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Space–time invariance in adult handwriting

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Abstract

Handwriting quality is commonly evaluated off-line using either subjective or pattern recognition techniques based on the static final output. Skilled performance is characterised in terms of legibility and as a minimisation of spatial variability. However, these techniques are subject to error, and provide little information about the underlying dynamics producing the movement. This study employed temporally sensitive techniques to investigate the relationship between spatial (i.e. legibility) and the kinematic (i.e. dynamic) aspects of handwriting production. Each of 18 adult subjects (7 male, 11 female) wrote the pseudo-word *MADRONAL* 10 times in their natural cursive handwriting. Horizontal (x), vertical (y) and pressure (z) coordinate data were collected using a Wacom 1212-R graphics tablet controlled by a laboratory computer. Spatio-temporal aspects of the x, y and z velocities of the stylus were analysed both between trials and within subjects using coherence analysis. Subjects previously rated as good handwriters by three independent judges displayed a greater degree of temporal consistency than the less proficient writers. The results showed that spatial inconsistencies are related to dynamic variability and demonstrated that the methodology employed can provide a useful tool for the quantitative assessment of handwriting quality. © 1997 Elsevier Science B.V.

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1. Introduction

Handwriting is an important complex psychomotor ability commonly used in most first world countries. However, researchers have found that more than 12% of primary school populations fail to learn how to perform this skill proficiently (Rubin and Henderson, 1982). The production of legible handwriting results from the efficient functioning of biomechanical systems which are controlled by both lower brainstem and higher cognitive levels of the brain (Stott et al., 1987). Disturbances in one or more of these areas can lead to poor handwriting, although poor handwriting often occurs in the absence of other physical, sensory or intellectual disabilities (Bonney, 1992). Further to this, there is currently no conclusive evidence for a strong relationship (apart from cases of gross deficiencies) between type of posture, pen grip, writing style, visual–motor control, fine motor control, or kinaesthetic sensitivity (once the skill is learnt) and the production of legible handwriting (Bonney, 1992).

Skilled motor performance, particularly where spatial and timing accuracy tasks are concerned, is characterised by a minimisation of outcome variability. It is not surprising therefore that the practical assessment of handwriting skill, particularly in educational environments, is frequently based on the static final product with little cognisance of the underlying complex dynamics (Bruinsma and Nieuwenhuis, 1991; Hamstra-Bletz and Blöte, 1993; Rubin and Henderson, 1982; Wann and Jones, 1986). For example, when a new scale for the diagnosis of handwriting problems was recently developed, the only real-time features studied were posture, pen grip and the position of the head, the rest of the scale relying on static features (Stott et al., 1987). The assessment of handwriting quality is generally based on visual inspection, commonly rated in terms of legibility, accuracy of letter formation, and consistency of letter size (Ratzlaff and Armitage, 1986; Rubin and Henderson, 1982; Stott et al., 1987). These criteria can be seen as subjective judgements of letter form variability.

This subjectivity can lead to erroneous judgements about fine motor skills. Rubin and Henderson (1982) report that often teachers were not sure what criteria to use to determine which children have serious difficulties with writing, pointing out the need for a reliable, systematic assessment procedure. Even where published handwriting scales are used, there is doubt about their reliability, validity and utility (Graham, 1986). These judgements can influence a teacher's perception of a student's intellectual ability, where a partially illegible essay can result in a lower mark, even when content is controlled (Briggs, 1970, 1980). What is clearly needed is a more objective and quantitative measure of handwriting ability. The development of a technique for the assessment of handwriting quality based on inter-trial variability which complements the existing visual methods would lead to more accurate judgements in such practical situations.

The production of legible writing, as in any skilled performance, requires movement patterns that can be reproduced with little variability. It also requires good visual perception and memory, an ability to integrate a visual image of a letter with the appropriate motor response and good control of the necessary muscles. Furthermore, efficient handwriting performance requires the storage and retrieval of motor information together with an ability to perceive the spatial requirements of the task (Connor, 1991; Ratzlaff and Armitage, 1986; Stott et al., 1987).

