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Neural and Kinematic Metrics of Handwriting in Neurotypical Adults

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Abstract

Detailed Assessment of Speed of Handwriting (DASH 17+) assessment provides information about the speed and legibility of handwriting. Handwriting difficulties in general and DASH17+ performance, in particular, are signs of neuromotor difficulties. Individualized interventions can be developed with a better understanding of both the biomechanical and neurological underpinnings of the task. We used a multimodal assessment strategy to deconstruct the product and process of handwriting measures in adults. A total of 23 neurotypical college age adults took part in the study. We combined the standardized norm-referenced test DASH17+ and explored the online process of handwriting using the MovAlyzeR software, and simultaneously explored prefrontal cortex activity, using functional near infrared spectroscopy (fNIRS), during the task execution. Our research indicated that underlying neural and kinematic mechanisms changed between tasks, within tasks, and even from one trial block to another that are *not* reflected in the DASH17+ performance assessment alone. Therefore, this multi-modal approach provides a promising method in clinical populations to further investigate any subtle change in handwriting.

Keywords

Handwriting, DASH, fNIRS, Functional Near-Infrared Spectroscopy, Biomechanics

1. Introduction

Many different populations experience motor difficulties that impact handwriting. Although handwriting difficulties are frequently not included as part of the diagnostic process, they are often one of the reasons for referral to allied health professionals. For example, motor difficulties such as bradykinesia, akinesia, and hypometria can directly influence handwriting, resulting in handwriting difficulties such as micrographia or dysgraphia [1]. In addition, handwriting difficulties could be used as a soft neurological sign in dyslexia, certain learning disabilities, and other developmental disorders. Kinematic aspects of handwriting (speed, acceleration, stroke duration) are often affected in neurodegenerative diseases such as Parkinson's disease (PD) [2] as well as in psychiatric disorders such as schizophrenia [3].

While different tools exist to assess handwriting [4] [5], the Detailed Assessment of Handwriting Speed or DASH, which is commonly used to assess the speed of performance on a range of writing tasks, is the only standardized and validated handwriting speed test with norms for 9 - 16-year-olds (DASH) [6] and 17 - 25-year-olds (DASH17+) [7]. The DASH and DASH17+ are widely used by education and health professionals, particularly, occupational therapists [8]. In fact, intervention, and provision of support in schools and in the higher education section, are commonly made on the basis of the DASH and DASH17+ standard scores [8]. While both DASH versions provide a standardized assessment related to the product of handwriting (e.g., writing speed, pauses), limitations exist in their ability to provide more detailed information about underlying mechanisms related to the production of handwriting. In other words, the DASH assessments indicate *where* speed differences exist but do not deconstruct these differences to provide more information on *why* they exist. By uncovering these underlying mechanisms, practitioners can get a more thorough understanding of what aspects of handwriting are affected and provide more targeted interventions to help improve it.

Several researchers interested in handwriting have taken advantage of recent technological advances such as the use of digitizing tablets, to explore underlying mechanisms in a number of developmental disabilities such as DCD [8] [9] [10]. One of the more interesting findings from this research was related to the presences of pauses in handwriting. Researchers such as Alamargot [11] previously suggested that pauses in writing may be associated with content planning on the part of the writer, and therefore, result in better compositional quality. In direct contrast to this, other researchers found that children with DCD are more likely to pause more frequently within words as well as for longer time periods (>10 s) than their typically developing counterparts while at the same time, which may suggest that these children lack automaticity in their writing [8]. In follow up research by Prunty [12], it was demonstrated that in children with DCD, excessive pausing does not, in fact, seem to be associated with better quality of writing. The technology that has been used to date to explore the product and on-line process of handwriting has provided information on the spatial and temporal features of handwriting, such as pen pressure, execution speed, and the existence of pauses. The authors speculated that these pauses might be a result of higher cognitive processing demands, fatigue, movement difficulties, or some combination of these factors. The intervention implications differ greatly for these potential mechanisms and require a better understanding of what is occurring within the cerebral cortex during handwriting.

Fortunately, emerging brain imaging technologies may provide a non-invasive, ecologically valid way in which to fill this knowledge gap. For example, functional near-infrared spectroscopy (fNIRS) is one such tool that has been used to study cognitive activity during behavioral tasks in ecologically relevant conditions [13] [14] [15] [16]. fNIRS is a neuroimaging tool that is non-invasive, safe for continuous and repeated measurements, portable, cost effective, and gives a quantitative temporal assessment of brain function [17] [18] [19]. Furthermore, fNIRS indirectly measures neural activity by measuring changes in oxygenated and deoxygenated hemoglobin concentrations [20] [21]. While fNIRS only maps surface cortical activity, it is a relatively robust technology that can cope with motion artifacts and as such, has been previously utilized in neuroimaging studies of a variety of motor skills including but not limited to bipedal ambulation [22] [23] [24] [25], fine motor skills [26] [27] [28] [29], and manual puzzle solving [14].

Of particular interest is the prefrontal cortex (PFC), which is implicated in motor planning, specifically in outlining the execution of programmed sequences of action and expected consequences [30]. In other words, the PFC is involved in active representation of future events arising from behavioral actions within a framework of problem-solving, with the dorsolateral PFC (dlPFC) particularly fitted to assisting in regulation of behavior and modulation of responses to environmental stimuli [31] [32]. The role of the right prefrontal cortex is related to sustained attention and spatial working memory [33] [34]. In addition, the medial prefrontal cortex (mPFC) has a prime role in decision making, error detection [35], and executive control [36] [37]. More recent work suggests the mPFC plays a critical role in remote, recent, and short-term memories over a broad range of tasks [38]. Relating to the context of this study, (*i.e.*, performing the DASH17+ handwriting tasks) a degree of planning, sustained attention, short-term working memory and on-line positioning of the hand are all required. Therefore, we would expect to see differences in PFC activity in the different regions across the range of DASH17+ tasks, due to the very nature of the tasks.

