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ADHD AND DYSGRAPHIA: UNDERLYING MECHANISMS

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Abstract

Multiple complaints in the domain of writing are common among children with Attention Deficit Hyperactivity Disorder (ADHD). In this work we sought to characterize the writing disorder by studying dysgraphia in twenty 6th grade boys with ADHD and normal reading skills matched to 20 healthy boys who served as a comparison group. Dysgraphia, defined as deficits in spelling and handwriting, was assessed according to neuropsychological explanatory processes within 3 primary domains: linguistic processing, motor programming and motor kinematics. Children with ADHD made significantly more spelling errors, but showed a unique pattern introducing letter insertions, substitutions, transpositions and omissions. This error type, also known as graphemic buffer errors, can be explained by impaired attention aspects needed for motor planning. Kinematic manifestations of writing deficits were fast, inaccurate and an inefficient written product accompanied by higher levels of axial pen pressure. These results suggest that the spelling errors and writing deficits seen in children with ADHD and normal reading skills stem primarily from non-linguistic deficits, while linguistic factors play a secondary role. Recommendations for remediation include educational interventions, use of word processing and judicious use of psychostimulants.

Key words: learning disabilities, agraphia, attention deficit hyperactivity disorder, handwriting, spelling

Introduction

The core symptoms of the neurobehavioral syndrome Attention Deficit Hyperactivity Disorder (ADHD) as defined by the DSM-IV (American Psychiatric Association, 1994) are inattention, impulsivity and hyperactivity. The level of attention of these children is inappropriate and they have difficulty concentrating, appear not to listen and are easily distracted. Their impulsivity is manifested by difficulty in self-restraint and the hyperactivity by fidgetiness or difficulty sitting in one place for any extended period of time. The symptoms present generally before age 7 years, for at least 6 months and significantly affect the social and academic domains. The prevalence of comorbid learning disabilities is high and overall ranges between 25%-50%; most notable are dyslexia, dyscalculia and disorders of spelling and written expression (Barkley, 1997; Mayes et al., 2000; Sattler et al., 2001).

Disorders of written expression are defined as a combination of difficulties in an individual's ability to compose written text that are manifested by illegible handwriting, letter shape distortions, dysfluent writing, spelling errors and difficulty in written expression of ideas that cannot be attributed to disabilities in reading or oral expression (DSM IV – American Psychiatric Association, 1994). The term dysgraphia, which is one component within the broad definition of disorders of written expression, refers to illegible handwriting and spelling errors (Deuel, 2001). Handwriting is one of the basic academic skills in which children with ADHD are impaired (Barkley, 1998) and spelling errors are also common in these children (Kroese et al., 2000; Mayes et al., 2000). Little is known about the underlying mechanisms of dysgraphia in ADHD and the neuropsychological processes that contribute to this deficit, although these two conditions are considered to have a shared genetic etiology (Stevenson et al., 1993).

Handwriting is a complex skill that combines motor and linguistic components and is acquired over an extended period of time. Neuropsychological models suggest that the linguistic component of handwriting matches words to their graphemic representation, whereas the non-linguistic, motor, component translates orthographic representations into writing (Ellis, 1982; Houghton and Zorzi, 2003; Margolin, 1984; Roeltgen, 2000).

In alphabetic scripts, the sequence of written symbols is intended to represent words, and written graphemes stand for spoken phonemes. Children use a sublexical sound – spelling conversion process by which phoneme-grapheme relationship is employed in order to convert a spoken word into corresponding graphemic representation, termed orthographic representation. As children become aware of the structure of words of their language, namely they learn the morphological units, and as children adept at writing, they enter into the orthographic phase, at which time they have memorized a lexicon of ready-to-use orthographic representations of frequent words (Frith, 1986; Houghton and Zorzi, 2003; Ravid, 2001). During writing, orthographic representations are channeled into a non-linguistic route, with motor programming and motor-kinematic components. The motor programming component comprises several subunits: the graphemic buffer, which is the short term working memory necessary for attention to and retention of the correct orthographic representation; the allographic mechanisms necessary for case selection and differentiation among similar shaped letters; the graphemic motor patterns related to letter production; and the spatial representations needed to write on a horizontal line (Ellis, 1982; Margolin, 1984; Roeltgen, 2000; Zesiger et al., 1997). The subsequent kinematic component is responsible for regulation of overall force level, tempo, size and consistency of written letters (Smits-Engelsman and Van Galen, 1997). Preschool children initially draw letters, but with practice during the first years of school, the graphic motor patterns, although visually guided, become established (Adi-Japha and Freeman, 2001; Berninger and Hart, 1992; Jones and Christensen, 1999). Writing skills shift from visually guided to automated writing at early adolescence (Adi-Japha and Freeman, 2001; Ravid, 2001).

