Handwriting Speed in Children with Developmental Coordination Disorder: Are They Really Slower?

Mellissa PRUNTY, Anna L. BARNETT, Kate WILMUT and Mandy PLUMB
Oxford Brookes University (School of Health & Life Science)
Gypsy Lane, Oxford, United Kingdom, OX30BP
mellissa.prunty-2010@brookes.ac.uk, abarnett@brookes.ac.uk

Abstract. Handwriting difficulties are often included in descriptions of Developmental Coordination Disorder (DCD). They are cited as the most common reason for referral to health professionals following parent and teacher concerns about slow and untidy writing. The aim of this study was to compare handwriting performance in English children with and without DCD across a range of writing tasks, to gain a better understanding of the nature of 'slowness' so commonly reported. Twenty-eight 8-14 year-old children with a diagnosis of DCD participated in the study, with 28 typically developing age and gender matched controls. Participants completed the four handwriting tasks from the Detailed Assessment of Speed of Handwriting (DASH) and wrote their own name; all on a digitizing writing tablet. The number of words written, speed of pen movements and the time spent pausing during the tasks were calculated. The findings confirmed what many professionals report, that children with DCD produce less text than their peers. However, this was not due to slow movement execution, but rather a higher percentage of time spent pausing. Discussion centres on the understanding of the pausing phenomenon in children with DCD and areas for further research.

1. Introduction

Developmental Coordination Disorder (DCD) is the term used to refer to children who present with motor coordination difficulties, unexplained by a general medical condition, intellectual disability or neurological impairment (American Psychiatric Association [APA], 2000). Children with DCD face many barriers to performance in everyday activities, both at home and at school (Mandich et al., 2003; Missiuna et al., 2007; Stephenson et al., 2008). At home, difficulties with dressing can manifest in tasks such as manipulating buttons and zips, where fine motor manipulation and organisational skills are required (Roger et al., 2003). Within the school environment, these difficulties transfer into a range of school activities (Wang et al., 2009), in particular, handwriting, which is significantly impacted (Miller et al., 2001). Handwriting difficulties are mentioned in the formal diagnostic criteria for DCD (APA, 2000), are frequently mentioned in parent and teacher reports and are the most common reason for referral to occupational therapy for this population (Asher, 2006). Despite this, surprisingly little research has been conducted to investigate handwriting difficulties in children with DCD, most of which, has been conducted in alphabets outside the Latin base (Rosenblum & Livneh-Zirinski, 2008; Chang & Yu, 2010), with very different demands such as writing from right to left and producing different types of letter-shapes (Hebrew & Taiwanese). This poses considerable barriers when attempting to inform best practice in countries using the Latin alphabet.

The complexity of handwriting is a particularly important aspect to consider when studying populations with motor co-ordination difficulties such as DCD, as there are many underlying cognitive factors, which can influence their handwriting performance (Van Galen, 1991). For example, before executing the motor component of handwriting, there are processes that must precede it such as activating the intention to write, generating ideas, retrieving semantics, spelling and selecting the correct allographs (Van Galen, 1991). Handwriting is a very important part of the overall writing process and is therefore recognised as a lower-level component in models of writing (Berninger & Swanson, 1994; Berninger & Amtmann, 2003). When limitations in lower level transcription skills (handwriting & spelling) occur, they can influence the overall writing procedure in terms of the amount of text produced and the quality of written composition (Graham et al., 1997; Berninger et al., 2008). According to Berninger (1999) children's ability to compose text is constrained by two important factors; transcription skills and working memory resources. The more automatic a child's handwriting is, the more working memory is made available to focus on the content of the writing (Berninger & Amtmann, 2003; Kellogg, 2008). However, if a child's handwriting is laboured and not yet automatic, the attentional resources available to focus on higher-level processes such as planning will be limited. It becomes even more complex when a child is asked to balance all of the above processes as quickly as possible during an examination. Handwriting speed becomes crucial in an exam environment, as the child needs to be able to transfer their ideas to the page while trying to keep up with their thoughts (Weintraub & Graham, 1996). Having to write quickly also adds the additional dimension of producing legible text, as there is a crucial trade-off relationship between handwriting speed and legibility (Weintraub & Graham, 1998). For example, when a child writes in their best handwriting, legibility increases while the speed at which it is produced decreases. Similarly, when writing quickly, the legibility will decrease (Weintraub & Graham, 1998). In DCD, the notion of quick movement poses a particular issue, as previous research suggests that children with DCD demonstrate longer movement times than their typically developing peers in a range of fine motor (reaching and/or grasping) tasks (Missiuna, 1994; Plumb et al., 2008; Hyde & Wilson, 2011; Wilmut et al., 2013).

In the available research on handwriting in children with DCD, on-line handwriting performance has been investigated using digitizing writing tablets, which measure the temporal characteristics of handwriting. It has been reported in the literature that children with DCD demonstrate a distinct slowness (produce less text and take longer to produce letter strokes) across a range of handwriting tasks, including copying (Rosenblum et al., 2003; Rosenblum & Livneh-Zirinski, 2008; Chang & Yu, 2010), writing from memory (Rosenblum et al., 2003, Chang & Yu, 2010) and the habitual task of writing ones name (Rosenblum & Livneh-Zirinski, 2008). However, it is not known to what extent these findings can be applied to the Latin based alphabets. Furthermore no study to date has examined speed of performance in the task of free writing, which is perhaps the most common in the classroom and the most demanding in terms of cognitive load. It is also not known whether the slow performance relates to slower movement time in the actual movement of the pen to form letters on the page or whether it actually reflects longer pauses between the formation of letters and words.

In other developmental disorders handwriting has been studied across a range of writing tasks. For example it has been reported that children with dyslexia (poor reading and spelling) produce fewer letters/words per minute both on the alphabet task and in compositional writing tasks (Sumner et al., 2012). This is important in relation to DCD, which is known to sometimes co-occur with dyslexia (Chaix et al., 2007). Surprisingly however, literacy skills such as reading, spelling and vocabulary have not previously been examined in studies of handwriting in children with DCD, even though these may have an impact on performance. The main aim of this study was therefore to assess the speed of handwriting performance in children with DCD in English using a range of writing tasks including free-writing. Measures of the handwriting product were supplemented with more detailed temporal aspects (process measures) of performance to understand the nature of any slowness in production. Finally, reading and spelling skill was also assessed, as these may have an impact on performance as well as the motor difficulties associated with DCD.

