



Automatic segmentation as a tool for examining the handwriting process of children with dysgraphic and proficient handwriting

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Abstract

The purpose of this study was to use an x – y digitizer to collect handwriting samples typical of those written by the child in his or her natural environment, to analyze these samples with novel segmentation algorithms, and to present them visually in ways that illuminate spatial and temporal dynamic features amongst children with dysgraphic and proficient handwriting. While using the POET software (Pennmanship Objective Evaluation Tool), a paragraph was copied onto paper affixed to an x – y digitizer by third-grade students, 14 with proficient and 14 with poor handwriting. A segmentation algorithm was developed to automatically isolate writing segments. Results yielded significant differences between the groups in various measures, including the number of the raw segments (i.e., the number of segments before combined with letters), the number of reverse segments (i.e., when the participant returned to correct or complete a previously written segment), the number of letters per minute, and the mean “In-Air” time between letters. Variability in both the spatial and temporal domains of instances of the same letter throughout the text was greater among the dysgraphic handwriters in comparison to the variability among the proficient. These results demonstrated the potential of using automated analytic techniques and visual display to achieve a more comprehensive understanding of handwriting difficulties.

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1. Introduction

Handwriting, which is a required activity among school-aged children, involves both spatial and temporal demands (Amundson & Weil, 1996; Tseng & Chow, 2000). Handwriting performance is considered to be proficient when legible text is produced at a minimum of effort. In this case, handwriting is automatic and does not interfere with the content as generated by the creative thinking process (Scardamailia, Bereiter, & Goleman, 1982). In contrast, poor writers are often unable to achieve a completely automated process, and their handwriting may be slow and unclear.

Handwriting difficulty, or dysgraphia, was defined by Hamstra-Bletz and Blöte (1993) as a disturbance or difficulty in the production of written language that is related to the mechanics of writing. Teachers have estimated that 11–12% of female students and 21–32% of male students have handwriting difficulties (Rubin & Henderson, 1982; Smits-Engelsman, Van Galen, & Michels, 1995).

Two main outcomes have been used to assess and define poor handwriting, namely, product readability or legibility and performance time. Product legibility has been evaluated in two ways: (1) by judging the readability of an entire paragraph (Ayres, 1912; Freeman, 1959), or (2) by analytic methods based on grading specific features that characterize readability (e.g., between letter and word spacing, letter formation, the degree of line slant, etc.) and then calculating an overall score (see Rosenblum, Weiss, & Parush, 2003, for more details).

There are a number of reasons why current handwriting assessments are of limited value. First, their reliability is low to moderate; second, they require prolonged processing time by the evaluator who needs to judge the writing product for each of the legibility criteria; and third, they do not provide substantive information about the writing process (Rosenblum et al., 2003, Rosenblum, Weiss, & Parush, 2004). The third reason poses a significant limitation, as it is believed that only a comprehensive description of the real-time, dynamic characteristics of a child's handwriting can provide insight into the motor control mechanisms of normal handwriting and an understanding of the underlying pathology of handwriting difficulties (Dobbie & Askov, 1995; Graham & Weintraub, 1996; Longstaff & Heath, 1997; Sovik, Arntzen, & Thygesen, 1987a, 1987b).

In recent years, more attention has been devoted to identifying the features of poor handwriting by children who have a variety of perceptual-motor and learning problems (e.g., Rosenblum, Parush, & Weiss, 2001; Rosenblum et al., 2003; Schoemaker & Smits-Engelsman, 1997; Smits-Engelsman, Van Galen, & Portier, 1994a; Smits-Engelsman, Niemeijer, & Van Galen, 2001). In most of these studies, children were asked to perform brief writing tasks (i.e., usually a single sentence). The testing of only brief writing tasks has limited ecological validity, since many clinicians and educators, as well as researchers, indicate that handwriting problems are particularly noticeable during the performance of tasks similar to those occurring in the children's natural learning environment (Rosenblum et al., 2003, 2004).