Therefore, the aim of this study is to examine handwriting pauses and other outcome measures from the DASH17+ in a typically developing adult population using a digitizing pad and MovAlyzeR software [39] while concomitantly measuring changes in PFC activity using fNIRS. We reasoned that understanding these relationships in a neurotypical cohort will provide us with benchmark measures which we can use in future research for comparison with individuals with disabilities such as DCD and Attention Deficit/Hyperactivity Disorder (ADHD) to unravel the complexities of the pauses, to ascertain whether there are deficits in motor planning, executive function, or cognitive task overload.

2. Method

2.1. Participants

Twenty-three neurotypical adults, age = 20.35 ± 1.27 were recruited within the University of Delaware and Newark communities and participated in this study. Participants were included if they had no or little difficulty with handwriting, no physical or visual impairment, no existing diagnosis of Developmental Coordination Disorder (DCD), Attention Deficit/Hyperactivity Disorder (ADHD), Autism Spectrum Disorder (ASD) nor a language disorder. Additionally, their first language had to be English. Participants were excluded if they had a concussion in the past 12 months, an open wound to the forehead or an allergy to rubbing alcohol. Two participants had to be removed due to equipment issues, leaving a total of 21 (F = 13, M = 8) participants with complete data sets.

2.2. Instrumentation and Tools

Functional Near-Infrared Spectroscopy (fNIRS)

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive, optical brain monitoring device that can quantify cortical activity by measuring the concentration of oxygenated and deoxygenated hemoglobin. This study utilized a 16-channel continuous-wave fNIRS device [40] (fNIRDevices LLC, Potomac, MD, USA) to observe neural activity in the prefrontal cortex (PFC). The sensor's layout resulted in 16 measurement locations (optodes) and a light penetration depth of approximately 1.2 cm [16], established by 10 light detectors and 4 light emitters that released light within the 730 - 850 nm wavelength window and were separated by 2.5 cm. fNIRS is widely utilized in research labs to assess PFC activation during different motor and cognitive tasks such as Go/NoGo [41] or even moral judgment tasks [42].

The fNIRS sensor band was placed on the participant's forehead and aligned so that the center of both the horizontal and vertical axes of the head aligned with those of the band, as seen in **Figure 1**. Particularly, the sensor's vertical axis was situated in the Fp1 and Fp2 locations defined in the international 10 - 20 system of cerebral electrode placement [43] [44].

Detailed Assessment of Speed of Handwriting (DASH17+)

The DASH17+ is a standardized test used to identify handwriting difficulties [7]. It includes five subtests, each testing a different aspect of handwriting speed (alphabet, copy best, copy fast, and freewriting). In copy fast (CF), participants were asked to copy a sentence with the highest possible speed, whereas in copy best (CB), they had to copy the same content with their best possible handwriting (**Figure 2**). In "freewriting" the subject is given a three-minute time to think about the topic of their own life story, called "my life", followed by 10 minutes of free writing related to "my life". The internal reliability for the test using Cronbach's alpha is a = 0.83 - 0.89 and the inter-rater reliability is 0.99. The subtests examine 1) fine motor and precision skills, 2) the speed of producing well-known symbolic material, 3) the ability to alter speed of performance on two tasks with identical content and 4) free writing competency.

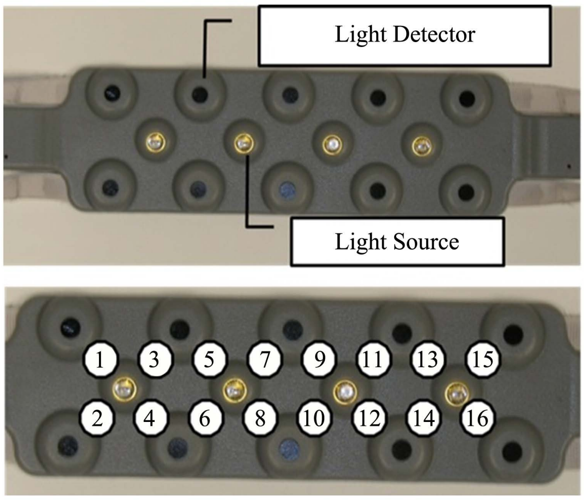


Figure 1. 16-channel Fnirs sensor pad utilozed for data collection. The top demonstrates the light sensors and sources. These optodes are divided into prefrontal cortex regions showed on the bottom. Four regions include left lateral, left medial, right medial and right lateral PFC.

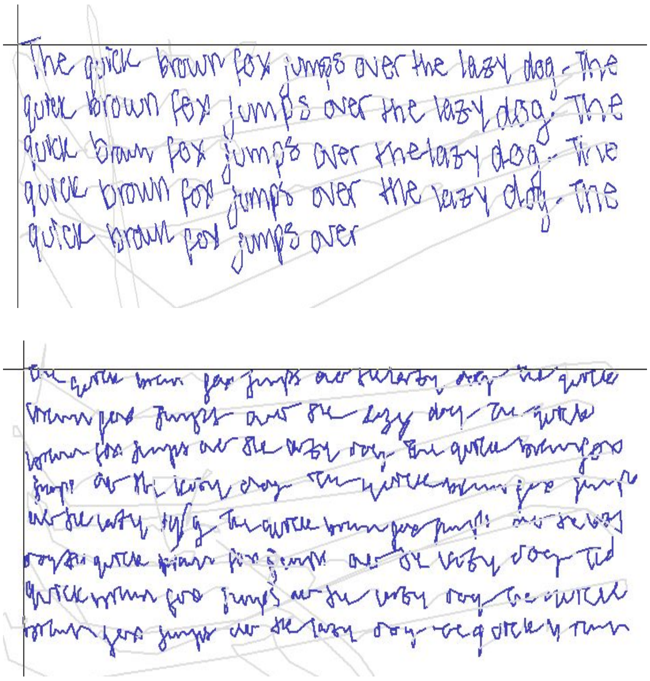


Figure 2. Sample of copy best (Top) and copy fast (Bottom) as captured by MovaLyzer for one subject. Subjects wrote the sentences "The quick brown fox jumps over the lazy dog" in their best handwriting and fast handwriting.

