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Handwriting process and product characteristics of children diagnosed with developmental coordination disorder

Sara Rosenblum [a,*], Miri Livneh-Zirinski [b]

[a] *Department of Occupational Therapy, Faculty of Social Welfare and Health Sciences, University of Haifa, Mount Carmel, 31905 Haifa, Israel*
[b] *Child Development Center, Kupat Holim Meuhedet, Haifa, Israel*

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Abstract

Deficits in handwriting performance limit the school participation of children with developmental coordination disorder (DCD). The aim of this study was to compare the handwriting process and product characteristics of children with DCD to those of typically developing (TD) children in order to determine the best means of differentiation between the groups. Participants were 40 children, from 7 to 10 years old. The experimental group consisted of 20 children who met the criteria of DCD, and the control group consisted of 20 age- and gender-matched controls. The children were asked to perform three graded writing tasks on an electronic tablet, which was part of a computerized handwriting evaluation system (ComPET), in order to obtain measures of their handwriting process. The children's handwriting product was then evaluated by the Hebrew Handwriting Evaluation (HHE). Results showed significant differences between the groups for the handwriting process measures (on-paper and in-air time, mean pressure) and for the handwriting product characteristics (global legibility, number of letters erased or overwritten, spatial arrangement, and number of letters written in the first minute). The discriminant analysis yielded a high significant discrimination (80–90%), with the 'number of letters erased or overwritten' variable as the most differentiating variable (−.67). We concluded that an evaluation of both handwriting process and product characteristics among children with DCD provides a more comprehensive picture of their deficits. Using this method may enable practitioners to focus on children's main deficits and to tailor intervention methods so as to prevent academic underachievement and its consequences on their emotional well-being.

* Corresponding author. Tel.: +972 4 8240474; fax: +972 4 8249753.
E-mail address: rosens@research.haifa.ac.il (S. Rosenblum).

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1. Introduction

Developmental coordination disorder (DCD) is characterized by motor impairment that interferes with a child's *activities* of daily living and *academic achievement* (Dewey & Wilson, 2001). Although the definition of the disability was established in 1994 (DSM-IV – American Psychiatric Association, 1994), there is still ongoing discussion in the literature about the characteristics of children with DCD, as well as the appropriate tools for DCD evaluation based on the definition (Dewey & Wilson, 2001; Flapper, Houwen, & Schoemaker, 2006; Green & Baird, 2005). There is still no "gold" standard that can be used to identify the condition (Dewey & Wilson, 2001; Green et al., 2005) or the exact processing mechanisms that give rise to the motor control difficulties (Mandich, Buckolz, & Polatajko, 2003). In fact, the issues of definition, the characteristics of this population, and appropriate evaluation tools are all tied to each other. Dunford, Street, O'Connell, Kelly, and Sibert (2004) emphasized the importance of knowledge and understanding of the DSM-IV criteria and their proper application in order to reduce the number of time-consuming, unnecessary assessments conducted for DCD.

Difficulties in handwriting among children with DCD have been formally recognized in Criteria A and B of the DSM-IV (Barnett, 2006). Handwriting proficiency is an essential *activity* required for children's success and *participation* in school, and is a key ingredient in their self-esteem as well as the most immediate form of graphic communication (Feder & Majnemer, 2007). Recently, Lollar and Simeonsson (2005) indicated that there are not enough tools with objective measures available to evaluate activity and participation, which are basic concepts set forth by the International Classification of Functioning, Disability, and Health (ICF, 2001). Furthermore, although children with DCD are particularly at risk for handwriting deficiency (O'Hare & Khalid, 2002), there is a lack of research and methods for the evaluation of handwriting deficits among children in general (O'Hare, 2004). This shortcoming is more significant for school-aged children in light of the fact that handwriting is an important activity of daily living required for 30–60% of the school day (McHale & Cermak, 1992; see Rosenblum, Weiss, & Parush, 2003 for more details).

