The influence of tremor on handwriting performance under conditions of low and intermediate physical stress

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The influence of tremor on handwriting performance under conditions of low and intermediate physical stress

M. G. Longstaff¹ & R. A. Heath²

Abstract. This study used a temporally sensitive technique (coherency analysis) to examine individual differences in handwriting dynamics of people with and without tremor, under conditions of low and mild physical stress. Participants with tremor maintained their axial pen pressure (APP), while those without tremor increased their pressure in conditions of mild stress. Both groups wrote at a similar speed with a small but significant increase in the stress condition. The between-trial coherency (i.e. temporal similarity) of velocity and APP profiles was greater for people without tremor. When writing in mildly stressful conditions, the coherency increased for people without tremor but tended to decrease or be maintained for people with tremor. These findings may be applied in the future to finding clues to the authenticity of documents written by people with tremor. The results are discussed in terms of the neuromotor noise theory.

Motor function impairment is a common symptom of neurological dysfunction and can be a primary cause of the loss of competence in everyday activities. Degradation of fine motor skills such as handwriting,

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is often the first sign of a problem that needs further investigation. In patients with Multiple Sclerosis (MS) for example, this impairment is due to demyelination of the cerebellum and manifests itself as a general weakness, clumsiness and tremor (Smith, Samkoff and Scheinberg, 1993). Tremor itself is associated with a broad range of possible causes. It is a symptom of several neurological disorders including Parkinson's disease (Phillips et al., 1993), and can result from exposure to environmental pollutants such as manganese (Beuter, et al 1999). It can also be due to normal aging (Schut, 1998).

Tremor is known to result in disturbances in the performance of fine motor skills. Part of this is due to difficulties in the appropriate modulation of force. For example, Britton et al (1994) found that people with hereditary essential tremor tended to overshoot targets in a wrist flexion aiming task. These overshoots were a result of a delay in the second agonist burst in an agonist-antagonist-agonist pattern of muscle activity, where an agonist or antagonist burst is related to force production.

Symptoms such as tremor, and the consequent degradation of fine motor skills, have important implications for the field of forensic documentation examination. For example, a forensic expert may be asked to determine whether a document has been written by a person who suffers from a neurological disease. This could be critical if there are questions about the authenticity of a document that is claimed to have been written by someone suffering from a motor dysfunction such as tremor. Alternatively, there may be a dispute over whether a document had been written before or after the onset of the disease. In this situation, experts need empirical evidence to guide them as to how handwriting changes in the presence of neurological disturbances. Furthermore, it is essential to ascertain the differential influence of stress on the movement characteristics of healthy people, and of those with motor function degradation.

Recent work has demonstrated that movement dynamics can be used to objectively assess how handwriting changes during the course of normal ageing, as well as in neurodegenerative processes such as Alzheimer's Disease (Wright, Lindemann and Dick, 1999). In a more general study of handwriting quality, Longstaff and Heath (1997) illustrate how dynamic movement characteristics can be used to differentiate between those who are proficient and those who are not proficient at this skill. For example, a coherency spectrum generated from two time series provides an estimate of the strength of their temporal relationship at various frequencies (Bloomfield, 1976). Coherency analysis is a standard time series analysis technique that evaluates the similarity of the rhythmic components of two or more time series. When applied to handwriting veloc-
ity time series, it provides a measure of how consistently a participant writes the same word from trial to trial. In the study by Longstaff and Heath, eighteen healthy adults wrote the pseudo-word “madronal” ten times in their normal cursive script. These samples were rated as being relatively legible or illegible by three independent judges. Participants who were rated as legible writers displayed a greater degree of temporal consistency (between-trial coherency) than the less legible writers. It was concluded that spatial consistency (or legibility) was related to temporal consistency. In other words, in order to produce a consistent and legible pen trace, you need to produce the movements with minimum temporal variability. This study demonstrated that the mean coherency between several samples of writing is analogous to a measure of proficiency at the skill of handwriting. The higher the coherency value, the more legible the writing tends to be.

