of children (Fig. 2A). Both at normal and fast speeds, there was no significant difference between the 3 groups (Table 2).

3.2.2. Mean duration of lifts

As can be seen in Table 1 and Fig. 2B, writing at a fast speed induced a decrease in the mean lift duration ($F_{(1,\ 78)} = 40.1$, $p < 0.001$). Moreover, the mean lift duration showed a significant between-groups difference ($F_{(2,\ 78)} = 23.2$, $p < 0.001$). Adults 'in air' time remained five times less than that of the PC group and six times less than that of DC group. Furthermore, this was true at both normal and fast speeds of writing (see Table 2). No difference, however, was observed between the two groups of children (Tables 1 and 2). The group by speed interaction was significant ($F_{(2,\ 78)} = 4.4$, $p < 0.05$). The speed effect was not the same for all three groups (Fig. 2B). Contrary to PC and DC, adults did not decrease the duration of their lifts at fast writing speed.

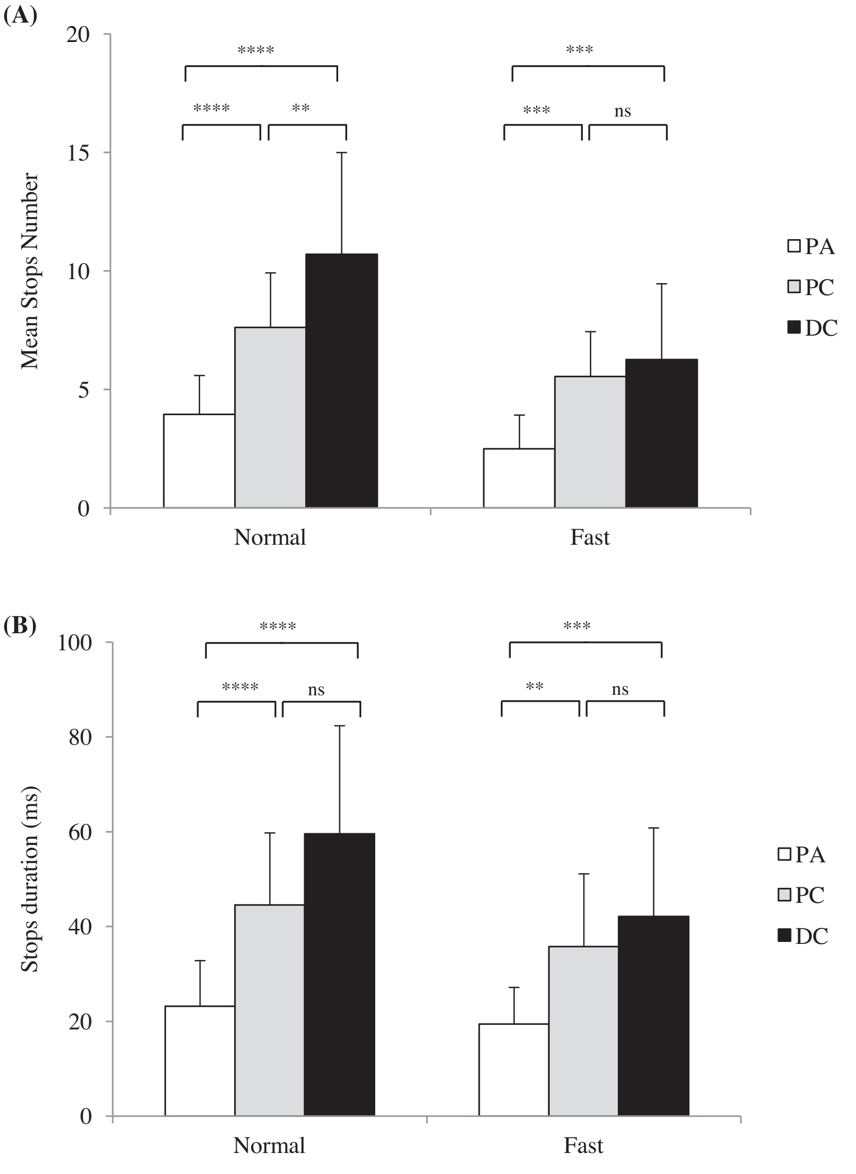

Fig. 3. (A) Number of stops and (B) stop duration for proficient adults (PA), proficient children (PC) and dysgraphic children (DC).at normal and fast writing speeds. $^{**}p < 0.01$; $^{***}p < 0.005$; $^{****}p < 0.001$.

