Predictors of handwriting performance among children with autism spectrum disorder

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A R T I C L E   I N F O

A B S T R A C T

Background: Literature indicates that deficient handwriting abilities among children with autism spectrum disorder (ASD) relate especially to their overall legibility and speed. The aim of this study was to investigate further whether the handwriting production process in children with ASD relates to lower-level processes, such as visual perception, motor coordination, and visual-motor integration, and to higher-level processes, such as executive functions.

Method: Sixty children aged 9–12 years, including 30 children with ASD and 30 controls with typical development participated in the study. Parents completed the Behavior Rating Inventory of Executive Function (BRIEF) questionnaire. The children were tested using the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI-V) and performed a story-writing task on a sheet of paper affixed to an electroic tablet of ComPET, a computerized penmanship evaluation tool.

Results: Significant differences were found between children with ASD and children with typical development in executive function, in all BRIEF scales, and in the visual-motor integration and motor coordination sections of the VMI-V, but not in the VMI-V visual-perception subtest. Visual-motor integration did not predict handwriting process measures. However, executive functions—specifically working memory and shifting—correlated with the handwriting process measures of children with ASD and were found to predict the handwriting.

Conclusion: The results of this study provide further insight into the handwriting difficulties of children with ASD by highlighting the role of executive functions, specifically working memory and shifting, in the story-writing process of children with ASD.

1. Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental condition that affects an individual's social communication and interaction. The Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM–5; American Psychiatric Association, 2013) defined that individuals with ASD display restricted, repetitive patterns of behavior and may have hyper- or hypo-reactivity to

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sensory input. These characteristics may affect an individual's academic progress and achievement. According to the DSM-5, three levels of severity are determined by the level of impact of the communication and behavioral symptoms and the amount of support required. Level 1 is the least severe and requires only partial support. Individuals diagnosed with Level 1 severity are often in-dependent in performing activities of daily living and can use language skills, including written language expression, to communicate and participate in typical school activities (Volkmar & Lord, 2007).

Written expression is a primary means through which students demonstrate their knowledge and views. Writing is a highly complex activity that requires coordination of multiple simultaneous demands involving (a) the mechanics of writing, including handwriting, spelling, sentence construction, and typing; (b) the written content, including ideation, genre, and vocabulary; and (c) organization (Finnegan & Accardo, 2018). The production of written text involves simultaneous processing of motor and cognitive demands (Jones & Christensen, 1999). Whereas the term *writing* includes production of the written content and grammatical aspects, the term *handwriting* describes the actual mechanical production of written letters, words, and sentences on paper (Graham, Harris, & Fink, 2000; Medwell & Wary, 2010; Ziviani & Wallen, 2006). Handwriting is essential for children's academic functioning because most of a child's school day is dedicated to written assignments, such as taking notes and tests, doing homework, and writing papers (McHale & Cermak, 1992; Weintraub, Drory-Asayag, Dekel, Jokobovits, & Parush, 2007). Enhanced handwriting skills, including automaticity and improved fluency, occur predominantly up through Grade 4 (Blote & Hamstra-Bletz, 1991; Karlsdottir & Stefansson, 2002). Difficulties in acquiring and applying these skills subsequently lead to problems such as slow writing and illegible written products (Rosenblum & Dror, 2017). Such difficulties may have implications on the child's successful participation in school and play activities, potentially leading to problems in academic performance and lowered self-esteem (Barnett, Prunty, & Rosenblum, 2018; Engel-Yeger, Nagauker-Yanuv, & Rosenblum, 2009). Therefore, students with handwriting difficulties are especially prone to frus-tration, disappointment, and underachievement (Sandler et al., 1992).

Previous studies indicated that children with ASD, including those who have intelligence levels within the normal range, have handwriting characteristics that differ from handwriting samples of children with typical development (TD). Among the few studies that characterized handwriting of children with ASD, commonly reported problems relate to poor overall legibility, letter formation, and spacing between words (Alaniz, Galit, Necesito, & Rosario, 2015; Cartmill, Rodger, & Ziviani, 2009; Fuentes, Mostofsky, & Bastian, 2009; Kushki, Chau, & Anagnostou, 2011), as well as difficulty maintaining consistent letter size (Cartmill et al., 2009; Hellinckx, Roeyers, & Van Waelvelde, 2013).

In a meta-analysis of 13 studies, Finnegan and Accardo (2018) compared the performance in written expression of individuals with ASD and their counterparts with TD. Finnegan and Accardo's results showed significant differences in performance of both spelling and handwriting, confirming lower performance in handwriting of those with ASD compared to children with TD. The individuals with ASD scored lower in handwriting measures such as legibility and speed, and their handwriting was larger in size. Although the above-mentioned studies related to the handwriting products of children with ASD, research about handwriting process characteristics that reflect their handwriting-production mechanisms is scarce.

In a previous study, significant differences were found between children with ASD and children with TD in handwriting process measures of three writing tasks: name-writing, paragraph-copying, and freestyle-writing tasks. Children with ASD wrote with sig-nificantly wider and higher pen strokes and required significantly more time to create the pen strokes on-paper and in-air, that is between letters and words, when the pen was not in contact with the paper (Rosenblum, Ben, Simhon, & Gal, 2016). Freestyle-writing tasks are commonly performed and essential for academics and self-satisfaction. Therefore, the previous studies' results raised questions concerning the possible mechanisms that underlie the handwriting performance of children with ASD.

Written text production involves lower-level perceptual–motor and higher-level cognitive processes that interact continuously (Abbott & Berninger, 1993; Graham & Weintraub, 1996; Van Galen, 1991). As soon as the low-level visual-motor processes become relatively automatic, the high-level processes (e.g., planning, language generation, reading, and editing) can be activated con-currently, as they are in adult writing. Without this automaticity, the relationships between motor and cognitive processes may disrupt the flow and planning of ideas and their translation into written form, affecting the complexity and coherency of the text (Graham & Weintraub, 1996; Jones & Christensen, 1999).