Since handwriting is the product of a dynamic process, it is reasonable and informative to look at the consistency of the dynamic characteristics of pen movement, such as velocity and acceleration profiles. While variability in movement dynamics is undoubtedly not the only cause of reduced legibility, it is likely to be an important contributing factor. The information gained from analysing the dynamics of the process generating the handwriting will also lead to a better insight into mechanisms underlying lack of motor control during the execution of handwriting movements. The dynamics of mature handwriting, as exhibited in adults, involves an automated sequence of motor actions, the entire sequence of actions being with minimal conscious control. Using this well-developed dynamic motor memory, the cognitive system can perform accurate movements with little sensory feedback.

This dynamic motor memory appears to be an abstract representation, most likely coded in the spatial domain (van Galen, 1991), and as such is not muscle specific (Thomassen and van Galen, 1992). Although a given movement sequence can produce a desired outcome in a large number of temporal and biomechanical circumstances, the dynamic characteristics of the movement sequence will be proportionally and recognisably similar (Castiello and Stelmach, 1993; Viviani and Terzuolo, 1980). Such a well-developed motor memory appears to be space–time invariant since the ratios between submovement velocities remain relatively constant when the actual movement is performed at different speeds and amplitudes (Viviani and Terzuolo, 1980). Although the precise form of this motor memory system is as yet unknown, the characteristics of its biomechanics are well documented.

It is generally agreed (Dooijes, 1983; Hollerbach, 1981; Maarse et al., 1989; Plamondon, 1993; Plamondon and Clement, 1991; Wann and Nimmo-Smith, 1991) that the movements performed in writing letters arise from the coupling of two velocity (or force) generating oscillators. The first is in the horizontal (x) direction and the second is in the vertical (y) direction. The x and y oscillations are mainly produced by modulating the force amplitude and duration generated from muscles in the hand and wrist, with some contribution from the rest of the arm (van Galen, 1991). A third parameter of interest is the pressure exerted by the stylus tip on the writing surface. Pressure is usually defined in terms of movement in the downward (z) direction with changes in the magnitude of the applied pressure modulating the frictional forces acting on the stylus (Wann and Nimmo-Smith, 1991). It is the complex dynamic interaction between these velocity generating oscillators which results in handwriting.

Recent empirical findings (Teulings et al., 1986; van Galen, 1991) suggest that it is the spatial features of handwriting that form the basis of the long-term motor memory. The dynamic characteristics, such as force amplitude and duration are traded off against each other to achieve the desired spatial outcome. The particular dynamic profile is an emergent feature of the realisation of the skill in a given environmental and biomechanical context. Temporal invariance is a natural consequence of the writing process if a stable outcome is to be achieved. Proficiency at this skill therefore requires fine control of the modulation of force amplitude and duration.

Several authors have demonstrated that good handwriting is characterised by smooth velocity profiles, while the velocity profiles of poor handwriting are disturbed by many inversions due to acceleration and deceleration of the pen motion (Van Galen et al., 1993; Wann, 1987; Wann and Jones, 1986). For example, Van Galen et al. (1993) applied Power Spectral Density Analysis (PSDA), a technique which is sensitive to rhythmic oscillations, to the velocity profiles generated by 24 good and 24 poor handwriters aged between 7 and 12 yr. The results showed that the velocity profiles of poor handwriters were much more variable than those of good handwriters. These authors proposed that an efficient motor system filters out unnecessary movements and neuromotor noise to produce an output that is kinetically optimal and spatially predictable. A less than optimal implementation of an adequate motor program, due to poor biomechanical filtering, will produce greater space–time variability.