2. Methods

2.1 Participants

Thirty children with DCD were initially recruited (28 boys, 2 girls) ranging from 8 to 14 years. Two were excluded due to non-compliance and difficulties with attention (1 girl, 1 boy). Subsequently, 28 children with DCD (27 boys, 1 girl) and 28 age (within 4 months) and gender matched typically developing (TD) controls were included in the study.

DCD Group:

The children with DCD were recruited from a database of children previously assessed and who met the formal diagnostic criteria for DCD from the DSM IV (APA, 2000). The children had significant motor difficulties, with performance below the 10th percentile (24 were below the 5th, 4 below the 10th) on the Movement Assessment Battery for Children 2nd edition Test (M-ABC-2; Henderson et al., 2007). These difficulties had a significant impact on their activities of daily living, as reported by their parents and evident on the M-ABC-2 Checklist (Henderson et al., 2007). A developmental, educational and medical history was taken from the parents, which confirmed that there was no history of neurological or intellectual impairment and no medical condition that might explain the motor deficit. The British Picture Vocabulary Scale 2nd edition (BPVS-2, Dunn et al., 1997) was used to give a measure of receptive vocabulary, which correlates highly with verbal IQ (Glenn & Cunningham, 2005). This was in at least the average range for all children. The Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997) was also used to note any other behavioural difficulties reported by the parent, which commonly occur with DCD such as attention deficit hyperactivity disorder (ADHD) (Miller et al., 2001). The parent interviews revealed that no child had received a formal diagnosis of ADHD, but a raised score in hyperactivity was revealed by the SDQ for seven children. Data from the handwriting measures for these seven children were compared against the rest of the DCD group and no differences were seen, therefore all children were included in the final DCD group. The children were also assessed on the reading and spelling components of the British Ability Scales 2nd Edition (BAS-II;Elliott, 1996). These revealed that eight children with DCD had literacy difficulties (1 in reading, 7 in spelling), as defined by a standard score of less than 85 on the BAS-II components, although none had a formal diagnosis of dyslexia.

Typically Developing (TD) Control Group:

The control group was recruited through local primary and secondary schools in Oxfordshire, England. Teachers were asked to use their professional judgement to identify children without any motor, intellectual or reading/spelling difficulties. To ensure the children identified were free of these difficulties, they were individually tested on the M-ABC-2 Test (Henderson et al., 2007), BPVS-2 (Dunn et al., 1997) and the reading and spelling components of the BAS-II (Elliott, 1996). Children were included in the control group if they scored at least at the level expected for their age on all measures.

Children from both groups with a diagnosis of dyslexia, and/or those who had English as a second language were excluded from the study. Children in both groups who had a reported physical, sensory or neurological impairment or who were born before 35 weeks gestational age were also excluded. This was to ensure that handwriting difficulties could not be attributed to other disorders. See Table 1 for performance profiles of both groups.

Table 1
Mean (SD) Age and Performance scores for DCD and TD groups on selection measures

Selection Measures	DCD n=28	Control n=28	p
Age in years	10.61 (2.23)	10.95 (2.12)	.441
M-ABC-2 Test percentile	3.45 (2.96)	43.37 (25.4)	<.001*
BPVS Standard Score	108.9 (14.4)	110 (12.2)	.655
BAS-Spelling Standard Score	95.8 (13.7)	111 (12.7)	<.001*
BAS-Reading Standard Score	109.5 (13.8)	122 (12.6)	.001*

*$p \leq .050$. M-ABC-2: Movement Assessment Battery for Children test component. BPVS: British Picture Vocabulary Scale, BAS: British Ability Scale

2.2 Measures

2.21 Speed of the Handwriting Product:

The Detailed Assessment of Speed of Handwriting (DASH; Barnett et al., 2007)
This was used to examine the handwriting product, assessing speed of performance on a range of writing tasks, which are often required in the classroom or written examinations. The DASH was chosen as it is the only standardised handwriting speed test with UK norms for 9 to 16 year olds. It also includes tasks that are ecologically valid (free-writing) and provides an opportunity to examine a range of different types of handwriting tasks (copying and writing from memory).
The four main DASH tasks were used in this study and are described below. The tasks were administered and scored using the instructions in the manual:

Copy Best: The child copied the sentence "The quick brown fox jumps over the lazy dog", in their best handwriting for two minutes. The number of words per minute was recorded. Totally illegible words, the final word (if incomplete) and punctuation marks were excluded from the score.

Copy Fast: As copy best, but with instructions to write as fast as possible, ensuring every word was readable.

Alphabet: The child wrote the alphabet repeatedly from memory as fast as possible for one minute. They were instructed to write it in the correct order using lower case letters, making sure that every letter was readable. A letter was not counted if it was out of sequence, reversed, capitalised (if it was a different form in uppercase) or could not be recognised out of the context of the task. The number of letters per minute was recorded

Free-writing: The child wrote on the topic of 'my-life'. A spider diagram, offering different writing suggestions, was presented prior to writing, in order to elicit ideas from the child. The content of their writing was not assessed, but they were instructed to try and write continuously over a 10-minute period using their everyday handwriting. They were given one minute prior to beginning the task in order to think of some ideas. The number of words per minute averaged over the 10-minute period was recorded.

The raw scores for each of these four writing tasks were then converted to standard scores, which have a mean of 10 and standard deviation of 3, using tables from the test manual. A total test score was also computed and a total standard score obtained (with a mean of 100 and standard deviation of 15). The standard scores were reported for the 9-14 year olds in this study. As there are no norms available for eight year olds, the raw scores were also used to incorporate all participants.

The internal reliability of the total score for the DASH is between α=.83 to .89 and the inter-rater reliability for all four tasks is .99, as reported in the test manual.

Name writing: While the DASH does not evaluate the child's performance on writing their name, it does suggest they write their name at the top of the writing paper before commencing. Rosenblum et al. (2008) found that children with DCD were slower in all tasks, including writing their own name, which should be a highly practised skill. To investigate whether there was a level of automaticity in writing their name, the name was recorded before the free-writing task. Since the letter content and length of names are different for each child, no product measures could be calculated for name writing, only the process measures (temporal features) featured below were recorded.