Handwriting assessment is required among children with DCD for a variety of reasons, including identification, description, quantification, monitoring, focused intervention, and evaluation of intervention efficacy (Barnett, 2006; Dunford et al., 2004; Miller, Missiuna, Macnab, Malloy-Miller, & Polatajko, 2001). The question remains as to which handwriting evaluation tools for children are the most suitable for meeting those requirements.

The familiar handwriting evaluation used by clinicians in the field measures handwriting *product* legibility or readability and performance time. Product legibility has been evaluated in two ways: (1) by judging the global readability of an entire paragraph (Ayres, 1912; Freeman, 1959; Ziviani & Watson-Weill, 1998) or (2) by analytic methods based on grading specific features that characterize readability (e.g., letter formation, spacing between letters and words, the degree of line slant, etc.) and then calculating an overall score (see Rosenblum, Parush, & Weiss, 2003, for more details).

There are a number of reasons why current handwriting assessments based on the handwriting *product* 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 mechanism of handwriting difficulties (Dobbie & Askov, 1995; Graham & Weintraub, 1996; Longstaff & Heath, 1997; Sovik, Arntzen, & Thygesen, 1987a; Sovik, Arntzen, & Thygesen, 1987b).

In recent years, more attention has been devoted to identifying the features of handwriting *process* deficits among children with a variety of perceptual-motor and learning problems (e.g., Rosenblum et al., 2003; Schoemaker & Smits-Engelsman, 1997; Smits-Engelsman, Niemeijer, & van Galen, 2001). In most of these studies, however, the children were asked to perform only brief writing tasks (i.e., usually a single sentence), which may not provide an accurate reflection of reality. Many clinicians and educators, as well as researchers, indicate that handwriting problems are particularly noticeable during the performance of longer tasks similar to those occurring in the children's natural learning environment (Rosenblum et al., 2003, 2004).

Although the use of informal assessment for handwriting deficiency is commonplace in clinical centers (Miller et al., 2001), there are few studies on the systematic evaluation of handwriting product and process characteristics among children diagnosed with DCD from the point of view of ecological validity (Magalhaes, Missiuna, & Wong, 2006). Ecological validity refers to the conditions under which generalizations can be made from controlled experiments to natural real-life scenarios (Tupper & Cicerone, 1990). In fact, despite the use of kinematic analysis in the drawing process of children with DCD (e.g., Flapper et al., 2006; Kagerer, Bo, Contreras-Vidal, & Clark, 2004; Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003; Smits-Engelsman et al., 2001), there is no knowledge about the kinematics of handwriting among these children. Thus, it appears that all of the evaluation methods used to characterize handwriting performance among children in general and among children with DCD in particular have their limitations. The aim of this study was to compare the handwriting process and product characteristics of children with DCD to those of typically developing (TD) children in order to determine the best means of differentiation between the groups. Identifying the best differentiators between the groups will be a first step towards the future development of a quick and practical evaluation tool for handwriting deficits among children with DCD.

The research assumption was that differences would be found between the DCD and control groups for the following handwriting measures/characteristics:

1. Handwriting process measures: temporal (on-paper and in-air time per stroke); spatial (height and width of the pen strokes for each task); mean pen tilt; and mean pressure.
2. Handwriting product characteristics: global legibility, the number of letters erased and/or overwritten, the number of unrecognizable letters; the spatial arrangement; and the number of letters written during the first minute.

Table 1
A comparison between DCD and control group for M-ABC and ChAS-P scores

Scores/percentiles	DCD				Control			
	Minimum	Maximum	*M*	SD	Minimum	Maximum	*M*	SD
M-ABC total impairment score	10.50	28.50	16.36	5.92	4.50	9.50	7.85	1.82
M-ABC percentile	1	13	5.63	4.93	16	49	25.55	11.55
ChAS-P total score	1.26	2.74	2.13	.54	4.30	5.00	4.69	.24

2. Methods

2.1. Participants

Twenty children with DCD (2 girls, 18 boys), ranging in age from 7 to 10 years, and 20 age- and gender-matched control children participated in the study.

The mean age of the DCD group was 8 years, and the mean age of the control group was 7 years and 9 months.