3.3. Stops

3.3.1. Number of stops

Taking into account all groups and speeds, the mean number of stops was 6.1 but, as can be seen in Table 1, this number differed significantly across the three individual groups ($F_{(2, 78)} = 33.1$, $p < 0.001$). Post-hoc tests (Table 2) showed that adults stopped less often than children and that, among the children, the PC group stopped less often than the DC group. The group by speed interaction was significant ($F_{(2, 78)} = 12.2$, $p < 0.001$), in other words, between group differences were not the same at normal and fast speeds. Post-hoc tests (Table 2) showed that, at normal speed, adults stopped less often than both groups of children, and that PC group stopped less often than DC group. At fast speed, while adults still stopped less than both groups of children, no difference was observed between PC and DC (Fig. 3A). Thus, writing at fast speed induced a global decrease in the stop number ($F_{(1, 78)} = 128.10$, $p < 0.001$). In all 3 groups, when the subjects were asked to write faster, their number of stops decreased significantly.

3.3.2. Mean duration of stops

Combining all speeds and groups, the mean time spent with the pen stopped was 37.4 ms, corresponding to 1.2% of the total 'on paper' writing time. However, this time significantly varied across groups ($F_{(2, 78)} = 28.37$, $p < 0.001$). Post-hoc comparisons (Table 2) showed that the stop durations were shorter in adults than in PC and DC children. Among the children groups, the PC group had a smaller stop duration than the DC group (Fig. 3B, Table 1). In general, writing at a fast speed induced a clear decrease in the stop duration ($F_{(1, 78)} = 36.48$, $p < 0.001$), but the group by speed interaction was significant ($F_{(2, 78)} = 4.81$, $p < 0.01$). As a matter of fact, only children decreased their stop duration significantly when asked to write faster. A comparison of the three groups revealed that adults always exhibited shorter stop durations than both groups of children, both at normal and fast speeds (see Table 2). A comparison of the children groups showed that the PC group exhibited a tendency for shorter stop durations than the DC group at normal speed ($p < 0.07$). In contrast, at fast speed, both children groups showed no significant difference (Fig. 3B).

3.3.3. Stops temporal distribution

The stops were ranked according to their duration. The duration of the great majority of stops ranged between 15 and 115 ms for all three groups (PA = 98.9%; PC = 94.3%; DC = 89.3%). In order to analyze more precisely the distribution of stops over the 15–115 ms range, we divided them into 20 ms time intervals, from 15–35 ms, 36–55 ms and so on up to 115 ms (Fig. 4). We then compared the distributions of stops across intervals by mean of a chi square goodness of fit. When necessary, we compared groups within given intervals by means of a Kolmogorov-Smirnov test.

On the whole, stops were mainly concentrated in the first (15–35 ms) interval: 94.6% for the PA group, 68.3% for PC group and 58% for DC group. As can be seen in Fig. 4A, at normal writing speed the stop distribution for PC and DC children was similar and did not differ significantly (χ^2 (4) = 2.92, ns). In all intervals, both groups of children showed no difference in their number of stops and had significantly more stops than adults. At fast speed (Fig. 4B), despite a global decrease in stop number, the same pattern was observed. Both children groups did not differ (χ^2 (4) = 1.55, ns) and presented a higher number of stops than adults in all intervals.

3.3.4. Stop positions within the word

A detailed examination of the stop positions within the word 'lapin' revealed that the majority of stops were localized at the level of inflection points where curvature is maximal and abrupt changes of direction are required. These stops may be considered as 'normal' stops, imposed by the geometrical shapes of the letters. In adults, stops were observed only at these positions, whereas in PC and DC, additional stops were also observed at other places in the written letter (Fig. 5).

