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Practice and the Dynamics of Handwriting Performance: Evidence for a Shift of Motor Programming Load

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ABSTRACT. Sixteen adult subjects served in an experiment in which the writing of six unfamiliar graphemes was practiced. To investigate the learning process, we analyzed the absolute and relative changes of movement time of the first three consecutive segments as a function of practice. The results showed that movement time of all three segments decreased. This decrease was significantly less in the first segment than it was in the second and third segment, however. We interpret these effects of practice, from an information-processing viewpoint, as follows: (a) Initially separate response segments become integrated in more comprehensive response chunks, and (b) the preparation of later segments of the grapheme is realized more and more during the real-time execution of the initial segment. The results further revealed that these learning effects were more pronounced in graphemes composed of familiar segments than in graphemes that contained unfamiliar segments. Finally, it turned out that similarity between initial and final segments hindered the writing speed of the first segment; the effect of similarity was independent of the above-mentioned effects of practice. The latter effect is interpreted as confirming evidence for the view that the preparation of later segments of a grapheme is reflected by changes of movement time of the first segments of a grapheme.

IN THEORIES OF COMPLEX MOTOR BEHAVIOR, a central role has been reserved for a process labeled *motor programming*. The concept of a motor program was described by Keele and Summers (1976) as a rivaling idea to a closed-loop theory of motor skills learning (Adams, 1971). Keele and Summers originally defined a motor program as a memory code containing a set of instructions concerning muscle innervations. In a later publication (Keele, 1981), the description shifted

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toward a less muscle-specific and more abstract definition. In recent models of skilled motor behavior (Van Galen & Wing, 1984; Van Galen, Meulenbroek, & Hylkema, 1986), the abstract motor program is considered to be retrieved from long-term motor memory, after which it is supposedly delivered to a transient buffer (Henry & Rogers, 1960), from which successive response elements are selected and initiated (Teulings, Thomassen, & Van Galen, 1986).

Teulings, Thomassen, and Van Galen (1983) investigated the size of the response elements in handwriting and tried to determine whether, in cursive handwriting, individual strokes or complete letters form the movement units during the preparation of execution. Their analysis of reaction times revealed that precuing of complete letters facilitated reaction time, but precuing of strokes within letters did not. These results indicated that the movement pattern of a well-practiced single letter is handled as one single unit and not as a sequence of separate strokes. Teulings, Mullins, and Stelmach (1986) replicated these findings but argued that the extent of the units of movement probably changes as a function of practice.

Hulstijn and Van Galen (1983) also attempted to determine the size of the chunks preprogrammed during the latency phase in drawing and writing tasks. In their experiment, subjects had to write as fast as possible one, two, three, or four characters, after a go signal. When subjects were unpracticed, an effect on reaction time was present, which was similar to the sequence-length effect reported by Sternberg, Monsell, Knoll, and Wright (1978). Reaction time increased with increasing sequence length. When subjects became more practiced, however, reaction time became unaffected by sequence length. Hulstijn and Van Galen (1983), indeed, concluded that the extent of preprogramming appears to be sensitive to the amount of practice a subject has in producing a movement sequence. As practice proceeds, subjects tend more and more to adopt a programming strategy in which only the general and abstract content of the motor act is programmed in advance of the start of movement execution, whereas the motoric unpacking of the consecutive segments is postponed to the movement phase. In order to relate the findings of the studies of Teulings, Mullins, and Stelmach (1986), Teulings, Thomassen, and Van Galen (1986), and Hulstijn and Van Galen (1983) to learning processes more explicitly than was done before, we devised an experiment in which adult subjects learned to write six unfamiliar writing patterns. By analyzing the movement time of consecutive segments, we tried to verify the finding that the size of the prepared movement units changes as a function of practice.

