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Signal-to-Noise velocity peaks difference: A new method for evaluating the handwriting movement fluency in children with dysgraphia☆

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ABSTRACT

This study evaluated handwriting movement dysfluency related to dysgraphia. A new variable, the Signal-to-Noise velocity peaks difference (SNvpd), was proposed to describe abnormal velocity fluctuations in cursive handwriting. This variable was compared to two variables most frequently used variables for assessing handwriting fluency. This comparison was carried out for three different groups, children with dysgraphia, proficient children, and adults, all of whom wrote the same single word. The adults were taken as the reference. Results revealed that, of the three variables studied, the SNvpd proved most efficient in discriminating children with dysgraphia, and that furthermore, it had the significant advantage of facilitating the localization of dysfluency peaks within a word. Our results also showed that the movement dysfluency of children with dysgraphia was specific to certain letters. In light of these results, we discuss the methodological and theoretical relevance of this new variable to the analysis of handwriting movement with the aim of characterizing dysgraphia.

Nearly a third of school-aged children fail to develop the efficient handwriting performance required to cope at school (Rosenblum, Weiss & Parush, 2003; Smits-Engelsman, Niemeijer, & van Galen, 2001). It is among this population that one finds children with dysgraphia. Here we adopt the traditional definition of dysgraphia, which describes it as a disturbance or difficulty in the production of written language that is related to the mechanics of writing and the result of a failure to acquire the fine motor task of handwriting (Hamstra-Bletz & Blöte, 1993; Smits-Engelsman & van Galen, 1997).

In most European countries, the diagnosis of dysgraphia is usually based on the Concise Evaluation Scale for Children's Handwriting (Brave Handwriting Kinder – BHK, Hamstra-Bletz, de Bie, & den Brinker, 1987). In this test two criteria of cursive handwriting are analyzed: the quality of the written trace and the speed of production. The quality of the produced trace refers to the legibility of letters and words, i.e., their conformity with the norm. The speed of production denotes the writer's ability to write without loss of time and to do so with ease. When the handwriting movement and trace of children with dysgraphia are scrutinized, it can be observed that, while most of them produce illegible handwriting, some succeed in

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writing fairly correctly but with movements that lack fluency and efficiency. Such children are not easy to diagnose given that the most common complaint made about children with dysgraphic handwriting regards the quality of their script (Smits-Engelsman & van Galen, 1997).

More recent clinical tests, such as the Evaluation Tool of Children's Handwriting (ETCH-C, Amundson, 1995) or the Hebrew Handwriting Evaluation (HHE, Erez & Parush, 1999), take into account another criterion based on the observation of the handwriting production. For example, in the ETCH-C, bio-mechanical aspects of handwriting are determined by observing pencil grasp, pencil pressure, and in-hand manipulation. In the HHE, ergonomic factors are determined by analyzing pencil position, paper position, body posture, body stabilization, and fatigue. However, determining most of these criteria involves subjective visual evaluation. Objective and reliable measures of the real efficiency of handwriting movements are, strictly speaking, still lacking.

Thanks to the development of new tools (e.g. graphic or digitalized tablets) and appropriate software, several 'hidden' variables of the handwriting process have now been made available, permitting a more complete characterization of handwriting performance. Studying the temporal, kinematic, and dynamic aspects of handwriting movements allows us to better characterize the handwriting difficulties of children with dysgraphia (Rosenblum et al., 2003). But, given all these variables, how can we know which one will offer the best characterization of dysgraphia? In the following two tables we report the variables used in 42 studies analyzing a range of very different movement disorders, 12 of which focused on dysgraphia. The aim of these two tables is to determine those variables most frequently investigated in studies aiming to characterize graphic movement disorders, and, on that basis, to establish the distinguishing feature of dysgraphia.

The variables are organized into three categories corresponding to the temporal, kinematic, and dynamical content of the handwriting movement. Temporal variables inform us about the duration of performance. Kinematic variables correspond, here, to variations in the first derivative (the velocity), or the second derivative (the acceleration) of the pen position as a function of time. Finally, the dynamic variables result from an analysis of the forces generating the handwriting movements. Because we focus on the handwriting movement, spatial variables are not reported. Concerning kinematic variables, we distinguish two categories of handwriting movement analysis: a first that informs us about speed, and a second that informs us about fluency (smoothness). In each category, the variables are arranged with respect to their occurrence in all studies (right column). In certain cases, several variables were analyzed in the same study with the result that the sum of all cited variables exceeds the number of reported studies. For the sake of clarity, the reported studies are referenced in Table 2.