This paper aims to achieve better insight about the relations between handwriting production via the handwriting process measures and the low- and high-level processes among children with ASD. Low-level processes include visual perception, motor coordination, and visual-motor integration (Cornhill & Case-Smith, 1996; Daly, Kelley, & Krauss, 2003; Goyen & Duff, 2005; Jones & Christensen, 1999; Karlsdottir & Stefansson, 2002; Volman, van Schendel, & Jongmans, 2006). Visual perception is an information process that takes place in the cortex (Rosblad, 2002). It includes several components, such as visual tracking, depth perception, and the perception of character and background. These elements are essential in movement planning and motor performance (Willoughby & Polatajko, 1995). Visual-motor integration is the coordination between visual perception and movement of fingers, typically assessed based on the children's ability to copy geometric forms using pencil and paper (Beery, Buktenica, & Beery, 2004).

Children's visual-motor integration abilities during kindergarten were found to correlate significantly with their school readiness (e.g., Daly et al., 2003). Furthermore, eye–hand coordination and visual-motor integration development is necessary for learning to write (Kaiser, Albaret, & Doudin, 2009). Moreover, visual-motor abilities significantly correlate with writing legibility among school-aged children (e.g., Goyen & Duff, 2005; Volman et al., 2006).

Motor skills are a main predictor of handwriting performance in children with ASD aged 8–13 years (Fuentes et al., 2009). In addition, age, gender, and visual-motor integration were found to be significant predictors of handwriting quality; and age, reading abilities, and fine motor coordination were predictors of handwriting speed among children with ASD (Hellinckx et al., 2013). Mayes and Calhoun (2007) directly compared grapho-motor abilities among children with ASD, children with dysgraphia, and children with TD using the Developmental Test of Visual-Motor Integration (VMI-4; Beery, 1997) and the coding subtest of the WISC-III (Kaufman,

1994). Their study revealed that children with ASD and children with dysgraphia performed significantly inferior both on the VMI and in their handwriting performance (Mayes & Calhoun, 2007). Beside deficient visual-motor integration abilities, deficient executive functions (EF) abilities were described among children with ASD (Hill & Bird, 2006; Hill, 2004). The EF are higher-order control abilities, such as attention, inhibition, planning, working memory, initiation, and shifting, necessary to guide behavior in changing environments (Dawson & Guare, 2018; Robinson, Goddard, Dritschel, Wisley, & Howlin, 2009).

Several authors linked nonsocial behavioral symptoms of children with ASD to possible EF deficiency (Ozonoff, Pennington, & Rogers, 1991; Rajendran & Mitchell, 2007). Following an extensive review, Hill (2004) marked the need for improved controlled studies to find the causal relationships between autistic symptomatology and executive deficits (Robinson et al., 2009). In that context, following the evidence from the available literature about visual-motor and EF deficits among children with ASD and their implications for movement planning and motor performance, the aim of this study was to find the relationships between the visual-motor and EF components and writing production measures within a story-writing task. Specifically, we aimed to investigate whether there are significant differences between children with and without ASD in their (a) visual, motor, and visual-motor abilities and (b) EF, assuming that visual-motor and EF ability measures will well differentiate between the two groups. We also investigated correlations between the handwriting process measures of the story-writing task and the visual-motor and EF abilities among children with and without ASD and whether visual-motor scores and EF domains contribute to predicting the mean time required for pen-stroke production in the story-writing task beyond group membership.

2. Method

2.1. Participants

A group of 60 children aged 9–12 years, including 30 children with ASD (27 boys and three girls) and 30 controls with TD (27 boys and three girls) participated in the study. The groups were matched by chronological age, school year, gender, and hand dominance. All the children had normal intelligence levels (ASD: 104.15 ± 12.96; Controls: 109.83 ± 7.81) based on the Peabody vocabulary subtest (Dunn & Dunn, 2007), and all the mothers had at least 12 years of education. No significant group differences were found in these or other demographic variables.

The participants with ASD were recruited from schools in Northern Israel. The children in the ASD group were diagnosed by a certified professional (i.e., developmental neurologist, psychiatrist, or clinical psychologist) and met the criteria for ASD according to the DSM-5 (APA, 2013) and the Autism Diagnostic Observation Schedule–Generic (ADOS-G) (Lord et al., 2000). All participants had a full-scale IQ score greater than 80, as determined by the Peabody Picture Vocabulary Test (Dunn & Dunn, 2007). They spoke fluent Hebrew, were in their third year of school, and had acquired basic writing skills. None of the children suffered from physical or mental conditions that may affect handwriting (e.g., seizures, fragile X syndrome, or cerebral palsy) or had uncorrected visual or hearing impairments. The control group was comprised of children with no record of neurological or developmental disorders as reported by the parents or teaching staff. For a detailed description of the study participants and demographic characteristics, see Rosenblum et al. (2016).

2.2. Instruments and measures

2.2.1. Computerized penmanship evaluation tool (ComPET; Rosenblum, Parush, & Weiss, 2003)

The ComPET is an online computerized handwriting evaluation tool comprised of a laptop computer, data collection and analysis software, and an electronic tablet (digitizer). It collects and analyzes objective measures while the child writes on a page affixed to a WACOM Intuos 2 (model GD 0912-12 × 18) x–y digitizing tablet with a wireless electronic ink pen that has a pressure-sensitive tip (Model GP-110). The data were sampled at 100 Hz on a laptop computer. The children were shown a social picture of children in a schoolyard and asked to write a story about what they saw in the picture. They also performed the Developmental Test of Visual-Motor Integration (VMI-V; Beery et al., 2004). The following measures were used to characterize the written strokes performed on paper:
  1. Temporal measures (in seconds):
      1.a. The mean on-paper stroke duration
      1.b. The mean in-air stroke duration (when the pen is raised above the paper)
  2. Spatial measures:
      2.a. The mean total stroke width (on the X-axis) in millimeters, a measure of the direct distance from the left to the right side of the stroke
      2.b. The mean stroke height (on the Y-axis) in millimeters, a measure of the direct distance from the lowest to the highest point of the written stroke

In addition, the mean pen tilt (i.e., the angle between the pen and its projection on the tablet's surface ranging from 0° to 90°) was measured.