In a previous study of 100 third-grade children using a computerized system, including a digitizer, laptop computer, and evaluation software developed by the authors (POET – Rosenblum, Parush, & Weiss, 2003a), we found that poor handwriters performed significantly worse on most of the tested temporal and spatial variables than did their peers (Rosenblum et al., 2001, 2003a; Rosenblum, Parush, & Weiss, 2003b). One of our most important findings was that poor handwriters held the pen above the writing surface for significantly larger percentages of the total writing time. Moreover, they did not simply pause in-air between the writing of successive segments, letters and words. Rather, the kinematic data demonstrated a considerable movement of the pen above the writing surface.

Regrettably, most of the findings from the computerized studies mentioned above have not yet been widely disseminated to the clinical and educational professionals who work directly with people that have handwriting difficulties, and remain, in large part, within the sphere of motor control or signal processing laboratories. Typically, clinicians and teachers are not sufficiently adept at the analytic skills required to interpret such results in the form in which they are normally presented. Moreover, the target of these studies tends to be that of performance between groups, whereas the handwriting process of individual handwriters has been insufficiently explored.

The purpose of this study was to use an x - y digitizer to collect handwriting samples typical of those written by the children in their natural environment, to analyze these samples with novel segmentation algorithms, and to present them visually in ways that illuminate spatial and temporal dynamic features amongst children with dysgraphic and proficient handwriting. Results for individual participants, as well as summary data for two groups are presented. The specific research questions included:

1. Can a segmentation algorithm automatically isolate single characters and character segments from passages of handwritten text?
2. Are differences in the handwriting of the two groups of children (proficient and dysgraphic writers) evident from the segmentation outcome measures?
3. Are these between-group differences comparable to those found previously for other spatial and temporal outcome measures?

2. Method

2.1. Participants

Two groups of handwriters (proficient and dysgraphic), each consisting of 14 third-grade male and female pupils, aged 8 and 9, were included in the study. Dysgraphic handwriters were identified via the standardized and validated Teachers' Questionnaire for Handwriting Proficiency (Rosenblum, Jessel, Adi-Japha, Parush, & Weiss, 1997) and the Hebrew Handwriting Evaluation (HHE) (Erez & Parush, 1999). All participants were born in Israel, used the Hebrew language as their primary means of verbal and written communication, and were right-hand dominant. The proficient handwriters were matched to the participants in the poor handwriting group on the basis of gender, age, school, and class. There were no significant differences between the two groups with respect to their age (8.38 ± 0.22 years for the proficient handwriters and 8.32 ± 0.30 years for the dysgraphic handwriters) and gender ratio (five girls and nine boys in each group). Children with known

psychiatric/emotional disorders, autistic tendencies, physical disabilities, or neurological or systemic disease were excluded from the study.

The data collection methods used in this study have been previously described in detail (Rosenblum et al., 2003a, 2003b, 2003, 2004), but are summarized here for the reader's convenience.

2.2. Instruments

2.2.1. Digitizing tablet and on-line data collection and analysis software

An on-line, computerized handwriting evaluation tool (*POET – Penmanship Objective Evaluation Tool*, Rosenblum et al., 2003a), developed by the researchers with the aid of Matlab software toolkits, was used to administer the stimuli and to collect and analyze the data. All writing tasks were performed on A4-size lined paper affixed to the surface of a WACOM (404 × 306 × 10 mm) x - y Intuos II digitizing tablet using a wireless electronic pen with a pressure-sensitive tip (Model GP-110). The pen's shape and size are similar to regular pens. The x - and y -position, pressure, and pen-tip angle were sampled at 150 Hz via a 650 MHz Pentium III laptop computer. All data analysis was performed off-line.

This software has been programmed to include two independent parts: the data collection software and the data analysis software. The data collection software was designed to be user-friendly for clinicians and educators and is currently in use in different clinical centers in Israel. To date, we support the field use of POET (and its more recent version), CompPET (Computerized Penmanship Evaluation Tool) by having clinicians and educators use the first part of the program to collect the data. These data are then transmitted to our laboratory via the Internet for analysis. The results are returned within one week.