As can be seen in Table 1, the temporal variables concern, mainly, the Movement Time (MT) at two time scales, global (total MT) or local (stroke duration), and the ratio between the 'In Air' time and the 'On paper' time. Regarding kinematics and making a distinction between speed and fluency variables, it can be observed that speed is usually evaluated using the mean or the maximum velocity, and that fluency is determined by analyzing the supernumerary fluctuations in the velocity profile. The supernumerary velocity fluctuations correspond to additional accelerations and/or decelerations of the pen that are caused by a lack of control. These fluctuations are generally quantified by summing the number of velocity peaks or the number of inversions of the velocity (the former being twice the latter). In some studies, while the underlying aim remained the same, the supplementary abnormal fluctuations of the first or the second derivatives of velocity (the acceleration or the jerk) were also considered. Finally, concerning the dynamic variables, the mean pen pressure was analyzed most frequently. Significant pressure differences were only apparent in patients suffering from Writer's Cramp (e.g. Baur et al., 2006), they did not arise in children with dysgraphia (Khalid, Yunus, & Adnan, 2010; Kushki, Schwellnus, Ilyias, & Chau, 2011). Two limits of the pressure quantification should be pointed out: Firstly, pressure depends heavily on the tilt of the stylus with respect to the writing surface. Secondly, with standard graphic tablets (Wacom Intuos, for example), the reported pressure depends on the stylus used (the same stylus model does not always yield the same pressure values). Each stylus should, thus, be calibrated to establish the exact correspondence between the real pressure (i.e., in g/cm^2) and the values supplied by the stylus/tablet. For both of these reasons, between-study comparisons of pressure should be made with caution.

On the basis of all these studies, it appears that the most noticeable difference between children with and without dysgraphia is the very long total movement time involved in producing sentences in the former group. This longer movement time cannot be systematically explained by a lower speed of production only (Feder, Majnemer & Synnes, 2000; Kushki et al., 2011; Paz-Villagrán, Danna, & Velay, submitted for publication); four other factors may also be involved: a tendency to write larger (Hamstra-Bletz & Blöte, 1993), a very long 'in-air' movement time (Rosenblum, Parush, and Weiss (2003b)), more movement stops on the paper (Paz-Villagrán et al., submitted for publication), and a dysfluency of handwriting movements (van Galen, Portier, Smits-Engelsman, & Shomaker, 1993). Note that, concerning this last point, differences in fluency between the two groups of children were not systematically observed (Rosenblum, Dvorkin, & Weiss, 2006).

The main drawback of all the variables used to evaluate handwriting movement fluency (for example the number of inversion of velocity – NIV, or the averaged normalized jerk – ANJ) is that they fail to differentiate clearly between normal speed fluctuations, resulting from changes in curvature of the trajectory (Lacquaniti, Terzuolo, & Viviani, 1983; Viviani & Terzuolo, 1982), and 'abnormal' speed fluctuations, which stem from 'neuromotor noise' and which give rise to irregularities in movement control (van Galen, Portier, Smits-Engelsman, & Shomaker, 1993). In order to differentiate abnormal and normal fluctuations in a velocity profile, Meulenbroek and van Galen (1986) suggested evaluating the "Signal-to-Noise

Table 1
Report of the temporal, kinematic, and dynamic variables analyzed in 42 studies examining different pathological cases of handwriting movement.

Variables	Studies	Total
Temporal		
Total Movement Time	[4], [8], [9], [10], [11], [12], [15], [16], [18], [20], [22], [26], [27], [28], [29], [31], [42]	17
Mean In Air Movement Time (Mean pen-up time)	[5], [7], [8], [9], [10], [20], [22], [25], [26], [31], [36]	11
Stroke duration	[1], [12], [17], [19], [20], [23], [35], [39], [40]	9
Mean On Paper Movement Time	[7], [8], [9], [10], [20], [22], [25], [31], [36]	9
In Air/On Paper Time Ratio	[9], [21], [22]	3
Stop duration	[5], [41]	2
Accumulated Stop Time	[18]	1
Variability of 'On Paper' Movement Time	[7]	1
Kinematic		
Speed		
Mean velocity	[2], [3], [5], [7], [8], [12], [13], [20], [21], [22], [24], [26], [31], [36]	14
Mean peak velocity (or maximum velocity)	[7], [14], [15], [16], [23], [30], [32], [34], [35], [37], [38], [39], [42]	13
Mean peak acceleration (or maximum acceleration)	[13], [17], [32], [35], [42]	5
Maximum negative acceleration	[16], [32], [42]	3
Frequency	[22], [29], [38]	3
Variability of velocity	[7], [21]	2
Minimum velocity	[16], [42]	2
Mean acceleration	[13], [17]	2
Asymetry phase duration in acceleration profile	[40]	1
Variability of peak velocity	[7]	1
Fluency		
Number of Inversion (or Change) of Velocity (NIV or NCV) or zero cross in acceleration	[7], [11], [16], [20], [22], [23], [24], [28], [30], [32], [33], [37], [38], [40], [42]	15
Averaged Normalized Jerk (ANJ)	[13], [14], [18], [34], [35]	5
Number of peaks velocity	[2], [4], [26]	3
Number of Inversion of Acceleration (NIA)	[16], [32], [42]	3
Power Spectral Density or Score (Noise in velocity profile)	[11], [12]	2
Variability of NIV (or NCV)	[7], [36]	2
Percent of strokes with NIV = 1	[22]	1
Fluctuation of velocity profile (specific equation)	[6]	1
Ratio of Peak-over-Mean Velocity	[27]	1
Dynamic		
Mean pen pressure ([18] Specific measure)	[2], [3], [20], [21], [22], [24], [25], [26], [27], [28], [29], [31], [36], [40], [41]	15
Number of pen touches (or lifts)	[5], [22], [26]	3
Grip force on the pen	[1], [3], [29]	3
Variability of pen pressure	[3], [40]	2
Variability of grip force on the pen	[3]	1
Maximum Grip force	[20]	1
Grip height	[20]	1