2.2.2. Behavioral rating inventory of EF (BRIEF)–parent form (Gioia, Isquith, Guy, & Kenworthy, 2000)

The BRIEF parent questionnaire was designed to assess EF of 5- to 18-year-old children. The BRIEF includes 86 statements divided into the behavioral regulation index, which incorporates three subdomains (inhibition, shifting, and emotional control), and the metacognition index, which incorporates five subdomains (initiation, working, memory, planning/organization, organization of

materials, and monitoring). Parents rate the frequency in which the behavior described in each statement occurs. The three optional responses are converted into numbers (1 = never, 2 = sometimes, 3 = always). The behavioral regulation and metacognition indexes scores are combined to obtain an overall global executive composite. A composite of 50 represents the average standard score. A standard score of 65 and above (1.5 *SD*) indicates an executive deficit.

2.2.3. The VMI-V (Beery et al., 2004)

The VMI-V is a standardized pencil-and-paper test for children aged 2–18 years. The test aims to identify difficulties in co-ordination between visual perception and motor abilities and includes 30 geometric forms of increasing complexity. Participants are instructed to copy without erasing. The test has two additional standardized subtests using the same geometric forms: (a) the visual-perception (VP) test, including identification of an identical form among other similar figures and (b) the motor-coordination (MC) test, including tracing the forms. Based on criteria in the manual, each form is scored as correct or incorrect. The figures drawn (VMI), identified (VP), or traced (MC) correctly are counted, and scores are converted into standard scores (*M* = 100, *SD* = 15).

2.3. Procedure

The study was approved by the institutional Ethics Committee of the University of Haifa and by the Israeli Ministry of Education and was performed in the participants' mainstream schools. Parents signed informed consent forms and completed the demographic and BRIEF questionnaires. After we obtained the parents' signed informed consent, the children signed the consent forms. The second author met each child in a quiet room at the school and confirmed their intelligence levels as normal according to the Peabody test (Dunn & Dunn, 2007). Then, the children completed the VMI-V and handwriting tasks on a page affixed to the electronic tablet of the ComPET (Rosenblum et al., 2003).

2.4. Statistical analysis

Data were analyzed using IBM SPSS Statistics 19. To examine whether the children with ASD and the controls differed with respect to the visual-motor and EF abilities, the Mann-Whitney U test for non-parametric variables (non-normal distribution of the dependent variables) was applied.

Discriminant analyses were conducted to determine which variables best predicted group membership. Correlations between the handwriting process measures and visual-motor and EF abilities were tested using Spearman analyses. Regression analysis was applied to test whether the visual-motor and EF measures predict the handwriting performance time per written pen stroke in the story-writing task.

3. Results

3.1. Comparison of VMI-V, VP, and MC abilities between groups

As presented in Table 1, the Mann-Whitney analysis for the VMI-V and its two subtests, VP and MC (Beery et al., 2004) indicated significant group differences only for the VMI and the MC scores. Medium to high effect sizes were found for the executive VMI (r ¼ .45) and MC (r ¼ .58) scores.

3.2. Comparison of EF between groups

As presented in Table 2, the Mann-Whitney analysis for the EF domains indicated significant group differences in all the BRIEF scale scores. Medium to high effect sizes were found for the eight scales (ranging from r ¼ .30 to r ¼ .79).

3.3. Group discrimination based on the handwriting-process kinematic measures, VMI-V (Beery et al., 2004) and EF domain scores (BRIEF)

To assess the relative importance of each variable in differentiating between the children with ASD and the controls, a discriminant analysis was performed. The independent variables included in the first stage were the story-writing task kinematic process

Table 1
Group Differences for VMI-V Scores.

Test	ASD (n = 30) M (SD)	TD (n = 30) M (SD)	U	Z	r
Visual-motor integration (VMI)	88.93 (16.725)	105.97 (11.705)	213.0	−3.51***	.45
Visual perception (VP)	97.47 (16.437)	104.73 (13.706)	348.0	−1.51	.19
Motor coordination (MC)	77.80 (18.230)	97.93 (10.810)	145.0	−4.51***	.58

Note. VMI-V = Developmental Test of Visual-Motor Integration; ASD = Autism Spectrum Disorder.
TD = typical development.
r = .1 small effect size, .3 medium effect size, .5 large effect size.
** *p* ≤ .01. *** *p* ≤ . 001.

Table 2
Comparison of BRIEF Scores Between Groups.