2.3. Data analysis and outcome measures

Data were filtered off-line with a fourth-order Butterworth low-pass filter (15 Hz cut-off frequency). The pen trajectory was reconstructed off-line, and the velocity was computed. Temporal and spatial measures of the handwriting process were then determined on letters, letter components, and segments of the written text. An automated segmentation algorithm, based on the magnitude of the pressure exerted on the writing surface, was used to segment the x - y data into separate fragments of text that the child had written as single, fluent units. The beginning and completion of each segment were determined as the times at which the pressure surpassed or fell below 4% of the maximum pressure, respectively.

The studies described in this paper focused on writing tasks written in the Hebrew language. Hebrew differs in several key ways from Latin-based scripts, as shown in Figs. 1 and 2. Hebrew writing progresses from right to left, successive letters are usually not connected, even during script (cursive) writing, and five letters differ in their form when they are written at the end of a word. As in other languages, some letters in the Hebrew alphabet are constructed from two separate, unconnected components. For example, in the right upper panel of Fig. 2, two components, labeled as segments 74 and 75, combine to form a single letter "alef", and two components, labeled as segments 81 and 82, combine to form the letter "hay", which is also shown in figure Fig. 2.

In order to be able to examine the basic building blocks of writing, related segments were combined into real Hebrew letters following the segmentation process. That is, for any letter or letter component that was constructed from more than one segment, the

different segments that contributed to the formation of that specific letter or component were combined. This procedure enabled the analysis of both individual writing segments and letters. Various temporal and spatial kinematic parameters were measured and analyzed for each segment and letter (e.g., Total “On paper” time and length; Total “In-Air” time; “In-Air” time between segments and within combined segments, Distance between segments, and Height and Width of segments).

Velocity and acceleration were obtained by numerical differentiation for the x and y coordinates from the measured digitizer data. The variables that were determined for each writing segment of selected letters included the number of changes of the direction of the velocity (NCV), which is a measure of the degree of movement automatization, and the mean peak velocity (mm/s). These variables have been used in previous studies for analyzing handwriting movements (e.g., Mavrogiorgou et al., 2001). The segmentation and combination processes also enabled identification of “direction reversal” segments, that is, when the participant returned to correct or complete a previously written segment.

Descriptive statistics (means, standard deviations) and ranges of the dependent variables were tabulated and examined. t -Tests on mean values or standard deviations of the different spatial and temporal variables were used for the statistical analysis. In order to avoid inflation of the probability values due to the use of multiple t -tests, the alpha level for this analysis was adjusted by Bonferroni’s method (Rothman & Greenland, 1998).

2.4. Procedure

The experiments have been carried out according to the ethical guidelines laid down by the Institutional Review Board at the University of Haifa. All participants performed the experiment under similar conditions in a quiet classroom in their school or in the clinic under similar environmental conditions that the child would normally experience. Each participant was tested individually during the morning hours. The handwriting task was presented on a computer screen located in front of the child, placed on a table at eye-level.

The testing took approximately five minutes. All computerized data collection sessions were carried out by the same individual. The participants were asked to copy a 107-character paragraph, which included all 22 letters in the Hebrew alphabet, from the computer screen to the A4 paper. Certain letters appeared more than five times throughout the paragraph. The samples were then analyzed off-line. All of the participants copied the same paragraph, which appeared on the computer screen during the whole trial. The paragraph, consisting of a short story, was translated to English and is shown in Fig. 1.

3. Results

Fig. 2 shows the results of a segmentation analysis for a four-word sentence that was written as part of the paragraph copied by representative proficient (right panels) and dysgraphic (left panels) handwriters. This figure illustrates the ability of these routines to automatically divide up the text into individual segments. Each segment is designated with a number that shows the order in which it was written, thus making it possible to track the sequence of writing.