In a later study (Hulstijn & Van Galen, 1988), the findings of Hulstijn and Van Galen (1983) were verified and refined. Not only was the trend to concurrent programming and execution replicated, but it was also found that more familiar graphemes were more explicitly affected by this strategy than unfamiliar graphemes. These latter findings led us to the second aim of our study, which was to investigate the effects of two stimulus dimensions of the graphemes, namely, the familiarity of the composing elements and their repetitive or nonrepetitive structure, upon the learning process. We wanted to investigate whether graphemes consisting of a combination of already familiar segments would benefit more from a learning process than graphemes consisting of unfamiliar segments. With regard to the second stimulus dimension, we wanted to investigate whether the degree of repetitiveness would influence the learning process. The production of identical strokes, for example, in the letters *n, m, v,* and *w,* resulted in a decrease in movement time of letters immediately preceding these letters, which can be said to have a repetitive stroke structure (Van Galen, in press).

Chunking and Concurrent Programming as a Result of Practice

In the early stages of a learning process, a psychomotor task might be represented as a nonintegrated sequence of separate subtasks. During this phase, each consecutive segment of an unpracticed grapheme is retrieved as a separate unit. This retrieval occurs only after the completion of a preceding segment. We assume that, with an increasing amount of practice, two integrative processes take place. First, the retrieval and motoric preparation of oncoming segments of a pattern will shift from the time interval between separate segments toward the execution phase of preceding segments; that is, practice will induce a type of concurrent programming. Second, the object of the preparation process itself is extended. Separate segments will be aggregated into larger sized chunks.

The Distribution of Movement Time: A Measure to Determine the "Locus of Programming"

A basic assumption underlying the present experiment was that an increase in the size of the unit of programming at the onset of a response would lead to a slowing down of the execution, as reflected by a relative increase of movement time, for the initial segments of the response. Van Galen et al. (1986) had already observed comparable movement-time effects in a word writing task. The preparation of longer letters was found to cause slower writing times of immediately preceding letters. He also found that the preparation of a word was reflected at least in the time interval between successive words. Because of the presumed increase of the retrieval load on the first segment as a result of practice, we predicted that the writing time of the first segment would decrease less, as a result of practice, than the writing time of subsequent segments. Thus, with practice, the writing time for the initial segments would be relatively delayed due to a shift of programming towards the initial segments.

Pattern Features and the Learning Process

Pattern features are known to play an important role in motor programming processes (Klapp & Wyatt, 1976). An important feature of graphemic patterns is the degree of familiarity of the individual segments of the pattern. In order to investigate the effects of familiarity upon the learning process, we varied the degree of familiarity of the composing elements of the grapheme. Familiar graphemes were composed of elements similar to letter forms. Unfamiliar graphemes were composed of elements that did not occur in common handwriting (see Figure 1). We assumed that familiar graphemes benefit more from the learning process than unfamiliar graphemes (see Hulstijn & Van Galen, 1983).

Besides familiarity, a second important aspect of the construction of unfamiliar graphemes in a learning task is the degree of repetitiveness of the individual grapheme segments. Teulings et al. (1983) investigated the effects of identical versus nonidentical letter pairs on reaction time and movement time in simple and choice reaction time tasks.