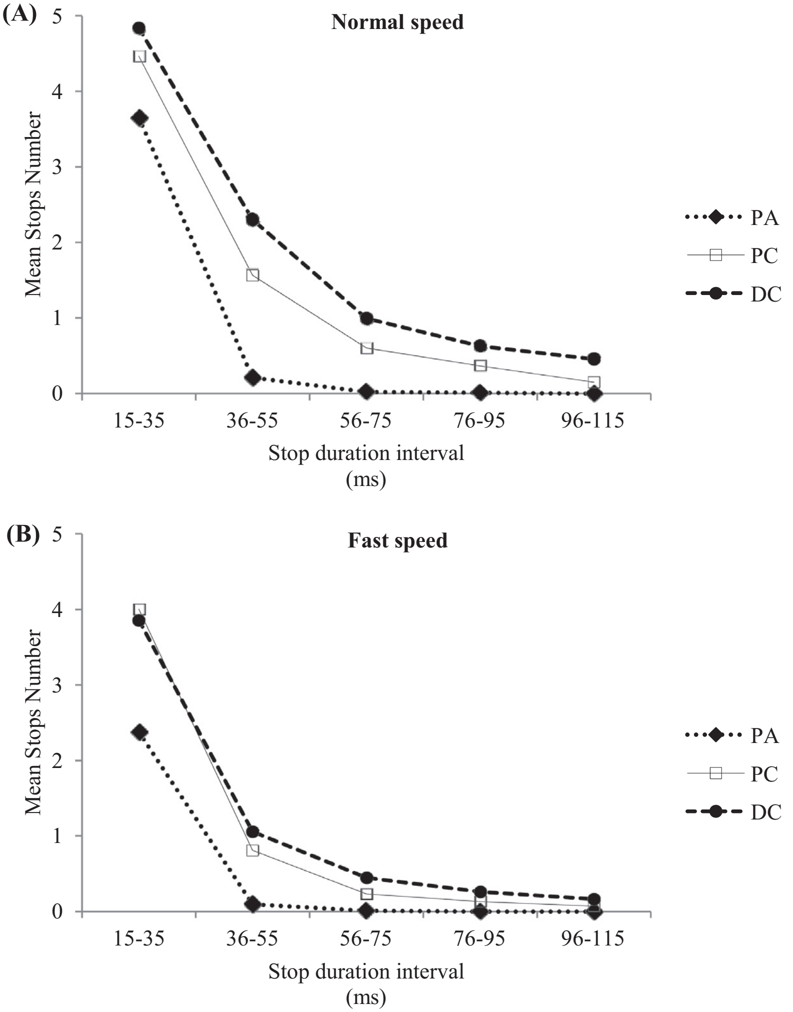

Fig. 4. Stop distribution for PA, PC and DC children at normal (A) and fast (B) writing speeds.

Fig. 5. Visualization of stops (grey points) on the word 'lapin' in PA (left), PC (center) and DC children (right). The dotted lines correspond to the (x,y) coordinates of movements during pen lifts.

4. Discussion

This study is the first to make a clear distinction between real pauses, for which we propose the name 'stops', and lifts in handwriting. Up until now, only lifts have been studied under the ambiguous appellation of 'pauses'. Here we proposed abandoning the term 'pause' and using, instead, the term 'stops', to refer to those time points when the pen is immobile but still in contact with the paper, and the term 'lifts', to refer to moments when the pen is 'in air'. We posited that stops may act as a good indicator of the fluency of the handwriting movement. Assuming that this is true, and given that handwriting fluency is known to be higher in adults than in children, we expected more stops in proficient children than in proficient adults. Furthermore, and for the same reasons, more stops were expected in dysgraphic children than in proficient children. Finally, since fluency is dependent on handwriting speed, we expected stops to be fewer in number and shorter when a faster speed was required.