2.2.1 The Handwriting Process: temporal features

When completing the DASH the participants wrote with an inking pen on paper placed on a Wacom Intuos 4 digitizing writing tablet (325.1mm x 203.2mm) to record the movement of the pen during handwriting. The writing tablet transmits information about the spatial and temporal data of the pen as it moves across the surface. Eye & Pen version 1 (EP1) software (Almargot et al., 2006) was used to analyze and reconstruct the written text. In this study a wireless inking pen (model KP-130-10) was used with an A4 page lined sheet of paper, which was trimmed to 18cm in length to accommodate the landscape orientation of the tablet. The paper was then secured to the writing tablet. The data was sampled at 100Hz via a Celeron Dual Core CPU T3500 @ 2.10GHz laptop computer.

The following variables obtained from EP1 were evaluated for each handwriting task:

1. Duration of the task (secs): To ensure that both groups had engaged in the tasks for an equal amount of time, the duration of the tasks were calculated. This was taken as the time between the first pen-contact with the paper after the 'go' prompt, to the last pen lift at the end of the task.
2. Execution speed (cm/sec): The speed of the pen when it is in contact and moving on the page. This does not include when the pen is pausing on the page.
3. Pause duration (% of writing time): The percentage of time during the task where the pen was either off the page (in-air pause), or halted on the page (on paper pause). A pause was defined as three successive digital samples without movement (a halt >30 ms) (Almargot et al., 2006). This threshold has been used by other researchers in the case of handwriting in dyslexia, speech and language impairments and in typically developing populations (Sumner et al., 2012, Connelly et al., 2012, Almargot et al., 2006). It is the minimum threshold available with the EP1 software and is thought to capture all writing events.

2.3 Procedure

The study was approved by the University Research Ethics Committee at Oxford Brookes University. Parents were required to sign a consent form and children were asked to either assent (below 11 years), or countersign the parent consent form (over 11 years).

The handwriting component of this study took place over one 60-minute session. Each child met with the first author and completed the reading, spelling and handwriting tasks, in the order suggested in the DASH manual. The sessions were completed either at the child's home, school or at Oxford Brookes University. During the handwriting tasks the children were seated at a height adjustable table and chair, with knees positioned at approximately 90 degrees and elbows approximately 2-4cms above the table. The participants were encouraged to position their paper as they would normally do in the context of their natural environment; therefore, they were invited to manoeuvre the tablet to a position that was comfortable for them.

2.4 Data Analysis

In order to consider the effects of literacy skill on handwriting speed the DCD group was initially divided into two sub-groups, one including those with at least average literacy skills (DCD, n=20) and the other including those with literacy difficulties (standard score below 85 on BAS-II reading, spelling or both) (DCD+, n=8). Scores for the handwriting measures and the MABC-2 were compared across these two groups using t-tests. No significant difference between the DCD and the DCD+ groups were found suggesting that literacy skill, as measured here, did not influence handwriting product or process or general motor ability. Therefore, the two groups were combined to form one DCD group for all subsequent analyses. This sub-group comparison can be found in Table 2.

Data from the handwriting tasks was analysed to consider duration of writing, the writing product and the writing process. The first analysis examined the duration of each task across the two groups. This showed whether the instructions had been followed correctly and whether the two groups had spent the same amount of time on each of the tasks.

Handwriting product was measured in the second and third analysis. The second analysis, examined the standard scores on the DASH (this allows a more direct comparison across DCD and TD groups in a format that would be employed in clinical settings). For both analyses differences across groups were examined using t-tests where data were normally distributed and using Mann-Whitney-U tests where data were not normally distributed. For both tests the significance level was set at p<.05. The third analysis examined the DASH raw scores (words/letters per minute). To do so two-way mixed ANCOVAs were used to examine group differences across the tasks. Age was used as a co-variate due to the wide age-range of participants. Significant main effects and significant interactions were broken down using post-hoc tests and simple main effects respectively. For both, Bonferroni correction with significance levels set at .05 were used to control for the elevated type I error. Finally the fourth and fifth analysis considered handwriting process again using ANCOVA as described above but this time considering execution speed and pause duration (as a percentage of writing time).

Bivariate correlations were also conducted to examine the relationship between reading/spelling/vocabulary skills with the handwriting process measures (execution speed and pausing).

Table 2

Mean Age and Performance scores (SD) for DCD sub-groups on selection measures.

Selection Measures	DCD n=20	DCD+ n=8	p
Age in years	10.09 (1.90)	11.91 (2.58)	.060
M-ABC-2 Test Percentile	3.67 (2.94)	2.88 (3.15)	.348
BPVS Standard Score	108.9 (14.1)	108.8 (16.3)	.877
BAS-Spelling Standard Score	102.5 (9.68)	79.25 (5.99)	<.001*
BAS-Reading Standard Score	114.8 (11.5)	96.3 (10.1)	<.001*

*$p \leq .050$

3. Results

3.1 Duration of handwriting tasks:

There was no significant effect of group for the copy best task (U=344.5, z= -.778, ns), copy fast task (U=385.5,z= -.107, ns), alphabet (U=385, z= -.115, ns) or 10-minute free-writing task (U=302.5,z= -1.47, ns) for the duration of the tasks. Therefore, the DCD group did not finish or terminate tasks any sooner than their TD peers.

3.2 Speed of the Handwriting Product:

For the measures of handwriting speed using the standard scores for the four DASH tasks, there were significant group differences on all four tasks. The DCD group had significantly lower standard scores than their TD peers on all tasks (see Table 3) and on the overall total test standard score. Eleven children in the DCD group scored below 84 on the total test standard score. In contrast, the TD group performed exactly as expected, with their mean standard score at 100. The standard scores exclude the 8 year old children, as norms are only available for 9-16 year olds.