The children with DCD were recruited from a child development center in Haifa, Israel. All of the children in the DCD group were first diagnosed by a pediatrician and met the criteria of DSM-IV for DCD (American Psychiatric Association, 1994). In order to verify their status as children with DCD, they were then tested with the Movement Assessment Battery for Children (M-ABC) (Henderson & Sugden, 1992) and the Children Activity Scale – Parents (ChAS-P), a standardized parents' questionnaire used for identifying children with DCD (see Rosenblum, 2006 for more details). Those children who scored below the 15th percentile for their age on the M-ABC and got a final score of lower than 3.82 on the ChAS-P (Rosenblum, 2006) were included in the DCD group.

The control group was recruited from the same local schools that the children from the DCD group attended. The 20 controls had no symptoms of DCD, as indicated by the children's parents and teachers, as well as their M-ABC scores (Henderson & Sugden, 1992) and ChAS-P scores (Rosenblum, 2006). A detailed description of the M-ABC and ChAS-P scores of both groups are presented in Table 1.

Children with known neurotic/emotional disorders, autistic disorders, physical disabilities, or neurological diseases were excluded from the study. All participants were native Hebrew speakers, were attending school, and reported no problems with hearing or vision.

2.2. Instruments

2.2.1. Handwriting process evaluation

Computerized Penmanship Evaluation Tool (*ComPET*, previously referred to as POET; Rosenblum et al., 2003). This standardized and validated handwriting assessment utilizes a digitizing tablet and on-line data collection and analysis software. It was developed for the purpose of collecting objective measures of the handwriting process (see Rosenblum et al., 2003 for more details). The ComPET system is non-language dependent and analyzes every writing stroke.

In the current study, three graded handwriting tasks were performed: writing one's name; writing the alphabet sequence from memory; and paragraph copying. These tasks were chosen from an ecological point of view as very familiar and common tasks routinely performed at school. The tasks were performed on A4-sized lined paper affixed to the surface of a WACOM Intuos II x–y digitizing tablet ($404 \times 306 \times 10$ mm), using a wireless electronic pen with a pressure-sensitive tip (Model GP-110). This pen is similar in size and weight to regular pens commonly used by children and thus does not require a change in grip that might affect their writing performance (see Fig. 1).

Displacement, pressure, and pen tip angle were sampled at 100 Hz via a 1300 MHz Pentium (R) M laptop computer. The primary outcome measures were comprised of temporal, spatial, and pressure measures for each writing stroke, as well as performance over the entire paragraph. The temporal measures included on-paper time and in-air time (i.e., the time during writing performance in which the pen is not in contact with the writing surface) (Werner, Rosenblum, Bar-On, Heinik, & Korczyn, 2006). In previous studies, we found that in-air time may supply information about the perceptual aspect of the motor act (e.g., Werner et al., 2006); hence, we decided to separate the temporal measure into on-paper time and in-air time. The spatial measure used was the mean stroke height and width for each task. In addition, the ComPET computes the mean pressure applied to the paper, as measured in non-scaled units from 0 to 1024, as well as the mean pen tilt in the range of 0–90° (i.e., the angle between the pen and its projection on the tablet).

The tasks were written in Hebrew, which progresses from right to left. Successive letters are usually not connected, even in script or cursive writing, and some letters are comprised of two separate, unconnected strokes. Moreover, five of the 22 characters change shape when they terminate a word (see Fig. 2). In order to enable comparison of the current study methodology and results with those of other languages, the measures were obtained for the writing strokes or for the whole writing task performance and were not based on letters.

2.2.2. Handwriting product evaluation

The Hebrew Handwriting Evaluation (*HHE*; Erez & Parush, 1999). The HHE was used to examine the handwriting *product*, assessing legibility through both global and analytic measures. The HHE has been found to be a reliable and valid tool (see Rosenblum et al., 2003 for details). The standardized paragraph employed in the HHE to assess copying/writing performance was used in the current study for both the product and process evaluation. The original text contains all of the letters in the Hebrew alphabet and includes 30

Fig. 1. The handwriting task performance on a digitizer, which is a part of the computerized system (ComPET – Computerized Penmanship Evaluation Tool).

words/107 letters (Erez & Parush, 1999). In the current study, the children were asked to copy only two sentences, which included 60 letters.