Spectral analysis has been used as an effective tool in the investigation of rhythmic movements (van Galen, van Doorn and Schomaker, 1990; Wann and Jones, 1986). It represents the relative importance of each frequency component within the original time series. The squared coherency provides a measure of the correlation between the spectral estimates of two time series at each frequency. The squared coherency values range from zero to one. A coherency of zero indicates no correlation, while a coherency value of one indicates a perfect correlation. A detailed description of the calculation of spectral and coherency estimates is beyond the scope of this paper, but can be found in numerous sources (see for example Bloomfield, 1976; Priestley, 1981). The specific application of coherency analysis used in the present study, as applied to velocity and axial pen pressure profiles, is described in more depth within the Methods section.

Recent theories of psychomotor skill performance propose that speed and axial pen pressure (which are partly a result of limb stiffness), are important variables in the control of accuracy while performing fine motor tasks (van Galen and de Jong, 1995; van Gemmert, and van Galen, 1997). The neuromotor noise theory described by van Gemmert and van Galen proposes that there is a degree of “noise” in the neuromotor system that influences the accuracy of movements. This level of background noise can be increased, for example, by imposing greater demands on the cognitive or motor system, or by stressing the psychomotor system. In circumstances where the accuracy demands of a task can be easily met with increased levels of noise, the increased level of noise activates the system, which results in faster reaction times and movement times. If the accuracy demands of the task require the system to be very accurate, an increase in the noise in the system results in an increase in limb stiffness.
This limb stiffness filters out some of the noise, allowing the movements to be more accurate. In other words, in healthy psychomotor systems, limb stiffness is a control mechanism that can be adaptively modulated in response to environmental and task demands. We argue that people with motor function degradation (for example, muscle tremor) would be less able to use these control mechanisms.

The present study extends the findings of Longstaff and Heath (1997) to examine individual differences in the graphic skills of people with and without tremor, under conditions of low and intermediate physical stress. Temporally sensitive techniques are used to investigate the impact of tremor on the dynamic aspects of handwriting. The aim of this study is to develop effective techniques to help differentiate between people who are healthy and those who are suffering from motor problems such as tremor. A further goal is to learn more about the control of fine motor movements. The findings of this study will be discussed in terms of the neuromotor noise concept (van Galen, Portier, Smits-Engelsman and Schomaker, 1993; van Gemmert, and van Galen, 1997).

This study used an annoying and distracting sound to raise the neuromotor noise, in a way that was similar to that used in a recent study by van Gemmert and van Galen (1998). The definition of stress will be that used by van Gemmert and van Galen. Stress is demonstrated by the need to increase effort in the presence of an external or internal stimulus. This effort is necessary in order to maintain task accuracy. An intermediate physical stress is applied. As was generally found by van Gemmert and van Galen (1997, 1998), it was expected that healthy people would respond to this mild stress with an increase in pen pressure that would facilitate accuracy. It was thought that due to a general degradation of motor function, people with tremor would be less able to modulate pressure in order to maintain temporal accuracy, particularly while writing under conditions of increased neuromotor noise. Van Gemmert, Teulings and Steilmach (1998), for example, found a decrease in the writing performance of people with Parkinson’s Disease under conditions of increased motor load.

Since weakness is a symptom of MS (Smith, Samkoff and Scheinberg, 1993), and most of the participants in this study with tremor also have MS, it was hypothesized that the people who display some degree of tremor would write with a lower axial pen pressure that would remain constant despite an increase in physical stress, and that people without tremor would write with a higher pressure that would increase with a mild increase in physical stress. It was also hypothesized that the
people who display some degree of tremor would produce lower coherency values than people without tremor. Finally, it was hypothesized that there would be an increase in coherency in the intermediate stress condition compared to the low stress condition for people without tremor, but not for people with tremor.