Table 3

A comparison of the mean DASH Standard Scores (SD) for the DCD and TD groups

Measures	DCD n=20[a]	Control n=23[a]	t(41)	p
DASH Standard Scores				
Total Standard Score[b]	84.3 (14.3)	100.3 (12.31)	3.93	<.001*
Copy Best[c]	8.15 (2.79)	10.6 (2.42)	3.14	.003*
Copy Fast	6.30 (2.63)	10.0 (2.82)	4.41	<.001*
Alphabet	7.70 (2.27)	10.13 (2.13)	3.62	.001*
Free-Writing	7.70 (2.57)	9.30 (2.11)	2.24	.031*

**p*≤ .050, [a]excludes 8 year olds, [b]Mean score 100±15, [c]Mean score 10±3

The DASH raw scores were calculated for all participants including the 8 year olds (see Table 4). The alphabet task was analysed separately, as the units were recorded in letters per minute rather than words. A one-way ANCOVA (group x writing task with age as covariate) indicated a significant effect of group for the alphabet task, as the DCD group produced fewer letters than their TD peers during the one minute task (F[1,53] = 14.54, p<.001, η^2=.215). The covariate, age, was significantly related to the number of letters produced in the alphabet task (F[1,53] = 26.82, p<.001, η^2=.336).

For the number of words written during the copy best, copy fast and free-writing task, a two-way mixed ANCOVA (Group x Writing Task with age as covariate) was used to examine group differences across the three tasks. The free-writing raw scores for the first two minutes of the free-writing task were included in the ANCOVA in order to make the three tasks more comparable. The covariate, age, was significantly related to the raw scores on the DASH (F[1,53] = 73.11, p<.001, η^2=.580). There was a significant effect of group (F[1,53] = 20.46, p<.001, η^2=.279), as the children with DCD wrote fewer words than their TD peers. There was no significant effect of task (F[2,106] = .679, p=.494, η^2=0.13) but there was a significant group-by-task interaction (F[2,106]=54.07, p<.001,η^2=.141) (df corrected for violation of sphericity with a Greenhouse-Geisser correction). Simple main effects indicated that the children with DCD were slower on all three of the writing tasks compared to TD children. However, this does not explain the interaction. Looking at the data, it seems that the interaction may be driven by a larger difference between the copy best and copy fast task in the TD children compared to the DCD group. In order to investigate this, the difference between the number of words written on these two tasks was calculated and analysed using a one-way ANCOVA (group, with age as covariate). A main effect of group was found (F[1,53] = 14.60, $p<.001$, $\eta^2=.216$) indicating that the TD group showed a larger change in the number of words between the copy best and copy fast task (mean increase of 5 wpm) as compared to the DCD group (mean increase of 2 wpm). The covariate age was significant (F[1,53] = 12.44, $p=.001$, $\eta^2=.190$).

Table 4

A comparison of the mean DASH Raw Scores (SD) for the DCD and TD groups

Measures	DCD n=28	Control n=28
Dash Raw Scores		
Alphabet (lpm)	37.64 (17.31)	53.57 (17.05)
Copy Best (wpm)	12.64 (5.76)	17.14 (5.52)
Copy Fast (wpm)	14.93 (6.28)	22.39 (7.09)
Free-Writing (wpm) (first 2 minutes)	13.25 (6.14)	17.01 (5.09)
Free-Writing (wpm) (10 minute task)	11.99 (6.07)	15.67 (4.41)

wpm= words per minute, lpm= letters per minute

3.3 The Handwriting Process: temporal features

For the analyses of process measures, only the first two minutes of the 10 minute free-writing task were included. This was to control for differences that may have occurred due to the length of the task.

Execution Speed:

The execution speed (the speed of the pen when it is in contact and moving on the page) for both groups averaged between 2-3 cm/s across all four DASH tasks and name writing. Figure 1 illustrates the execution speed of both groups during the five tasks. A two-way mixed ANCOVA (Group x Writing Task with age as covariate) was used to examine group differences across the five tasks. The co-variate age was significantly related to the execution speed $F[1,53]=10.03$, $p=.003$, $\eta^2=.159$. There was no effect of group ($F[1,53]=.008$, $p=.927$, $\eta^2<.001$), indicating that the children with DCD had a similar execution speed to their TD peers. There was also no effect of task $F(3.28,174.2)=.1.04$, $p=.377$, $\eta^2=0.19$ (df corrected for violation of sphericity with a Greenhouse-Geisser correction).

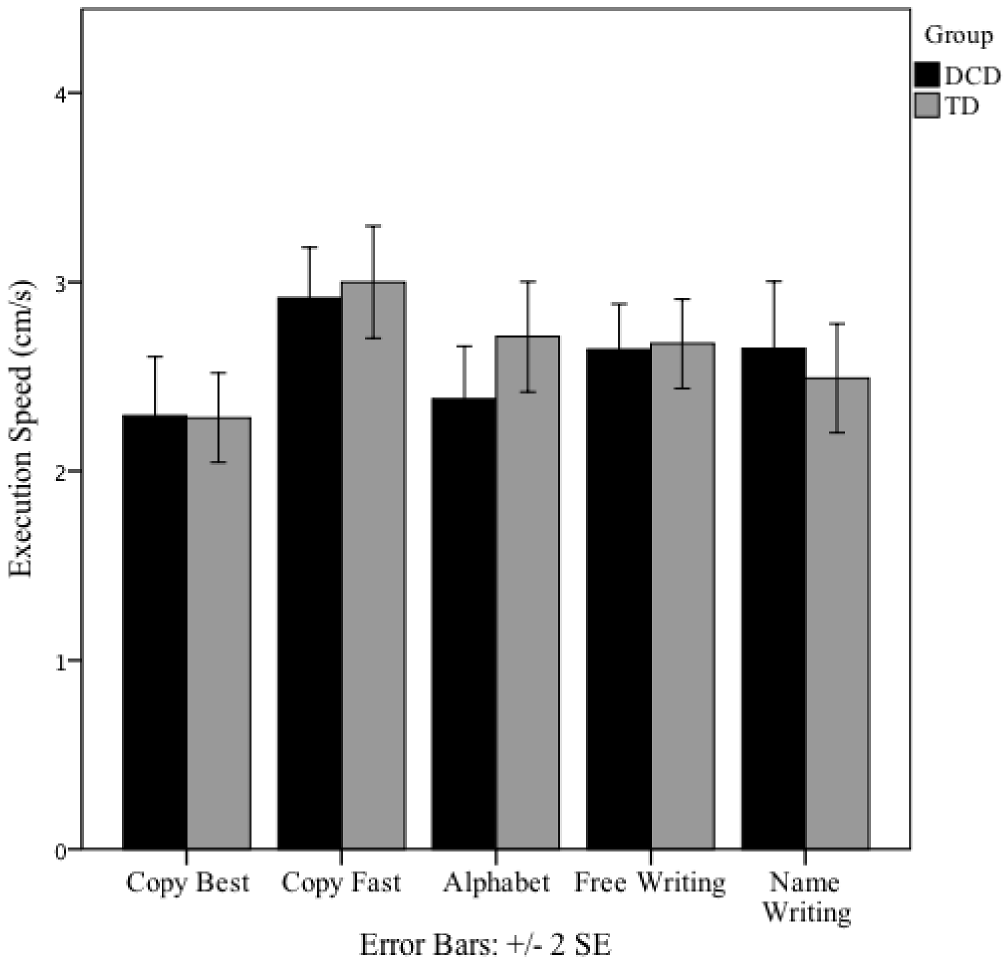

Figure 1. Execution speed (cm/s) for both groups across the handwriting tasks

Pausing Percentage:

Figure 2 illustrates the percentage of time spent pausing by both groups during the four DASH tasks and name writing. A two-way mixed ANCOVA (age as covariate) was used to examine group differences across the five tasks. The co-variate age was significantly related to the pausing percentage $F[1,53]=10.51$, $p=.002$, $\eta^2=.166$. There was a significant group effect ($F[1,53]= 9.52$, $p=.003$, $\eta^2 =.152$), as children with DCD spent a significantly longer percentage of time pausing than their TD peers. There was also a significant effect of task ($F[3.04,161.1]=2.75$, $p=.044$, $\eta^2=.049$). Pairwise post hoc comparisons indicated that both groups spent a greater percentage of time pausing during the alphabet task, followed by the free-writing task ($p<.001$). The copying tasks were not different from each other ($p=1.00$) but were significantly different from the free-writing task ($p<.001$) and the name writing task ($p<.001$). Both groups spent the least amount of time pausing on the name writing task. Finally a significant group-by-task interaction was also found (F[3.04,161.1]= 4.10, p=.008, η^2=.072) (df corrected for violation of sphericity with a Greenhouse-Geisser correction). Simple main effect tests were used to break down this interaction by considering whether a group effect was present for each writing task. A main effect of group was found for copy best (p=.006), copy fast (p<.001) and free writing (p=.008). There was no group difference in the alphabet task (p=.573). Following Bonferroni adjustment the name writing task did not meet the critical value (p<.01), therefore it showed only weak significance (p=.038).

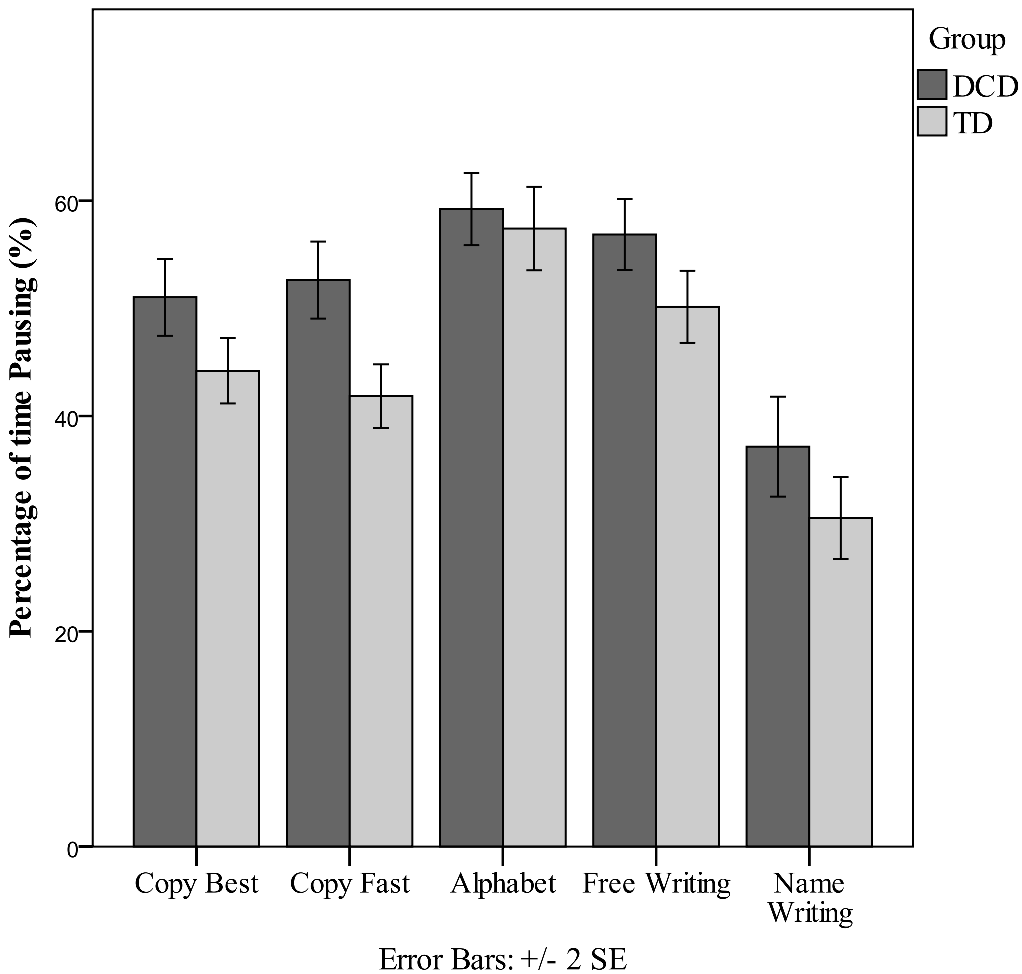

Figure 2. Percentage of time spent pausing for both groups across the handwriting tasks

Correlations with Vocabulary, Reading & Spelling Measures:

Partial correlations controlling for age were conducted with both groups separately to examine whether a relationship existed between any of the literacy measures (vocabulary, reading, spelling) and the handwriting process measures on the DASH (execution speed and pausing percentage). No significant correlations were found between any of these variables.

4.0 Discussion

The previous studies that have investigated temporal characteristics of handwriting in children with DCD were conducted in alphabets outside the Latin-base and in languages other than English (Rosenblum & Livneh-Zirinski, 2008; Chang & Yu, 2010). The purpose of the present study was to compare the speed of handwriting performance between children with DCD and typically developing children, in English. The DCD sample in this study met the DSM-IV (APA, 2000) criteria and were also examined in reading, spelling and receptive vocabulary. Following a detailed examination of handwriting speed, considering both the product and the process measures, the current study has found very different performance profiles between the two groups. The children with DCD performed below their peers on the DASH scores, but this was not attributed to a slower execution speed, but rather a higher percentage of time pausing while writing.