In the sentence written by the proficient writer, just two segment combinations were necessary, namely, the combination of segments 74 and 75, which has been labeled as A in

a עידן הולך כל יום עם אסף לאן המחקים. יש שם נדנדות מציץ ואם סכסאים אישימה. אכצמים אסף רץ מהר ואז עידן צועק חכה רצע אף תרוץ אני לא לריץ כמוך. אסף חמר טוב, צוחק עוצר ומחכה. אחר כך הם הולכים לקנות ארטיק ומיץ בטל, וחוזרים הביתה.

b Idan goes with Asaf to the playground every day. There are swings made from wood and benches for sitting. Sometimes Asaf runs quickly and then Idan shouts, “wait a minute, do not run, I am not as quick as you are.” Asaf, a good friend, laughs, stops and waits. Afterwards, they go to buy an ice cream cone and raspberry juice and go back home.

Fig. 1. The paragraph copy task, in Hebrew (a) and translated to English (b).

Fig. 2 (lower right panel), and the combination of segments 81 and 82, which has been labeled as B in the same panel. Since both of these characters are normally constructed from two components, these combinations are entirely expected. In contrast, when comparing the upper and lower left panels, one can notice that six segment combinations were required for the sentence written by the writer with dysgraphia (labels A to F in the lower left panel of Fig. 2). One letter in this same panel (the letter “Pey” in its complex form, indicating word termination) was combined from seven segments (segments 99–107 in the upper left panel, labeled as D in the lower left panel). The same letter was written in one segment (77) by the proficient writer (upper and lower right panels). For clarity’s sake, this letter and its segments are shown separately in Fig. 3. Note that this letter is normally written as a single unit and has been done so by the proficient writer, as demonstrated by the lack of combinations in the lower right panel of Fig. 2.

אכצמים אסף רץ מהר

Dysgraphic writer showing original strokes	Proficient writer showing original strokes
Dysgraphic writer with original strokes combined to show their contribution to each letter (A to F)	Proficient writer with original strokes combined to show their contribution to each letter (A, B)

Fig. 2. The target sentence as it appears on the computer screen (above the panels), and as written by a dysgraphic writer (left panels) and by a proficient writer (right panels) showing the results of automatic segmentation.

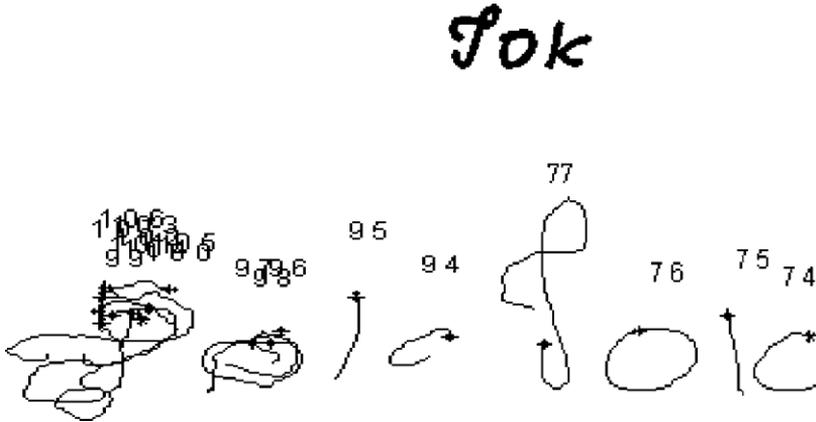


Fig. 3. The target word as it appeared on the computer screen (one of the words from the sentence displayed in Fig. 2) is shown above. The word on the right, written by a proficient writer, required just four segments, the minimum possible number. In contrast, the word on the left, written by a dysgraphic writer, required 14 segments.

Several outcome measures were analyzed for the whole paragraph, performed by the 14 dysgraphic and 14 proficient handwriters (see Table 1). The means and standard deviations for these measures are presented in Table 1.

Group differences in the temporal and spatial measures, calculated from the segmentation analysis, were analyzed using *t*-tests. The Bonferroni corrected significance level of $\alpha = .012$ was applied to all *t*-test calculations. Only results less than these adjusted alpha levels were deemed to be significant. Significant differences between the dysgraphic and proficient handwriting groups were found for the number of raw segments (i.e., the number of segments before the combination process) ($t(26) = 2.62, p = .01$); the number of ‘direction reversal’ segments ($t(26) = 2.51, p = .01$); the number of letters for the first minute ($t(26) = 3.42, p < .001$); and the number of letters per minute for the whole paragraph ($t(26) = 3.6, p < .001$). These latter two variables have already been shown to differentiate between children who are proficient writers and those who are poor writers (Rosenblum et al., 2003a).