Note: The left column reports the variables used in the studies referred to in the right column. In the list of references that follows, we refer to the studies with respect to their number.

Amplitude ratio'' (SNA ratio). The SNA ratio corresponds to the ratio between the amplitude frequency spectra of two frequency bands, the first (between 0 and 5 Hz) characterizing controlled movement, and the second (between 5 and 10 Hz) reflecting non-controlled fluctuations in the motor system (see also Teulings & Maarse, 1984). On the basis of this distinction, and for evaluating abnormal fluctuations only, we propose calculating the Signal-to-Noise velocity peaks difference (SNvpd). The SNvpd is built from two existing variables: the SNA ratio and the number of velocity peaks. It is computed by subtracting the number of velocity peaks when the velocity is filtered with a cutoff frequency of 5 Hz, from the number of velocity peaks when the velocity is filtered with a cutoff frequency of 10 Hz (see Fig. 1 in methods for an example). By suppressing the velocity peaks caused by normal macro-fluctuations arising from variations in the curvature (those observed at 5 Hz), the SNvpd can inform us about the movement fluency corresponding to abnormal micro-fluctuations of velocity, irrespective of the pen trajectory.

We posited that this new variable would be more precise and more suitable than previous ones for characterizing a lack of movement fluency. To verify this assumption, we had to compare the SNvpd with the NIV and ANJ of writers with different fluency levels. To this end, we evaluated the movement fluency of the cursive handwriting of three groups of writers: a group of children with dysgraphia, a group of proficient children and a group of proficient adults. Finally, given that another advantage of the SNvpd is that it allows us to localize when and where, within the letters, dysfluency occurs,

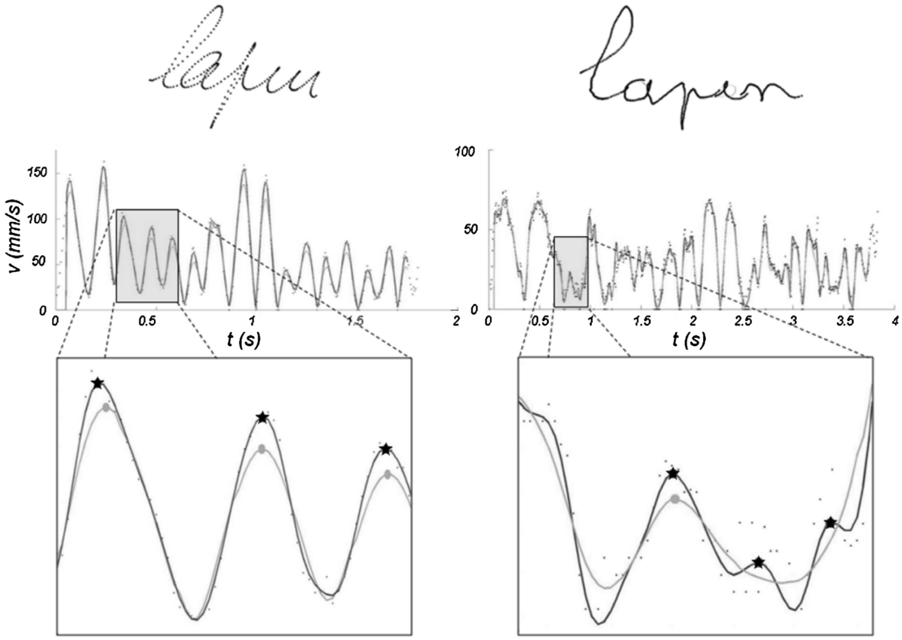

Fig. 1. Example of the French word 'lapin' written by a proficient adult (left) and a child with dysgraphia (right). Upper part: the two written traces (gray points correspond to pen lifts). Middle part: absolute velocity (black points), velocity filtered with cutoff frequency (f_c) of 10 Hz (black curve), and velocity filtered with f_c of 5 Hz (gray curve). Lower part: magnified portion of the framed, gray area of the tangential velocity. The black stars and the gray bold points correspond to the velocity peaks after filtering with the two values of f_c, (10 Hz and 5 Hz, respectively).

in a second analysis, the distribution of the supernumerary velocity peaks, computed using the SNvpd, was analyzed letter-by-letter.