Mastering reading together with writing leads to the creation of connections among word orthography and word phonology, handwriting and spelling skills, with subsequent linkage of linguistics and motor components of writing (Berninger et al., 2002). According to Duel (2001), developmental dysgraphia can result from deficits in the domains involved, i.e., dyslexic (linguistic) dysgraphia and dysgraphia due to motor clumsiness, or from defect in understanding of space. The linguistic component of spelling assumes that reading speeds up acquisition of lexical semantic writing processes, suggesting that dysgraphia is secondary to insufficient exposure to the written word (Abbott and Berninger, 1993; Goswami, 1992). One report implicates impaired phonemic processing for spelling errors in children with ADHD and normal reading skills (Kroese et al., 2000), a finding that needs to be confirmed. Automaticity of phonemic processes is necessary for fluency of writing and reading (Nicolson and Fawcett, 1990).

The motor programming component of spelling and writing presumes that spelling mistakes and handwriting difficulties stem from impaired retention of graphemes and their related motor patterns. Deficits to the motor kinematic component result in impaired parameter setting of force level, tempo and size, in inefficient and dysfluent writing, that interrupts the acquisition of automaticity (Smits-Engelsman and Van Galen, 1997). One study reports an impaired graphic parameter setting in children with ADHD and inaccurate spatial performance (Schoemaker et al., 2005), an impairment that characterizes dysgraphic children (Smits-Engelsman and Van Galen, 1997).

The object of this study was to examine the dysgraphic elements, spelling and handwriting, in children with normal reading skills and ADHD and to identify underlying explanatory mechanisms of dysgraphia in this syndrome. We assessed dysgraphia using standardized spelling tests and handwriting production that provide information on both linguistic and motor components of writing. Given that the group of children with ADHD had normal reading skills, we hypothesized that dysgraphic elements would result primarily from non-linguistic components.

Methods

Subjects

The participants in the study were 20 right handed (determined by the hand used for writing, verified by parental or teacher report), 6th grade boys, aged 11-13 year olds (mean age, mean = 145.25 month, SD = 5.76) with ADHD-combined type (i.e., characterized as inattentive, and hyperactive-impulsive), normal IQ (mean = 108.25, SD = 12.51), and a comparison group of boys without ADHD, matched according to age (mean = 146.80, SD = 3.65), handiness and IQ (mean = 107.60, SD = 11.32). All children attended mainstream schools and were fluent Hebrew speakers (see Appendix on features of the Hebrew writing system). Children who had a history of reading problems were excluded a priori. The diagnosis of ADHD was made by a competent pediatric neurologist from the Neuropediatric Unit (one of two authors of this study, Varda Gross-Tsur or Ruth S. Shalev) and was based on DSM-IV criteria (American Psychiatric Association, 1994). Each child underwent a clinical neurological examination according to a modified version of Touwen and Prechtl (1970) neurodevelopmental examination. The 20 boys who served as a comparison group did not have ADHD based on their developmental history and confirmed by the DSM-IV criteria (American Psychiatric Association, 1994) as reported by teachers. None of the participants in the study had a reading disability, as reported by the parents and verified from school records. All participants were from middle to upper-middle class socio-economic backgrounds (Abramson, 1982). Inclusion criteria were an IQ score of 85 or above, performance within 1.6 standard deviation on the reading assessment (Hammill, 1990) and ability to reasonably copy a picture of a flower. The drawing or copying of a flower and other more complex items are part of visual-motor dysfunction assessments (e.g., Bertrand et al., 1997; Marshall and Halligan, 1993), and flower recognition is the simplest item and takes the shortest time to produce (Bertrand et al., 1997). One child tested for the comparison group was excluded from the study because he failed this test. The group of children with ADHD and the comparison group did not differ in terms of age, IQ, or speed of reading (Z = 1.13, .14 and 1.40, respectively, p's > .1). The assessment took place during school holidays and those participants normally treated with psychostimulants were off medication for at least a week. The research protocol was approved by the institution's internal review board and parental consent was obtained for all children participating in the study.

