Low-frequency periodicity in the coordination of progressive handwriting

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Abstract

The paper addresses the question how the effector segments are coordinated during handwriting, in particular as a function of the left-to-right progression within words. It studies the phase relations between wrist and finger-joint rotations during a repetitive graphic task (long words consisting of letters ‘e’), and it subjects the resulting continuous phase-relation plots to autocorrelation analysis. A novel phenomenon, viz. that of low-frequency (1-Hz) periodicity, is observed which presumably reflects adjustments of the coordination pattern about once per second, i.e., after every three or four letters ‘e’. Moreover, word length and word position are found to affect this periodicity in a predictable manner. These results are related to those of an earlier study which used an ad-hoc method of analysing wrist-finger coordination adjustments. The paper underlines the value of phase-relation analysis for certain graphic tasks, but it also points out its limitations for this purpose. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

For the sake of its function in communication, handwriting should proceed efficiently, that is to say, at a reasonable speed and with a minimum of effort. Experimentation as well as the development of handwriting in most cultures have shown that these requirements are fulfilled best by keeping the writing instrument down on the writing surface as much as possible, so as to produce connected, ‘cursive’ script. The additional task constraints on the legible production of any particular cursive script, however, are more specific. For our Latin script these may be summarised as follows. The writer is expected to produce letters of approximately constant shape, slant and size, and to join these to form connected words progressing from left to right, following a straight horizontal baseline. After years of practice, a proficient writer can meet these requirements, although his or her effector system is built up of segments that can only produce curvilinear trajectories. Indeed, the biomechanical arm–hand–finger system has many degrees of freedom, and the skilled writer readily exploits its redundancy to achieve the demanding graphic task. The present paper addresses the question of how the degrees of freedom problem is solved, i.e., how the effector segments are coordinated, especially as a function of the left-to-right progression within words.

An illustration of the coordination problem is the following. When the wrist joint is adducted, the hand’s orientation in work space is different from when the joint is abducted. The fingers making the same movement with respect to the hand to which they are attached, will thus describe trajectories in different directions depending on the rotation of the wrist. Since handwriting requires invariant slant, the coordination of the wrist–finger system must be adapted somehow, either continuously or intermittently. And because the letters are expected to be on a straight baseline (instead of following the curved hand sector centred around the wrist joint), the coordination problem becomes even more complex.

Earlier studies concerning progressive handwriting have shown that the requirement of progression indeed adds considerable complexity to the task, especially for inexperienced writers (Thomassen and Teulings, 1983a,b), and that the trace and kinematics of handwriting are substantially altered when progression is introduced (Maarse et al., 1986; Maarse and Thomassen, 1983), manipulated visually (Thomassen and Meulenbroek, 1993), or controlled externally (Thomassen et al., 1994). Moreover, modelling handwriting in a relatively parsimonious manner (i.e., following Hollerbach, 1981) has shown that certain common phenomena, like subtle slant and size changes with progression, may be due to the geometry of the hand rotating in the wrist (Lelivelt et al., 1996).

In our recent research (Thomassen et al., 1996), we studied the co-activated involvement of wrist and fingers in terms of their joint-angle amplitudes per stroke when writing progresses rightward, within and between words, across the page. We found that stepwise adaptations – in the form of well defined discontinuities in the co-activation pattern – occur not only between words, where they are a universal pen-up phenomenon, but also frequently within words, while the pen point continues to move in the writing plane. The latter adaptations generally implied the adoption,
later in the word, of a wider range of movement directions by the fingers, leading to increased wrist–finger co-activation. Another important finding was that, early in the word, the subjects tended to adopt a specific coordination pattern as a function of word length and word position.

When closely inspecting the spatial trace and the kinematics of long, cursively written long words, a striking feature in most cases is that there are several instances of imperfect constancy of the size, slope and width of the word’s loops, and even of shape distortions and jerks, and of jumps in the baseline. Furthermore, it appears that these irregularities do not occur completely at random, but tend to fluctuate at intervals of about 3 to 4 letters. It might be that these fluctuations somehow reflect the adaptation events that were observed in the previous study. The primary goal of the present research is to detect and analyse any such fluctuations in the coordination of hand and finger excursions by studying the phase relations between the involved joint excursions. As a secondary goal, our study attempts to contribute to the assessment of the suitability of the phase-relation approach to graphic tasks like handwriting. In order to establish the utility of our measures, and to gain further insight into the implied mechanisms, we chose to investigate the two independent variables that proved to be co-determinants of coordination in our previous study, namely word length and word position on the writing line.