1. Methods

1.1. Participants

Three groups of writers were compared: children with dysgraphia (DC, $N = 16$, 1 girl, mean age 10 years 3 months), proficient children (PC, $N = 16$, 6 girls, mean age 8 years 4 months), and proficient adults (PA, $N = 16$, 8 women, mean age 31 years). All children were attending grade 3 at two separate French primary schools. The task used was very simple: it involved writing a single word presenting no spelling difficulty. Nevertheless, children who had difficulties with spelling the word were excluded. All children were native French, all had normal or corrected-to-normal vision and none presented any known neurological or attentional deficits, as determined by a detailed questionnaire completed by parents prior to the experiment. As the questionnaire included a question on the parents' profession, it also allowed us to confirm that all children had a similar socioeconomic status (the French middle to low class). Their handwriting was assessed using the BHK test (Hamstra-Bletz et al., 1987; French adaptation: Charles, Soppelsa, & Albaret, 2003) and the global score obtained in this test constituted the criterion for inclusion in the DC group.

This study was conducted in accordance with local norms and guidelines for the protection of human subjects. Data were collected directly by the co-authors (both researchers at the National Center of Scientific Research) within the two schools. This research project was approved by the school inspector, the school director, and the teachers. Furthermore, parents signed an informed consent sheet prior to the experiment.

1.2. Task and procedure

Participants were required to write the same word eight times at a spontaneous handwriting speed. 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 that can be easily written without a visual model. Participants wrote the word on a sheet of paper (A5 format: 21.0 cm × 14.8 cm) affixed to a graphic tablet (Wacom, Intuos3 A4, sampling frequency 200 Hz) using an inkling pen. Eight rectangles (5.0 cm × 1.5 cm) were drawn on the sheet of paper, inside of which the children had to write each word. The word was presented in cursive letters before the handwriting test. The participants were asked to practice writing the word three times without the tablet to ensure that they wrote it correctly in cursive letters. In all, 384 trials were analyzed (8 trials × 16 writers × 3 groups).

1.3. Data analysis

Data was analyzed with Matlab®. Only data corresponding to moments when the stylus was in contact with the paper were used to compute the variables. From the (x, y) coordinates, three variables, corresponding to three different ways of measuring handwriting fluency, were calculated: the Signal-to-Noise velocity peaks difference (SNvpd), the Number of Inversions of Velocity (NIV), and the Averaged Normalized Jerk (ANJ).

SNvpd. In order to compute the SN velocity peaks difference, the coordinates were filtered with a 4th order low-pass Butterworth filter. Two filtering methods were applied: one with a cutoff frequency (f_c) of 10 Hz, and one with a f_c of 5 Hz. Then, the difference between the number of peaks after filtering with a f_c of 10 Hz and the number of peaks after filtering with a f_c of 5 Hz was computed (see Fig. 1).

As can be seen in the magnified portion of the velocity curve on the left-hand side of Fig. 1 (proficient adult), both the number and location of velocity peaks (represented by black stars and gray points) remains the same regardless of the value of f_c. In particular, that the number of velocity peaks is the same for both values of f_c confirms the absence of abnormal fluctuations in this segment. In the magnified portion of the velocity curve on the right-hand side of Fig. 1 (child with dysgraphia), three velocity peaks emerge after filtering the velocity with a f_c of 10 Hz (black curve) and only one when it is filtered with a f_c of 5 Hz (gray curve). This difference in peak number reveals the presence of abnormal velocity fluctuations in this segment.

NIV. The number of inversions of velocity was computed by adding the maximal and minimal velocity peaks. Because all reported studies used different values of f_c (between 7 Hz and 15 Hz), we decided to filter the velocity using a 4th order low-pass Butterworth filter with a f_c of 10 Hz (Philips, Ogeil, & Müller, 2009). This filter was the same as that used in the SNvpd calculation.

ANJ. The average normalized jerk was determined using the same method as that employed by Van Gemmert, Teulings, and Stelmach (1998). Data was low-pass filtered (f_c of 7 Hz) then, after establishing the different stokes comprising the word, the Normalized Jerk (NJ) was calculated and averaged. These strokes were determined from the correspondence of the local minima of the absolute velocity. For each written stroke, the NJ was calculated by the following equation:

$$\mathrm{NJ} = \sqrt{\frac{1}{2}\int \mathrm{dt}\, jerk^2(t) \times \frac{\text{stroke duration}^5}{\text{stroke length}^2}}$$

where jerk corresponds to the third derivate of position as a function of time, t. NJ is unit free, therefore variations of writing length or duration do not affect this measure. ANJ is the across-stroke average of NJ.