Procedure

All children underwent the following tests in a quiet room. The testing procedure lasted for 50-55 minutes. In tests assessing spelling and handwriting, children wrote on lined paper-sheets, with red marked right margin (because Hebrew is written from left to write, see Appendix), similar to those used at school. A separate sheet of paper was provided for each task, and each item was written in a separate line.

I.Q. WISC-R IQ (shortened version based on scores of vocabulary and block design subtests; Sattler, 1990).

Linguistic Knowledge

Children's linguistic knowledge was assessed using standardized reading tests, standardized reading related tests, and standardized spelling tests. The Shani and Ben-Dror pivotal test (reported in Shani et al., 2001), and the Nitzan Battery (Shalem and Lachman, 1998) were used to assess reading and reading-related abilities. We used the following subtests: speed of reading, phonemic awareness, rapid naming test for letters [Shani and Ben-Dror pivotal test (Shani et al., 2001)] and basic level of orthographic knowledge [Nitzan Battery (Shalem and Lachman, 1998)]. The Shani and Ben-Dror pivotal test (Shani et al., 2001) was used to assess spelling. We used the following subtests: high frequency function words (13 words), free morphemes (12 words), derivational words (10 words), and words with similar sound letters (e.g., b-p sounds, as in marble, 8 words). Each of the dictated words was written by participants after being articulated for 3 times: separately, as part of a sentence, and again separately [Shani and Ben-Dror Pivotal Test (Shani et al., 2001)]. We also assessed the writing of nonsense derivational words (12 words; for screening phonologic dysgraphia, see Roeltgen, 2000).

The words in the spelling test were further analyzed using lexical (omission of silent letter resulting in a non-word, e.g., whether – wether, 8 words of the original list), semantic (e.g., knight – night, 6 words) and phonologic plausible (substitution for similar but mostly identical sounding letters, e.g., vacation – vacation) categories. Because of the special features of the Hebrew language, see Appendix, the possibility of phonologic plausible error applies to all 43 words in the spelling test.

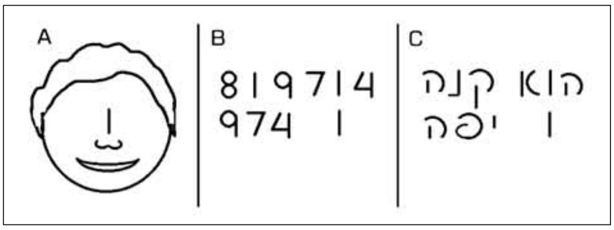

Fig. 1 – *A) Drawing the eyes of a face. B) Completion of two zeros. C) Completion of two circular letters.*

Motor Programming

The following components of motor programming of writing were assessed: graphemic buffer errors, allographic errors, motor patterns of graphemes, and spatial disorders. Graphemic buffer errors were tested by reanalyzing the spelling test for letters' insertions, substitutions, transpositions and omissions, that are not semantic, lexical or phonological errors. The number of committed errors in a task of 3 two-word combinations (8 repeats each) that include similar shaped Hebrew script letters (e.g., [illegible], [illegible], total of 24 two-word combination), was used as a measure of allographic errors. Fluency of written letters (measures as explained below, in the kinematic production section), was used to evaluate the quality of graphemic motor patterns (Zesiger et al., 1997). Deflection from horizontal line in writing of 10 lines was used as a measure of spatial disorder (Roeltgen, 2000).

Motor Kinematic Production

Motor kinematic production was tested for writing efficiency and consistency, writing practice and graphic accuracy. Writing efficiency and consistency was assessed by writing single Hebrew letters, each with 8 repeats (1 cm spacing between letters) and words of different length (3-4 letters and 6-8 letters; Tov-Lee, 2000). Words in the spelling test (item 2 in the linguistic component assessment) were analyzed for type-of-letter correction and shape correction. For assessing writing practice (Adi-Japha and Freeman, 2001), children were asked to produce the same geometrical shapes (circles) in different notation systems: Drawing the eyes of a face, completion of two zeros in a string of 0l0 (zero one zero) and completion of two circular identical letters (O) in a 3 string word (סוס translates in Hebrew to horse; see Figure 1). Graphic accuracy was tested by asking subjects to draw repetitively an ellipse (Viviani and Schneider, 1991).