2. Method

2.1. Subjects

Ten right-handed subjects, four male and six female, participated in the experiment. They were students aged between 18 and 25, earning course credits or Dfl. 15. Subjects were adopted in the experiment if they could write a cursive eight-letter word fluently, without lifting the pen off the paper, using wrist–finger coordination.

2.2. Writing task

The subjects were required to write repetitive, cursive graphic sequences, to be called ‘words’, on prepared A4 response sheets. Three words were written from left to right on each line, starting at an indicated position (left, middle, right) on that line, immediately below the model for the current word. This model was a regular, computer generated example with a letter height of 0.35 cm; it specified the type of word (consisting of letters ‘n’ or ‘e’) and its length (24, 30, or 36 strokes, corresponding to a horizontal extent of 3.8, 4.7, or 5.6 cm). Their left extremes were 0.7, 7.3, and 13.9 cm from the left-hand edge of the sheet. Each word type and length was randomly presented 10 times in each of the three positions on the writing line. This implied $2 \times 3 \times 10 \times 3 = 180$ trials. A response sheet contained six writing lines for three words each, so that 10 such sheets were used per subject. The subject was required to shift the response sheet an indicated distance upwards after completion of each line of writing, so that the vertical position in graphic space was held
constant during the experiment. The orientation of the writing lines (i.e., of the response sheets) was $+15^\circ$ with respect to the table edge. The subjects received an adequate amount of practice. The exact number of letters in each word was not emphasized in the instruction, but the requirement was to copy the model words fluently, without pen lifts, in one’s habitual cursive writing style and at one’s normal speed. Trials in which this was not achieved were repeated. Note that the analyses for the present study are concerned with the 90 trials of the words consisting of letters ‘e’ only. We selected these words because they seemed maximally suited for the cyclical type of analysis (see below) that we wished to explore.

2.3. Apparatus

A normal ball-point pen was used as the writing tool. Attached to the top of its barrel was a small triangle on which three infrared light emitting diodes (IREDs) were placed, enabling the determination of the position of the pen point. The subject was equipped with 14 such IREDs to record the position of the effector segments (index finger, hand, forearm, upper arm). Sampling these IREDs was done during 6-s periods at a rate of 100 Hz with an accuracy of 0.2 mm by means of an Optotrak 3020 3D motion-tracking system. (For more details, see Meulenbroek et al., 1996.) Trials were marked by tones, following which the sampling periods started.

2.4. Analysis

For the present purpose, we analysed the joint rotations of the wrist (abduction–adduction movements approximately parallel to the writing plane) and of the index finger (extension–flexion movements of the joint between its first and second phalanx). For details of the off-line derivation of the joint angles from the sampled $X,Y,Z$ coordinates, we refer to Schillings et al., (1996). Furthermore, joint-rotation velocities were derived, following which we eliminated the mean rightward progression component from the velocity signal, leaving only the cyclical joint excursions for further analysis. Next, we normalised the cycles and we determined the continuous relative phase between wrist and finger. We refer to Section 2.3 in Meulenbroek et al., (1998) for details of this procedure and of other methodological aspects of the present study. The relative-phase functions were subsequently subjected to a time-series analysis by means of autocorrelation functions to reveal any systematic fluctuations in the form of regularly recurring phase relationships (see Kaplan and Glass, 1995, pp. 291–297). We are particularly interested in the shape and the temporal features of these autocorrelation functions that may reflect the dynamics of the adaptations that are the subject of this study. Since in the previous experiment (Thomassen et al., 1996) we observed a longer delay of adaptive shifts (in terms of the changes in the coordinated action of wrist and fingers) in longer words and in words more to the right-hand side of the page, we expected to find delays, i.e., prolonged phase-relation fluctuation periodicities, as a function of the two independent variables in the present analysis.
3. Results

Fig. 1 shows a representative example of a cursively written word containing 17 letters ‘e’. In its upper part it can be seen that both the baseline and the letter shapes are somewhat irregular. The next two panels depict the joint-rotation velocities of finger and wrist, respectively, as a function of time over a period of 5 s. The bottom panel presents the relative-phase plot derived from the latter two time functions. The negative relative-phase values indicate that wrist abduction leads finger extension in the cyclical movements. More importantly, the panel reveals that there may be some
periodicity in the phase relation. It is this periodicity at which our further analyses are aimed.