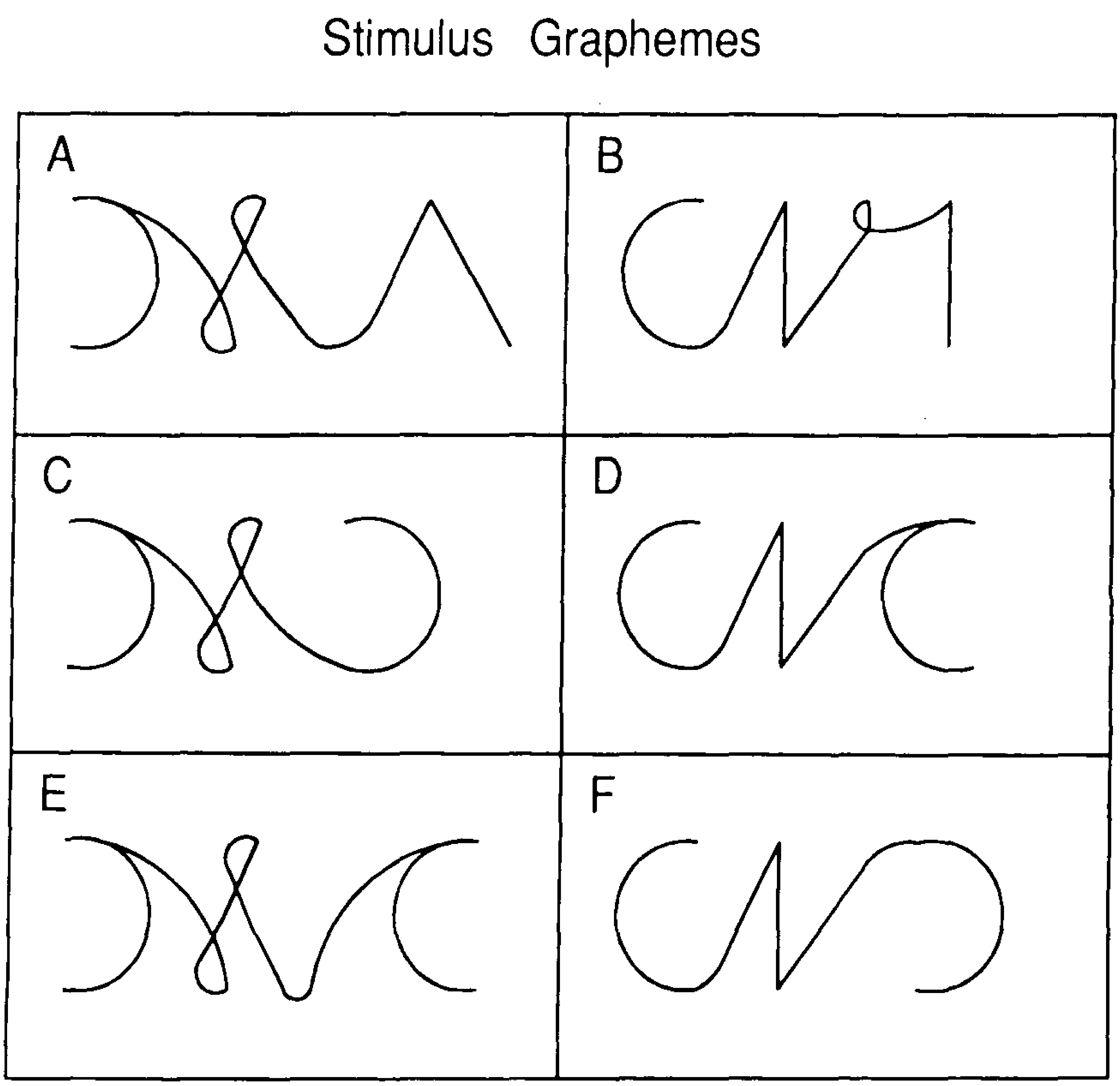

Figure 1. The unfamiliar graphemes, as presented to the subjects. Similarity of the first and last segment was varied by (a) repetition of the first segment (C & D), (b) mirroring of the first segment (E & F), and (c) alteration of the first segment (A & B). The degree of familiarity was varied at the following two levels: (a) graphemes composed of segments that resembled those of normal handwriting elements (B, D, & F), and (b) graphemes composed of segments that hardly occur in cursive handwriting (A, C, & E).

Movement time increased when identical letter pairs had to be written. Van Galen, Smyth, Meulenbroek, and Hylkema (1989) found evidence that it is more difficult to retrieve subsequent strokes from a motoric buffer that is loaded with similar elements than from a buffer that is loaded with dissimilar elements. In order to investigate the interaction between pattern features and writing performance, we varied the similarity of the individual grapheme segments at three levels. Unlike the experiment described by Van Galen et al. (1989), in which the similarity of early, consecutive elements in graphemes was varied, we varied the similarity between initial and final segments (See Figure 1). At the first (most repetitive) level, graphemes were constructed that contained a complete geometric repetition of the first element at the last segment position. At the second level, graphemes were chosen in which a left-right mirroring of the first element at the last segment position was used. At the third level, the graphemes contained an alteration, that is, the final element was completely different from the first element. In the above-mentioned studies, writing patterns containing a repetition probably caused heavier processing demands on the short-term motor buffer during the writing of the actual segment to be repeated than did writing patterns containing an alteration (Van Galen et al., 1989). With regard to similarity, we predicted on the basis of the earlier studies an extra increase of the movement time of the first segment in the graphemes containing a geometrical repetition or a mirroring. In order to ensure a learning process in which the graphemes were executed on the basis of an internal representation and not by a mere copying strategy, we used four modes of presentation. This control aspect of the experiment is fully described in the following section.