1.4. Statistical analysis

Three different statistical analyses were carried out on the data. Firstly, the three variables (SNvpd, NIV, and ANJ) were averaged across all eight trials for each writer and submitted to a repeated measures ANOVA with AD, PC, and DC as group factors.

In a second analysis, the three variables were compared in order to ascertain which variable was the most efficient for evaluating handwriting movement fluency. However, as their values were very different, a direct comparison of them was not possible. To render them comparable, we carried out a data transformation using, as a baseline, the group of adults who mastered handwriting and wrote fluently. More precisely, we computed a dimensionless ‘fluency ratio’ for each variable by dividing the children’s scores by the mean adult score. This procedure made it possible to carry out a direct comparison of the three fluency ratios in an ANOVA with both children groups (PC and DC) as group factor and the three fluency variables as repeated measures.

Finally in the third analysis, we computed the distribution of supernumerary velocity peaks across the five letters composing the word. To segment the cursive word into five letters, we used either the pen lifts, when the writer lifted the pen between letters, or the minimal absolute velocity between two written strokes, when the writer did not lift the pen. This distribution was submitted to an ANOVA with AD, PC, and DC as group factors and the letters as repeated measures. All significance thresholds were set to $p < 0.05$. For all ANOVAs, Bonferroni’s post hoc tests were used when necessary.

2. Results

2.1. Analysis of the three fluency variables

The results of calculating the mean fluency of each variable are presented in Fig. 2. The ANOVA revealed a main effect of group for the SNvpd, the NIV, and the ANJ ($F(2,45) = 19.93$, $p < 0.001$, $\eta^2 = 0.47$; $F(2,45) = 18.74$, $p < 0.001$, $\eta^2 = 0.45$, and $F(2,45) = 14.71$, $p < 0.001$, $\eta^2 = 0.39$ respectively). Post hoc tests revealed that DC had a lower score than the two other groups for the three variables ($p < 0.001$).

2.2. Comparison between the three fluency variables

The results of the comparison of fluency ratio are presented in Fig. 3. Because the performances of the adult group were set as the reference when computing the fluency ratio for the three variables, this comparison only concerned the two groups

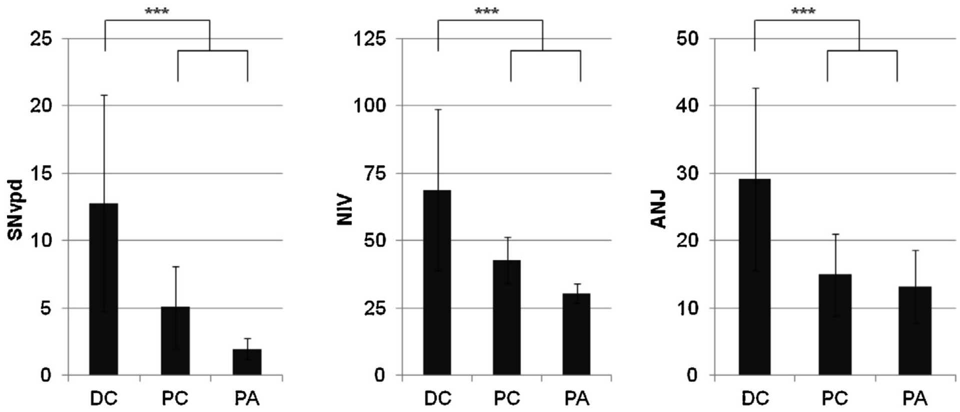

Fig. 2. Mean fluency obtained with the three variables (SNvpd, NIV, and ANJ) for the three groups (DC, children with dysgraphia; PC, proficient children; PA, proficient adults). Error bars correspond to inter-individual variability. Scales were chosen to render DC scores similar.

of children. The repeated measures ANOVA revealed a main Group effect ($F(1,30) = 13.36$, $p < 0.001$, $\eta^2 = 0.31$), a main effect of Variable ($F(2,60) = 42.75$, $p < 0.001$, $\eta^2 = 0.59$), and a Variable by Group interaction ($F(2,60) = 11.95$, $p < 0.001$, $\eta^2 = 0.28$). Post hoc tests of the interaction showed a significant difference between the DC group and the PC group for the SNvpd ($p < 0.01$), but not for the NIV or for the ANJ.