Table 1

A comparison between proficient and dysgraphic handwriting performance along whole paragraph copy and in sentence writing

Measures	Proficient <i>n</i> = 14		Dysgraphic <i>n</i> = 14		<i>t</i>	<i>p</i>
	<i>M</i>	SD	<i>M</i>	SD		
<i>Measures of writing for the whole paragraph</i>						
Number of raw segments	131.71	5.97	141.14	12.05	2.62	.01
Number of “direction reversal” segments	3.07	3.14	6.64	4.27	2.51	.01
Number of letters for the first minute	49.71	16.61	32.64	8.46	3.42	<.001
Number of letters per minute for the whole paragraph	47.82	17.85	27.98	9.35	3.61	<.001
<i>Measures of writing for a single sentence</i>						
The distance between letters on the <i>x</i> axis (mm)	1.46	.68	1.61	.77	.56	ns
“In-Air” time between letters (s)	.39	.67	1.05	1.48	2.5	<.001

Several additional ‘inter-letter’ outcome measures were analyzed for a single sentence that appeared in the middle of the paragraph (the sentence shown in Fig. 2). The inter-letter distance on the x axis (DX, in millimeters) and the “In-Air” time between successive letters (in seconds) in the sentence were measured (see Table 1). Whereas no significant differences were found between the mean DX values when comparing the dysgraphic and proficient handwriters, significant differences were found for mean inter-letter “In-Air” time between the two groups ($t(26) = 2.5, p < .001$).

In order to examine between-character variability, the fifth letter of the Hebrew alphabet, “hay”, was chosen as an example. This letter is normally formed from two components, a larger, outer curved segment followed by a smaller, inner curved segment. The segmentation algorithm was performed on the five occurrences of this letter that appeared throughout the paragraph. This enabled us to compare different spatial and temporal measures of the same letter (i.e., number of raw segments, letter height, width, length on paper, total time, and “In-Air” time between the two segments that combined to form the same letter).

Fig. 4 shows an example of the five times that the letter “hay” appeared in the text, as was written by one dysgraphic handwriter and one proficient handwriter. One can clearly see the differences in the variability of this letter’s form between the two handwriters. Subsequent analysis of the number of raw segments used to create each letter indicated that for three out of the five times, the dysgraphic handwriter wrote the letter with three segments although the letter is usually constructed from only two single segment components. That is, the pen was lifted one or more times during the writing of what should have been a single segment component.

The means and standard deviations across all five “hays” (with both the outer and inner components together) for each group of writers were computed for inner or outer outcome measure. Significant differences between the dysgraphic and proficient handwriters were found for the SD of letter height ($t(26) = 3.86, p < .001$).