All 40 handwriting product samples were analyzed by the same evaluator. The outcome measures of the HHE assessment of the written product included global legibility (scored on a 4-point Likert scale, from the most legible (American Psychiatric Association, 1994) to the least legible (Barnhart, Davenport, Epps, & Nordquist, 2003), which refers to the overall clarity of the handwriting. The number of letters written during the first minute was also recorded.

The analytic measurement of legibility used in the HHE examined the following three variables:

1. Letters erased and/or overwritten – the number of letters that were erased and/or written over.
2. Unrecognizable letters – the total number of letters that could not be recognized due to the quality of letter closure, rounding of letters, or letter reversals.
3. Spatial arrangement of the written text, as determined according to precise criteria, utilizing a caliper that is calibrated to the millimeter. Specifically, these criteria refer to the vertical alignment of letters (including the extensions of letters above and below the lines); the spacing of words and letters (whether too wide or overlapping); and letter size. The minimum score for spatial arrangement is six, and the maximum score is 24.

For all four legibility outcome measures of the HHE (i.e., the three described above plus global legibility), a low score indicates good performance and a high score indicates poor performance.

2.3. Procedure

The study design conformed to the instructions stipulated by the University of Haifa's Ethics Committee. When children were diagnosed by the pediatrician with DCD, their parents were requested to sign an informed consent and to complete the ChAS-P parents' questionnaire. The children were evaluated at the developmental center by the same evaluator who administrated to them the M-ABC test and the handwriting (ComPET) evaluation and who also scored their handwriting products based on the HHE criteria. Children who did not meet both the M-ABC and ChAS-P criteria were excluded from the study. For each child in the DCD group, an age- and gender-matched control child was chosen from the same school and was administered the same procedure described above.

2.4. Statistical analysis

Descriptive statistics of the dependent variables were tabulated and examined. *t*-Tests were calculated to compare differences in the handwriting process measures, which refers to differences in the mean values of the spatial, temporal, and pressure variables of the three handwriting tasks. In order to avoid inflation of the probability values due to the use of multiple *t*-tests for each handwriting task, the alpha level for this analysis was adjusted by Bonferoni's method (Rothman & Greenland, 1998), with a .008 threshold set for statistical significance.

The Mann Whitney procedure was used for analysis of the handwriting product measures (HHE) because the data represent an ordinal scale and the scores did not follow a normal distribution. Finally, discriminant analyses were conducted in order to determine which handwriting process and product variables are the best predictors of group membership (i.e., DCD versus control).

3. Results

Representative samples of the paragraphs written by a child with DCD and a child without DCD are illustrated in Fig. 2. The paragraph copying task presented to the child is shown in Fig. 2a. The paragraph copying task performed by the two children is presented in Fig. 2b, and the in-air and on-paper temporal measures while writing are presented in Fig. 2c. In addition, several variables, including performance time, stroke time, and product scores, are presented for each child in order to illustrate the differences in performance.

Comparison of performance for the two tasks shows that the child with DCD took more time than the control child to perform the paragraph copying task (see Fig. 2b). Furthermore, a visual examination of the extent of the gray line trajectories, as well as the mean air time per stroke (see Fig. 2c), reveals that the child with DCD spent considerably more in-air time and had much more complex transitions between letters and words than the control child. As shown in both Figs. 2b and c, the writing product of the child with DCD was less legible, less organized, had more letter corrections, and had fewer letters (almost half) written within the first minute of the task (as evaluated by the HHE criteria) in comparison to the child from the control group.

Temporal, spatial, pressure, and tilt measures were analyzed for the name writing, the alphabet sequence, and the paragraph copying tasks for both groups. The means and standard deviations for these measures are presented in Table 2. The SDs for each of the measures in both groups were very high, showing considerable individual variation in handwriting performance.