Method

Participants

Seven people with Multiple Sclerosis and seven people without Multiple Sclerosis volunteered to participate in this study. Using spirometry (Bain and Findley, 1993), the participants were rated as either displaying no tremor, or some degree of tremor. Spirometry is a standard test used by neurologists to assess the degree of tremor severity. In this test, a patient draws a spiral from the center with an increasingly larger radius until they complete at least five revolutions. This spiral is then compared to a set of “standard” spirals. The standard spiral that is most similar to the spiral drawn by the patient is used to rate tremor severity on a scale from 0 to 9 (Bain and Findley, 1993). Six people with MS and one without MS were rated as displaying some degree of tremor (3 Male, 4 Female, mean age = 55, mean tremor rating = 3.3). Six people without MS and one with MS were rated as not displaying tremor (2 Male, 5 Female, mean age = 36, mean tremor rating = 0.9).

Apparatus

An IBM compatible computer and a WACOM 1212-R graphics tablet were used to collect the horizontal and vertical position, as well as the axial pen pressure of a stylus as the participants wrote the pseudoword “lanordam”. The data was collected at a frequency of 206 Hz and a spatial resolution of 0.02 cm. The data collection and control program was written using the OASIS programming language (de Jong, Hulstijn, Kosterman, and Smits-Engelsman, 1996). The stylus was a modified WACOM inking pen, similar in appearance and use to a normal ballpoint pen. A modified WACOM pen was used, as an unmodified pen suffers from low temporal resolution of the axial pen pressure. This would not have allowed us to perform an accurate coherency analysis of the pen pressure. The sound was generated through TEAC HF-11TV headphones attached to a soundblaster sound card, controlled by the OASIS program.
Procedure

The participants practiced writing the pseudo-word “lanordam” several times until they were comfortable with the task and apparatus. They then wrote “lanordam” six times on a sheet of paper attached to the graphics tablet, under conditions of low or intermediate physical stress. The only guides given were two columns of six horizontal lines. In the low physical stress condition there was minimal additional sound. In the intermediate physical stress condition the participants wrote the words while listening to an annoying 65 decibel, oscillating two-tone sound (880 Hz, 1760 Hz) that alternated at a rate of approximately 5 Hz. This level of sound is of similar intensity to a busy street. A low intensity sound was chosen to ensure that the task was not unnecessarily stressful for the participants. This sound was presented through a set of headphones. The tangential velocity (pen speed) and axial pen pressure were analysed, with separate, one between (tremor group) and two within (sound condition and trial number), analyses of variance. The squared integrated between-trial coherency for the horizontal, vertical and tangential velocity, as well as the axial pen pressure, were analyzed, with separate, one between (tremor group) and one within (sound condition), analyses of variance. Alpha was set at 0.05 for determining the statistical significance of the results.

Writing speed is related to movement time (MT), a variable commonly reported in studies of motor skills. When the spatial characteristics of a movement are similar across all participants, individual differences in MT are directly related to differences in movement speed. In the present study, however, there was a degree of variability between participants in the style in which they wrote the pseudo-word. In this case, MT would reflect gross differences in handwriting style rather than in how quickly the words were written. On the other hand, mean tangential velocity is a more direct measure of movement speed, allowing a more meaningful comparison between groups. Furthermore, the mean writing speed can be more directly related to the results of the coherency analysis.

The application of coherency analysis is as follows: Figures 1, 2, 3, and 4 present plots of two trials of the written word ‘lanordam’, with their corresponding tangential velocity profiles, for a person suffering from tremor and for a healthy person. The tangential velocity profiles represent the speed of the tip of the stylus as it moves across the graphics tablet as the participant writes the word.
Figure 1. A plot of the word “lanordam”, written in two separate trials by a person suffering from a tremor.

Figure 2. A time series plot of the tangential velocity of the word “lanordam”, written in two separate trials by a person suffering from a tremor.
Figure 3. A plot of the word “lanordam” written in two separate trials by a healthy person.