Method

An experiment was run in which subjects practiced the drawing of six nonsense graphemes. The experiment was extended over two training sessions, each session consisting of 240 trials.

Subjects

Sixteen adult subjects, students and staff members, served as paid volunteers in the experiment. No specific criterion was used to select the subjects.

Design

In the experiment, the effects of four independent variables were studied: practice, by means of having two training sessions of 240 trials each; grapheme familiarity and grapheme similarity, through the construction of the stimulus material; and segment position, defined as the consecutive segment number. Similarity between grapheme segments was varied by manipulating the degree of repetitiveness of the first and last segment at three levels: (a) repetition of the first segment, (b) mirroring of the first segment, and (c) alteration of the first segment (see Figure 1). The degree of familiarity of the graphemes was varied at two levels as follows: (a) graphemes composed of familiar segments and (b) graphemes composed of unfamiliar segments. The experimental variables were introduced according to a completely hierarchical design, with repeated measurements for six separate graphemes within blocks of 40 trials, and we used a counterbalanced order of presentation of these blocks, across subjects and practice sessions. An overview of the experimental design is depicted in Table 1.

Procedure and Apparatus

Prior to the actual experiment, each subject was allowed to write in his or her own handwriting for about 5 min, in order to become familiar with the apparatus. The experiment was subdivided in two sessions of one hour each, and each session was held on a different day. Each subject performed in a session six practice blocks of 40 trials each. In each block, a different grapheme was trained.

Within one block of 40 trials, four presentation modes were used, in a fixed sequence, in order to ensure that within one block the grapheme eventually was produced on the basis of memory recall. In Mode 1, a grapheme, together with a letter code below, was clearly depicted on a visual display. In Mode 2, the grapheme was depicted in a "faded" manner, together with the clearly depicted letter code below. In Mode 3, mark points at the beginning and at the end of each segment of the grapheme, together with the clearly depicted letter code below, were presented. In Mode 4, only the letter code was presented. Within each block of 40 trials, this sequence was repeated 10 times. This procedure is based upon an existing handwriting method.

TABLE 1
The Experimental Design[a]

Variable	Level	Number of trials	Description	Grapheme
DAY	1	240	First day	All
	2	240	Second day	All
FAM	1	120	Familiar	B+D+F
	2	120	Unfamiliar	A+C+E
SIM	1	80	Alteration	A+B
	2	80	Repetition	C+D
	3	80	Mirroring	E+F
SGP	1	240	Segment 1	All
	2	240	Segment 2	All
	3	240	Segment 3	All

[a]*N* = 16 subjects.

Stimuli were presented for 4 s in each trial by a computer-managed visual display, about 120 cm in front of the subject. A high tone at the end of the stimulus presentation interval indicated the start of the execution interval, which lasted for 5 s in each trial. Subjects wrote with a stylus (Maarse, Janssen, & Dexel, 1988) with built-in registration apparatus, on a CALCOMP 9000 digitizer tablet, monitored by a DIGITAL PDP-11/45 computer. The *x*- and *y*-position of the pen, as well as the axial pen pressure exerted on the pen point, were sampled with a frequency of 105 Hz, with a measuring accuracy of 0.2 mm.

Data Analysis

After filtering the digitized writing movements with a low-pass FIR filter (Rabiner & Gold, 1975) of 12 Hz, by means of which the spatial resolution of the recordings was increased (Teulings & Maarse, 1984), the writing trajectories were displayed for inspection and analyzed by means of an interactive computer program. Segment boundaries were determined by searching for the minima within the absolute velocity pattern of the recorded writing movement that occurred immediately before the large velocity increases associated with the production of a subsequent grapheme segment. To determine how far the velocity minima were located between two successive samples, we used a quadratic interpolation technique (Teulings & Maarse, 1984). This procedure ensured that the temporal resolution of the recordings increased.