For the three tasks, no significant differences were found between the groups in stroke width, stroke height, or mean pen tilt. However, children with DCD required significantly more on-paper and in-air time per stroke (with an adjusted alpha of .008) in both the alphabet sequence and paragraph copying tasks. A significant difference was also found for the mean pressure applied in both the paragraph copying and name writing tasks, with the DCD children exerting less pressure when writing. The standard deviations of those measures in the DCD group were always higher than those of the TD group, indicating a higher variability in their performance.

Next, analyses were performed to draw a comparison between the handwriting product measures of the study groups, and the results are presented in Table 3. Handwriting fluency, as measured by the HHE in terms of the number of letters written in the first minute, yielded significant differences ($t = 3.99$, $p < .001$), with a big gap between the groups (DCD: $M = 28.55$, SD = 16.66; Control: $M = 50.05$, SD = 17.35).

Results of the Mann Whitney U-test on the other four HHE outcome measures yielded significant differences for three of them. Specifically, the participants in the DCD group performed significantly less well than those in the control group for global legibility, $U = 124.50$, $n = 40$, $p = .03$, number of letters erased or overwritten $U = 78.00$, $n = 40$, $p = .001$, and spatial arrangement, $U = 117.50$, $n = 40$, $p = .02$.

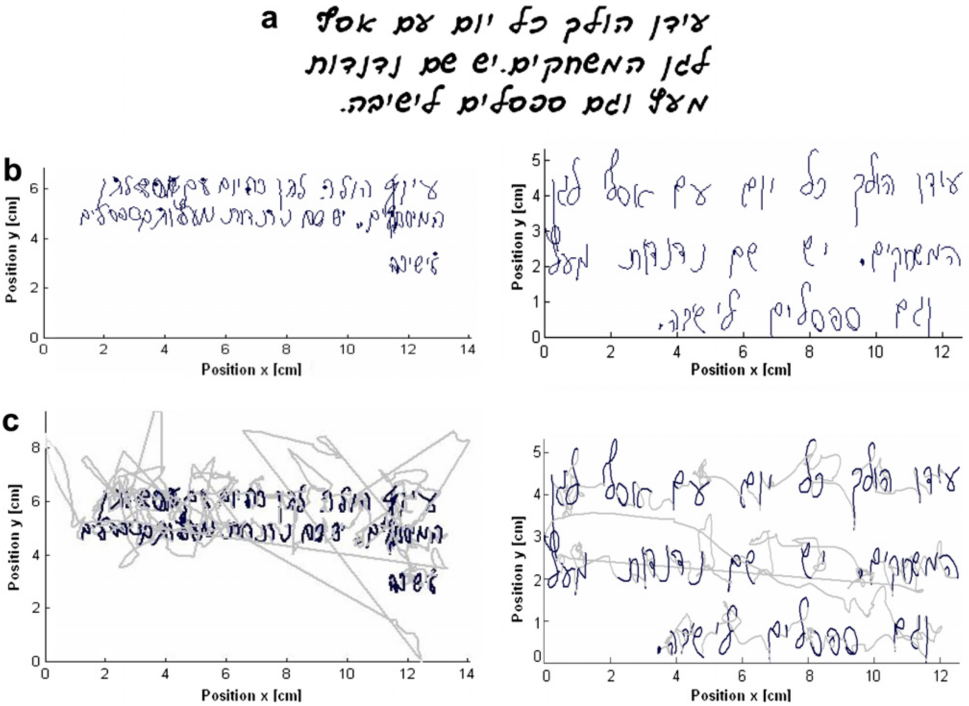

Fig. 2. The paragraph copying task as presented to the child (2a); The paragraph copying by a representative child with DCD and by a representative child from the control group (2b); in-air motions by the same children (2b). (a) The paragraph copying task, as presented to the child. (b) The paragraph copying task written by a representative child with DCD (left) and by a representative child from the control group (right). The product variables for each of those representative children are presented under the figures. Paragraph performance time: 167.82 s. Paragraph performance time: 60.62 s. Number of letters for the first minute: 24. Number of letters for the first minute: 46. Global legibility: 4. Global legibility: 2. Letters erased or overwritten: 2. Letters erased or overwritten: 0. Spatial arrangement: 9. Spatial arrangement: 6. (c) On-paper and in-air writing comparison between a representative child with DCD (left) and a representative child from the control group (right). The black lines represent the actual trajectory of the writer's pen when in contact with the writing surface, and the gray lines show the in-air trajectory, i.e., when the pen was above the writing surface. The temporal process variables for each of those representative children are presented under the figures. Stroke time on-paper: $M = 0.47$ $SD = 0.31$ s Stroke time on-paper : $M = 0.36$ $SD = 0.18$ s Stroke time in-air $M = 1.22$ $SD = 2.03$ s Stroke time in-air: $M = 0.57$ $SD = 0.85$ s.