BRIEF domain	ASD ($n = 26$) M (SD)	TD ($n = 27$) M (SD)	U	Z	r
Inhibition	57.54 (12.17)	42.44 (5.17)	78.0	− 4.89***	.67
Shift	68.85 (12.71)	50.30 (8.77)	77.0	− 4.89***	.67
Emotional control	61.81 (13.02)	46.59 (8.67)	122.5	− 4.07***	.56
Initiative	59.50 (9.56)	46.44 (7.16)	102.0	− 4.45***	.61
Working memory	60.85 (7.62)	42.93 (4.44)	26.0	− 5.79***	.79
Planning/organization	58.15 (10.07)	44.56 (6.09)	83.0	− 4.78***	.66
Organization of materials	50.88 (9.84)	45.00 (9.34)	227.5	− 2.20***	.30
Monitoring	57.08 (12.51)	40.74 (7.10)	95.0	− 4.56***	.63

Note. BRIEF = Behavior Rating Inventory of Executive Function; ASD = Autism Spectrum Disorder; TD = typical development. The sample size of the BRIEF scores is 26 (ASD) and 27 (TD) because seven BRIEF questionnaires were not filled in and returned.
$r = .1$ small effect size, .3 medium effect size, .5 large effect size.
$^{**}p \leq .01. ^{***}p \leq .001.$

measures (mean pen stroke for duration on paper and in air, height, width, and pen tilt), visual-motor (VMI, VP, and MC), and EF scores (inhibition, shift, emotional control, initiation, working memory, planning/organization, organization of materials and monitoring). As based on one function ($\Lambda = .233$; $p < .001$), 96.2% of the children were correctly classified. Variable reduction resulted in the most differentiating variables without a decrease in the discriminant value. At the end of this process, based on one function ($\Lambda = .275$; $p < .001$), 96.2% of all the children, 92.3% of the children with ASD, and 100% of the controls were correctly classified. A Kappa value of .94 ($p < .001$) was calculated, demonstrating that group classification did not occur by chance. As presented in Table 3, the variables found to have the highest predictive values were the working memory (.91) and shifting (.54) EF (BRIEF) domains.

3.4. Correlations between handwriting-process kinematic measures and visual–motor scores

No significant correlations were found between handwriting kinematic measures (mean pen stroke tilt, time on paper, in air, pen stroke width, and height) of the story-writing task and visual-motor scores (VMI, VP, and MC) in the control group. Significant correlations were found in the ASD group between the MC score and both the pen stroke duration on paper ($r = -.363, p > 05$) and the mean stroke height ($r = -.409, p < .01$).

3.5. Correlations between handwriting-process kinematic measures and EF domains scores

Significant correlations were found in the control group between the mean handwriting pressure and the BRIEF EF domain *inhibition* (r = .392, p < .05). The significant correlations found between the handwriting-process kinematic measures and EF domains among the ASD group are presented in Table 4.

In the next phase, a stepwise regression analysis was performed with the VMI-V and BRIEF scores included as predictors of the mean stroke duration above group membership. As presented in Table 5, the group accounted for 17% of the variance to prediction of mean stroke duration ($F(1,52) = 10.42$, $\beta = -.41$, $p = .002$), and working memory added 15% to prediction of stroke's duration ($F(2,50) = 11.73$, $\beta = .69$, $p < .001$).

4. Discussion

The purpose of this study was to investigate whether low-level processes such as visual perception, motor coordination, and visual-motor integration, and high-level processes, such as EF, differ in children with ASD compared to controls with TD and to assess how the processes relate to the handwriting production measures of a story-writing task in these groups. A previous study (Rosenblum et al., 2016) suggested differences between children with ASD and those with TD in both the handwriting product and

Table 3
Discriminant Analysis Structure: Matrix Predictor Loading Values.

BRIEF domain	Function
Working memory	.908
Shifting	.536
Planning/organization	.518
Inhibition	.511
Monitor	.507
Initiate	.487
Emotional control	.434

Table 4

Significant Correlations ($r > .3$) Between Handwriting Kinematic Measures of Story-Writing Task and BRIEF EF Domains, ASD Group.

Test	Mean stroke duration on-paper	Mean stroke duration in-air	Mean stroke width	Mean stroke height	Mean pen stroke tilt
Working memory	.491**	.509**			
Shifting	.	.			−.476*

BRIEF = Behavior Rating Inventory of Executive Function; EF = Executive functions; ASD = Autism Spectrum Disorder.

Note. *$p < .05$. **$p < .01$.

Table 5

Predicting Mean Stroke Duration by VMI-V and EF (BRIEF) Domain Scores.

Variable	Model 1			Model 2		
	b	SE b	β	b	SE b	β
Group	−.317	.098	−.412	.122	.160	.158**
Working memory				.024	.007	.689**
R^2 (Adjusted r^2)	.17			.32		
F change in R^2	17**			15**		

Note: VMI-V = Developmental Test of Visual-Motor Integration; EF = executive functions; BRIEF = Behavior Rating Inventory of Executive Function.

**$p < .01$.

the process measures. Specifically, compared to the children with TD, the handwriting of children with ASD was less legible and organized, and the children were slower to produce the written outcome. The results of the current study add to the previous literature and suggest further significant differences between the two groups in low- and high-level processes.

The significantly lower scores in the visual-motor integration and motor coordination domains of the VMI-V for the children with ASD support previous literature that indicated poor motor and visual-motor deficits in children with ASD (Alaniz et al., 2015; Fuentes et al., 2009; Johnson et al., 2013). However, our study did not reveal differences between children with and without ASD in visual perception. This suggests that the major contributor to the visual-motor integration challenges that children with ASD face is the motor domain rather than the visual-perception domain. Moreover, the large standard deviation found in the visual-perception test in both groups suggests there were children in both groups with visual-perception skills above the norm. This aligns with previous studies demonstrating that children with ASD have an average or above-average range of visual perceptions (Hellinckx et al., 2013; Schlooz & Hulstijn, 2012). Evidence suggests that individuals with ASD have some superior visual-performance skills, such as visual search abilities (Simmons et al., 2009) and in performing visual tasks that require attention to local details (Happé & Frith, 2006).