Kinematic production aspects of writing, including writing time, speed of writing, axial pen pressure, time utilization, fluency and consistency, basic graphic and writing practice, were assessed

TABLE IA

Linguistic component: z-scores of reading related abilities and spelling of different morphological categories, for children with ADHD and for the comparison group

	ADHD		Comparison group		
	Mean	SD	Mean	SD	Z*
Reading related abilities					
Letter naming	.66	.84	.32	.66	1.74
Phoneme omission	.19	.68	.23	.89	.48
Phoneme manipulation	.06	.68	.32	.61	.76
Orthographic (% correct)	99.41	.35	98.87	.61	.9
Spelling					
Function words	– .33	.67	.37	.69	3.27**
Free morphemes	– .12	.92	.66	.68	3.07*
Derivational words	– .40	1.33	.81	.79	3.11*
Similar sound letters	– .91	1.23	– .46	.88	1.17
Nonsense words (% correct)	86.67	1.00	90.67	.97	1.01

Note. Z denotes value of the Mann-Whitney test.
*p < .01, **p < .001.

directly and by further analysis of the graphic production. The kinematic and spatial aspects of graphic production were recorded using a digitized graphics tablet (WACOM; sampling rate 200Hz, nominal accuracy .02 mm) attached to a portable computer. Children wrote on lined paper-sheets similar to those used at school. Writing stylus resembles a ball-point pen and is sensitive to pressure of 30-400 g. Each shape produced yielded 3 target kinematic measures consisting of: (a) shape production time (measured in sec); (b) speed of writing (measured in mm/sec); and (c) number of acceleration-alternations as a measure of fluency. As a spatial measure, each shape produced yielded the length of the writing sample along the X-axis and Y-axis (measured in mm). Writing time was further divided into time spent while writing on paper and time spent in the air while moving from letter to letter (air time). Time utilization refers to their relative proportion. Fluency measures accelerations and de-accelerations in the velocity of writing and was quantified by the number of acceleration alternations during the production of a letter (Adi-Japha and Freeman, 2000; Tucha and Lange, 2001). Consistency was appraised by the coefficient of variation (CV = SD/mean). The lower the noise (variance) relative to the signal (the mean) the more consistent is the writing sample. Production time, speed of writing and pressure were analyzed in all motor-kinematic production tasks: ellipse tracing, writing practice, single letters, short and long words. Fluency of writing is assessed only during writing (where air periods are not considered), and hence only in the writing practice task and single letters task. Time utilization is appraised only for word production, where both writing time and air time are relevant to the task. Consistency was appraised only in the single letter tasks.

Data Analysis

Differences between children with ADHD and their comparison group were analyzed using Mann-Whitney test for two independent samples and using Fisher's exact test for the number of children in each group presenting specific writing behavior. Differences within groups were analyzed using the nonparametric Friedman test for repeated measures. For *post-hoc* analysis we used the Wilcoxon signed ranks test for 2 related samples. Nonparametric tests were chosen because parametric tests, for this sample size, require normally distributed data. This requirement is not fulfilled for some of our measures as errors committed by participants and the fluency of handwriting, which are based upon discrete (rather than continuous) calculation. In using nonparametric test we follow a similar study testing kinematic aspects of handwriting in similar populations and using similar sample size (Tucha and Lange, 2001). Statistical tests are two-tailed, alpha level is .05.

Results

The results are presented according to the three components of dysgraphia tested: linguistic, motor programming and motor kinematic production.

Linguistic Knowledge

The results demonstrated that the group with ADHD and the comparison group performed similarly on reading speed, letter naming and phoneme manipulation (Table IA). The achievement in reading related tasks of the children with ADHD was in sharp contrast to their poor performance on most of the spelling tests although facets of writing were differentially affected.

Significantly more spelling errors were seen in children with ADHD in the categories of word morphology tested: function words (high frequency words), free morphemes (i.e., house or horse) and derivational words (i.e., their house or his horse), but not similar sound letters. Within groups analyses demonstrated that the effect of word

TABLE IB

Linguistic component: spelling errors distribution by number of children and number of errors

	N of children with spelling errors		Fisher's exact test	N of errors		
	ADHD	Comparison	P	ADHD	Comparison	Z*
Lexical	15	9	.053	45	18	2.27*
Semantic	8	6	.741	17	11	.72
Phonologically plausible	16	11	.088	61	21	2.24*
Overall	18	15	.204	123	50	3.56**

Note. Z denotes value of the Mann-Whitney test.
*p < .05, **p < .01.

category on spelling of children with ADHD was not significant (χ^2 = 2.15, df = 2, p > .1), whereas this effect for the comparison group was significant (χ^2 = 16.30, df = 2, p < .001). *Post-hoc* analysis revealed, as expected, that frequently appearing function words were, for the comparison group, the easiest to spell (comparing function words to free morphemes and to derivational words Z = 3.00, p < .01; and Z = 2,21, p < .03, respectively, with no significant difference between the two latter, Z = 1.46, p > .1).