It is important to note that throughout the four DASH handwriting tasks, both groups were writing for the same overall duration, as computed and verified through the writing tablet data. This would therefore suggest that the performance of the DCD group cannot be attributed to early termination of tasks. The DASH is widely used by education and health professionals in the UK (mainly occupational therapists) and decisions in relation to intervention and provision of support in schools are commonly made on the basis of the DASH standard scores. If we begin by considering the DASH scores in isolation, it is apparent that the DCD group produced significantly less text than their TD peers. By taking the raw scores and the standard scores of the DASH at face value, it would appear that the DCD group were ‘slower’ than the TD group at producing text. This was apparent in all DASH handwriting tasks, each with different demands. The DCD group produced fewer legible words per minute on the copy best task and free-writing task and the group difference was even more pronounced when asked to speed up on the copy fast task. Similarly, on the alphabet task, they were slower than their TD peers, notable by the production of fewer letters per minute. Many teachers and therapists may be familiar with this outcome, as there is anecdotal evidence to suggest that many children with DCD exhibit ‘slowness’ in writing. However, in terms of empirical evidence, few studies have quantified or documented the amount of text produced by children with DCD compared to their TD peers. Barnett et al. (2011) reported fewer words produced per minute by a teenager with DCD in a case study related to the development of the DASH 17+ (an extension of the test for older students, Barnett et al., 2010). Elsewhere, Rosenblum et al. (2008) characterised handwriting performance in children with DCD in Hebrew and reported that children with DCD produced significantly fewer letters per minute than their TD peers during a two-sentence copying task. It was unclear however, whether the children were instructed to copy in their everyday handwriting or meet different demands. Nevertheless, the findings were similar to the current study, despite the differences in task protocols and between the Hebrew and English languages (e.g. direction of text, continuity of writing).

A closer examination of the handwriting process through the use of the writing tablet revealed that the DCD group did not actually execute text at a slower speed than their TD peers on any of the handwriting tasks. In-fact, while the pen was moving on the page, it was moving at a similar speed in both groups. This finding of similar execution speed suggests that the children with DCD did not have difficulty moving the pen at speed. Moreover, they were observed to increase their speed during the copy-fast task, indicating an ability to alter their speed with task demands. This was unexpected given that in the DCD literature, children with DCD are reported to demonstrate slower movement time during the performance of many manual tasks (Henderson et al., 1992; Missiuna, 1994; Plumb et al., 2008; Wilmut et al., 2013). However, whether or not they were proficient at controlling the pen at this speed is another question, as the relationship between handwriting speed and legibility is a complex, trade-off relationship (Weintraub & Graham, 1998). Although the focus of this study was handwriting speed, the DASH scoring protocol involves identifying illegible words and excluding these from the word count. It was apparent through this process that there were issues with legibility in the DCD group. This is an area that warrants further investigation in the future. Thus, although the execution speed in the DCD group was just as fast as the TD group, one possible explanation for their lower score on the DASH could be attributed to difficulties with legibility.

A further look at the handwriting process, particularly the pausing profiles, helps shed more light on the reduced performance on the DASH by the DCD group. Indeed, the analysis indicated that the children with DCD paused for a significantly longer percentage of time on the tasks, with the exception of the alphabet task. The extent of the pausing also seemed to depend on the type of task demands, as compared to the two copying tasks both groups paused for a greater percentage of time in the alphabet and free-writing task. This could be attributed to the increase in cognitive load associated with particular tasks such as free-writing and writing from memory, where cognitive and linguistic processes (planning, semantic retrieval, spelling etc) are competing for limited working memory resources (Van Galen, 1991; Berninger & Amtmann, 2003). In contrast, copying tasks provide visual feedback for the writer, which reduces the demands for spelling and letter retrieval. Copying tasks also provide an opportunity for the child to ‘imitate’ (Levene, 1993) what they see. When handwriting is automatic and fluent it allows for attentional resources to be made available for higher order aspects of writing such as planning and revision (Berninger & Amtmann, 2003). However, if the writer needs to focus their attention on the process of producing the letters and words on the page, then this inhibits the ability to concentrate on the important aspects of writing such as content and ideas. Although the percentage of time spent pausing increased in both groups during the free-writing task, the DCD group paused for over half the time. This suggests that when asked to write independently, as would be the case in an academic environment such as an examination, the DCD group demonstrated difficulty with handwriting fluency evident through the pausing. This impacted on the amount of text they produced on the DASH. Importantly, this did not relate to any difficulties with other aspects of literacy (spelling and reading).

This finding of longer pauses in writing for the DCD group is consistent with that of Rosenblum et al. (2008), where children with DCD were found to spend more time than controls with the pen in the air. It seems to be that in the tasks where the DCD group executed at a similar rate to their peers, such as in the copy best, free-writing and copy fast tasks, their ‘slowness’ on the DASH scores was related to their longer percentage of time pausing. The amount of time spent pausing appears to be significantly limiting the handwriting performance of children with DCD, but little is known about this pausing phenomenon. Interestingly, it is not limited to children with DCD. Indeed, this issue of longer pausing has also been found to be the case in other developmental disorders such as speech and language impairment (SLI) (Connelly et al., 2012), dyslexia (Sumner et al., 2012) and attention deficit hyperactivity disorder (ADHD) (Rosenblum et al., 2008). Sumner et al. (2012) found that children with dyslexia execute handwriting at a similar speed to TD peers, but have a tendency to pause for a greater percentage of the task. In dyslexia, the pausing was found to be related to spelling, based on the location of pauses and the difficulties demonstrated in the spelling measures (Sumner et al., 2012). However in the current study, both groups were within the average range for reading and spelling and there were no significant correlations between reading and spelling with any of the handwriting measures. This therefore reduces the possibility of spelling being a contributing factor.