Some literature suggested that visual-motor integration abilities form the basis for and are predictive of handwriting quality (Cornhill & Case-Smith, 1996; Kaiser et al., 2009; Maki, Voeten, Vauras, & Poskiparta, 2001; Weintraub & Graham, 2000). However, the results of the current study only partially supported this notion. The significant correlations between the VMI motor score and the mean pen stroke duration on paper and the mean stroke height of the story-writing task were found in the ASD group only, and not among the TD controls. These correlations indicate relationships between the motor ability and the temporal and spatial aspects of the handwriting production in children with ASD. However, these results are not fully in accordance with those of Hellinckx et al. (2013), who found significant correlations between all three VMI scores and both handwriting quality and fluency. This dissimilarity may be explained by the different task type and measures used in the different studies. Hellinckx et al. asked children to copy a standard text as quickly and neatly as they were used to doing, on unruled paper for 5 min or until the first five sentences had been written. However, in the current study, children were asked to freely write a story based on a picture. Furthermore, the written quality in Hellinckx et al.'s study was analyzed by judgment of varied criteria on a scale of 0–2 (with an alpha Cronbach of .67), whereas the focus of the current study was on varied objective kinematic measures of the process of the story-writing. Thus, further studies may evaluate the correlations between VMI scores and objective measures of both the writing process and the written quality of varied prolonged writing tasks such as those required in school (copying, free writing, dictation, etc.)

Similar to part of the current study results, other studies did not support the predictive value of visual-motor integration to the quality of handwriting measured concurrently or longitudinally (Goyen & Duff, 2005; Marr & Cermak, 2002). Nevertheless, both previous studies that identified or rejected such relationships had investigated the quality of handwriting by means of legibility and speed, whereas the current study addressed handwriting-process kinematic measures.

Investigation of EF via the BRIEF assessment (Gioia et al., 2000) revealed significant differences between the children with ASD and those with TD in the general score and in all the BRIEF domains with high effect sizes. Indeed, previous studies that investigated EF in ASD revealed constant EF impairments, especially in cognitive flexibility, planning, and working memory, but also in shifting attention and response inhibition (Brian, Tipper, Weaver, & Bryson, 2003; Courchesne et al., 1994).

In the current study, EF significantly differed between children with and without ASD and correlated with handwriting-process kinematic measures among the children with ASD. Results found among the TD controls linked the mean writing pressure with the inhibition ability. These findings may present evidence of the importance of inhibition for daily performance (Barkley, 1997), as expressed through the production of handwriting activity.

Among participants with ASD, significant correlations were found between working memory and the stroke duration on-paper and in-air, and shifting significantly correlated with the mean pen stroke tilt. These correlations were not observed among the children with TD. Moreover, not only did working memory have the highest predictive values in discriminating between children with and without ASD, but a stepwise regression analysis also showed that this variable added 15% above group membership to the prediction of the stroke's duration among children with ASD. Working memory is typically described as a central EF system used for temporarily processing, manipulating, storing, and retrieving information to help complete cognitively demanding tasks (Baddeley, 2012). Working memory is in fact responsible for active maintenance and manipulation of information over brief periods (Miyake & Shah, 1999). Some studies related working memory to higher-level cognition, including measures of episodic memory, reasoning, and reading comprehension (Barrouillet & Lecas, 1999; Kane & Engle, 2000; Lustig, May, & Hasher, 2001). Working memory processes also constrain the development of composition skills in students with and without learning disabilities (Berninger, 1999). The current study further relates working memory to the handwriting process and specifically to the duration of the pen stroke on paper and in air.

Interestingly, this relationship was observed only among the children with ASD and not among the children with TD. Investigation of individual differences of working memory in young adults related working memory to the ability to control attention, particularly under conditions of interference or distraction (Engle & Kane, 2004). Handwriting for children aged 9–12 years with TD is an automatic activity. However, one can assume that for children with ASD—who are known to have more EF problems—handwriting, and specifically within the context of story-writing, may be challenging and particularly affected by even minor distractions. The performance time of written tasks in schools has been found to relate to writing quality (Connelly, Dockrell, & Barnett, 2005). As such, exposure of the underlying mechanism for slowness among children with ASD may lead to development of intervention methods that improve performance duration and written quality.

Shifting is another EF domain we found to have a high predictive value of the mean stroke time, although it was not as highly predictive as working memory. This gap may be explained by the fact that working memory is needed for the actual handwriting production (Rosenblum et al., 2016); however, when the pen is on the paper and in the air between the letters or words, shifting is mainly required for the motions and is, therefore, less predictive than working memory.

Shifting ability was also found in correlation with the mean pen stroke tilt. Pen tilt, the angle between the pen and its projection on the tablet, ranges between 0 and 90˚. In an earlier study, the pen tilt of children with ASD was significantly lower than that of children without ASD. That is, children with ASD do not change the angle of the pen in relation to the tablet, as required when forming the shapes of the different letters (Rosenblum et al., 2016). Similar differences were observed in a previous paragraph-copying task among children with and without developmental coordination disorders (Rosenblum & Livneh-Zirinsky, 2008). The pen tilt coefficient of variance is a normalized measure of dispersion in a probability distribution, which may in fact reflect the variability of an individual's performance related to pen movements. This was previously associated to the motor abilities of children with developmental coordination disorders and to their daily organizational ability in class (Rosenblum, 2015; Rosenblum & Livneh-Zirinsky, 2008).

However, in the current study, pen tilt was related to shifting in children with ASD. Shifting involves the ability to consciously or unconsciously shift attention between one task and another. It is a subcategory of the broader cognitive-flexibility concept. Task switching or shifting allows a person to adapt rapidly and efficiently to different situations. Deficits in task switching are common among individuals with ASD and has been linked to restricted interest or repetitive-behavior symptoms used to diagnose ASD (Brady et al., 2013; Yerys, Wallace, & Kenworthy, 2009). The current finding is particularly interesting because it attributes a dysfunction in a motor task, such as the pen tilt, to the EF cognitive ability of shifting.

Besides working memory and shifting, the contribution of further EF measures to handwriting production performance time is interesting. Inhibition, monitoring, initiation, and emotional control are required to perform every task (Dawson & Guare, 2018). Therefore, in line with previous literature, it seems that those EF components are inferior among children with ASD (Hill & Bird, 2006; Hill, 2004) and thus contributed to group differentiation.