A digitizing pad (Wacom Intuos Pro Paper L) was utilized to administer the DASH17+ test and the MovAlyzeR (Neuroscript, 2018) specialized software to assess quantitative aspects of handwriting. MovAlyzeR records the pen movement on the digitizer during movement and pauses. The writing tablet transfers the temporal, pressure, and spatial information about the location of the pen during the writing performance to the software, which allows further analysis of the time and location of the pauses during writing. Performance on the DASH17+ was videoed; the camera was placed above and behind the participants and was focused on the digitizing pad, computer, and hands (See Figure 3(a) & Figure 3(b) for experimental set up).

2.3. Outcome Measures

fNIRS

ΔHbO. The fNIRS system provides measures of hemodynamic change in concentration in oxygenated hemoglobin (ΔHbO) measured and reported in µM.

DASH17+

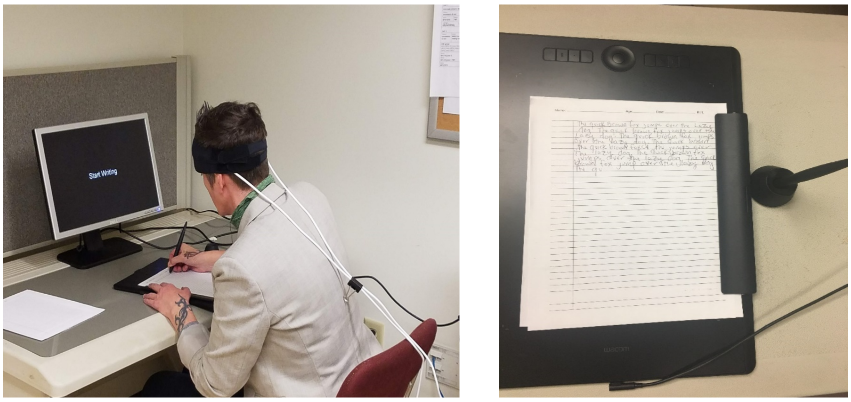
Words per minute. In each condition, a raw and standardized words per minute (wpm) score was calculated.

Pauses. Pausing during writing was measured as either short (30 - 250 ms) or long (251 - 2000 ms) pauses, consistent with Prunty [8] [12]. Pen tip pressure data were exported from MovAlyzeR to MATLAB (Version 2018a) for further analysis. MATLAB was used to calculate the duration of pauses, defined as pen off the tablet, when the pen tip pressure became zero. Pauses were categorized as short (30 - 250 ms) or long (251 - 2000 ms).

MovAlyzeR measures

Pen Pressure. Pressure is a MovAlyzeR software outcome measure. It is the amount of pen pressure exerted on the writing tablet during the handwriting tasks as measured in Newtons.

Average Absolute Velocity/Execution speed (cm/sec). Average velocity is a MovAlyzeR outcome measure. Execution speed is 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 or off the page. Execution speed is calculated by MovAlyzeR as the distance covered by the pen (cm) divided by the writing time (time between the first time the pen touches the tablet to the last pen lift of the task).



(a) (b)

Figure 3. Experimental set-up. (a) Participant performing freewriting task while wearing fNIRS sensor pad; (b) Wacom Intuos Pro digitizer, which recorded pen pressure tip, timing, and coordinates of each point.

Slant. Slant is a MovAlyzeR outcome measure. Slant is the inclination of handwriting relative to the perpendicular.

Relative pen down duration. Relative pen down duration is a MovAlyzeR outcome measure. Pen down duration is amount of time pen is contact with tablet divided by duration of writing.

Road length. Road Length is a MovAlyzeR outcome measure. It is the length of a segment from beginning to end. It is calculated by summing the distance between all consecutive samples.

Straightness Error. Straightness Error is a MovAlyzeR outcome measure. Straightness error is the normalized standard deviation from a straight line. The estimation is calculated by fitting a straight line between beginning and the end and calculating the perpendicular distance from this line.

Jerk. Jerk is a MovAlyzeR outcome measure. Jerk is the third derivative of position with regards to time.

2.4. Protocol

Prior to data collection participants were educated on study procedures using an informed consent form. After signing the consent form, participants began a 30-minute session where brain activity was monitored during the DASH17+ assessment.

Signal acquisition was optimized by 1) cleaning the participants' forehead with an alcohol swab prior to positioning the sensor band, 2) excluding any hair between the sensor and the participants' forehead, 3) adjusting Gain and LED Current until raw wavelength signal was verified to be between 40 - 4000 mV, and 4) reducing the ambient light in the testing room. Each participant began with a 1-minute resting period in which they sat with their eyes open looking at a black cross sign on the computer screen [14].

The data collected in this time period was used as the baseline. Then, participants performed DASH17+ sub-tests presented on the computer screen using a custom-written code with PsychoPy (3.2.4), a software originally developed for neuroscientific and psychological investigations [45]. PsychoPy also triggered the fNIRS device and sent markers corresponding to presentation events.