4.1. Lifts

Even if their usual name 'pauses' is inappropriate, lifts are an important component of handwriting. Studying lifts in the context of the writing of a long text can pose several problems because of the involvement of high-level cognitive processes (Olive & Piolat, 2002; Peverly, 2003). The presentation of the text may be either visual or auditory (in which case, dictated). In the case of a visual presentation, corresponding to the BHK test conditions, some time is spent reading the model text and memorizing the words to be written during the writing time. It is likely that this reading occurs during the between-word lifts, but may also appear elsewhere, within words. In the case of an auditory presentation (dictation), the writer has to cope with spelling problems, which induce slower writing. Some studies suggest that in such cases, cognitive processes of writing are implicated, such as planning, translating and revising, where working memory is involved (Alamargot & Chanquoy, 2001; Kellogg, 1996; McCutchen, 1996, 2000; Peverly 2003). Under such conditions, it becomes hard to know exactly what processes are at play during the lifts and stops and, thus, to interpret the number and duration which might be more reflective of reading difficulties, often associated with writing problems (Sumner et al., 2012). The principle aim of our study, in contrast to many studies devoted to the lifts in dysgraphia in which copying a text was required, was to focus exclusively on low-level graphomotor processes. To avoid undesirable effects not purely related to handwriting difficulties, we decided to use a simple writing task involving neither reading nor linguistic processes: namely the writing of a single word. This word was written in cursive, few lifts were imposed by the letters composing it. It can be seen that adults had less lifts than children, and that only dysgraphic children exhibited a significant difference. In addition, the adults' pen lifts were of shorter duration than those of the children. As a result, adults wrote faster, not necessarily because their graphic movements were faster, but mainly because their pen lifts were fewer in number and shorter in duration than those of children. Finally, adults were able to reduce their lift durations when required to write at a fast speed, a strategy that children were not able to adopt. Both lift number and duration showed no difference in PC and DC groups. This result is inconsistent with previous observations. A study in which children with poor handwriting were required to draw a flower showed that they made fewer and shorter lifts than proficient children (Smits-Engelsman, Niemeijer, & Van Galen, 2001). In another work dedicated to handwriting, Rosenblum and coll. (2003b,c) showed that dysgraphic children spent more time 'in air' than proficient children. However it should be pointed out that the present study and that of Rosenblum are barely comparable for two main reasons: firstly, in Rosenblum's study, a long text was copied and secondly, the text was written in Hebrew, a language requiring more lifts than the Roman writing system. In summary, the absence of a significant difference between the two groups of children suggests that lifts would not act as a relevant cue for identifying dysgraphia.

4.2. Stops

Unlike lifts, detecting the occurrence of stops is not simple: it depends on several aspects of the handwriting data, in particular the spatial and temporal precision of the writing acquisition. The performances of current tablets make it possible to detect very short stops. We chose to work on the initial (x,y) position and not on the derivative velocity signal, thus avoiding filtering the data, a procedure that can pose some problems when accurate movement onset is required (Teasdale et al., 1993). We then considered that 15 ms, i.e. three identical pairs of (x,y) coordinates for a 200 Hz sampling rate, was a relevant minimal duration for a stop (see Methods). On the basis of this calculation, the stop number was clearly related to the writers' expertise: adults made less stops than proficient children who, themselves, made less stops than dysgraphic children. The same pattern of results was obtained for the stop duration: stops generally lasted between 15 ms and 115 ms and were clearly shorter in adults than in all children and in PC than in DC, particularly at normal speed. The cumulated stops duration obtained in the present study for the five letter word (from 100 ms in PA to 600 ms in DC) were in the same range as those reported in another study where a five letter word was also used ('level', from 200 ms in PA to 600 ms in patients suffering from Parkinson disease (Van Gemmert et al., 1998).