The written product was further analyzed using lexical (omission of silent letter resulting in a non-word, e.g., whether – wether), semantic (e.g., knight – night) and phonologically plausible (substitution for similar but mostly identical sounding letters, e.g., vacation – vakation) categories. Children with ADHD made significantly more errors in the lexical and phonologically plausible categories, although these errors were apparent in the comparison group as well (Table IB). There were no differences in their written product when analyzed for orthographic representations of nonsense words indicating that children with ADHD do not have problems in phoneme-grapheme conversion.

In summary, the children with ADHD had reading and reading-related abilities that were similar to those of the children in the comparison group. By contrast, children with ADHD made more spelling errors in the morphological categories tested (function words, free morphemes, and derivational words). Their errors were also qualitatively different from those of the children in the comparison group in that their spelling did not benefit from frequently appearing words. Although many children from both groups had lexical and phonologically plausible errors, children with ADHD made significantly more errors.

Motor Programming

A second analysis of the words in the spelling test focused on graphemic errors in writing manifested by letter insertions, substitutions, transpositions and omissions (see Table IIA for analysis and Table IIB in Appendix for examples). Errors were counted as graphemic errors only if they could not be attributed to semantic, lexical or phonologically plausible errors, that is, errors in Table IIA are different than those reported in Table IB. These graphemic buffer letter errors were seen predominantly in the group of children with ADHD to the extent of 65% of children with ADHD *versus* 15% of the comparison group. Of the four types of graphemic buffer errors, children with ADHD mostly displayed transpositions (Table IIA), and most insertions were repetition of letters (Table IIB).

Analysis of writing of words with similar shaped letters demonstrates that children with ADHD mistakenly retrieve letters with similar shapes (Table IIA). They also tend to replace an end-of-word letter with its simpler and more common version for middle-of-the-word (9/20 children in the ADHD group, 1/20 in the comparison group (see Appendix for end-of-word *vs.* middle-of-word letters) (Fisher's Exact test, p < .01). In contrast, writing fluency of single letters did not differ between children with ADHD and children in the comparison group (Z = 1.72, p >

TABLE IIA

Motor programming component: spelling errors distribution by number of children and number of errors

	N of children with spelling errors		Fisher's exact test	N of errors		
	ADHD	Comparison	P	ADHD	Comparison	Z*
Graphemic buffer letter errors						
Insertions	4	1	.091	6	1	1.48
Substitutions	3	0	.115	4	0	1.77
Transpositions	10	2	.007**	14	2	2.82*
Omissions	2	0	.244	2	0	1.00
Overall	13	3	.003***	26	3	3.52**
Similar shaped letters						
Letter confusion	19	13	.044*	59	24	2.27**

Note. Z denotes value of the Mann-Whitney test.
*p < .05, **p < .01, ***p < .001.

TABLE IIB
Typical graphemic buffer letter errors

Type of error	Correct Hebrew spelling and its English pronunciation		Letter errors embedded in words and their English pronunciation	
Repetition	אהבותיהם	AHAVOTIEHEM	אהבוותיהם	AHAVVOTIE
	יזכור	YIZCOR	יזכורר	HEM YIZCORR
Omission	יתקדם	YITKADEM	יתקם	YITKAM
	מחשבתו	MAHSHAVTO	מחשב	MAHSHV
Substitution	אם	EIM	תם	TIM
	מדפסת	MADPESETH	מדפמת	MADPEMET
Transposition	חקלאי, אהב	HAKLAI, AHAV	חקלאי, אהב	HAKALI, HAV

.08) and the written product of the children with ADHD showed no spatial disturbances and was placed straight on the lines (Z = .20, p > .1).

In summary, children with ADHD made more graphemic buffer letter errors (letter insertions, substitutions, transpositions and omissions). They also confused similar shaped letters, and replaced end-of-word letter with its simpler and more common middle-of-the-word version. By contrast, fluency did not differ significantly between groups nor were there spatial disturbances as measured by the deflection from horizontal line.