From the sub-tests "Alphabet" was presented as the first block for all subjects, followed with the "Free writing" sub-test. However, "Copy best" and "Copy fast" were randomized between subjects to avoid an order effect. A 12 - 18 second rest [13] was included in between all blocks to allow hemodynamic flow to return to the baseline. This rest time permits more accurate hemodynamic responses and avoids the generation of responses due to expectation of activity [46]. Performance on the DASH17+ was video recorded; the camera was placed behind the participants and was focused on the digitizing pad, computer, and hands to detect and remove motion artifacts.

2.5. Data Acquisition

Prior to data collection sampling rate was recorded for the digitizer through

MovAlyzeR. Additionally, to check for sampling rate, a recording was performed while continuously making circles for 10 seconds. The number of samples were checked and divided by 10 to get the sampling rate in Hz which was approximately 200 Hz.

Data collected with the fNIRS device were sampled at 2 Hz, acquired through Cognitive Optical Brain Imaging (COBI) studio software [16], and processed using fNIRSoft Software (Version 4.9, fNIR Devices LLC, Potomac, MD, USA)

The device was then initiated, and the first 10 seconds of recording were set as a baseline. During this period, the participant remained still and focused on a cross located opposite in a computer screen. Participants kept their eyes open during the rest periods, as it has been shown to provide a better baseline [47].

2.6. Data Processing

Researchers visually inspected raw light intensities and individual optodes, which were rejected when data did not reflect hemodynamic activity due to lack of proper contact between the sensors and the forehead or inevitable placement on top of hair in smaller sized foreheads. If optodes were removed, this was performed in accordance with methods described by Ayaz [16].

Researchers then used a finite impulse response (FIR) filter (20th order, Hamming window) to low pass filter the raw light intensity data at 0.1 Hz, which removes input from physiological signals, such as respiration and heartbeat. Data were subsequently converted to changes in concentration through the modified Beer-Lambert law [48] and depicted into 4 outcome measures: change in oxygenated hemoglobin (ΔHbO), change in deoxygenated hemoglobin (ΔHbR), total change in hemoglobin (ΔHbT) and total change in oxygenation (ΔOxy). We restricted our analysis to ΔHbO because preliminary analysis from our previous work found a high correlation among ΔHbO, ΔHbR, ΔHbT, and ΔOxy [14]. Furthermore, ΔHbO has been shown to have stronger and more widespread signals than those from ΔHbR and ΔHbT [49] [50] [51]. Evidence suggests that ΔHbO has a strong correlation to BOLD signal whereas ΔHbR has a weak correlation [52], in addition to a better signal-to-noise ratio (SNR) than ΔHbR [49] [53]. Finally, we applied the pre-set detrending filter to data representing changes in concentration, which removes a drift in the data using linear parameters that convert the slope of the baseline to zero.

2.7. Statistical Analysis

A total of 21 subjects completed all components of the DASH17+ with scores ranging from 31st - 98th percentile, which indicate no difficulties with handwriting speed (>15th percentile) [7] and also had complete data sets from all experimental measures of the subsets were analyzed and pauses, and corresponding hemodynamic responses were calculated. Then, the sub-tasks of copying a sentence containing all letters of the alphabet were explored further, while fNIRS was used to collect brain oxygenation from the prefrontal cortex. The order of tasks was randomized, and each task lasted for one minute with rest periods jittered between 12 - 18 seconds [13] before and after each task.

Paired t-tests were used for statistical analysis in CF and CB tasks to compare the frequency of pauses, MovAlyzeR measures, and changes in oxygenation in PFC. All measures were checked for Normality using the Shapiro-Wilk test ($p > 0.05$). Outliers were removed if they were >(Q3 + (1.5) IQR) [54]. A one-way Anova was used in Freewriting task to compare the same measures across the 3 tertials.

In order to compare changes that occur across the entire free writing condition, we divided the 10 - minute block into thirds, creating three equal time tertials. A repeated measures ANOVA was used to compare tertials in the freewriting task. Simple linear regression was used to investigate the associations between fNIRS measures, DASH17+ behavioral measures and frequency of pauses in three consecutive 3-minute blocks of free writing task. For all analyses, an alpha of 0.05 was used. The Statistical Package for Social Sciences (SPSS for Windows, version 27) (IBM Corp., Armonk, NY, USA) was used for all statistical analyses.

3. Results

3.1. Dash 17+ Measures

DASH 17+ provides raw and standard scores as well as the number of words per minute. A summary of measures from our sample is presented in **Table 1**. These include words per minute for CB, CF, and Free writing expressed as raw and standard scores, as well as total scores (including Alphabet) for the entire DASH17+ as a raw score and percentile rank.

3.1.1. Copy Best and Copy Fast Words per Minute

When comparing CB and CF, significant differences existed in the number of words per minute in both Blocks 1 and 2. In Block 1, CF (41.75 ± 5.14) had a higher number of words than CB (27.25 ± 5.61; $t(15) = -8.55$, $p < 0.05$, cohen's $d = -2.14$). This result was repeated in Block 2 (CF: 42.063 ± 5.74; CB: 28.75 ± 5.14; $t(15) = -8.58$, $p < 0.05$, cohen's $d = -2.15$).

3.1.2. Freewriting Words per Minute

Participants performed at T1 (28.57 ± 4.13) WPM during the first tertial, T2 (30.14 ± 4.9) WPM during the second tertial, and T3 (30.76 ± 5.16) WPM during the third tertial. A one-way ANOVA revealed there were no statistically significant differences among three tertials of freewriting in terms of the number of the words per minute. ($F(1, 15) = 1.58$, $p = 0.227$).

3.2. MovAlyzeR Measures

The MovAlyzeR allowed us to quantify specific features of handwriting samples including peak vertical velocity and acceleration, average velocity and acceleration straightness error, absolute and normalized jerk, road length, and slant. In

Table 1. Summary scores for DASH17+.