Figure 4. A time series plot of the tangential velocity of the word “lanordam”, written in two separate trials by a healthy person.
In Figure 2, it appears from visual inspection that the person with tremor did not write with smooth, rhythmic movements. Furthermore, when comparing Figure 1(a) to Figure 1(b) and Figure 2(a) to Figure 2(b), the movements do not appear to be very consistent from trial to trial. A visual inspection of the tangential velocity of the healthy person shown in Figure 4, reveals that he appears to write with smoother, more rhythmic movements. When comparing Figure 3(a) to Figure 3(b) and Figure 4(a) to Figure 4(b), the movements seem relatively consistent from trial to trial.

From these velocity time series, spectral estimates were initially calculated. The coherency between these time series was then evaluated to determine how similar the rhythmic movements were. In Figures 5 and 6, the spectrum for each time series, as well as the squared coherency spectrum for the person with tremor and for the healthy person, can be seen.

![Figure 5](attachment:image.png)

**Figure 5.** A spectrum (in decibels) and squared coherency spectrum of the tangential velocity of the word “lanordam”, written in two separate trials by a healthy person.

Figures 5(a) and 6(a) respectively display the spectrum for the two tangential velocity time series for the person with tremor and for the healthy person. As was noted from the visual inspection of the tangential velocity time series, it appears from the spectral analysis that the rhythmic movements used by the healthy person are more similar from trial to trial than the movements of the person displaying tremor. Figures 5(b) and 6(b) display the squared coherency spectrum for the two participants. It is clear from these figures that there is a stronger relationship between
the two time series (i.e. coherency values closer to one) at most frequencies for the healthy person when compared to the person with tremor.

![Figure 6](image)

**Figure 6.** A spectrum (in decibels) and squared coherency spectrum of the tangential velocity of the word “lanordam”, written in two separate trials by a healthy person.

There are several ways that this coherency analysis can be used to investigate individual differences in the rhythmic movements used to write words. For example, average coherency values at a range of frequencies of theoretical importance can be compared. For this present study we were interested in how similar two time series were over the entire frequency range that is available, as this would take into account both low and high frequency processes. As such, we estimated the squared coherency over the entire frequency range for each pair of time series comparisons up to the Nyquist frequency (i.e. half the sampling frequency). We then integrated these values in order to calculate the overall coherency between the two time series for that frequency range. The mean integrated squared coherency for the pairwise comparisons is then calculated. This gives us an indication of the degree of control of the fine motor movements required when writing a word.

The coherency analysis presented below compares the spectrum of the velocity in the horizontal and vertical directions, the tangential velocity, as well as the axial pen pressure. The velocity time series in the horizontal and vertical directions are calculated by dividing the distance from one sample to the next sample in time by the time elapsed between the two samples (in this case 1/206 seconds). This raw velocity signal is
then filtered, using a seven point median filter. The tangential velocity is calculated using a Pythagorean transformation of the velocity in the x and y directions. All velocity time series were calculated using OASIS (de Jong et. al., 1996).

For each time series, the spectrum from trial 1 is compared to the spectrum from trial 2, trial 1 to trial 3, and so on, for all combinations (of which there are six) of 4 trials. The total integrated squared coherency for frequencies 0 to 103 Hz is calculated for each comparison, and the mean integrated squared coherency for each participant is used for further analysis. The procedure used for coherency analysis is similar to that used by Longstaff and Heath (1997).

Results

Differences in handwriting speed between tremor groups and sound conditions

The mean tangential velocity used by participants is collated in Table 1. While it appears that people without tremor write slightly faster than people with tremor, the main effect for groups was not significant. Both groups exhibited a small increase in speed in the “additional sound condition”, resulting in a significant main effect for sound, $F(1,12) = 4.98, p = 0.045$. There was no significant interaction effect. There were no significant effects for trial, the group by trial, condition by trial, or group by condition by trial interactions. The degree of variability (i.e. the standard errors) of the speed at which people wrote was similar for both groups and conditions.