Motor Kinematic Production

Time utilization results showed that for children with ADHD, air time depended on the complexity of the letter. A main effect of letter appeared only for the ADHD group (χ^2 = 13.60, df = 4, p < .01), but not for the comparison group (χ^2 = 5.88, df = 4, p > .1), suggesting that production of complex letters requires expenditure of more time. The longest air time was measured for the complex end-of-word letter ץ (see Appendix). The second task for which time utilization was measured was writing two word lists: short and long words. Children with ADHD required more time to produce long (but not short) words, (Z = 2.24, p < .03). The difference was the added time children with ADHD needed to write the letters, (Z = 2.62, p < .01), and not due to the time spent moving from letter to letter.

Consistency assessed by the repeated letter task, showed that the mean height of the letters was significantly inconsistent for the ADHD group, (Z = 3.21, p < .001). The poor quality of handwriting in children with ADHD was manifested both on tests of spelling and writing. Individual letters were spatially disproportionate and significantly wider than expected when writing single letters or short and long words (Table IIIA). In addition, children with ADHD made more corrections of the shape of the letter (Z = 3.03, p < .01).

Graphic tests were administered to differentiate between impaired motor regulation seen in ADHD (Barkley, 1997) and insufficient writing experience resulting in poor motor programming. Writing practice was assessed using graphic tests that discriminate between writing (letters and numbers) and drawing (circles). Results demonstrated that both the comparison group and the group of children with ADHD, had learned how to write adequately, as evidenced by the fact that writing required less time to produce (ADHD: χ^2 = 8.31, df = 4, p < .02; comparison group: χ^2 = 9.33, df = 4, p < .01), with no group differences (drawing: Z = .06, p > .1; letters: Z = .34, p > .1; numbers: Z = .31, p > .1). *Post-hoc* tests revealed significant differences in production time between drawing and letter writing (Z = 3.68, p < .001), and drawing and number writing (Z = 2.40, p < .02), with no significant difference between letter and number writing (Z = 1.87, p > .06). Fluency of writing presented a similar picture, accordingly, writing was more fluent than drawing, significant only for the comparison group (ADHD: χ^2 = 8.31, df = 4, p < .1; comparison group: χ^2 = 9.33, df = 4, p < .01) with no group differences (drawing: Z = .02, p > .1; letters: Z = .14, p > .1; numbers: Z = .05, p > .1). *Post-hoc* tests revealed that letter writing was more fluent than drawing for both children with ADHD (Z = 2.18, p < .03), and children in the comparison group (Z = 2.94, p < .01). Children with ADHD differed somewhat from children in the comparison group in that they demonstrated a continuum of fluency, with writing

TABLE IIIA
Kinematic production: components of writing – Mean size of item in task

	Width (mm)					Height (mm)				
	ADHD		Comparison			ADHD		Comparison		
	Mean	SD	Mean	SD	Z*	Mean	SD	Mean	SD	Z*
Single letters	5.55	1.26	4.73	1.70	2.60**	10.46	1.96	9.37	2.44	1.79
Short words	15.26	3.87	11.00	3.62	3.64***	10.21	2.83	8.99	2.64	1.62
Long words	29.51	7.95	20.38	6.21	3.79***	11.67	4.15	9.13	2.63	2.35*

Note. Z denotes value of the Mann-Whitney test.
*p < .05, **p < .01, ***p < .001.

TABLE IIIB

Kinematic production: components of writing – Speed and axial pen pressure

	Speed (mm/sec)					Axial pen pressure (g)				
	ADHD		Comparison			ADHD		Comparison		
	Mean	SD	Mean	SD	Z*	Mean	SD	Mean	SD	Z*
Ellipse tracing	125.20	79.09	60.05	57.97	3.37***	196.68	22.17	188.22	31.86	.76
Writing practice	12.97	4.29	5.26	3.79	4.27***	323.75	38.30	289.79	32.39	2.18*
Single letters (8 repeats)	10.71	3.69	10.20	3.82	.24	320.12	33.77	298.38	34.32	2.00*
Short words (7 words)	7.95	2.08	7.55	2.27	.63	300.33	34.55	260.01	28.15	3.51**
Long words (7 words)	7.83	2.00	7.30	2.31	.87	289.33	37.86	251.64	32.73	2.95**

Note. Z denotes value of the Mann-Whitney test.
*p < .05, **p < .01, ***p < .001.

letters as most fluent, followed by numbers while the drawing was the least fluent. Comparison group children significantly wrote numbers more fluently than they drew circles (Z = 2.11, p < .04), while for children with ADHD this difference was only marginal (Z = 1.73, p < .09).