Discriminant analysis was then conducted in order to determine whether the eleven variables of the paragraph copy task (six process and five product variables) could predict group membership (i.e., children with DCD versus children without DCD). One discriminate function was found for group classification of all participants (Wilks' Lambda = .51; $p < .0001$). As shown in Table 4, the highest predictor was the number erased or overwritten letters (.67). Based on this one function, 85% of the original grouped cases were found to be correctly classified (80% of the DCD group and 90% of the control group). A Kappa value of .70 ($p < .0001$) demonstrated that the group classification did not occur by chance.

The other variables that contributed to group differentiation were global legibility (.55); mean pressure for the whole task (−.54); mean tilt for the whole task (−.53); spatial

Table 2
A comparison between DCD and control handwriting process measures: name writing, alphabet sequence, and paragraph copying tasks

Measures	DCD $n = 20$		Control $n = 20$		$t(38)$	p
	M	SD	M	SD		
Name writing task						
On-paper time per stroke (s)	.58	.28	.38	.15	3.08	.010
In-air time per stroke (s)	.86	.81	.37	.13	2.94	.01
Mean stroke width (mm)	.22	.07	.24	.07	.43	.54
Mean stroke height (mm)	.45	.11	.47	.12	.64	.49
Mean pressure of the whole task (non-scaled units 0–1024)	680.56	168.64	841.25	117.52	3.13	.002**
Mean tilt for the whole task	59.59	9.26	63.91	7.84	1.52	.13
Alphabet sequence task						
On-paper time per stroke (s)	.64	.44	.33	.08	3.62	.005**
In-air time per stroke (s)	1.05	.54	.54	.19	3.74	.001**
Mean stroke width (mm)	.26	.07	.25	.07	.43	.74
Mean stroke height (mm)	.45	.11	.42	.12	.55	.52
Mean pressure of the whole task (non-scaled units 0–1024)	755.46	126.47	826.09	115.42	1.66	.07
Mean tilt for the whole task	59.36	7.54	64.05	8.37	1.96	.05
Paragraph copying task						
On-paper time per stroke (s)	.63	.41	.37	.08	3.18	.008**
In-air time per stroke (s)	1.27	1.00	.61	.27	3.27	.007**
Mean stroke width (mm)	.24	.05	.23	.06	.65	.55
Mean stroke height (mm)	.47	.12	.45	.14	.68	.58
Mean pressure of the whole task (non-scaled units 0–1024)	708.21	134.02	832.63	105.11	1.66	.002**
Mean tilt for the whole task	56.09	6.76	61.56	8.09	2.42	.020

** $p \leqslant .008$.

Table 3
Means and standard deviations of the handwriting product measures (HHE) for both groups

Measures	DCD $n = 24$		Control $n = 20$		p
	M	SD	M	SD	
Number of letters written in the first minute	28.55	16.66	50.05	17.35	<.001**
Global legibility	2.45	1.05	1.25	1.94	.03*
Letters erased or overwritten	2.70	1.71	.90	1.02	.001**
Unrecognizable letters	2.15	3.74	1.75	.78	.62
Spatial arrangement	9.00	2.36	7.35	1.38	.02*

* $p < .05$; ** $p < .01$.

arrangement (.45); and number of letters written in the first minute (−.43). The values of the other measures are presented in Table 4.