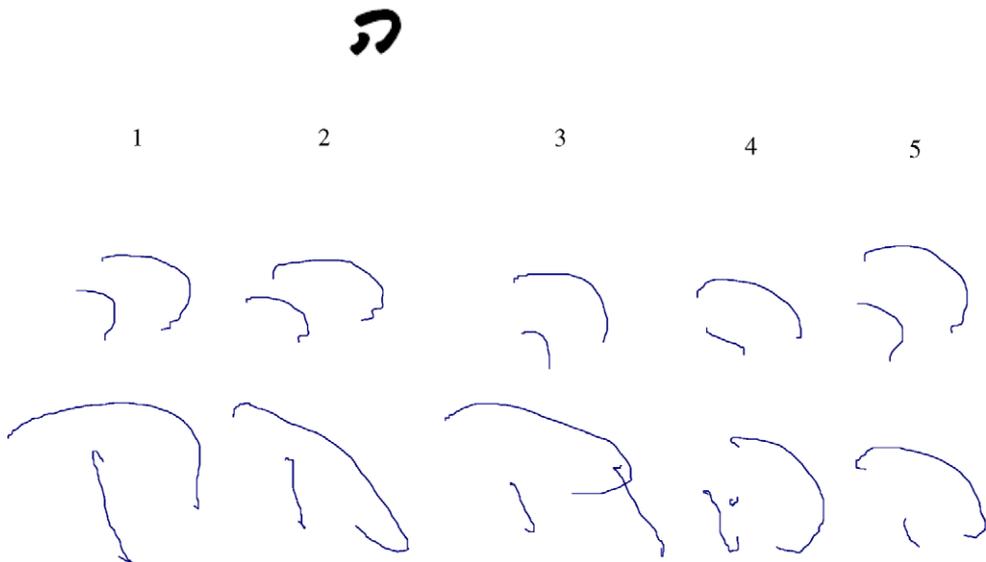


Fig. 4. Five repetitions of the letter “hay” (shown above as it was presented on the computer screen) and as written by one proficient handwriter (top panels) and by one dysgraphic handwriter (bottom panels).

Temporal outcome measures for each group of writers were then computed separately for the two components (outer and inner) of the letter “hay”. The differences in means and standard deviations of the outcome measures are presented separately for the five outer segments and for the five inner segments in Table 2.

The Bonferroni corrected significance level of $\alpha = .006$ was applied to all t -test calculations regarding the outer and inner components of the letter “hay”.

Significant differences between proficient and poor writers were found for the outer component of the letter “hay” (standard deviation of number of changes of the direction of the velocity, $t(26) = -2.86, p < .001$) and, especially, for the inner component of the letter “hay” (mean number of changes of the direction of the velocity $t(26) = -3.06, p < .001$, mean on paper time $t(26) = -4.26, p < .001$, and the standard deviation of on paper time $t(26) = -3.15, p < .001$).

4. Discussion

X – Y digitizing tablets for the quantitative measurement and analysis of handwriting have become a more frequently used research tool in recent years (e.g., Athènes, Sallagoity, Zanone, & Albaret, 2004; Smits-Engelsman et al., 2001; Tucha, Kaunzinger, & Lange, 2005). This tool enables examination of the dynamic processes taking place as a writer formulates, executes and monitors handwritten text. Nevertheless, despite the considerable advances in our understanding of both proficient and poor handwriting achieved with the

Table 2

A comparison of temporal measures between proficient and dysgraphic handwriting performance for the outer and inner components of the five repetitions of the letter “hay”

Measures	Proficient $n = 14$		Dysgraphic $n = 14$		t	p
	M	SD	M	SD		
<i>Temporal measures of the outer component of the letter “hay”</i>						
Mean absolute velocity	26.97	7.68	25.62	6.03	.51	ns
Mean Number of inversions of the direction of the velocity (NCV)	3.21	1.50	4.29	2.09	-1.57	ns
Mean peak velocity (mm/s)	39.66	10.56	41.99	7.36	-.67	ns
Mean on paper time	.18	.06	.26	.14	-1.95	ns
Standard deviation of absolute velocity	3.87	1.21	4.88	2.31	-1.44	ns
Standard deviation of number of inversions of the direction of the velocity (NCV) – SD	.87	.44	2.19	1.66	-2.86	<.001
Standard deviation of peak velocity (mm/s)	6.10	2.13	7.98	3.86	-1.59	ns
Standard deviation of on paper time	.02	.01	.12	.21	-1.66	ns
<i>Temporal measures of the inner component of the letter “hay”</i>						
Mean absolute velocity	23.10	9.80	17.51	5.41	1.86	ns
Mean number of inversions of the direction of the velocity (NCV)	2.72	.67	3.79	1.11	-3.06	<.001
Mean peak velocity (mm/s)	49.56	25.29	36.30	14.55	1.70	ns
Mean on paper time	.10	.02	.17	.05	-4.26	<.001
Standard deviation of absolute velocity	15.46	12.09	5.94	2.61	2.88	<.001
Standard deviation of number of inversions of the direction of the velocity (NCV) – SD	1.77	.73	1.80	.62	-.12	ns
Standard deviation of peak velocity (mm/s)	51.00	39.90	19.21	22.07	2.60	ns.
Standard deviation of on paper time	.02	.01	.05	.03	-3.15	<.001

aid of this tool, its potential has not yet been fully exploited, and there is a need for the continuing development of additional analytic methods that will provide more in-depth information about the process. The aim of the current study was to develop a method wherein passages of written text could be automatically segmented into the most basic units of the task, that is, into separate fragments written as single, fluid units. Various outcome measures calculated from these segments were then used to compare the performance of children with dysgraphia to those classified as proficient writers.