Table 1: The mean and standard error of the pen speed (in cm/sec) used by people with and without tremor while writing “lanordam”, under conditions of low (no additional sound) and intermediate (additional sound) physical stress.
Differences in Axial Pen Pressure between tremor groups and sound conditions

The mean axial pen pressure used by the participants is collated in Table 2. It can be seen that people with tremor generally write with less pressure than people without tremor. On average, the participants wrote with higher pressure in the “additional sound” condition than in the “no additional sound” condition. However, these differences were not statistically significant.

Table 2: The mean and standard error of the axial pen pressure (in grams) used by people with and without tremor while writing “landerdam”, under conditions of low (no additional sound) and intermediate (additional sound) physical stress.

<table>
<thead>
<tr>
<th></th>
<th>No additional sound</th>
<th>Additional sound</th>
<th>Both conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with tremor</td>
<td>116.27 . 6.60</td>
<td>107.01 . 6.25</td>
<td>111.64 . 4.55</td>
</tr>
<tr>
<td>People without tremor</td>
<td>112.14 . 10.59</td>
<td>135.83 . 11.72</td>
<td>123.98 . 7.97</td>
</tr>
</tbody>
</table>

Table 2 shows that the pressure used by the people with tremor drops slightly in the “additional sound” condition, but increases for the people without tremor. This interaction between tremor group and condition was statistically significant, $F(1,12)=9.78$, $p=0.009$. There were no significant effects for the trial, group by trial, condition by trial, or group by condition by trial interactions.

Differences in the coherency of the velocity profiles between people with tremor and people without tremor writing under conditions of low or intermediate physical stress

Table 3 details the mean total between-trial integrated squared coherency of the horizontal velocity for people with and without tremor, who wrote under conditions of low (no additional sound) and intermediate (additional sound) physical stress. It appears that people with tremor display a lower coherency than people without tremor, and that both groups display lower coherency in the “no additional sound” condition. These differences are both statistically significant, $F(1,12)=5.51, p=0.037$ for tremor group, and $F(1,12)=5.27, p=0.041$ for the sound condition. There is no significant interaction between tremor group and sound condition on coherency in the horizontal direction.
Table 3: The mean and standard error of the total between-trial integrated squared coherency of the horizontal velocity for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress.

<table>
<thead>
<tr>
<th></th>
<th>No additional sound</th>
<th>Additional sound</th>
<th>Both conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with</td>
<td>9.56 ± 0.82</td>
<td>10.22 ± 1.01</td>
<td>9.89 ± 0.64</td>
</tr>
<tr>
<td>tremor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>People without</td>
<td>11.37 ± 0.99</td>
<td>13.58 ± 0.74</td>
<td>12.46 ± 0.66</td>
</tr>
<tr>
<td>tremor</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mean total between-trial integrated squared coherency for the vertical velocity can be seen in Table 4. It appears that people with tremor display lower coherency than people without tremor. This difference is highly significant, $F(1, 12) = 20.11$, $p = 0.001$. There was a non-significant main effect of sound condition on the coherency of the vertical velocity profiles. As is shown in Table 4, people without tremor increase their coherency in the “additional sound” condition, while the people with tremor decrease their coherency. This interaction is highly significant, $F(1, 12) = 9.78$, $p = 0.009$.

Table 4: The mean and standard error of the total between-trial integrated squared coherency of the vertical velocity for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress.