Wann and Jones (1986) also looked at the consistency of velocity profiles as a measure of children's handwriting proficiency concluding that a variable graphic product is a result of an inability to reproduce stable spatio-temporal patterning. They calculated the velocity of the stylus tip in the x and y directions, as well as the two dimensional tangential (xy) velocity. The Cross Correlation Function (CCF) was calculated for each combination of pairs of xy velocity time series from one trial to the next. The highest value of the CCF, an estimate of the similarity between the two time series, provides a quantitative index of handwriting consistency.

The subjects, who were aged between 8 and 10, consisted of 16 good and 16 poor handwriters. Each subject wrote the letters *v*, *n*, *w*, *o* and *a* for eight trials each and the words *nun* and *nine* for four trials each. The highest CCF value was calculated for each pairwise comparison, and the mean and the variance for each condition were compared to determine the average degree of correspondence between the handwriting samples.

In the Letter condition, there was a significantly greater degree of correspondence between separate trials for good writers when compared with poor writers. There was no significant difference for words, although the mean correspondence values were much lower overall for words then for letters. This would suggest that the lack of a difference between poor and good writers may be due to their both being at a relatively earlier stage of learning to write words, when compared with the easier and more practised task of letter writing.

Wann and Jones (1986) found no significant differences in handwriting consistency between the two groups using coherence analysis, which involves computing the correlation between the spectral estimates of the two time series at each spectral frequency. Whereas cross-correlation provides information in the time domain, coherence provides information about performance consistency in the frequency domain.

The following experiment was designed to investigate the relationship between the spatial inconsistency and dynamic variability of adult handwriting. The aims were to determine if handwriting proficiency, assessed in terms of the legibility of the static handwriting trace, was indeed related to temporal variability. In other words, can skill in handwriting be discriminated on the basis of the consistency of the dynamic characteristics of the motor system output. Secondly, we wished to determine if the findings of researchers such as Wann and Jones (1986) and Van Galen et al. (1993), could be reproduced with adult subjects.

It is proposed that the dynamics of the handwriting trace is less variable for good handwriters, when compared to poor handwriters. Since all the subjects had many years of experience in the handwriting of words, it was thought that any difference in intratrial variability between poor and good handwriters would be evident. It is therefore hypothesised that, when compared to poor handwriting, good handwriting will display less space–time variability as revealed by a greater degree of coherence between velocity profiles from one trial to the next. Coherence analysis was used rather than cross-correlation because consistent spatial output is thought to be a result of good control of the underlying dynamics, which are oscillatory in nature. Since coherence is interpreted in the frequency domain, this method would provide more theoretically relevant information.

2. Method

2.1. Subjects

Eighteen subjects (7 male, 11 female) aged between 20 and 41 volunteered to participate in this study. All were recruited from the general university population. No special criteria were used to select the subjects, however all subjects wrote naturally with their right hand.

2.2. Apparatus

A Wacom 1212-R graphics tablet connected to a Macintosh IIci personal computer was used to collect the data. The data recorded by this setup were the x, y and z (pressure) coordinates of the stylus, as it moved across the tablet surface. The coordinate data were sampled at a frequency of 100 Hz, and at a spatial resolution of 0.02 cm. The stylus used was approximately the same size (14 cm long, with a diameter of 0.9 cm) and weight (8 g) as a normal ball point pen. It contained a pressure sensitive polyester nib giving readings on a linear scale from 1 to 60. A piece of plain white paper was secured onto the face of the tablet to provide a more natural writing surface. A single horizontal line on the page was the only directional guide provided.

2.3. Procedure

The subjects were seated at a desk of normal height (60 cm) which contained both the computer and the graphics tablet. The subjects were asked to write the character string "madronal" in their normal cursive script. This pronounceable pseudo-word was created by the experimenter using the criteria that the pen does not need to leave the page while writing the component letters (e.g. not *i* or *t*), that successive letters were not too similar (e.g. *m* and *n*), and that the pseudo-word was long enough to ensure that the resulting pen trace contained at least 300 coordinate samples.