2.3. Localization of movement dysfluency

An example of the word written by one participant from each group is illustrated in Fig. 4A. The repeated measures ANOVA revealed a main Group effect ($F(1,45) = 20.04$, $p < 0.001$, $\eta^2 = 0.47$), a main effect of Letter ($F(4,180) = 7.85$, $p < 0.001$, $\eta^2 = 0.15$), and a Letter by Group interaction ($F(8,180) = 7.58$, $p < 0.001$, $\eta^2 = 0.25$). A post hoc test of the Group effect showed that supernumerary velocity peaks were more numerous in the DC group than in the other two groups ($p < 0.001$). As can be seen in Fig. 4B, this increase in the number of peaks concerned all the letters of the word, but the post hoc test of the interaction revealed that a difference in dysfluency between letters was present in the DC group only. More precisely, for the DC group the written letters, *l* and *p*, showed more supernumerary velocity peaks than the three other letters ($p < 0.01$).

3. Discussion

Nowadays, it is accepted that the addition of objective criteria, thanks to the use of graphic tablets, improves the characterization of handwriting difficulties. While some studies have highlighted the advantage of computerized analysis for evaluating the spatial characteristics of handwriting (e.g. Falk, Tam, Schellnus, & Chau, 2011), the present study examined the handwriting movement, based on the assumption that the quality of the written trace also depends on the fluency of the movement which generates it. To investigate this premise, we developed a new variable, the Signal-to-Noise velocity peaks difference (SNvpd), which we used to evaluate handwriting movement dysfluency in cursive handwriting. We hypothesized that this variable could prove more efficient for assessing handwriting fluency than those classically used. We compared the

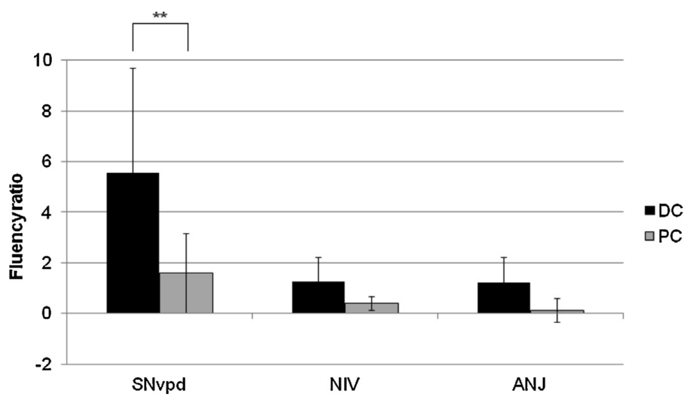

Fig. 3. Comparison of the fluency ratio computed from the three variables (SNvpd, NIV, and ANJ) in the two groups of children (DC, children with dysgraphia; PC, proficient children). Error bars correspond to the inter-individual variability.

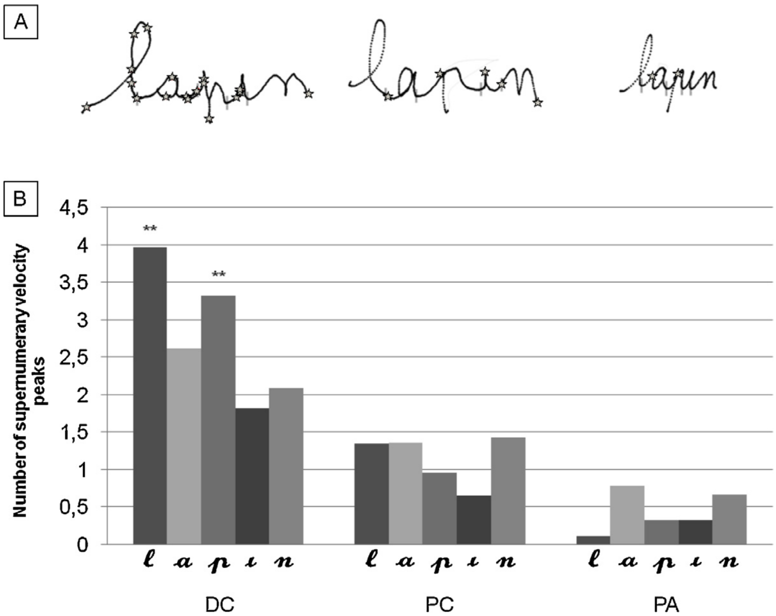

Fig. 4. In (A), an example of the localization of supernumerary velocity peaks in the word 'lapin' (rabbit) written by a child with dysgraphia (left), a proficient child (middle), and a proficient adult (right). The gray stars correspond to supernumerary velocity peaks, as determined by the SNvpd, and the vertical gray lines correspond to the segmentation of the letters. In (B), the number of supernumerary velocity peaks in each letter for the three groups of writers (DC, children with dysgraphia; PC, proficient children; PA, proficient adults).

SNvpd to two classic handwriting fluency variables in a task that involved children with dysgraphia, proficient children, and proficient adults writing a single word.