A sample of the segmentation procedure is depicted in Figure 2, which presents a recording written after 70% of all practice trials. The absolute velocity function clearly shows a succession of peak velocities, one for each segment, which reflects the highly ballistic performance of these segments. The above-mentioned segmention strategy was based upon the ballistic structure of the velocity profiles illustrated in Figure 2. For each grapheme segment, the movement time (MT), writing size (WS), writing pressure (WP), and writing disfluency (WD) were determined. Writing disfluency was defined as the absolute number of velocity maxima within the velocity profile of one grapheme segment (Meulenbroek & Van Galen, 1988). The analysis of the dependent variables was restricted to the first three segments because, in earlier experiments (Hulstijn & Van Galen, 1983; Van Galen et al. 1986), it was found that the movement time of the final segments of a grapheme was affected by the oncoming stop at the end of the grapheme.

Further data analyses consisted of two analyses of variance (ANOVA). In order to investigate the effects of the four modes of presentation, we performed a first ANOVA on the means of 10 replications according to a 16 $\times$ 2 $\times$ 4 $\times$ 2 $\times$ 3 $\times$ 3 [Subject (SS) $\times$ Days (DAY) $\times$ Mode of Presentation (MP) $\times$ Degree of Familiarity (FAM) $\times$ Degree of Similarity (SIM) $\times$ Segment Position (SGP)] design. After having established that MP indeed resulted in significant learning effects, without showing any interaction with the effects of the other indepen-