<table>
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<tr>
<th></th>
<th>No additional sound</th>
<th>Additional sound</th>
<th>Both conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with</td>
<td>10.30 ± 0.60</td>
<td>9.39 ± 0.39</td>
<td>9.85 ± 0.35</td>
</tr>
<tr>
<td>tremor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>People without</td>
<td>11.62 ± 0.68</td>
<td>14.19 ± 0.76</td>
<td>12.90 ± 0.60</td>
</tr>
<tr>
<td>tremor</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The mean total between-trial squared coherency for the tangential velocity is collated in Table 5. From this table it can be seen that people with tremor display a lower coherency than people without tremor. This difference was statistically significant $F(1, 12) = 11.86$, $p = 0.005$. There was a non-significant main effect of sound condition on the coherency of the tangential velocity profiles.
Table 5: The mean and standard error of the total between-trial integrated squared coherency of the tangential velocity for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress.

<table>
<thead>
<tr>
<th></th>
<th>No additional sound</th>
<th>Additional sound</th>
<th>Both conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with tremor</td>
<td>9.89 . 0.68</td>
<td>9.21 . 0.87</td>
<td>9.56 . 0.54</td>
</tr>
<tr>
<td>People without tremor</td>
<td>10.86 . 0.41</td>
<td>13.20 . 0.62</td>
<td>12.03 . 0.49</td>
</tr>
</tbody>
</table>

Figure 7 displays the interaction between the integrated squared coherency of the tangential velocity for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress. This interaction is statistically significant, $F(1,12) = 6.34$, $p=0.027$. While the coherency for people with tremor decreases in the “additional sound” condition, the coherency increases for the people without tremor.

![Figure 7](image-url)

Figure 7. The mean of the total between-trial squared coherency of the tangential velocity for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress.
Table 6 details the mean of the total between-trial integrated squared coherency of the axial pen pressure for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress. People without tremor display significantly higher coherency of axial pen pressure, $F(1,12) = 6.76, p = 0.023$. There was a non-significant main effect of sound condition on the coherency of the axial pen pressure profiles. There is no significant interaction between tremor group and sound condition on the coherency of the axial pen pressure.

**Table 6:** The mean and standard error of the total between-trial integrated squared coherency of the axial pen pressure for people with and without tremor, writing under conditions of low (no additional sound) and intermediate (additional sound) physical stress.

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<th></th>
<th>No additional sound</th>
<th>Additional sound</th>
<th>Both conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>People with tremor</td>
<td>4.60 ± 0.23</td>
<td>4.62 ± 0.27</td>
<td>4.61 ± 0.17</td>
</tr>
<tr>
<td>People without tremor</td>
<td>6.29 ± 0.68</td>
<td>7.43 ± 1.17</td>
<td>6.86 ± 0.67</td>
</tr>
</tbody>
</table>

**Discussion**

The results of this study support the hypothesis that people with tremor would be less able to modulate axial pen pressure to maintain temporal accuracy while writing in mildly stressful conditions. As hypothesized, people without tremor increase their axial pen pressure when there is a mild stress. This is known to be one mechanism the body can use to filter out noise in the neuromotor system (van Gemmert and van Galen, 1997, 1998), and is related to stiffening of the limb system. This speculation was further confirmed by support for the second hypothesis. For movements in the horizontal, vertical, tangential and axial directions, people with tremor displayed significantly lower between-trial coherency. This indicates a general reduction in the proficiency at this skill (Longstaff and Heath, 1997). More importantly, for both the vertical and tangential velocities, there is an increase in between-trial coherency for people without tremor writing under conditions of mild stress. The between-trial coherency for people with tremor remains fairly stable or drops slightly under conditions of mild stress.

This significant interaction between tremor group and sound condition indicates that the people without tremor are able to filter out the increased neuromotor noise, while the between-trial, temporal similarity of
the writing of the people with tremor is adversely affected by this noise. In fact, it appears that the noise has a slight arousal or facilitating effect for people without tremor, leading to an improvement in between-trial similarity. This finding is compatible with the neuromotor noise theory (van Gemmert and van Galen, 1997). It is worth noting that while the interaction was not statistically significant for the horizontal velocity and axial pen pressure, the trend was in the same direction.