SS #	CB		CF		FWR		Total Score	
	Raw	Standard	Raw	Standard	Raw	Standard	Raw	Percentile
1	20	6	32	8	25	10	92	23.8
2	31	12	42	14	29	12	111	78.9
3	28	11	45	15	32	14	118	88.5
4	29	13	47	17	27	12	127	99
5	35	15	45	15	28	12	119	53
6	35	15	45	15	36	16	130	97
7	27	11	36	12	25	11	111	78.9
8	23	8	39	12	28	12	105	62.8
9	26	11	49	17	29	13	118	88.5
10	30	12	45	15	31	14	115	85
11	28	10	39	11	26	10	103	61.1
12	37	17	44	16	33	15	135	97
13	29	11	33	9	24	9	98	45.8
14	24	8	49	17	35	16	123	97
15	18	3	45	15	29	11	101	55.7
16	22	7	36	12	22	8	175	97
17	22	7	46	16	30	13	228	97
18	23	8	48	18	33	15	234	98
19	27	11	30	6	23	9	168	97.3
20	23	8	33	9	37	17	210	97.3
21	31	12	36	12	28	12	175	95

Summary table of DASH17+ raw and standard scores in sub-tasks of CB (CB), Copy Fast (CF), and Freewriting (FWR) along with overall DASH17+ scores based on all sub-tests.

addition, we could examine these data for handwriting pauses, which [12] determined to be important indicators when children with DCD performed the DASH.

3.2.1. Copy Best and Copy Fast

We compared the number and duration (msec) of pauses between CF and CB. When examining only short pauses in block 1, CF (116.22 ± 23.96) had significantly more short pauses than CB (83.69 ± 22.59), both in block 1 ($t (20) = 5.859$, $p < 0.001$, Cohen's $d = 1.279$) and block 2 ($t (20) = 4.479$, $p < 0.001$, Cohen's $d = 0.977$). In contrast, CB had significantly more long pauses than CF, both in block 1 (25.41 ± 6.30 vs. 15.33 ± 6.55) (t (20) = −5.368, p < 0.001, Cohens' d = −1.171) and block 2 (24.20 ± 6.57 vs. 15.14 ± 7.28) (t (20) = −4.861, p < 0.001, Cohen's d = 1.061). Results for pauses for each subtask are shown in **Figure 4** and **Figure 5**, using raincloud plots [55].

When comparing CB and CF in the MovAlyzeR measures, five of seven measures mentioned in the methods were statistically significantly different, and the remaining two approached significance (see **Table 2**). As one might predict, CF had greater Road Length, average absolute velocity, and less relative pen down duration. Interestingly, the peak vertical acceleration was higher in CB than in CF. Pen pressure and slant were both greater in CB, suggesting these may be indicative of more controlled penmanship.

3.2.2. Freewriting

No significant differences existed among the three tertials in either the number of short or long pauses (see **Table 3**). Short Pauses (F (2,32) = 0.511, p = 0.605) Long Pauses (F (2,32) = 1.126, p = 0.337).

When looking at the DASH scores alone, there were no significant differences among the three freewriting tertials. MovAlyzeR provides several more measures that can be grouped into 3 categories: Static, dynamic, and dysfluency features. Results from the MovAlyzeR indicate that significant differences did exist in three measures from two of these features. Static (shape) differed in straightness error (T1 < T2 (p = 0.016), T3 (p = 0.011) and slant (T1 < T2 (p = 0.011), T3 (p = 0.001) and Dysfluency differed in number of peak acceleration points (T1 < T2 (p = 0.01), T3 (p = 0.003).

Table 2. Average MovAlyzeR measures for the CB and CF.

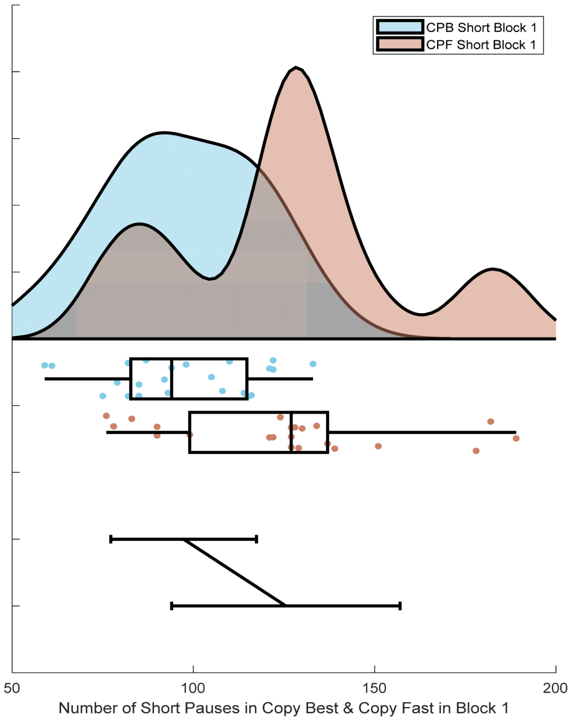
MovAlyzeR Measure	CB	CF	p Value
Slant (radians)	0.90 ± 1.35	0.13 ± 1.61	0.049*
Average Absolute Velocity (cm/s)	2.20 ± 0.67	2.90 ± 0.09	0.0001*
Relative Pen Down Duration	0.16 ± 0.16	0.71 ± 0.61	<0.0001*
Road Length (cm)	153.31 ± 111	486 ± 370	0.011*
Average Pen Pressure	122.80 ± 117.21	286.7 ± 247.50	<0.001

Summary table MovAlyzeR measures for copy best and copy fast.

Table 3. Number of short and long pauses in freewriting task.

	T1	T2	T3	p value
Short Pauses	275 ± 72	276 ± 69	281 ± 72	0.60
Long Pauses	73 ± 23	69 ± 21	69 ± 20	0.20

There were no significant differences in the number of long or short pauses between 3 tertials.