However, in a graphic accuracy test requiring repetitive tracing of an ellipse, the children with ADHD were faster but less accurate than children in the comparison group. The variance for children with ADHD was .61 ± .16 cm, almost twice as that of the comparison group .29 ± .13 cm (Z = 3.32, p < .01). There was a speed-accuracy trade off; their erratic performance correlated positively with speed (Table IIIB) (Pearson's r > .9, df = 20, p < .001, for both groups). Their graphic product was characterized by higher speed of production for both drawing and writing while increased axial pen pressure was seen only in the writing exercises, accentuated by task complexity (see Table IIIB).

In summary, when writing, children with ADHD displayed poor time utilization, produced inconsistent and disproportionate writing accompanied by high levels of pressure and multiple corrections. The results of the graphic tests suggest that these writing deficits do not stem from insufficient writing experience.

We attempted to categorize a child as dysgraphic according to the following criteria: if there were spelling errors of over 1.6 SD than the mean of those obtained by the comparison group and secondly if the handwriting was disproportionately wider for the long word task, again 1.6 SD wider than the mean obtained by the comparison group. Twelve children in the ADHD group and 1 of the comparison group fulfilled both criteria (Fisher's exact test, p < .001).

Discussion

The objective of the study was to assess the presence of dysgraphic elements in the written product of children with ADHD and normal reading skills within the context of neuropsychological processes. The majority of our group of children with ADHD demonstrated dysgraphia, a finding consistent with parental reports that children with ADHD make multiple spelling errors and their writing is difficult to read. We found that the dysgraphic elements that were present in this group of children with ADHD, i.e., spelling errors and illegible handwriting, could primarily be attributed to motor programming (Ellis, 1982; Margolin, 1984; Roeltgen, 2000; Zesiger et al., 1997) and motor kinematic production (Smits-Engelsman and Van Galen, 1997) components of handwriting.

The spelling errors made by children with ADHD were multifaceted and present in different word categories. We found that both study and comparison group children made lexical and phonologically plausible spelling errors and mistakes between similar shaped letters. However, the children with ADHD were unique in the frequency with which they inserted superfluous letters and omitted, substituted or transposed letters, error types predicted by disruption of the graphemic buffer. They also made end-of-word letter substitutions with the simpler middle-word letter, as predicted by disruption at the allographic level. These error types are known to be typical for adult patients with attention deficits (Friedmann and Gvion, 2001; Glosser et al., 1999) or with lesion sites associated with impaired attention (Hillis and Caramazza, 1989), but have not been reported in children with ADHD.

Kinematic production aspects of writing were also impaired in this group of children with ADHD, impacting on their everyday function in school. We found that children with ADHD spent more time when writing, foremost when writing long words and due to their excessive corrections. Furthermore, they produced letters and words that were inconsistent and disproportionate in size. These factors probably contribute to their inefficient and illegible written production and inability to stay within the predetermined time limits for writing and copying in the schoolroom.

Our results indicate that handwriting problems of this group of children with ADHD and normal reading skills result from impaired motor processes rather than lack of experience or training. Indeed, assessment of writing demonstrated that children with ADHD had acquired the writing basics. However, to gain better control when writing, children with ADHD increased the mean pen pressure and the resulting product was still disproportionate with no effect on fluency. Increasing pen pressure has been reported to exist in the graphic production of children with ADHD (Schoemaker et al., 2005) but has been shown to only partially improve handwriting (Van Gemmert and Van Galen, 1997). Clinically this may correspond to the complaint these children have that their hand is stiff, hurts and tires quickly when writing.

It remains to be determined whether the graphemic buffer letter errors encountered by our group stem from impaired orthographic representation or from impaired retention of the orthographic representation within the graphemic buffer (Mather, 2003). In our group of children with ADHD with age appropriate phonological and reading skills, letter errors were mostly not-phonologically plausible. Thus it is more likely that impaired retention of the orthographic representation accounts for their spelling errors rather than impaired orthographic representation. The finding that word frequency did not affect spelling errors in the group of children with ADHD further supports this assumption (Miceli et al., 1997). Lexical knowledge in this group was somewhat impaired, as demonstrated by the omission of silent letters embedded in words. Perhaps impaired lexical knowledge may trigger graphemic buffer errors.