Significant differences were found between the proficient and dysgraphic groups in the number of segments used to construct individual letters or letter components, as well as the number of occurrences of direction reversals. These variables provided information about the letter-by-letter fluency with which a child writes (as revealed by the number of segments used when writing a passage of text) and the child's ability to plan and execute the task in an efficient and accurate manner (as revealed by the number of direction reversals). The formation of letters with more than the minimum number of segments, as well as the use of multiple direction reversals, are both clearly inefficient writing techniques, likely associated with fatigue and less readable writing. Both would likely negatively influence a child's ability to focus on writing content (Graham, Weintraub, & Berninger, 2001).

The need to measure such writing difficulties, and their importance for handwriting proficiency, has long been recognized in the literature (Berninger et al., 1997; Eidlitz & Simner, 1999; Karlsdottir & Stefansson, 2002; Simner, 1990). We have suggested that it is particularly important to assess these difficulties while a child is writing functionally relevant passages of text whose content has meaning for the writer (as was the case in the tasks used in the present study), rather than artificial tasks such as isolated letters or pseudo-words (Rosenblum et al., 2003a, 2003b, 2004). The writing of meaningful tasks will be more likely to challenge the handwriter's motor planning and execution skills in a realistic and ecologically valid manner and result in data more indicative of his or her true abilities.

The results presented in this paper provide direct quantitative evidence demonstrating differences in fluency between proficient and dysgraphic writers at the level of the basic building blocks of writing – what we have referred to as segments. These, and additional documentation of handwriting performance, are needed in order to achieve a greater understanding of and to provide evidence for the mechanisms underlying letter production. A number of different processes have been suggested over the years.

Stott, Henderson, and Moyes (1987) have suggested that the graphic production of a letter involves two complementary processes. The first relates to the formation of a cognitive (or visual) schema of the letter, including knowledge of its defining features and recognition of its variant forms. The second process involves the development of a motor schema of the letter by which the visual picture is translated into a sequence of movements. The failure to form letters in an acceptably legible and efficient manner may result from a deficiency in either of these processes. While copying, the child alternates his gaze between the computer screen and the writing surface. Children, whose cognitive schema for letters is unstable, will need to repeatedly glance at the screen and may therefore write more slowly.

Eidlitz and Simner (1999) have suggested a process wherein errors of form characterizing the writing of children with dysgraphia may result from a poorly developed or unstable memory image which gradually fades and then disappears as children learn to print. The children examined in that study made significantly greater errors than did proficient writers, especially errors of form including turns that were too acute, misalignment of letters, broken letters, or irregular letter spacing. They suggested that these errors are a symptom

of an underlying memory problem that interferes with a child's ability to retain information taught in school (Eidlitz & Simner, 1999).

The results of the current study provide additional temporal and spatial variables documenting errors of form, including significantly longer inter-letter "In-Air" times for the group with dysgraphia. The findings indicate that these children may need more time to plan and execute successive letters. Moreover, the inconsistent appearance of the same letter when repeated five times throughout the same paragraph (e.g., the letter "hay" shown in Fig. 4 for one child with dysgraphia and summarized for all 14 children with dysgraphia in Table 2) highlights these children's difficulties related to consistency of letter formation.