As an example, the autocorrelation function of the bottom panel of Fig. 1 is presented in Fig. 2. It can be seen that the curve drops from the (definition-bound) value of 1.0 at lag 0.0 s, to zero at a lag of about 0.25 s; here we observe the 'first zero crossing', to which we will refer repeatedly below. Furthermore, the function fluctuates (with large, but decreasing amplitudes), so that several zero crossings appear. At a lag of about 0.5 s, the minimum between the first and second zero crossing is reached; this will be called the 'first minimum' in the rest of this paper. The frequency of the fluctuations in this example is seen to be a little higher than 1 Hz.

Analysis of the complete data set shows that the mean periodicity of the autocorrelation function is 1.135 Hz, which implies an average period duration of 0.881 s. Given the two-stroke build-up of the letter 'e', and a mean stroke duration of 125 ms, this periodicity corresponds to a sequence of 3 to 4 letters 'e' in the word.

Fig. 3 presents the frequency distribution of the periodicity of the fluctuations in the autocorrelation functions of all the words written in the experiment. The data are grouped into 0.5-Hz frequency bands. Although there is considerable variability in this periodicity, as must be concluded from the figure, it is clear in this representation that the modal periodicity is in the 1.0-Hz category, and that by far the most words fall in the periodicity range 1.0–2.0 Hz.

![Autocorrelation](image-url)  
**Fig. 2.** Illustrative autocorrelation function obtained from the relative-phase function of the bottom panel in Fig. 1; 'first zero crossing' and 'first minimum' as defined in the text, are indicated.
The effect of the independent variables on the periodicity of the pattern of autocorrelation fluctuations (i.e., on the time lags to reach the first zero crossing and the first minimum) may be read from Table 1. Their mean values are 0.347 and 0.462 s, respectively. It appears that both these variables tend to decrease the fluctuation frequency in the sense that (a) longer words, and (b) words more to the right on the

Fig. 3. Frequency distribution of the periodicity of the fluctuations in the autocorrelation functions of the 900 ‘e-words’ written in the experiment.

<table>
<thead>
<tr>
<th></th>
<th>Lag at first zero crossing</th>
<th>Lag at first minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td><strong>Word length</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short</td>
<td>275 (246)</td>
<td>391 (295)</td>
</tr>
<tr>
<td>Medium</td>
<td>331 (313)</td>
<td>446 (348)</td>
</tr>
<tr>
<td>Long</td>
<td>434 (474)</td>
<td>549 (516)</td>
</tr>
<tr>
<td><strong>Word position</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>309 (325)</td>
<td>416 (366)</td>
</tr>
<tr>
<td>Middle</td>
<td>355 (354)</td>
<td>467 (393)</td>
</tr>
<tr>
<td>Right</td>
<td>378 (404)</td>
<td>503 (442)</td>
</tr>
</tbody>
</table>

*Note.* The means and standard deviations (SD, in brackets) are presented in ms, as a function of word length (top) and word position (bottom).
page, are characterised by periodicities of longer duration. The data are always in the expected direction as stated in Section 1, and significant in Anovas in three out of the four cases, as follows. *First zero crossing*: Word length $F(2,18) = 8.45, p < 0.01$; Word position $F(2,18) = 2.55$, n.s. *First minimum*: Word length $F(2,18) = 4.97, p < 0.05$; Word position $F(2,18) = 7.76, p < 0.01$. Although there is a tendency of word-size effects to be larger towards the right-hand side of the page, there were no significant interactions in the Anovas. An overview of the relationships amongst the two independent variables is provided in Fig. 4.