The subjects were allowed to practise writing the pseudo-word using a normal pen and paper, and then for a few times on the graphics tablet until they felt comfortable with the task. The subjects were then required to write the pseudo-word 10 times in their normal cursive handwriting, firstly on a lined sheet of writing paper with a normal ball point pen, and then on the graphics tablet using the stylus. Each instance of writing the pseudo-word on the graphics tablet was a separate trial. There was no immediate visual feedback to the subjects of their pen trace.

3. Results

3.1. Pre-processing of data

The samples of handwriting for each subject written on the lined writing paper were ranked from best to worst by the experimenter and two independent judges, one of whom had been a high school teacher. Particular attention was given to criteria such as general legibility, accuracy of letter formation and consistency of letter size both within and between word samples. These criteria were similar to those compiled by Rubin and Henderson (1982) and also used, e.g., by Schneck (1991) and Wann and Jones (1986). Although there were minor variations in the order in which the samples were ranked, the same samples were ranked as the nine best (designated as good handwriters), and nine worst (designated as poor handwriters) by all three judges. In other words, there was an inter-rater reliability of 1.0 for the assignment of subjects to the two groups.

Since this study was looking at space–time variability in a typical example of the subjects' handwriting, uncharacteristically fast or slow trials provide a confounding factor. Such trials were removed prior to data analysis, and from the remaining trials, the five that were closest in length were selected for further study. For each set of five trials of the pseudo-word for each subject, the length of the series was reduced so that each sample had the same number of coordinates. The left to right trend in the x direction was removed from the raw x coordinate data, and the x, y and z time series were all normalised to a mean of zero and a standard deviation of one.

Velocity profiles were calculated by taking the first difference of each normalised time series, and labelled x velocity (V_x), y velocity (V_y) and z velocity (V_z). The tangential velocity, (i.e. the speed of the tip of the stylus) was also calculated (V_{xy}) by applying a Pythagorean transformation to the x and y velocities. Time series plots of V_x, V_y, V_{xy} and V_z for one trial of the pseudo word for one subject can be found in Figs. 1–4 respectively. All show typical rhythmic patterns.

4. Coherence analysis

Coherence analysis provides a convenient method for evaluating the multidimensional similarity between two or more time series of observations. The coherence between velocity series V_{ki} and V_{kj}, $k = x, y, z$, $1 \leqslant i, j \leqslant 5$, is given by

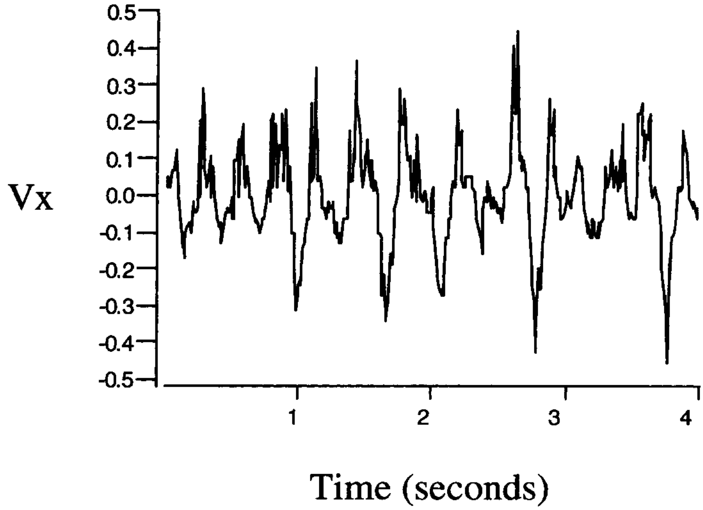

Fig. 1. A time series plot of the x velocity (V_x) for one trial of the pseudo word for one subject.

$$C_{ij}^k(\omega) = \frac{S_{ij}^k(\omega)}{\sqrt{S_i^k(\omega)S_j^k(\omega)}},$$

where $S_{ij}^k(\omega)$ is the cross-spectrum between series i and j and $S_p^k(\omega)$ the spectrum for series p, $p = i, j$.