Because visual-motor integration, and specifically its motor-coordination component, influences the automatization of handwriting, we assumed that deficits in these low-level skills may reflect in the process of handwriting. The results of the current study suggest that the high-level process of working memory and shifting mostly affect handwriting production within the story-writing context among children with ASD, rather than low-level processes such as visual-motor integration. Further research that investigates the various writing tasks (i.e., copying, dictation, and story-writing) in children with ASD is needed to further confirm the roles of low- and high-level underlying mechanisms that affect each type of writing task.

5. Implications

The results of the study may have clinical implications. Accurate assessment by occupational therapists can assist in identifying EF deficits of each individual and determining specific occupation-based handwriting intervention goals directed to improve their EF (Josman & Meyer, 2018) and, accordingly, their handwriting production.

In addition, these results may call for an integrated approach in clinical application that considers both a bottom-up approach focused on improving EF and the more common top-down approaches to improve handwriting quality of children with ASD. Preplanned strategies should be provided at the levels of the handwriting constructions such as letter formation, writing tool precision, and the written content. Further research that includes various writing tasks is recommended to broaden understanding of the mechanisms that specifically affect the handwriting of children with ASD.

6. Limitations

Although the current study shed light on the relationships between visual-motor, EF abilities, and handwriting production process measures, the final quality and quantity of the written products were not evaluated. Hence, the results do not indicate whether visual-motor and EF abilities affect the overall quality of the written composition. Further studies, including measures of the written product, need to be conducted among larger and more representative samples.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgement

References

Abbott, R. D., & Berninger, V. W. (1993). Structural equation modeling of relationships among developmental skills and writing skills in primary-and intermediate-grade writers. *Journal of Educational Psychology, 85*, 478–508. https://doi.org/10.1037/0022-0663.85.3.478.

Alaniz, M. L., Galit, E., Necesito, C. I., & Rosario, E. R. (2015). Hand strength, handwriting, and functional skills in children with autism. *American Journal of Occupational Therapy, 69*. https://doi.org/10.5014/ajot.2015.016022 6904220030p1–6904220030p9.

American Psychiatric Association (2013). *Diagnostic and statistical manual for mental disorders* (5th edition). Washington, DC: Author.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*, 1–29. https://doi.org/10.1146/annurev-psych-120710-100422.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*, 65. https://doi.org/10.1037/0033-2909.121.1.65.

Barnett, A. L., Prunty, M., & Rosenblum, S. (2018). Development of the Handwriting Legibility Scale (HLS): A preliminary examination of reliability and validity. *Research in Developmental Disabilities, 72*, 240–247. https://doi.org/10.1016/j.ridd.2017.11.013.

Barrouillet, P., & Lecas, J. (1999). Mental models in conditional reasoning and working memory. *Thinking & Reasoning, 5*, 289–302. https://doi.org/10.1080/135467899393940.

Beery, K. E. (1997). *The Beery-Buktenica developmental test of visual-motor integration (VMI)* (4th edition). Parsippany, NJ: Modern Curriculum Press.

Beery, K. E., Buktenica, N. A., & Beery, N. A. (2004). *The Beery-Buktenica developmental test of visual-motor integration* (5th edition). Minneapolis, MN: NCS Pearson.

Berninger, V. (1999). Coordinating transcription and text generation in working memory during composing: Automatic and constructive processes. *Learning Disability Quarterly, 22*, 99–112. https://doi.org/10.2307/1511269.

Blote, A. W., & Hamstra-Bletz, L. (1991). A longitudinal study on the structure of handwriting. *Perceptual and Motor Skills, 72*, 983–994. https://doi.org/10.1177/002221949302601007.

Brady, D. I., Schwean, V. L., Saklofske, D. H., McCrimmon, A. W., Montgomery, J. M., & Thorne, K. J. (2013). Conceptual and perceptual set-shifting executive abilities in young adults with Asperger's syndrome. *Research in Autism Spectrum Disorders, 7*, 1631–1637. https://doi.org/10.1016/j.rasd.2013.09.009.

Brian, J. A., Tipper, S. P., Weaver, B., & Bryson, S. E. (2003). Inhibitory mechanisms in autism spectrum disorders: Typical selective inhibition of location versus facilitated perceptual processing. *Journal of Child Psychology and Psychiatry, 44*, 552–560. https://doi.org/10.1111/1469-7610.00144.

Cartmill, L., Rodger, S., & Ziviani, J. (2009). Handwriting of eight-year-old children with autistic spectrum disorder: An exploration. *Journal of Occupational Therapy, Schools, & Early Intervention, 2*, 103–118. https://doi.org/10.1080/19411240903146426.

Connelly, V., Dockrell, J. E., & Barnett, J. (2005). The slow handwriting of undergraduate students constrains overall performance in exam essays. *Educational Psychology, 25*, 99–107. https://doi.org/10.1080/0144341042000294912.

Cornhill, H., & Case-Smith, J. (1996). Factors that relate to good and poor handwriting. *American Journal of Occupational Therapy, 50*, 732–739. https://doi.org/10.5014/ajot.50.9.732.

Courchesne, E., Townsend, J., Akshoomoff, N. A., Saitoh, O., Yeung-Courchesne, R., Lincoln, A. J., ... Lau, L. (1994). Impairment in shifting attention in autistic and cerebellar patients. *Behavioral Neuroscience, 108*, 848–865. https://doi.org/10.1037/0735-7044.108.5.848.

Daly, C. J., Kelley, G. T., & Krauss, A. (2003). Relationship between visual-motor integration and handwriting skills of children in kindergarten: A modified replication study. *American Journal of Occupational Therapy, 57*, 459–462. https://doi.org/10.5014/ajot.57.4.45.