In contrast to the illustration in Fig. 2, the absolute minimum in the autocorrelation function did not always coincide with the first minimum. Its mean value was $R = -0.395$, and this minimum was reached, on average, at a lag of 0.903 s, with large differences among word lengths (short 0.691 s; medium 0.871 s; long 1.148 s). Apparently, even during the first second of writing a long word, the pattern of wrist–finger coordination in terms of their phase relations, depends on the length of the word to be completed only 2–4 s later. We take this as further evidence of anticipation and advance planning of the coordination pattern, confirming the above findings of extended period durations for longer words.

### 4. Discussion

Both our earlier study (Thomassen et al., 1996) and the present analysis have revealed variations in the pattern of coordination between hand and fingers during progressive handwriting. These variations are seen as adaptations which presumably compensate for the geometrical changes that occur due to the curvilinear rightward rotation in the wrist joint under the requirement of rectilinear progression of cursive handwriting. To our earlier observations of increased finger involvement and increased co-activity of wrist and finger as a function of this rightward rotation, we may now add that these variations are associated with periodic fluctuations in the

![Graph](image-url)

Fig. 4. Shifts in the lags corresponding to the ‘first zero crossing’ (left-hand panel) and the ‘first minimum’ (right-hand panel) in the autocorrelation as a function of word length and word position.
phase relations between the relevant joints. The anticipation of a longer word, and the start of a word more to the right of the writing line, presumably elicit the adoption of somewhat different initial postures; these should then imply a more appropriate overall arm geometry, so that the adaptive variations accommodating the increased biomechanical constraints, may be somewhat delayed. Empirical evidence for slightly different starting postures at different positions on the writing line was presented in our earlier paper (Thomassen et al., 1996, Table 1).

It should be noted that not all recurring patterns of change were captured by exclusively inspecting the first zero crossing and the first minimum as defined above. In fact, some autocorrelation functions had large numbers of local minima. Our automatic algorithm, however, focussed on the major periodicities and intended to avoid such minimal fluctuations. Moreover, there is the theoretical possibility that our finding of a 1-Hz periodicity in the autocorrelation function of wrist–finger coordination is due to an artefact resulting from the type of data processing in the analysis that we pursued in our present approach. But this seems unlikely in view of the fact that the word-length and word-position variables affect its frequency in a systematic and predictable fashion.

Two important aspects of our results should be noted at this point. First, the present analysis was concerned with joint-rotation data that were normalised per half cycle, so that the relative increase or decrease of the current joint involvement (rotation-angle amplitude) is not assessed here. Second, the results show that, although the phase relations fluctuate around a mean, there is also a gradual tendency in ‘e-words’ towards zero phase difference by the end of the sequences (as may also be seen in the bottom panel of Fig. 1). This distal phenomenon is presumably associated with adaptive shifts at more proximal levels. Indeed, it is feasible that the hand’s rightward translation parallel to the baseline of writing is achieved (even within words) by discrete events of exorotation of the shoulder or extension of the elbow joint, or both. It is an issue of further investigation to relate the distal periodicities that we observed in this paper to such proximal mechanisms.

In a related study involving the same task and the same subjects (Meulenbroek et al., 1998), we studied the coordination of a larger set of 3D joint excursions in arm, hand and index finger, and their relation to 2D pen movements in handwriting. The focus there was on the ‘stability’ of the coordination of pairs of mechanical degrees of freedom in terms of invariance in the relative-phase relationships. The assumption was that the most stable pair should represent the joint combination under primary control by the motor system. In contrast to the present paper, which addresses altered coordination in the continued within-word progression, the Meulenbroek et al. study concentrates on a selected, single letter in the middle of the word. For this letter, the standard deviation of the relative-phase signal between joint rotations and pen excursions was determined in order to assess their stability. Of the six inter-joint combinations, wrist–finger coordination appeared to rank second in stability, below elbow–wrist coordination which showed the smallest standard deviation. Although there were significant interactions, the main effects of word length and word position were not significant in that study. Here it should be noted that only the central letter was analysed. In particular, letters beyond the
middle of the word could still have a different degree of variability in words of
different length and written in different horizontal positions on the page.