A discrete Fourier transform of the time series data is used to estimate the spectrum. The squared modulus of the periodogram was smoothed by a sequence of

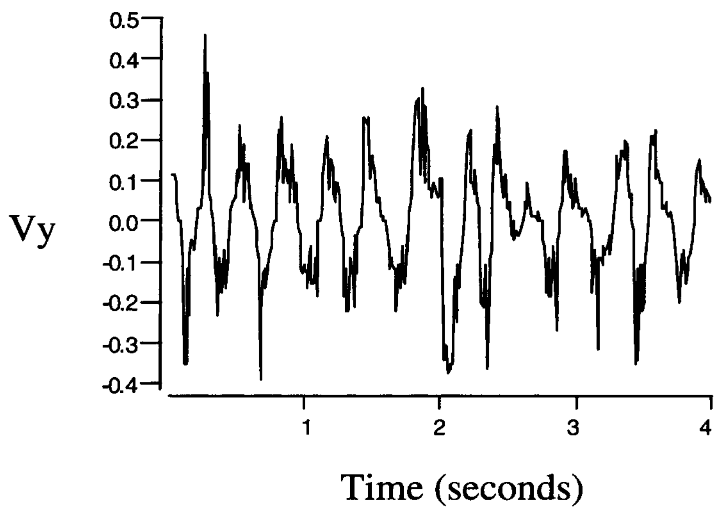

Fig. 2. A time series plot of the y velocity (V_y) for one trial of the pseudo word for one subject.

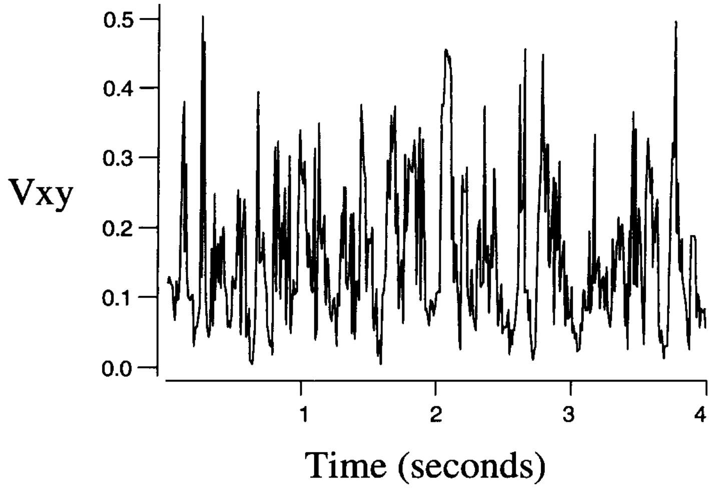

Fig. 3. A time series plot of the *xy* velocity (V_{xy}) for one trial of the pseudo word for one subject.

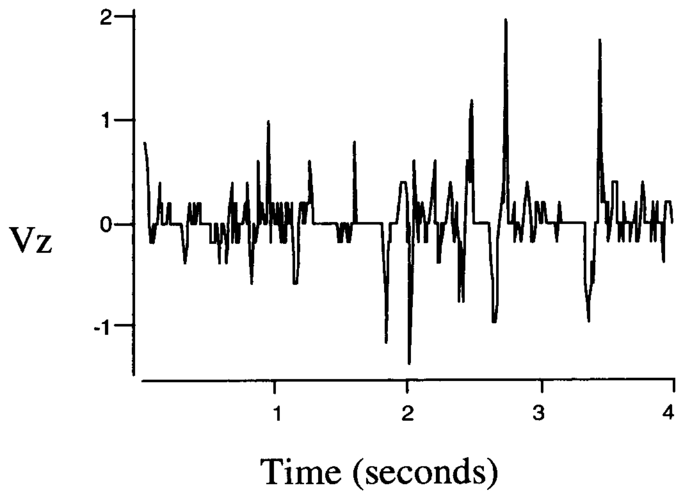

Fig. 4. A time series plot of the *z* velocity (V_z) for one trial of the pseudo word for one subject.