Dawson, P., & Guare, R. (2018). *Executive skills in children and adolescents: A practical guide to assessment and intervention* (3rd edition). New York, NY: Guilford Press.

Dunn, L. M., & Dunn, D. M. (2007). *PPVT-4: Peabody picture vocabulary test.* Bloomington, MN: Pearson Assessments.

Engel-Yeger, B., Nagauker-Yanuv, L., & Rosenblum, S. (2009). Handwriting performance: The relationships between process and product measures, children's self-reports, and perceived self-efficacy. *American Journal of Occupational Therapy, 63*, 182–192. https://doi.org/10.5014/ajot.63.2.182.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Vol. Ed.), *The psychology of learning and motivation: vol. 44*, (pp. 145–199). New York, NY: Elsevier.

Finnegan, E., & Accardo, A. L. (2018). Written expression in individuals with autism spectrum disorder: A meta-analysis. *Journal of Autism and Developmental Disorders, 48*, 868–882. https://doi.org/10.1007/s10803-017-3385-9.

Fuentes, C. T., Mostofsky, S. H., & Bastian, A. J. (2009). Children with autism show specific handwriting impairments. *Neurology, 73*, 1532–1537. https://doi.org/10.1212/WNL.0b013e3181c0d48c.

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2000). *Behavior rating inventory of executive function: BRIEF.* Odessa, FL: Psychological Assessment Resources.

Goyen, T. A., & Duff, S. (2005). Discriminant validity of the Developmental Test of Visual-Motor Integration in relation to children with handwriting dysfunction. *Australian Occupational Therapy Journal, 52*, 109–115. https://doi.org/10.1111/j.1440-1630.2005.00488.x.

Graham, S., & Weintraub, N. (1996). A review of handwriting research: Progress and prospects from 1980 to 1994. *Educational Psychology Review, 8*, 7–87. https://doi.org/10.1007/BF01761831.

Graham, S., Harris, K. R., & Fink, B. (2000). Is handwriting causally related to learning to write? Treatment of handwriting problems in beginning writers. *Journal of Educational Psychology, 92*, 620–633. https://doi.org/10.1037/0022-0663.92.4.620.

Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders, 36*, 5–25. https://doi.org/10.1007/s10803-005-0039-0.

Hellinckx, T., Roeyers, H., & Van Waelvelde, H. (2013). Predictors of handwriting in children with autism spectrum disorder. *Research in Autism Spectrum Disorders, 7*, 176–186. https://doi.org/10.1016/j.rasd.2012.08.009.

Hill, E. L. (2004). Evaluating the theory of executive dysfunction in autism. *Developmental Review, 24*, 189–233. https://doi.org/10.1016/j.dr.2004.01.001.

Hill, E. L., & Bird, C. M. (2006). Executive processes in Asperger syndrome: Patterns of performance in multiple case series. *Neuropsychologia, 44*, 2822–2835. https://doi.org/10.1016/j.neuropsychologia.2006.06.007.

Johnson, B. P., Phillips, J. G., Papadopoulos, N., Fielding, J., Tonge, B., & Rinehart, N. J. (2013). Understanding macrographia in children with autism spectrum disorders. *Research in Developmental Disabilities, 34*, 2917–2926. https://doi.org/10.1016/j.ridd.2013.06.003.

Jones, D., & Christensen, C. A. (1999). Relationship between automaticity in handwriting and students' ability to generate written text. *Journal of Educational Psychology, 91*, 44–49. https://doi.org/10.1037/0022-0663.91.1.44.

Josman, N., & Meyer, S. (2018). Conceptualization and use of executive functions in pediatrics: A scoping review of occupational therapy literature. *Australian Occupational Therapy Journal.* https://doi.org/10.1111/1440-1630.12525 Advance online publication.

Kaiser, M. L., Albaret, J. M., & Doudin, P. A. (2009). Relationship between visual-motor integration, eye-hand coordination, and quality of handwriting. *Journal of Occupational Therapy, Schools, & Early Intervention, 2*, 87–95. https://doi.org/10.1080/19411240903146228.

Kane, M. J., & Engle, R. W. (2000). Working memory capacity, proactive interference, and divided attention: Limits on long-term memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 336–358. https://doi.org/10.1037/0278-7393.26.2.336.

Karlsdottir, R., & Stefansson, T. (2002). Problems in developing functional handwriting (monograph supplement 1-V94). *Perceptual and Motor Skills, 94*, 623–662. https://doi.org/10.2466/PMS.94.2.623-662.

Kaufman, A. S. (1994). *Intelligent testing with the WISC-III.* New York, NY: Wiley.

Kushki, A., Chau, T., & Anagnostou, E. (2011). Handwriting difficulties in children with autism spectrum disorders: A scoping review. *Journal of Autism and Developmental Disorders, 41*, 1706–1716. https://doi.org/10.1007/s10803-011-1206-0.

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Leventhal, B. L., DiLavore, P. C., ... Rutter, M. (2000). The Autism Diagnostic Observation Schedule–Generic: A standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30*, 205–223. https://doi.org/10.1023/A:1005592401947.

Lustig, C., May, C. P., & Hasher, L. (2001). Working memory span and the role of proactive interference. *Journal of Experimental Psychology, 130*, 199–207. https://doi.org/10.1037/0096-3445.130.2.199.

Maki, H. S., Voeten, M. J. M., Vauras, M. M. S., & Poskiparta, E. H. (2001). Predicting writing skill development with word recognition and preschool readiness skills. *Reading and Writing, 14*, 643–672. https://doi.org/10.1023/A:1012071514719.

Marr, D., & Cermak, S. (2002). Predicting handwriting performance of early elementary students with the Developmental Test of Visual-Motor Integration. *Perceptual and Motor Skills, 95*, 661–669. https://doi.org/10.2466/PMS.95.5.661-669.