As previously mentioned (see the methods section), the SNvpd was computed by subtracting the velocity peaks, when the velocity was filtered with a cutoff frequency (f_c) of 5 Hz, from the velocity peaks, when the velocity was filtered with f_c of 10 Hz. The SNvpd thus counts the velocity fluctuations in a specific waveband corresponding to neuromotor noise, i.e., uncontrolled manifestations of the neuromuscular system. This noise arises from a failure of the motor system to limit the inherent and natural degree of movement variability (Meulenbroek & van Galen, 1986; van Galen et al., 1993).

The first advantage of the SNvpd is that, by subtracting the velocity fluctuations related to curvature variations, it reveals movement fluency independent of the changes of the pen trajectory (Lacquaniti et al., 1983; Viviani & Terzuolo, 1982). This subtraction establishes a theoretical zero baseline for perfectly fluent movements, whatever the written words. From this reduced baseline, a comparison of the three fluency variables confirmed that the SNvpd was more discriminatory than both the NIV and the ANJ for the evaluation of handwriting dysfluency related to dysgraphia.

The second advantage of the SNvpd is that it allows a spatial and temporal localization of the movement dysfluency; this is in contrast to both the NIV and ANJ, which give only a global score of fluency. Various other variables were also used in the fluency evaluation (e.g. Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2009; Caligiuri, Teulings, Dean, Niculescu, & Lohr, 2010; Hepp-Reymond, Charakov, Schulte-Mönting, Huethe, & Kristeva, 2009) but the resulting spatiotemporal resolution was poor (the unit was the stroke) and the segmentation of strokes proved fastidious and was sometimes unclear. Indeed, different methods of segmentation can be conducted, as a function of pressure or as a function of the vertical or tangential velocity. In the latter case, an increase in velocity fluctuations could be interpreted either as an increase in the number of strokes or as a lack of fluency in the stroke.

To our knowledge, no study has previously examined the localization of movement dysfluency in word production. In the case of the word used in the present study, supernumerary velocity peaks were present before the children made lifts between letters (between *l* and *a*), and also within letters (*a* and *p*). Some letters were, thus, more difficult to write, or to link together, and they induced less fluent movements. Furthermore, children with dysgraphia wrote the letters *l* and *p* less fluently than the three other letters. Four non-mutually exclusive explanations can be advanced to account for this observation. Firstly, it can be explained by a 'biomechanical' hypothesis related to the vertical amplitude of these two letters, which is twice that of the three other letters. This greater amplitude might impose an inadequate contraction of the muscles involved in the flexion and extension of the fingers and wrist. Children with dysgraphia, who tend to write larger than proficient children, may have a particular difficulty with such fast flexion and extension movements (Hamstra-Bletz & Blöte, 1993; van Galen et al., 1993). Secondly, this difference might also have a more 'linguistic' origin: the frequency of occurrence of letters. As a matter of fact, in French, *l* and *p* are two times less frequent than *a*, *i*, and *n* (*l*: 4.72%, *p*: 2.48%, *a*: 8.73%, *i*: 8.49%, and *n*: 7.07%; data extracted from the '*Lexique*' database (http://www.lexique.org/listes/liste_lettres.php)). Thirdly, a greater dysfluency for the letter *l* may also be explained by its position at the beginning of the word, where, for various reasons,

Table 2
References of the studies reported in Table 1.