What is the neurological substrate involved in dysgraphia in children with ADHD? Areas that are known to subserve writing and are altered in ADHD are the premotor cortices and right cerebellum (Roeltgen, 2000; Docking et al., 2003; Seidman et al., 2005). The left premotor cortex is thought to play a role in retrieval of graphic letter images from given phonemes (Tohgi et al., 1995) while the cerebellum, with its rich neuroanatomical connections with premotor cortices, impacts on writing, visuomotor skills, and linguistic non-motor skills (Docking et al., 2003; Fabbro et al., 2004; Katanoda et al., 2001). These network connections may possibly suggest that the dysgraphic elements: spelling errors, poor proficiency and automaticity, in children with ADHD are linked. A linkage between the cerebellum and impaired automaticity of motor and linguistc processes has been reported for dyslexia (Nicolson et al., 1995; Fawcett and Nicolson, 1995).

The conclusions must be considered within the limitations of the study. Our sample was composed of only 20 boys with ADHD. Three of the children in our ADHD group and one of the children in the comparison group were reported as having undefined writing problems. However, neurological assessment proved that they were not dyspraxic, nor did they have non-writing graphical problems as tested by their ability to draw. Our tests of visual-motor ability were limited to deflection from the horizontal line so that we could rule out dysgraphia secondary to spatial disorder (Roeltgen 2000; Deuel, 2001). Future studies should include dysgraphic children who do not have ADHD to enable exploration of mechanisms specific to ADHD. Standardized motor tests or tests of working memory are relevant in this context and may clarify the relation between motor skills, writing, spelling disorders and higher order executive function in ADHD.

In summary, we suggest that, at least in part, spelling and writing problems in children with ADHD are associated with attentional problems, are non linguistic in nature, and, more specifically, reflect an impairment in the graphemic buffer and in kinematic motor production. The combined therapeutic interventions for children with ADHD and dysgraphia should address these deficits and include both pharmacological therapy to enhance attention skills and educational interventions. Teaching children to use written language is one of the main goals of school curriculum and, in spite of their normal intelligence and reading skills, children with ADHD are more likely to experience difficulty in this domain. In addition to acquiring conventional writing skills, word processing software may prove to be very valuable. Innovative programs that provide letters shapes and spell check possibilities reduce the complexity of the motor demands of writing (Deuel, 2001; Hetzroni and Shrieber, 2004) may free children from the constant need to check and correct their spelling and handwriting and enable them to utilize those higher cognitive processes needed for competent written expression.

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Appendix

Features of the Hebrew writing system

Hebrew reading and writing is from right to left. The Hebrew writing system consists of 22 letters and from second grade onward children use script writing only. Hebrew writing is discontinuous. Writing duration is composed of two components: writing the letters themselves and the time it takes moving from letter to letter.

Hebrew words, from third grade onwards, are written without their vowels and hence can be read in more than one way, i.e., they become homographs. Their meaning can be determined only by top-down processing, by considering the context in which they appear. In an analogy with English, this situation may be said to appear in "unvoweled" English words. Consider the letter string SNG as if it is the root of the words: sing, song and sung. The result is that Hebrew readers rely more heavily on contextual, semantic and pragmatic information (Shimron, 1999).

The result of the above orthography is two fold: to write a word correctly, the writer has to identify the root letters and the morphological structure. This is the reason for using linguistic based spelling lists [Shani and Ben-Dror Pivotal Test (Shani et al., 2001)]. In addition, when vowels do appear in words (as silent letters), they may be considered by the unskilled writer as redundant information and dropped, or be less attended to. This is a source for lexical difficulty. Written Hebrew words only rarely contain double consonant letters.

There are two types of one-to-many relationships between Hebrew phonology and unvoweled spelling: Firstly, a number of phonemes are expressed each by two graphemes, e.g., c/k sounds. Conversely, three letters denote two distinct sounds, e.g., the letter B indicates both the phonemes b and v. Spelling errors typically occur in the 13 homophonous Hebrew letters that together designate 6 phonemes (Ravid, 2001).

In Hebrew writing there are 5/22 letters that are written differently when they appear as the last letter in the word. These five letters are כ,מ,נ,צ,פ and are written as ך,ם,ן,ץ,ף when they appear as end-of-word letters. The last two (ף,ץ) are both complex to produce and are frequently confused by beginning writers.