Mayes, S. D., & Calhoun, S. L. (2007). Learning, attention, writing, and processing speed in typical children and children with ADHD, autism, anxiety, depression, and oppositional-defiant disorder. *Child Neuropsychology, 13*, 469–493. https://doi.org/10.1080/09297040601112773.

McHale, K., & Cermak, S. A. (1992). Fine motor activities in elementary school: Preliminary findings and provisional implications for children with fine motor problems. *American Journal of Occupational Therapy, 46*, 898–903. https://doi.org/10.5014/ajot.46.10.898.

Medwell, J., & Wary, D. (2010). Handwriting and writing. In D. Wyse, R. Andrews, & J. Hoffman (Eds.). *Routledge international handbook of English, language and literacy teaching* (pp. 193–202). New York, NY: Taylor & Francis Group.

Miyake, A., & Shah, P. (1999). *Models of working memory: Mechanisms of active maintenance and executive control.* New York, NY: Cambridge University Press.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology and Psychiatry, 32*, 1081–1105. https://doi.org/10.1111/j.1469-7610.1991.tb00351.x.

Rajendran, G., & Mitchell, P. (2007). Cognitive theories of autism. *Developmental Review, 27*, 224–260. https://doi.org/10.1016/j.dr.2007.02.001.

Robinson, S., Goddard, L., Dritschel, B., Wisley, M., & Howlin, P. (2009). Executive functions in children with autism spectrum disorders. *Brain and Cognition, 71*, 362–368. https://doi.org/10.1016/j.bandc.2009.06.007.

Rosblad, B. (2002). Visual perception in children with developmental coordination disorder. In S. Cermak, & D. Larkin (Eds.). *Developmental coordination disorder* (pp. 104–116). Albany, NY: Delmar Thomson Learning.

Rosenblum, S. (2015). Do motor ability and handwriting kinematic measures predict organizational ability among children with developmental coordination disorders? *Human Movement Science, 43*, 201–215. https://doi.org/10.1016/j.humov.2015.03.014.

Rosenblum, S., & Dror, G. (2017). Identifying developmental dysgraphia utilizing handwriting classification methods. *IEEE Transactions on Human-Machine Systems, 47*, 293–298. https://doi.org/10.1109/THMS.2016.2628799.

Rosenblum, S., & Livneh-Zirinsky, M. (2008). Handwriting process and product characteristics of children diagnosed with developmental coordination disorder. *Human Movement Science, 27*, 200–214. https://doi.org/10.1016/j.humov.2008.02.011.

Rosenblum, S., Ben, A., Simhon, H., & Gal, E. (2016). Unique handwriting performance characteristics of children with high-functioning autism spectrum disorder. *Research in Autism Spectrum Disorders, 23*, 235–244. https://doi.org/10.1016/j.rasd.2015.11.004.

Rosenblum, S., Parush, S., & Weiss, P. L. (2003). Computerized temporal handwriting characteristics of proficient and non-proficient handwriters. *American Journal of Occupational Therapy, 57*, 129–138. https://doi.org/10.5014/ajot.57.2.129.

Sandler, A. D., Watson, T. E., Footo, M., Levine, M. D., Coleman, W. L., & Hooper, S. R. (1992). Neurodevelopmental study of writing disorders in middle childhood. *Journal of Developmental & Behavioral Pediatrics, 13*, 17–23. https://doi.org/10.1097/00004703-199202000-00005.

Schlooz, W. A., & Hulstijn, W. (2012). Atypical visuomotor performance in children with PDD. *Research in Autism Spectrum Disorders, 6*, 326–336. https://doi.org/10.1016/j.rasd.2011.06.006.

Simmons, D. R., Robertson, A. E., McKay, L. S., Toal, E., McAleer, P., & Pollick, F. E. (2009). Vision in autism spectrum disorders. *Vision Research, 49*, 2705–2739. https://doi.org/10.1016/j.visres.2009.08.005.

Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10*, 165–191. https://doi.org/10.1016/0167-9457(91)90003-G.

Volkmar, F., & Lord, C. (2007). Diagnosis and definition of autism and other pervasive developmental disorders. In F. R. Volkmar (Ed.). *Autism and pervasive developmental disorders* (pp. 1–33). (2nd edition). New York, NY: Cambridge University Press.

Volman, M. J. M., van Schendel, B. M., & Jongmans, M. J. (2006). Handwriting difficulties in primary school children: A search for underlying mechanisms. *American Journal of Occupational Therapy, 60*, 451–460. https://doi.org/10.5014/ajot.60.4.451.

Weintraub, N., & Graham, S. (2000). The contribution of gender, orthographic, finger function, and visual-motor processes to the prediction of handwriting status. *OTJR: Occupation, Participation and Health, 20*, 121–140. https://doi.org/10.1177/153944920002000203.

Weintraub, N., Drory-Asayag, A., Dekel, R., Jokobovits, H., & Parush, S. (2007). Developmental trends in handwriting performance among middle school children. *OTJR: Occupation, Participation and Health, 27*, 104–112. https://doi.org/10.1177/153944920702700304.

Willoughby, C., & Polatajko, H. J. (1995). Motor problems in children with developmental coordination disorder: Review of the literature. *American Journal of Occupational Therapy, 49*, 787–794. https://doi.org/10.5014/ajot.49.8.787.

Yerys, B. E., Wallace, G. L., & Kenworthy, L. E. (2009). Set-shifting in children with autism spectrum disorders. *Autism, 13*, 523–538. https://doi.org/10.1177/1362361309335716.

Ziviani, J., & Wallen, M. (2006). The development of graphomotor skills. In A. Henderson, & C. Pehoski (Eds.). *Hand function in the child: Foundations for remediation* (pp. 217–236). St. Louis, MO: Mosby.