Dysgraphia (*or poor handwriting*)	*Developmental coordination disorder*
[1] Falk, Tam, Schellnus, and Chau (2011)	[24] Chang and Yu (2010)
[2] Khalid, Yunus, & Adnan (2010)	[25] Rosenblum and Livneh-Zirinski (2008)
[3] Kushki, Schwellnus, Ilyias, & Chau (2011)	[26] Smits-Engelsman, Niemeijer, and van Galen (2001)
[4] Overvelde and Hulstijn (2011)	[27] Smits-Engelsman, Wilson, Westenberg, & Duysens (2003)
[5] Paz-Villagrán, Danna, and Velay (submitted for publication)	
[6] Rosenblum and Roman (2009)	*Writer's Cramp*
[7] Rosenblum, Dvorkin, and Weiss (2006)	[28] Baur et al. (2006)
[8] Rosenblum, Parush, and Weiss (2003a)	[29] Hermsdörfer, Marquardt, Schneider, Fürholzer, & Baur (2011)
[9] Rosenblum, Parush, and Weiss (2003b)	[30] Schenk, Bauer, Steidle, and Marquardt (2004)
[10] Rosenblum, Weiss, and Parush (2004)	
[11] Smits-Engelsman and van Galen (1997)	*Hyperactivity disorder*
[12] van Galen, Portier, Smits-Engelsman, and Shomaker (1993)	[31] Shen, Lee, and Chen (2012)
	[32] Tucha and Lange (2001)
Parkinson	[33] Tucha and Lange (2005)
[13] Broderick, Van Gemmert, Shill, and Stelmach (2009)	
[14] Caligiui, Teulings, Filoteo, Song, and Lohr (2006)	*Others*
[15] Oliveira, Gurd, Niwon, Marshall, and Passingham (1997)	[34] Caligiuri, Teulings, Dean, Niculescu, and Lohr (2009)
[16] Tucha et al. (2006)	[35] Caligiuri, Teulings, Dean, Niculescu, & Lohr (2010)
[17] Van Gemmert, Adler, and Stelmach (2003)	[36] Gilboa, Josman, Fattal-Valevski, Toledano-Alhadef, & Rosenblum (2010)
[18] Van Gemmert, Teulings, and Stelmach (1998)	[37] Mavrogiorgou et al. (2001)
[19] Van Gemmert, Teulings, and Stelmach (2001)	[38] Mechtcheriakov et al. (2006)
	[39] Mergl et al. (2004)
Physical disabilities	[40] Philips, Ogeil, and Müller (2009)
[20] Chau, Ji, Tam, and Schwellnus (2006)	[41] Reinders-Messelink et al. (2001)
[21] Li-Tsang et al. (2011)	[42] Tucha et al. (2001)
[22] Hepp-Reymond, Charakov, Schulte-Mönting, Huethe, and Kristeva (2009)	
[23] Schenk, Walther, and Mai (2000)	

children with dysgraphia might encounter greater difficulties. Finally, that the letter *p* proved difficult to write may be explained by its morphological complexity: *p* is the only letter requiring four strokes with two abrupt changes in direction and a pen lift within the letter. In conclusion, thanks to the localization of dysfluency within letters, it is now possible to rank the letters according to their difficulty of production. This classification might be useful for rehabilitation protocols in dysgraphia.

Interestingly, the baseline used, adults' handwriting, was not exactly equal to zero. A visual inspection of the supernumerary velocity peaks for the adult group revealed that 30% of the supernumerary velocity peaks preceded the pen lifts within a 100 ms interval. These fluctuations might reflect the contraction of antagonist muscles used to stop the movement in the horizontal plan in order to control the oncoming pen lift. The remaining peaks (70%) might be explained by the need to visually control the spatial organization of strokes within or between letters (Smyth & Silvers, 1987). If handwriting is not totally automated, this visual control is likely to reduce the movement fluency (Marquardt, Gentz, & Mai, 1999). Indeed, it should also be considered that not all adults had perfectly automated handwriting: some of them admitted that they wrote more often using a keyboard than with a pen.

The supernumerary peaks were more numerous in children with dysgraphia than in proficient children, but only 13% of them were located within a 100 ms interval before the pen lifts: the majority was not directly connected to the pen lifts. This very significant lack of fluency in dysgraphic handwriting may be explained by two factors: the first could be a deficit in motor development generating an increase in neuromotor noise (Smits-Engelsman & van Galen, 1997; van Galen et al., 1993). The findings of Smits-Engelsman, Schoemaker, van Galen, and Michels (1996) support this hypothesis. They showed that children with writing problems improved their handwriting after a specific physiotherapy program. An alternative origin of dysfluency may be a sensorimotor deficit, resulting from a visuo-motor impairment (Khalid et al., 2010). Support for this hypothesis can be found in the study of Volman, van Schendel, and Jongmans (2006) who showed that the score in the developmental test of Visual Motor Integration (Beery, 1997) constituted the only significant predictor of handwriting quality in children with writing problems; this was not found to be true for fine motor coordination.

4. Conclusions

A new variable was proposed to assess, with greater precision, the abnormal fluctuations of the velocity profile of handwriting movement. Two important advantages of using this variable were highlighted: Firstly, it facilitates a better distinction between children with and without dysgraphia on the basis of their handwriting fluency. Secondly it allows us to localize, in both space and time, the occurrences of undesirable velocity peaks. Of course, additional data are necessary, particularly for tasks in which children are required to write sentences instead of isolated words, but the present results suggest that measuring handwriting fluency with this variable might be a relevant way of adding supplementary information to the classical pen and paper BHK test for diagnosing dysgraphia.

Finally, beyond aiding a diagnosis, this new variable could also be helpful for the rehabilitation of dysgraphia. For instance, the possibility of localizing the supernumerary velocity peaks in given letters might facilitate focused rehabilitation work on the letters in question. More interestingly, computing this new variable in real time allows us to detect the supernumerary velocity peaks and to transform them into sounds to give the writer online information regarding his/her movement fluency. This method of handwriting sonification for children with dysgraphia is currently being evaluated and appears to be efficient (Danna et al., 2013; Danna et al., in press).

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