4. Discussion

The aim of this study was to compare the handwriting process and product characteristics of children with DCD to those of typically developing (TD) children in order to find the variables that will best differentiate between the two groups. This would represent a

Table 4
The discriminant analysis structure matrix including process (ComPET) and product (HHE) variables of the paragraph copy task

	Function 1
Letters erased or overwritten (HHE)	.67
Global legibility (HHE)	.55
Mean pressure of the whole task (ComPET)	−.54
Mean tilt for the whole task (ComPET)	−.53
Spatial arrangement (HHE)	.45
Number of letters written in the first minute (HHE)	−.43
Mean stroke duration on-paper (ComPET)	.24
Mean stroke duration in-air (ComPET)	.24
Unrecognizable letters (HHE)	.13
Mean stroke width (ComPET)	−.09
Mean stroke height (ComPET)	.035

first step towards developing a practical and ecologically valid handwriting evaluation for the needs of this population.

Previous studies have emphasized two main components for evaluation of the effectiveness of handwriting performance: speed and legibility (see Rosenblum et al., 2003 for more details). Speed was measured in the current study by the number of letters per minute (HHE measure), on-paper and in-air time (ComPET measures), while legibility was measured in accordance with HHE criteria.

When considering the handwriting process results, it is interesting that in two out of the three tasks – the building blocks task (alphabet sequence) and the more prolonged and demanding task (paragraph copying) – significant differences were consistently found between the groups in the temporal measure means for on-paper and in-air time per stroke (ComPET variables). These results were further supported by the number of letters written in the first minute of the paragraph copying task (HHE variable).

These results are compatible with previous findings about deficits among children with DCD in relation to timing, duration, and sequencing of movement (Barnhart et al., 2003; Missiuna, Rivard, & Bartlett, 2003), as well as those on the "slowness in movement" among this population (Henderson, Rose, & Henderson, 1992; van der Meulen, Denier van der Gon, Gielen, Gooskens, & Willemse, 1991). It seems that the temporal processing deficit is inherent and is not dependent on the kind of task that the child with DCD performs. Even while writing their name, which is very familiar and assumed to be automatic after at least 1 year of handwriting practice in school, the children with DCD were slower than the TD children. More studies are required in order to examine whether the current study results provide evidence for abnormal cerebellar function among children with DCD, as indicated by O'Hare and Khalid (2002).

In that context, it is interesting that no significant differences were found for stroke height and length, despite previous results showing that letter size is an indicator of handwriting development, with smaller letters representing greater sensory-motor maturity (Levine, 2001). If letter size is actually indicative of the degree of sensory-motor maturity, the results of the current study hint of no differences in that regard between children with DCD and TD children. These findings are compatible with previous conclusions that sensory-motor deficits are not the sole or principal cause for handwriting deficiency (Barnhart et al., 2003).

Similar to the findings for stroke height and length, no significant differences were found between the groups for pen tilt. Pen tilt refers to the angle between the pen and its projection on the tablet. This measure may be influenced by the pen grip pattern, which is in turn affected by the level of sensory-motor maturity. Smyth and Mason (1997) found that children with DCD did not differ from controls in selecting pen grips which would allow end-state comfort for writing performance. However, there is no clear link between Smyth and Mason (1997) study and the current study results. Further research is required in order to examine whether there is a correlation between the objective pen tilt measure and the measures used to evaluate pen grips, and whether pen tilt and other objective measures provided by the digitizer, such as pen azimuth (see Rosenblum, Chevion, & Weiss, 2006 for more details), may reinforce previous descriptions about immature pencil grasp among children with DCD (Missiuna & Pollock, 1995).