The limited research available on handwriting in children with DCD has proposed a variety of possible explanations for the pausing phenomenon, which is seen both in the current study using a Latin based alphabet and in previous studies using a non-Latin based alphabet (Rosenblum & Livneh-Zirinski, 2008; Chang & Yu, 2010). There are essentially two lines of enquiry in the literature. The first is comprised of physiological theories proposed by Chang and Yu (2010), which suggests that reduced strength and endurance among children with DCD and/or a possible lack of tonic stiffness in the hand while writing, are contributors to slower performance. While there is evidence to suggest that children with DCD demonstrate reduced strength and endurance compared to typically developing peers (Raynor, 2001), in the current study the children with DCD were able to execute as quickly as their TD peers for the duration of the 10-minute free-writing task. This would suggest that they do have some endurance for this type of handwriting task. However, the excessive pausing noted in the DCD group could be due to small periods of rest, which is an area for future investigation.

The second line of enquiry proposes a lack of automaticity in the lower-level, motor components of the handwriting process (Van Galen, 1991), including possible slow movement time, difficulties with the perceptual aspect of the movement, difficulties with motor memory for letter formation and/or difficulties in visualizing the letters prior to forming them, all of which were proposed by Rosenblum (2008). In terms of movement time, the current study found no group differences regardless of task. However, a lack of automaticity was indeed apparent, not only in the longer pausing and possible issues with legibility, but also in name writing which showed a weak group difference. The weak group difference was an indication that some of the children in the DCD group did not achieve a level of automaticity even with a task as highly practiced as writing ones name.

Outside the literature on handwriting there are other possible avenues to explore in the search for an understanding of the pausing phenomenon in children with DCD. One such avenue is that of deficits in motor learning. A study by Smits-Engelsman et al. (2008) found that children with DCD demonstrated difficulties with fine-tuning forces in manual tasks, while other studies have reported difficulties in sequence learning (Gheysen et al., 2011). However, these motor learning deficit theories have yet to be examined in ecologically valid tasks such as that of handwriting and are areas that warrant further investigation. Another area that could be considered is the cognitive abilities of children with DCD. Research has shown that children with DCD demonstrate difficulties with executive function (Piek et al. 2004). While measuring cognitive profiles was outside the scope of this study, examining executive function may have strengthened it.

It is apparent through the results of this study and that of Rosenblum (2008) that a lack of automatization exists in the handwriting of children with DCD regardless of language and cross-cultural differences. However, further research is needed to unpick the pausing profiles in greater detail. One such method of differentiating lower level processes from physiological factors such as fatigue, would be to manipulate the threshold at which a 'pause' is defined. For example, it would be interesting to investigate whether children with DCD pause more frequently for shorter lengths of time i.e. less than 1 second, or whether they pause more frequently for longer periods. The nature of these pauses would be different, as shorter pauses are likely to represent between stroke, muscular adjustments (Schoemaker et al., 1994), while longer pauses reflect higher cognitive processes of writing (planning) or physiological factors such as fatigue. This would provide a much-needed advancement in characterising handwriting difficulties in children with DCD.

This study served to provide a greater understanding of the handwriting speed of children with DCD in English. The results advance our knowledge of handwriting speed in children with DCD, demonstrating that the 'slowness' so commonly reported in this group was not due to slow movement time, but due to excessive pausing. Further research needs to unpick this in more detail to aid in the provision of evidence for planning future interventions.

Acknowledgements

This study was funded by the Doctoral Training Programme for Children and Young People at Oxford Brookes University. We would like to thank all of the participants, their families and the schools who took part in this study.

References

Alamargot, D., Chesnet, D., Dansac, C. & Ros, C. (2006). Eye and Pen: a new device to study reading during writing. *Behaviour Research Methods, Instruments and Computers, 38(2),* 287-299.

American Psychiatric Association. (2000). DSM-IV-TR. *Diagnostic and Statistical Manual of Mental disorders* (4th ed.). Washington: American Psychiatric Association.

Asher, A. V. (2006). Handwriting instruction in elementary schools. *American Journal of Occupational Therapy, 60,*461–471.

Barnett, A., Henderson, S., Scheib, B., Schulz, J. (2011). Handwriting difficulties and their assessment in young adults with DCD: Extension of the DASH for 17-25 year olds. *Journal of Adult Development, 18,* 114-121.

Barnett, A., Henderson, S., Scheib, B., & Schulz, J. (2007). *The Detailed Assessment of Speed of Handwriting*. London: Harcourt Assessment.

Barnett, A., Henderson, S., Scheib, B., & Schulz, J. (2010). *The Detailed Assessment of Speed of Handwriting 17+ (DASH 17+)*. London: Pearson Assessment.

Berninger, V. (1999). Coordinating transcription and text generation in working memory during composing: Automatized and constructive processes. *Learning Disability Quarterly, 22*, 99-112.

Berninger, V., & Amtmann, D. (2003). Preventing written expression disabilities through early and continuing assessment and intervention for handwriting and/or spelling problems: Research into practice. In H. Swanson, K. Harris, & S. Graham (Eds.) *Handbook of learning disabilities* (pp 323- 344). New York: Guilford Press.

Berninger, V. W., Nielson, K. H., Abbott, R. D., Wijsman, E., & Raskind, W. (2008). Writing problems in developmental dyslexia: Under-recognized and under-treated. *Journal of School Psychology, 46*, 1-21.

Berninger, V. W., & Swanson, H. L. (1994). Modifying Hayes & Flower's model of skilled writing to explain beginning and developing writing. In E. Butterfield (Ed.), *Children's writing: Toward a process theory of development of skilled writing* (pp. 57-81). Greenwich, CT: JAI Press.

Bourdin, B., & Fayol, M. (1994). Is written language production more difficult than oral language production? A working memory approach. *International Journal of Psychology, 29*, 591-620.

Chaix, Y., Albaret, J.-M., Brassard, C., Cheuret, E., Castelnau, P., Benesteau, J., et al. (2007). Motor impairments in dyslexia: The influence of attention disorders. *European Journal of Paediatric Neurology*, *11*, 368 - 374.

Chang, S., & Yu, N. (2010). Characterization of motor control in handwriting difficulties in children with or without developmental coordination disorder. *Developmental Medicine and Child Neurology, 52(3)*, 244-250.

Connelly, V., Dockrell, J., Walter, K., & Critten, S. (2012). Predicting the quality of composition and written language bursts from oral language, spelling and handwriting skills in children with and without specific language impairment. *Written Communication*, *29*, 278-302.