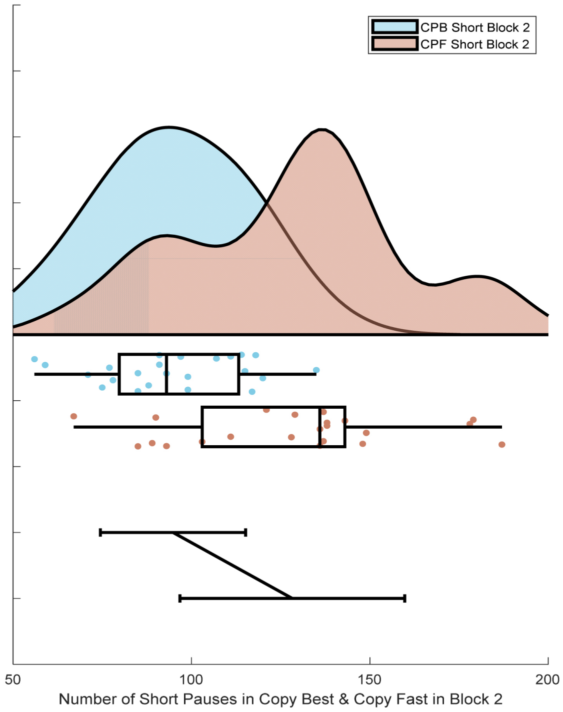


Figure 4. A comparison of short pauses (30 - 250 ms) between CB (blue) and CF (brown) in raincloud plots. Horizontal axis shows the number of long pauses and the vertical axis indicates the distribution. The top part of the graph illustrates the distribution of results, below that is a box plot of the results, with dots corresponding to actual data, and below that is the mean and standard deviation. Across the two conditions, participants had significantly more short than long pauses. Top: Number of short pauses in block 1. Within short pauses, CF had significantly more short pauses than CB ($p < 0.01$). Bottom: Number of short pauses in block 2. CF had significantly more long pauses than CB ($p < 0.001$).

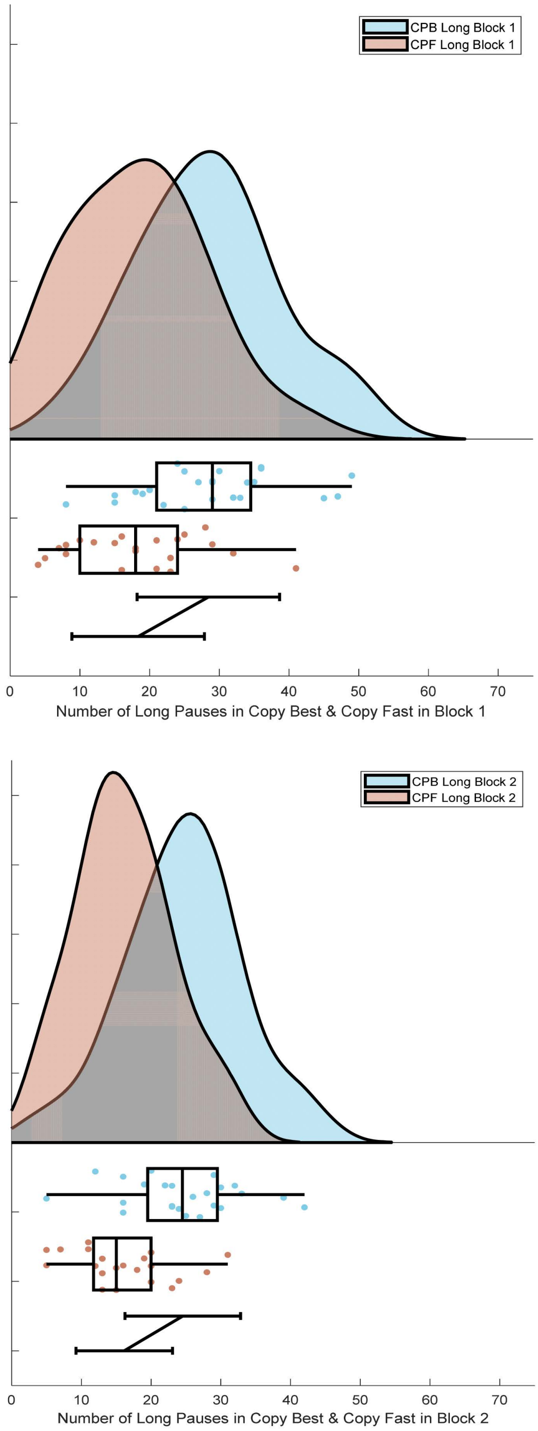


Figure 5. A comparison of long pauses (251 - 2000 ms) between CB (blue) and CF (brown) in raincloud plots. The Horizontal axis shows the number of long pauses and the vertical axis indicates the distribution. Top part of the graph illustrates the distribution of results, below that is a box plot of the results, with dots corresponding to actual data, and below that is mean and standard deviation. Across the two conditions, participants had significantly more short than long pauses. Top: Number of long pauses in block 1. Within long pauses, CB had significantly more long pauses than CF in block 1 ($p < 0.001^*$). Bottom: Number of long pauses in block 2. CB had significantly more long pauses than CF in block 2 ($p < 0.001^*$).

3.3. fNIRS Measures

With the addition of fNIRS data, we could explore overall PFC activation through oxygenation changes that occurred during the subsets of the DASH17+ test. Addition of ecologically valid neuroimaging tools during activities such as writing allows us to gain a better understanding of the neural demand of each task and its correlation with kinematic measures of writing and pauses.