The phenomenon of anticipating increased co-activity in longer words and in
words more to the right on the page, as shown by different means in our previous and
present analyses, may be related to the following behavioural tendency. Most sub-
jects adjust their effector system’s starting posture for complex movements such that
the middle of its range of movement will coincide not with initial, but with later
components of the task. (See Rosenbaum et al., 1990). For handwriting this has also
been shown (Van der Plaats and van Galen, 1990), while for drawing it explains (part
of) the start-rotation principle, which holds that the clockwise or counterclockwise
performance in drawing a circle depends on the location on the contour where the
graphic movement starts (Meulenbroek and Vinter, 1993).

The 1-Hz periodicity that we observed could well be directly associated with
discrete rightward progressive movements made by the writers’ elbow and shoulder
joints, resulting in stepwise hand-translation shifts along the baseline. In our anal-
ysis, we merely treated this global rightward movement component (Hollerbach’s
parameter c) as a uniform vector, supposing that for this purpose it could be con-
sidered to have constant velocity. In several earlier studies we have reported evidence
that this assumption is not justified to the extent that the trend is not entirely in-
dependent, but interacts with the movements of the wrist and the fingers (e.g.,
Thomassen and Meulenbroek, 1993). Consequently, our subtraction of the constant-
velocity vector may lack a sufficient empirical basis. As it appears now, writers
progress in discrete steps, adjusting their wrist–finger coordination more or less
regularly, approximately once per second, after 7 or 8 strokes on average. This
covers 3 to 4 letters ‘e’ in the present experiment. The result is a (partial) reset of the
wrist–finger relationship. But, as stated, the biomechanical loci of these adaptations
as well as their association with the observed phase-relation shifts demand further
study to answer the question to what extent they are interdependent, and perhaps
coupled one-to-one.

Unfortunately, we have, as yet, no data to decide what the precise relation is
between the numerous ‘discontinuities’ of effector-joint involvement as observed
previously and the present 1-Hz phase-relation periodicity. In a pilot attempt, we
explored the occurrence of major abrupt shifts in phase relation; the number of
instances that we found was too small, however, to serve as a basis for a comparative
analysis. We also looked for episodes of relatively unstable phase relations imme-
diately preceding the sudden transitions that we observed (see Wagenaar and van
Emmerik, 1994), but the paucity of these data again prohibited a quantitative
analysis.

Going over to the secondary goal that we formulated in Section 1, we may ten-
tatively state that in the present study phase-relation analysis in combination with
the application of autocorrelarion functions has proved to be a useful tool. It re-
vealed an important feature of progressive handwriting, viz., a low-frequency peri-
odic variability which went unnoticed in our previous analysis (Thomassen et al.,
1996), using a less sophisticated, ad-hoc measure of coordinated joint action. At the
same time, the present analysis confirmed most of the results obtained in the earlier
studies. In particular, we mention the finding here that the phase difference in ‘e-words’ gradually declines towards zero (full co-activation) nearer the end of the word and nearer the right-hand extreme of the writing line. Moreover, the fact that not only the phase-relation periodicity, but also its variability as such, in terms of its standard deviation (Thomassen et al., 1997, Table 1), appeared to be dependent on sequence length rather than on the ordinal position of the current letter in the word, we regard as a confirmation and extension of our earlier findings.

To conclude, our application of phase-relation analysis at joint level was fairly successful and seems to hold promise as an additional tool for the study of certain repetitive forms of graphic behaviour. However, even with the continuous features of the graphic patterns (long ‘e-words’) selected for the present exploration, we encountered limitations. First, we are left in some doubt as to the constant-velocity assumption regarding the progression component. Second, we located only a few abrupt phase transitions and we failed to obtain substantial evidence of increased variability preceding such transitions. It is to be expected that these limitations will be considerably more severe in any attempts to study the grapho-motor data resulting from realistic tasks such as the cursive writing of normal words with their variable stroke sequences. Moreover, the precise associations of the present fluctuating phase relations with the changing joint-rotation amplitudes on the one hand, and with the engagement of proximal joints on the other, remain to be clarified in further studies if the phenomena of progressive handwriting are to be fully understood.

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References