modified Daniell windows of lengths 3, 5, 7, 9 in order to calculate squared coherence coefficients between each pair of velocity profiles. Squared coherence values for the velocity profiles at frequencies up to the Nyquist frequency (50 Hz in this study) were calculated. For each subject, pairwise comparisons were made between the V_x from the first trial and that from the second trial, V_x from the first trial and that from the third trial and so on for all possible pairings (of which there were 10) of V_x for the five trials. This procedure was also applied to the five trials of the V_y, the V_z and the V_{xy} time series. An example of a typical squared coherence spectrum for one V_x–V_x comparison and one V_y–V_y comparison for good and poor handwriters can be found in Figs. 5 and 6 respectively.

The mean and the standard error of the maximum squared coherence over the 50 Hz range were calculated for both the good and poor handwriting groups. A summary of these results can be found in Table 1. For both good and poor handwriters the maximum squared coherence values were low for V_z–V_z coherence (good: 0.47, poor: 0.44), high for V_x–V_x (good: 0.75, poor: 0.64) and the V_y–V_y coherences (good: 0.72, poor: 0.66), and very high for the tangential velocity V_{xy}–V_{xy} coherence (good: 0.99, poor: 0.98). Table 1 shows that, for all combinations, there was a higher maximum squared coherence for good handwriters compared to poor. This difference was significant for the V_x–V_x coherence ($F(1,16) = 6.77$, $p = 0.019$).

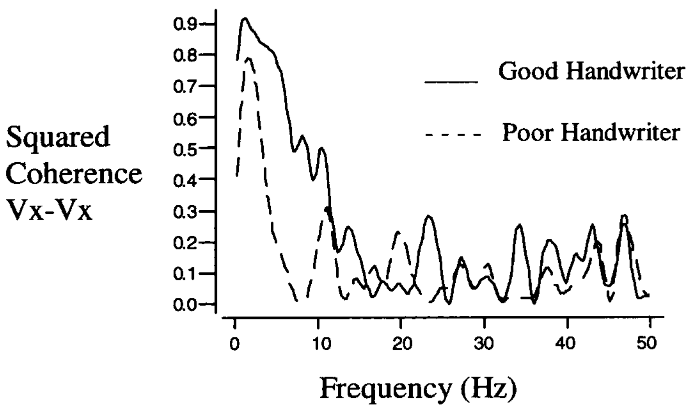

Fig. 5. A V_x–V_x squared coherence spectrum for one trial of the pseudo word for one poor and one good subject.

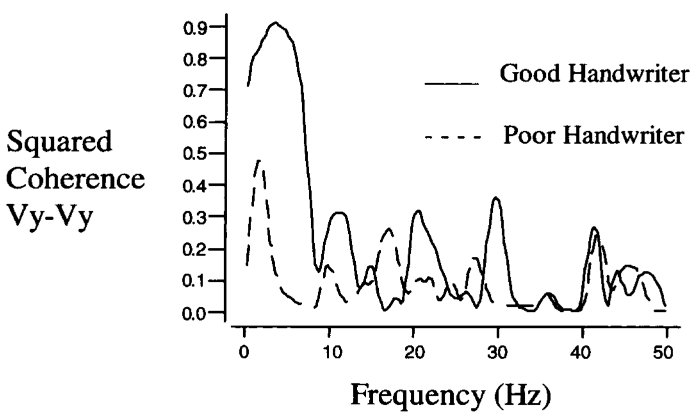

Fig. 6. A V_y–V_y squared coherence spectrum for one trial of the pseudo word for one poor and one good subject.