3.3.1. Copy Best and Copy Fast

Paired t-test analysis revealed no significant differences in the overall PFC activation between CB and CF tasks. We then divided the PFC into specific regions of interest corresponding to the left dorsolateral (LD), left medial (LM), right medial (RM), and right dorsolateral (RD) PFC, then compared the two tasks in each of the trial blocks. In the first block, the two tasks significantly differed in ΔHbO only in the RDPFC, with CF having a higher average value than CB (CF: 0.38, CB: 0.15, $p < 0.0001^*$). Similarly, in the second block differences only existed in RDLPFC (CF: 0.37, CB: 0.35, $p < 0.02^*$).

3.3.2. Free Writing

Significant differences in overall PFC activity were found among the different tertials during the free writing task ($p = 0.008$). Post Hoc analysis revealed that the third tertial had significantly lower values of average HbO than T1 and T2, which did not differ from each other (see **Figure 6**).

Additionally, there were differences within the specific regions of interest across the different tertials (see **Table 4**). In all of the PFC regions, a significant difference between groups was found ($p < 0.05$), post hoc analysis indicated a significant difference between T1 and T3 ($p < 0.05$) and T2 and T3 ($p < 0.05$).

Table 4. Change in HbO over tertials of freewriting in each specific region of PFC and the overall PFC region).

	Tertial				
PFC region	T1	T2	T3	p Value	Significant (*) Post hoc p values
LD	0.70 ± 12	0.73 ± 1.13	−0.05 ± 0.35	0.01*	T1/T3, p = 0.02* T2/T3, p = 0.02*
LM	0.74 ± 1.3	0.90 ± 1.8	−0.15 ± 0.4	0.01*	T1/T3, p = 0.005* T2/T3, p = 0.006*
RM	0.60 ± 0.83	0.70 ± 0.8	−0.12 ± 0.3	0.003 *	T1/T3, p = 0.015* T2/T3, p = 0.004*
RD	0.60 ± 0.6	0.60 ± 0.7	−0.11 ± 0.27	0.001*	T1/T3, p ≤ 0.001* T2/T3, p ≤ 0.001*
Overall	0.68 ± 0.103	0.45 ± 0.102	−0.12 ± 0.075	0.001*	T1/T3, p = 0.001* T2/T3, p = 0.005*

In all of the PFC regions, a significant difference between groups was found ($p < 0.05$), post hoc analysis indicated a significant difference between T1 and T3 ($p < 0.05$) and T2 and T3 ($p < 0.05$).

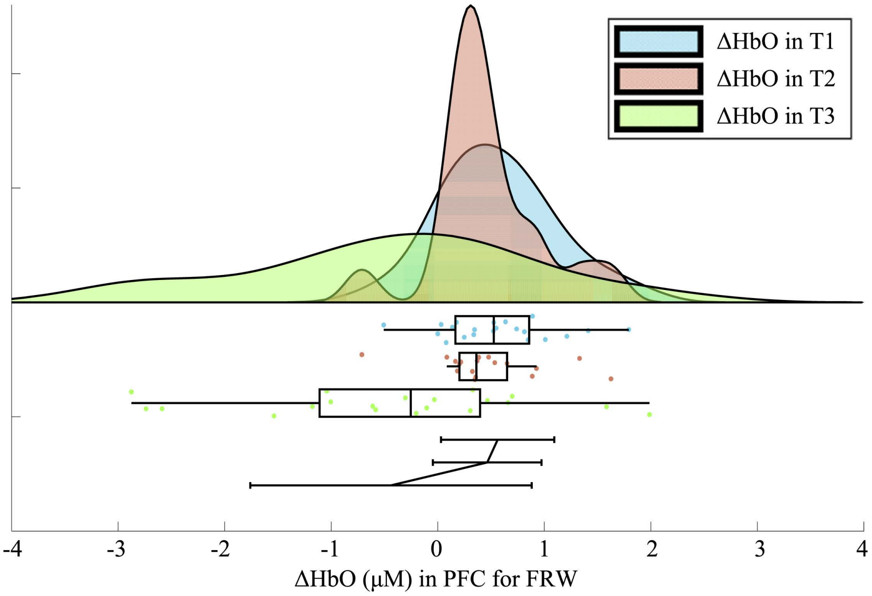


Figure 6. Overall change in PFC oxygenation over three tertials of freewriting. The Horizontal axis shows the number of long pauses and the vertical axis indicates the distribution. The top part of the graph illustrates the distribution of results, below that is a box plot of the results, with dots corresponding to actual data, and below that is the mean and standard deviation. The first tertial is represented in blue, the second in red, and the third, in green. The third tertial had significantly lower oxygenation than tertials 1 and 2 at p = 0.008.

4. Discussion

In the current study, technological advancements allowed us to use a multimodal assessment strategy to deconstruct the product and process of handwriting in a typically developing cohort of adults. We were able to examine relationships among behavioral, performance, and brain activation measures by combining a standardized referenced norm test of handwriting, the DASH17+, utilizing the MovAlyzeR software to explore the online process of handwriting during the DASH17+ and simultaneously exploring changes in prefrontal cortex oxygenation using functional near-infrared spectroscopy (fNIRS), during task execution. By adding two forms of technology to DASH17+ measures, we provided a richer, more nuanced picture of the underlying mechanisms behind the performance outcome scores.