In the present study, differences in writing performance between the proficient and poor writers were particularly noticeable for the smaller, inner curved component of the letter "hay" in comparison to the larger, outer curved component. Previous studies have described the deficits of children with different learning disabilities in terms of their difficulties with organization in space and time manifested in many of their occupations, including work, play and self-care (e.g., organizing their school bag and handwriting) (Blanch & Parham, 2001; Farnworth, 2003). Previous studies indeed found deficits in spatial and temporal aspects of dysgraphic handwriting (e.g., Hamstra-Bletz & Blote, 1993; Schoemaker & Smits-Engelsman, 1997; Stott et al., 1987). The current study provides further evidence regarding dysgraphic children's difficulties with organization in both the spatial and temporal domains and for different task lengths (paragraph, sentence, letters and segments).

We were intrigued to note that differences between the two groups for many features (e.g., the velocity measures, such as the mean number of changes of the direction of the velocity, the standard deviation of the absolute velocity, and on-paper time) of the inner component of the "hay" were significant, whereas the two groups differed less for features related to the outer component. Difficulties in the writing of the inner component of the "hay" by the dysgraphic writers may be understood within the context of the theoretical model proposed by Feuerstein and colleagues (Feuerstein, Rand, Hoffman, & Miller, 1980). They noted that children with learning disabilities have difficulty when they need to cope simultaneously with two or more sources of information, for example, when they need to jump a certain distance at a particular tempo while refraining from bumping into an obstacle on the floor.

When a child writes a single component letter, he likely formulates it as a single unit, even if he only succeeds in creating it from two or more segments. In contrast, in the case of two-component letters, such as the "hay", the child must consider simultaneously the size, shape, and location of both components (i.e., two sources of information). The second component may be more difficult to construct than the first component, simply because it must be adapted to fit the latter's temporal and spatial characteristics. Analyses such as these may be a first step towards understanding handwriting deficits as part of a wider phenomenon with a unifying principle, as has been suggested for movement sequencing and phonological fluency among children with reading difficulties (Carello, LeVasseur, & Schmidt, 2002).

It is interesting to note that the spatial differences (e.g., large letters) between dysgraphic and proficient handwriters may occur as a result of the dysgraphic children's efforts to compensate for unclear writing. From a developmental perspective, as writing matures, the height of letters become smaller and more accurate (Alston & Taylor, 1987). The writing of larger letters, such as those shown in the bottom panel of Fig. 4, may help the dysgraphic

children to achieve greater legibility or may simply be easier for them to perform because it requires less precision in letter formation (Mojet, 1991). Further research should aim to identify why dysgraphic writers tend to write larger letters.

In addition to the ability to provide information about letter-by-letter and intra-letter fluency and proceeding in space and time, the techniques described in this paper provide the possibility of presenting a readily understood display of objective measures of handwriting to a child with handwriting difficulties as well as to the parents and teachers. This visual presentation of the results of the segmentation analysis may contribute to the client's participation in the evaluation process. The graphic representations of both dysfluencies and direction reversals illustrate disturbances of handwriting that would have been otherwise obscure to non-expert viewers. The contribution of visualization to other disciplines has been recognized as nurturing a meaningful dialogue between researchers and practitioners. For example, visualization techniques have led to advances in medical informatics research, as well as in medical education, and have also had significant clinical implications for applications in both diagnosis and intervention (Gorbis & Hallgren, 1999; Shah & Hunter, 2000).

In conclusion, the methods developed in this study serve to expand on the information provided by previous digitizer-based handwriting research. Specifically, they illustrate how automated segmentation can lead to a detailed analysis of the stroke sequences used to create letters and words and provide evidence for disruptions in fluent motor planning. The current study constitutes one phase of a comprehensive research program aimed at developing an accessible computerized handwriting evaluation for clinicians and educators. Collaborations between our research group and a number of clinical centers in Israel and Hong Kong are currently studying the feasibility of using digitizer-based handwriting evaluation under clinical conditions.

The development of additional analytic techniques, as well as the use of novel writing tasks, is required to establish the source of dysfluent writing and to develop a model which will be able to account for the various mechanisms suggested in the literature to date. Future studies with larger samples should include tasks designed to identify the way in which different children perform handwriting tasks in order to achieve an understanding of the underlying difficulties that limit the performance of children with dysgraphic handwriting.

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