Table 1
Mean and standard error of maximum squared coherence for good and poor handwriting samples: V_x with V_x, V_y with V_y, V_z with V_z and V_{xy} with V_{xy}

		V_x–V_x	V_y–V_y	V_z–V_z	V_{xy}–V_{xy}
Maximum: good	Mean [a]	0.75	0.72	0.47	0.99
	SE	0.03	0.02	0.03	0.00
Maximum: poor	Mean	0.64	0.66	0.44	0.98
	SE	0.03	0.04	0.02	0.00

[a] The maximum squared coherence from 0 to 50 Hz for the pairings of V_x with V_x, V_y with V_y, V_z with V_z and V_{xy} with V_{xy} was calculated, and the mean computed for each group (good and poor handwriters).

The mean and the standard error of the total squared coherence were calculated for both the good and poor groups by summing up the squared coherence values for each frequency over the 50 Hz range. A summary of these results, in Table 2 showed that, for all combinations, there was a higher total squared coherence for good handwriters compared to poor.

There were significant differences between the squared coherence scores for the good and poor writers for the V_x–V_x coherence ($F(1,16) = 8.38$, $p = 0.011$), and for the V_y–V_y coherence ($F(1,16) = 6.25$, $p = 0.024$). The difference approached significance for the V_{xy}–V_{xy} coherence ($F(1,16) = 4.46$, $p = 0.051$), but there was no difference for the V_z–V_z coherence.

5. Discussion

The main hypothesis of this paper, that there would be a greater degree of space–time variability in the handwriting output of adult subjects who were poor handwriters, compared to those who were more proficient, was supported by the data. The mean total squared coherence values for the group of subjects who had been independently rated as relatively good handwriters were all higher than those for the poor handwriting group. This supports the findings of researchers such as Van Galen et al. (1993), who used spectral analysis of pseudo-words and Wann and Jones (1986) who used cross-correlation of letter velocity profiles.

Table 2
Mean and standard error of total between trial squared coherence for good and poor handwriters: V_x with V_x, V_y with V_y, V_z with V_z and V_{xy} with V_{xy}

		V_x–V_x	V_y–V_y	V_z–V_z	V_{xy}–V_{xy}
Total: good	Mean [a]	8.3	8.4	6.6	8.7
	SE	0.3	0.2	0.5	0.3
Total: poor	Mean	6.9	7.3	5.8	8.0
	SE	0.3	0.4	0.4	0.2

[a] The mean total squared coherence from 0 to 50 Hz for the pairings of V_x with V_x, V_y with V_y, V_z with V_z and V_{xy} with V_{xy} was calculated, and the mean computed for each group (good and poor handwriters).

In a more general sense, the results support the common finding in the motor control literature that for spatial and timing accuracy tasks, the degree of output variability is related to skill. The results also indicate that quantitative handwriting assessment based on dynamic characteristics is at least as accurate as the qualitative assessment based on the static final output but provides a richer source of information about possible underlying causes of poor handwriting.

These results do not support the findings of Wann and Jones (1986) who found no difference in both the cross-correlation for pseudo-word velocity profiles, and the squared coherence values for poor and good handwriters. However, the study by Wann and Jones (1986) differed from this study in several important respects. Firstly, their subjects, who were all young, had only recently been introduced to cursive handwriting. Consequently, for this more difficult task, it is likely that neither group had mastered the skill. This explanation, suggested by Wann and Jones, is supported by their subjects' relatively low cross-correlation values for the word condition and low mean coherence scores for both conditions. In the present experiment, the maximum squared coherence scores achieved by all subjects were high indicating that they had all achieved a generally competent level of handwriting proficiency.

A second difference between this study and that of Wann and Jones (1986) is that these authors only calculated cross-correlation values for the tangential velocity (V_{xy}). Although this non-significant difference between good and poor writers for V_{xy} was also confirmed in the present study, significantly lower squared coherence values were observed for the horizontal velocity, V_x. This result suggests that mature writers may differ in the consistency with which they move the pen across the page, as both vertical and pressure velocity components were not related significantly to writing proficiency. Furthermore, Wann and Jones only calculated average coherence values for the y displacement data, and only examined the dynamics at frequencies up to 5 Hz. The present study, on the other hand, examined coherence values for frequencies up to 50 Hz which provides a more accurate assessment of the dynamic motor output (see e.g. Van Galen et al., 1993).