Another interesting finding is that in both the name writing and the paragraph copying tasks, the children with DCD exerted significantly lower mean pressure in comparison to the control children. These results are not in line with clinical reports about the excessive pressure applied by children with DCD on the writing surface (Missiuna & Pollock, 1995). However, it may be that this result is a manifestation of the decreased strength and power found among children with DCD between the ages of 6 and 9 years (e.g., O'Beirne, Larkin, & Cable, 1994; Raynor, 2001). If indeed the pressure applied on the writing surface is a manifestation of this decrease in strength, then it would be a valuable indicator in light of the secondary effects on children's participation in sports and leisure activities (Missiuna et al., 2003). In any case, it is important to note that this finding requires further research using a system that will enable a more precise measurement of pressure as gram per area in order to compare across studies. The system used in the current study was limited and in fact measured the pressure in non-scaled units. Based on the results of high discriminant values for both tilt (−.54) and pressure (−.53), it appears that further research on those measures while implementing more sophisticated analysis methods is needed (e.g., Rosenblum et al., 2006).

A clue to the handwriting performance mechanism of children with DCD can be found in the results of the in-air measure. In previous studies, we found that the in-air time measure may supply information about the perceptual aspect of the motor act (e.g., Werner et al., 2006). Practically, in considering the results of both on-paper and in-air movements, it is not yet clear as to whether children with DCD have slow movements per se or whether they have difficulty with motor memory for letter formation or difficulty in visualizing the letters as needed to form them rapidly. Those difficulties may stem from the kind of deficits previously found among children with DCD, such as deficits in speed of kinesthetic information processing (Smyth & Mason, 1997); visual memory (Dwyer & Mckenzie, 1994); motor programming and motor imagery (Wilson, Maruff, Ives, & Currie, 2001); or visual spatial organization (Piek & Dyck, 2004). Additional clues about the mechanism of their writing may be concealed in the product variables and in the results of the discriminant analysis.

The results of the HHE product measures in the current study demonstrated deficits in spatial organization among the children with DCD. Although, as mentioned previously, no significant differences were found between the groups for stroke length and height, significant differences were found for global legibility, letters erased or overwritten, and spatial arrangement. Moreover, these product variables appear to be the best discriminators between the groups and may provide support for previous findings on visuo-spatial processing deficits (Wilson & McKenzie, 1998) and deficits in spatial accuracy (Kagerer et al., 2004) among children with DCD.

Hence, the combination of both prolonged in-air time as well as more letters erased or overwritten indeed points to deficits in the ability to keep letter formation in memory and to form the letters in a sequenced manner within an organized pattern in time and space. Based on process and product variables, the results of the current study show that children with DCD have deficits in both factors required for functional handwriting: speed and legibility. It seems that children with DCD write significantly slower, apply less pressure on the writing surface, invest more energy in time-consuming overwriting and erasures, and still have a more unreadable handwriting product than their typically developing peers.

Previous studies have indicated that such deficits may influence other aspects of the lives of children with DCD, including their overall academic success, emotional well-being, and social functioning (Cornhill & Case-Smith, 1996; Graham, Harris, & Fink, 2000; Martlew, 1992). These literature findings reinforce the importance of identifying handwriting difficulties as early as possible, both as a preventive and as a corrective aid (Phelps & Stempel, 1988). This need is especially pressing among children with DCD because of possible relationships between coordination problems, handwriting deficits, dyspraxia and dyslexia, which may signify that they are at risk for literacy acquisition problems (O'Hare & Khalid, 2002).

Study limitations: The study group was small (although even smaller sample sizes are conventional in previous studies about DCD). Most participants were boys, thus raising a question about the ability to generalize the results to girls. Furthermore, the study was done in Hebrew, which involves non-continuous writing. More studies are required in order to examine the meaning of such measures as in-air time in other languages with continuous writing, such as English or French.

5. Conclusions

Evaluation of children with both process and product measures provides an impression about handwriting performance while raising further questions regarding the handwriting mechanisms of these children. Based on the results, focusing on the kind of tasks given and on sophisticated analysis methods may advance our knowledge about handwriting performance among this population. From a practical point of view, the attention of teachers and parents to children who are not managing to write within a reasonable time, who are busy in letter corrections, and whose handwriting is illegible can assist in identifying children with DCD who are struggling with handwriting difficulties.

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