It is worth noting that, in spite of a similar writing speed, the children with dysgraphia still exhibited more and longer stops. This is important from a methodological point of view because it denotes that stops were not mechanically connected to writing speed and, thus should not be suspected as constituting processing artifacts (Teasdale et al., 1993). Furthermore, from the stops distribution observed in adult proficient writers, who showed only very small number of stops longer than 35 ms (5%), we assumed that stops shorter or equal to 35 ms correspond to the normal stops of handwriting. This assumption was supported by the localization of stop positions. In adults, they were mainly located at the ends of the vertical strokes composing the cursive letters (p, n; see Fig. 5) where there are abrupt changes of direction. These 'normal' stops are thus imposed by the geometrical constraints of the letters. In proficient children, they were more frequent because children did not always join the letters to each other in a single movement, the 'a' and 'p' in 'lapin', for instance. Young children have not yet automatized their handwriting movements (Amundson & Weil, 1996; Berninger et al., 1997; Meulenbroek & Van Galen, 1984; Oliver, 1990) and the presence of stops might, therefore, reveal that they cannot simultaneously control the execution of the current stroke and program the next stroke required to complete the letter. This lack of automatization was evidenced in a work by Van Mier (2006). In two drawing tasks, a discrete one (zigzag) and a continuous one (slalom), she studied stop times as a function of child age (the children were aged between 4 and 12 y-old). She observed that the discrete drawing task was performed in a discrete way, while the slalom task was performed in a continuous way, except for the youngest children, who performed both tasks in a discrete manner. In the present experiment, it is likely that proficient children tended to stop more often than adults because they had a tendency to write in a discrete way.

This phenomenon was still more marked in dysgraphic children who often had longer 'normal' stops and, moreover, stopped within strokes. These last supplementary and 'abnormal' stops are particularly interesting because they may result from a dysfluency problem related to neuromotor noise in children with dysgraphia (Van Galen, Portier, Smits-Engelsman, & Schomaker, 1993). In addition, these abnormal stops generally have a longer duration than the normal ones. Therefore, increasing the number of points taken into account to have a stop, in other words increasing the minimal stop duration up to 35 ms, would allow us to discard the normal stops and to conserve only the abnormal ones, those generated by the writers' lack of fluency. This would emphasize the difference between proficient and dysgraphic writers.

Practically speaking, considering only longer abnormal stops would minimize the importance of the graphic tablet temporal definition. As a matter of fact, a lower sampling rate acquisition (100 Hz) would be sufficient for accurately detecting stops of 35 ms duration. Another advantage is that these abnormal stops should be theoretically independent of the written words and even of languages, making a comparison between various studies possible.

4.3. Handwriting speed

It appeared that, at both normal and fast speeds, the 3 groups did not write at different velocities. However, it is worth noting that here, writing velocity refers to the real speed of writing, when the pen is actually in contact with the paper and tracing the letters. Writing velocity is thus quite distinct from 'written production' as assessed in the BHK by counting the number of letters written within a given time interval. Dysgraphics generally demonstrate less written production (this is one of their characteristics) but not, systematically, a slower writing movement (Feder et al., 2000; Kushki et al., 2011; Paz-Villagrán et al., 2011). In other words, when writing a text, dysgraphics produce less letters either because they waste time during the pen lifts between letters and words (Rosenblum, Parush, & Weiss, 2003c; Rosenblum et al., 2003b), because they write bigger (Hamstra-Bletz & Blöte, 1993) or because they are less fluent (Van Galen et al., 1993), but not because they write slower *per se*. On the contrary, in the present study, dysgraphic children exhibited the greatest increase in velocity when asked to write at a fast speed. It may be that writing a single word was too short to allow us to observe a difference in velocity between dysgraphic and proficient children.

At fast speed, the number of stops decreased in the three groups and, interestingly, that of dysgraphic and proficient children became similar. Furthermore, stop duration also decreased at fast speed in children and they reached the same duration in proficient and dysgraphic children. Therefore, increasing the speed could be a good way to improve handwriting fluency, as has been shown previously in proficient children (Chartrel and Vinter, 2008).It is, however, be important, to check that the velocity increase did not induce a decrease in legibility; and a visual inspection of their written production did not indicate that it was the case.

In conclusion, stop number and duration appear to be good indicators of graphomotor expertise: stops are more numerous and of longer duration in dysgraphic children. More precisely, abnormal stops (longer than 35 ms) may constitute an index of dysfluency, as has been proposed for velocity or acceleration maxima, and may be a distinguishing characteristic of children with dysgraphia. Moreover, that the number and duration of stops decrease when dysgraphic children write faster, suggests that they are more fluent at faster speed. If this observation is confirmed in further, more complex writing conditions (words, sentences…), one could envisaged asking dysgraphic subjects to write faster in order to make their graphic movements more fluent, provided their legibility is not reduced at faster speed.

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