Dunn, L., Dunn, L., Whetton, C., & Burley, J. (1997). *The British Picture Vocabulary Scale* (2nd ed.). London: nferNelson Publishing Company Ltd.

Elliott, C. (1996). *British Ability Scales (II); Administration and Scoring Manual*. London: nfer Nelson Publishing Company Ltd.

Gheysen, F., Van Waelvelde, H., & Fias, W. (2011). Impaired visuo-motor sequence learning in Developmental Coordination Disorder. *Research in Developmental Disabilities, 32*, 749–756.

Glenn, S., & Cunningham, C. (2005). Performance of young people with Down syndrome on the Leiter-R and British picture vocabulary scales. *Journal of Intellectual Disability Research, 49*, 239-244.

Goodman, R. (1997). The strengths and difficulties questionnaire: A research note. *Journal of Child Psychology and Psychiatry*, *38*, 581-586.

Graham, S., Berninger, V.W., Abbott, R.D., Abbott, S.P., & Whitaker, D. (1997). Role of mechanics in composing of elementary school students: A new methodological approach. *Journal of Educational Psychology, 82*, 781-791.

Henderson, L., Rose, P. & Henderson, S. (1991). Reaction time and movement time in children with developmental coordination disorder. *Journal of Child Psychology and Psychiatry, 33*, 895-905.

Henderson, S., Sugden, D., Barnett, A. (2007). *Movement Assessment Battery for Children-2* (2nd ed.). London: The Psychological Corporation.

Hyde, C., & Wilson, P. (2011). Dissecting online control in Developmental Coordination Disorder: A kinematic analysis of double-step reaching. *Brain & Cognition, 75*(3), 232-241.

Kellogg, R.T. (2008). Training writing skills: A cognitive developmental perspective. *Journal of Writing Research, 1*(1), 1-26.

Levine, M.(1993). *Developmental Variation and Learning Disorders*. Cambridge, MA: Educators Pub'.

Mandich, A., Polatajko, H., & Rodger, S. (2003). Rites of passage; understanding participation of children with developmental coordination disorder. *Human Movement Science*, *22*, 583-595.

Miller, L., Missiuna, C., Macnab, J., Malloy-Miller, T., & Polatajko, H. (2001). Clinical description of children with developmental coordination disorder. *Canadian Journal of Occupational Therapy, 68,* 5-15.

Missiuna, C. (1994). Motor Skill Acquisition in Children With Developmental Coordination Disorder. *Adapted Physical Activity Quarterly,11*(2), 214-235.

Missiuna, C., Moll, S., & King, S., et al. (2007). A trajectory of troubles: parent's impressions of the impact of developmental coordination disorder. *Physical and Occupational Therapy in Pediatrics*, *27*(1), 81-101.

Piek, J., Dyck, M., Nieman, A., Anderson, M., Hay, D., Smith, L., et al. (2004). The relationship between motor coordination, executive functioning and attention in school aged children. *Archives of Clinical Neuropsychology, 19*(8), 1063-1076.

Plumb, M., Wilson, A., Mulroe, A., Brockman, A., Williams, J., Mon-Williams, M. (2008). Online corrections in children with and without DCD. *Human Movement Science, 27,* 695-704.

Raynor, A. (2001). Strength, power and coactivation in children with developmental coordination disorder. *Developmental Medicine and Child Neurology, 41*(10), 676-684.

Roger, S., Ziviani, J., & Watter, P. (2003). Motor and functional skills of children with developmental coordination disorder: a pilot investigation of measurement issues. *Human Movement Science, 22*(4-5), 461-478.

Rosenblum, S., Epsztein, L., Josman, N.(2008). Handwriting performance of children with attention deficit hyperactive disorders: a pilot study. *Physical & Occupational Therapy in Pediatrics*, *28*(3), 19-34.

Rosenblum, S., Livneh-Zirinski, M. (2008). Handwriting process and product characteristics of children diagnosed with developmental coordination disorder. *Human Movement Science, 27*(2), 200-214.

Rosenblum, S., Parush, S., & Weiss, P. (2003). Computerized temporal handwriting characteristics of proficient and non-proficient handwriters. *The American Journal of Occupational Therapy, 57*(2), 129-138.

Schoemaker, M. M., Shellekens, J. M. H., Kalverboer, A. F., & Kooistra, L. (1994). Pattern drawing by clumsy children: a problem movement control. In. M. L. Simner, W. Hulstujin, & P. Girouard (Eds.), *Contemporary issues in the forensic, developmental, and neurological aspects of handwriting* (pp. 45-64). Toronto: Association of Forensic Document Examiners.

Smits-Engelsman, B. C., Westenberg, Y., & Duysens, J. (2008). Children with developmental coordination disorder are equally able to generate force but show more variability than typically developing children. *Human Movement Science, 27*, 296–309.

Stephenson, E., & Chesson, R. (2008). 'Always the guiding hand': parent's accounts of the long-term implications of developmental coordination disorder for their children and families. *Child Care Health Development, 34*(3), 335-343.

Sumner, E., Connelly, V. & Barnett, A. (2012). Children with dyslexia are slow writers because they pause more often and not because they are slow at handwriting execution. *Reading & Writing*, DOI 10.1007/s11145-012-9403-6.

Sumner, E., Connelly, V. & Barnett, A. (2013, January 13th). *Dyslexia: The influence of spelling on handwriting*. Paper presented at The teaching of Handwriting and Spelling in Primary and Secondary Schools, Oxford, United Kingdom.

Van Galen, G. (1991). Handwriting: issues for a psychomotor theory. *Human Movement Science, 10*, 165-191.

Wang, T., Tseng, M., Wilson, B., & Hu, F. (2009). Functional performance of children with developmental coordination disorder at home and at school. *Developmental Medicine and Child Neurology, 51*(10), 817-825.

Weintraub, N. & Graham, S. (1998). Writing legibly and quickly: A study of children's ability to adjust their handwriting to meet common classroom demands. *Learning Disabilities Research and Practice*, *13*, 146-152.

Wilmut, K., Byrne, M. & Barnett, A. (2013). Reaching to throw compared to reaching to place: A comparison across individuals with and without developmental coordination disorder. *Research in Developmental Disabilities, 34,* 174-182.

Figure 1. Execution speed (cm/s) for both groups across the handwriting tasks

Figure 2. Percentage of time spent pausing for both groups across the handwriting tasks