It could be argued that the differences between groups for the coherency analysis merely reflects a difference in the mean speed at which the two groups wrote. It could be that if the speed of writing increases, the coherency may also increase by default. However, the results indicate that there was no significant difference in speed at which the two groups wrote the words. While there was a small but significant increase in the speed in the mild stress (additional sound) condition, this was not accompanied by a systematic increase in coherency. As noted above, this small change in speed corresponded to increases in coherency for people without tremor, but to decreases or no change in the coherency for people with tremor. Furthermore, it is possible that the coherency values reflect the overall level of variability of the velocity profiles. This assertion is not supported by the finding that the variability in movement speed was similar for both groups and both conditions.

Taken together, these results, along with those of Longstaff and Heath (1997, 1999), demonstrate the validity and utility of temporally sensitive techniques such as coherency analysis in the assessment of motor skill function in general, and handwriting quality in particular. These techniques could be employed to initially diagnose degradation of fine motor skills and perhaps provide an early warning for more serious neurological dysfunction such as Multiple Sclerosis, Parkinson’s disease or nerve damage due to environmental pollutants such as lead.

The present study further proposes that people whose motor systems are damaged would be less able to modulate the control mechanisms that healthy people use to filter out unwanted neuromotor noise. When neuromotor noise increases due to a mild physical stress, healthy people increase their axial pen pressure. This in turn filters out some of the neuromotor noise to produce more consistent movements, as measured by coherency analysis. For people with damaged motor functionality, there seems to be a reduced ability to use an increase in axial pen pressure to filter out the neuromotor noise. This leads to either no change in the consistency of movement (which is already less than that of healthy people) or to a drop in consistency.
In the present study, most of the participants with tremor also suffered from Multiple Sclerosis (MS). Part of the difficulty they experience when trying to increase axial pen pressure (APP) may be due to the weakness often associated with MS. However, this would not necessarily be the case for the participant who displayed tremor but not MS. Furthermore, there was one participant with MS who did not display tremor, and overall (contrary to the hypothesis), there was no significant difference between groups for APP. It is likely, therefore, that the difficulty relates to a reduced ability to appropriately modulate force production, given particular task or environmental circumstances. This is emphasized by the finding that participants without tremor could adaptively increase their APP to minimize the dynamic variability of their movements. In other words, the base level of the APP is less important than the ability to effectively modulate APP in light of the task constraints. For the majority of participants in this study, force modulation may be restricted by a general weakness and/or disruption of force production due to tremor, resulting in a tendency towards lower levels of APP. However, modulation of the force applied on the paper would also be difficult if the participants had a relatively high level of APP.

These results also provide further support for the neuromotor noise theory (van Gemmert and van Galen, 1997). A damaged neuromotor system is less able to use the modulation of axial pen pressure by increasing muscle stiffness to filter out a rise in neuromotor noise to maintain accuracy. Mild increases in the level of neuromotor noise in a healthy system can lead to a stiffening of the muscle system, thus effectively filtering out the noise and resulting in more accurate movements.

The results presented in this study have several practical implications for the field of forensic document examination. The handwriting of a person with motor function degradation will be generally less consistent across repetitions of the same word than will the handwriting of healthy people. This lack of consistency, which is related to legibility, increases when the person with tremor writes in situations involving mild physical stress. The inter-trial variability appears to decrease for healthy people writing under conditions of mild physical stress.

While the dynamic inter-trial variability cannot be established from the static pen trace, there are measures of general legibility that may be used by forensic document examiners in light of the above findings (see for example Graham, 1986; Longstaff and Heath, 1997). Future research could establish the validity of this approach. It also appears that healthy people increase the axial pen pressure they use when writing under conditions of mild physical stress, while people with tremor maintain their
pen pressure. There is some evidence to suggest that the pressure used while writing can be estimated from the static pen trace (Sita and Rogers, 1999). Future developments may allow forensic document examiners to use the information related to movement dynamics discussed in this study when assessing the handwriting of healthy people and those with motor function degradation.

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