Most researchers dealing with handwriting quality, specifically choose subjects who are unusually poor or good at the skill (Schneck, 1991; Wann and Jones, 1986). The present study did not use any special criteria to choose subjects, merely visually ranking their handwriting from best to worst after they had completed the task. Consequently, the handwriting observed in this study is most likely a representative sample of normal handwriting quality. The discovery of higher squared coherence values for the good handwriters compared to the poor, and the observation that these differences were significant for the x and y velocities reinforces the power of this technique for assessing handwriting skill. That these results occur in the frequency domain has important implications for motor control and skill development theory.

The development of the skill of handwriting may consist of learning the translation of spatial codes held in long-term motor memory into consistent spatial output. This translation relies on an accurate modulation of dynamic characteristics such as force amplitude and duration. A failure to achieve appropriate dynamic control, perhaps from an inefficient filtering of biomechanical noise, will lead to the higher degree of spatial variability as displayed by the poor handwriters (van Galen, 1991).

Skilled control may be achieved by learning to vary the stiffness of the limbs, and by the simultaneous co-contraction of agonist and antagonist muscles. This stiffening of muscles leads to a filtering out of low frequency noise, which may originate from muscle tremor (Van Galen et al., 1993).

It may be that good handwriters master this stiffness control, moving onto more consistent handwriting dynamics, while poor handwriters remain less proficient at motor control (Van Galen et al., 1993). Further evidence for this proposal might be found from an analysis of the dynamic characteristics of a subject's handwriting output, as they learn how to write a new allograph. The consistency of dynamics should increase as the skill is mastered, and becomes more automatic.

Meulenbroek and van Galen (1988) have provided evidence for a progressive automatisation of writing dynamics with experience. These researchers had five different groups of school children ranging from 8 to 12 yr of age perform a grapheme copying task on a small digitising pad. It was found that the mean writing time for a grapheme decreased steadily with age and attained stability for 11 yr old children. Writing speed, as measured by mean writing velocity, initially decreased for 9 yr old children and then increased steadily for ages 10–12 yr. There was a corresponding non-monotonic relationship for a dysfluency index measured by the number of velocity inversions per centimetre. In this case performance reached a peak at 9 yr and then decreased thereafter.

These research findings, as interpreted by Meulenbroek and van Galen, suggest that there may indeed be three stages of motor skill acquisition in children, an initial stage in which there is little cognisance of the need to write accurately, leading to fast but inaccurate grapheme reproduction; a second stage involving greater attention to the error feedback provided by comparing the motor output to the memorised grapheme; and a third stage in which kinematic performance becomes faster and more accurate suggesting a tendency to employ open-loop rather than closed-loop motor control. These findings further emphasise the consistent finding that as a skill improves with practice, inter-trial variability decreases.

Evidence from the present study now needs to be supplemented by further work involving a thorough investigation of writing automaticity in adults who exhibit large individual differences in writing proficiency. These differences in writing proficiency may be the result of a steady decline in writing efficiency that is observed as early as the primary school years, once the fundamental handwriting skill has been learned (Hamstra-Bletz and Blöte, 1993). These authors have confessed that their subjective analysis of the finished handwriting product could be much refined by the use of on-line dynamical analyses, especially since the primary determinant of individual differences in writing clarity appears to be fine-motor ability.

The results of our own study demonstrate that handwriting legibility is, at least in part, related to inter-trial dynamic variability. In other words, spatial variability in a stable physical environment is partly a result of dynamic variability. The results suggest that accurate quantitative assessment techniques, based on the dynamic characteristics of handwriting, can be useful diagnostic techniques for evaluating handwriting quality both in studies of movement behaviour as well as in an educational setting.

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