In isolation, the DASH17+ revealed a significant difference in words per minute produced during CB and CF. This alone is not surprising, given the differing performance goals of each sub-task. Exploring this further with the MovAlyzeR, these DASH17+ sub-tasks also differed in the number and duration of pauses. Overall, there were more short than long pauses in both conditions, which suggests the majority of pauses were at the letter level rather than the word level. CF had significantly more short pauses than CB both in block 1 and block 2, which had significantly more, longer (e.g., word level) pauses than CF both in block 1and block 2. In addition, five different measures differed significantly between the two sub-tests. CB showed higher average pen pressure and relative pen down duration compared to CF. CF resulted in higher average absolute velocity and road length compared to CB. These findings suggest that participants exerted higher pressure on the pen and spent more time with the pen pressed to the tablet in CB compared to the CF condition, whereas in CF subjects wrote with higher average velocity and put in more text compared to CB. Altering mechanical impedance is a major factor in the control and stabilization of hand-held objects and its navigation. These results suggest subjects may be increasing their fine motor control through increasing impedance and pressure to reach finer motor control [56] and better handwriting in CB. The current study aimed to delve deeper into the pauses and try to identify and provide a neural context for these differences by gathering hemodynamic data from the prefrontal cortex using fNIRS, during the task execution of the DASH17+, to try and unravel the complexities of the pauses.

When we combine all sources of information for CF vs CB, we can begin to get a better understanding of how cognitive resources are being allocated in these tasks. The lack of long pauses over 2 seconds suggests that few cognitive resources were spent on generating higher-order executive function in either of the conditions. At the same time, hemodynamic differences existed between CB and CF, with CF having greater overall oxygenation. Differences in ΔHbO are likely due to motor planning and regulation differences between the tasks, with CF producing a higher cognitive load on working memory. The fact that CF has higher ΔHbO, but there is *not* a positive association between this, and speed measures (average velocity, road length) suggests these resources are used for online task monitoring.

Also, significant differences existed in specific regions of interest in the PFC, between the first and second trial blocks in two subtasks. In both trial blocks, CF has significantly higher ΔHbO in the RD PFC. Lateral portions of PFC may be involved in online maintenance and manipulation of information (e.g., working memory) and play a critical role in the planning of action sequences, mental conception and evaluation of sequences, and associate outcomes before execution [57]. Further, the right dorsolateral region is associated with temporal and dynamic aspects of planning and attention as part of intrinsic cognitive load. Some research has implicated the RDPFC is activated in visual working memory tasks and setting up cognitive oversite of the motor task (that is, setting up guidelines to perform an automated task at a much faster rate). Further, the CF sub-task appeared to require more cognitive resources throughout the entire task (*i.e.*, blocks 1 & 2). Finally, the allocation of cognitive resources stayed the same from the first to the second block of the task. Observing these same measures within populations with DCD or ADHD should provide insight into differences in the allocation and distribution of cognitive resources.

Examining multiple measures also sheds light on underlying changes within the freewriting task. Looking at the DASH 17+ alone, no differences existed in

WPM throughout the entire free writing period; this was also true of the frequency or duration of pauses change. Further, the majority of pauses were between 30 - 250 ms, placing the majority of them at the letter level. However, differences in MovAlyzeR measures existed, primarily between the first and second, and first and third tertial. Straightness error increased as participants moved from first to second and third tertials and slant changed from negative to positive moving from T1 to T3. This change in slant was also present when comparing CB (positive slant) and CF (negative slant). Additionally, the number of peak acceleration points decreased from T1 to T3. All of these changes point toward a shift of kinematics in tertials. One might expect these measures to change towards the end of the freewriting period as participants begin to experience muscular fatigue. However, analysis of ΔHbO indicates that there is a significant drop overall in oxyhemoglobin within the last tertial. A closer look at the different areas indicates that these changes occur most significantly in the dorsolateral regions of the PFC. Within the available research on pauses in writing, it is generally accepted that longer pauses are capturing higher-level writing processes [11] [58], while shorter pauses reflect transcription [11]. Because the majority of pauses in the freewriting task are less than 2000 ms, that suggests that participants are not actively composing their story throughout the 10-minute period. Rather, they compose their story beforehand and keep their story in memory during the 1st and 2nd tertial. Since pauses do not change and remain at the letter level throughout, plus the WPM does not decrease, participants appear to be prioritizing the task of non-stop writing over storytelling. In functional imaging studies, the prefrontal cortex (PFC) has been identified to be among the relevant areas for memory-related tasks such as the My Life task. Further, straightness error increases from t1 to t3, and slant shifts from negative to positive, while the number of peak acceleration points decreases. These three changes together suggest that, across the 10-minute period, handwriting becomes sloppier but also more "fluent".

When combining the fNIRS and MovAlyzeR measures across the entire free writing task, the initial higher values of ΔHbO combined quality measures suggest an emphasis on actively maintaining the story information in working memory and transferring it to the written word. The declines in ΔHbO and quality measures in the third tertial that co-occur with increases in fluency measures suggest that the task may have become more automatic, using less active control of PFC.

Implications for clinical applications of handwriting research

Understanding these relationships in a typically developing cohort will then allow future studies to evaluate individuals with different types of disabilities or conditions and unravel the complexities of the pauses, to ascertain whether there are deficits in motor planning, executive function, or cognitive task overload. Additionally, it is possible to collect electromyography (EMG) data to monitor muscular activity in conjunction with biomechanical analysis of handwriting and cortical activity to further dissect if problems are muscular in nature and can benefit from specific muscle feedback as has been done in handwriting and other skills [59] [60]. Handwriting difficulties are common in populations such as DCD, ADHD, and others where manual dexterity is impaired and can have lasting consequences on academic achievement and self-esteem [61]. Our purpose was to better understand the neural and biomechanical components of the DASH17+ subtests in a healthy, adolescent populations so that we can now compare them to populations with DCD, ADHD, and other populations with neurobehavioral difficulties. In our research, we introduced an emerging technology, fNIRS, to look at neural correlates during handwriting performance along with more advanced output variables from MovAlyzeR software, in order to further dissect the DASH17+ assessment. Our research indicates that even in typically developing populations, underlying mechanics and mechanisms change between tasks, within tasks, and even from one block to another that are not reflected in the DASH17+ assessment alone.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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