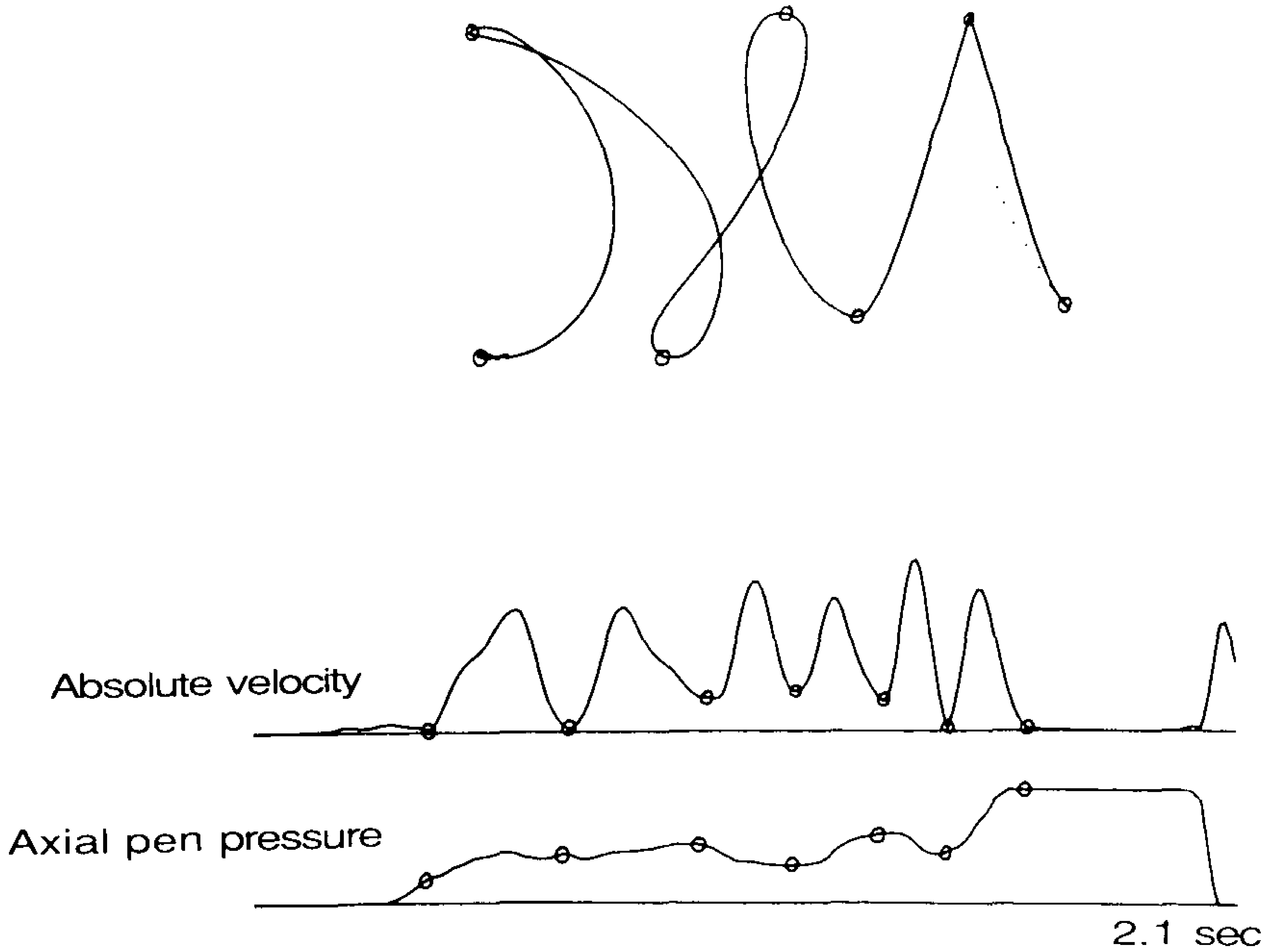

Figure 2. An example of the data analysis of one record, written after 70% of all practice trials. The pen position was sampled with a frequency of 105 Hz. These recordings were filtered with a low-pass filter of 12 Hz. The written grapheme is depicted together with the corresponding absolute velocity and axial pen pressure pattern. Circles indicate segment boundaries, which were used to measure the dependent variables of the target segments within the grapheme.

dent variables, we performed a second ANOVA according to a 16 × 2 × 2 × 3 × 3 (SS × DAY × FAM × SIM × SGP) design. Newman-Keuls tests (SNK; $p = .05$; Ferguson, 1981) were used to test the significance of differences between factor levels.

Results

Records were defined as an error when either segments were missing or incorrectly written, that is, segments contained a wrong direction of rotation or overall movement direction as compared with the stimulus grapheme. The mean error rate across subjects amounted to 3%. Errors were excluded from further analysis. As a summary, means and standard deviations of movement time, writing size, writing pressure, and writing disfluency, as a function of segment position and practice, are presented in Table 2.

Effects of Practice Upon the Distribution of Movement Time (MT) Across Segments

The results of the first ANOVA showed that there were neither first- nor second-order interactions between MP and the other experimental

TABLE 2
Means and Standard Deviations of Four Performance Measures, as a Function of Segment Position and Practice

	MT(ms)		WS(cm)		WP(gr)		WD(nvmax/seg)	
SGP	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
				Day 1				
1	452	142	1.41	.49	139	40	3.06	1.30
2	424	112	1.44	.51	151	37	2.92	1.09
3	379	100	1.08	.33	147	41	2.86	1.07
				Day 2				
1	406	146	1.26	.40	131	44	2.72	1.25
2	347	112	1.30	.42	140	41	2.26	.94
3	306	98	.92	.26	135	40	2.21	.87

TABLE 3
Results of Analysis of Variance on Movement Time

Source	Degrees of freedom	*F*	*p*
DAY	1, 15	24.74	< .001
FAM	1, 15	6.73	< .05
SIM	2, 30	5.46	< .01
SGP	2, 30	13.01	< .001
DAY × SGP	2, 30	4.01	< .05
SGP × FAM	2, 30	6.05	< .01
SGP × SIM	4, 60	1.71	ns
DAY × SGP × FAM	2, 30	.12	ns
DAY × SGP × SIM	4, 60	2.23	ns

variables. The factor levels of MP could therefore be pooled. The results of the second ANOVA are summarized in Table 3. Figure 3 depicts the effects of practice on the MT of the first, second, and third segment of the six graphemes. Comparing the first session with the second, we found that the overall MT of all three segments decreased significantly, $F(1, 15) = 24.74$, $p < .001$. As may be seen in Figure 3, however, the MT decrease was different for each of the three segments, in the sense that it decreased less in the first segment than it did in the second and third segment. The interaction between practice and segment position was significant, $F(2, 30) = 4.01$, $p < .05$. The Newman-Keuls analysis of the MT-decrease differences confirmed that, as a result of practice, the MT decrease was more pronounced (and of equal size) in the second and third segment than in the first segment ($p < .05$).

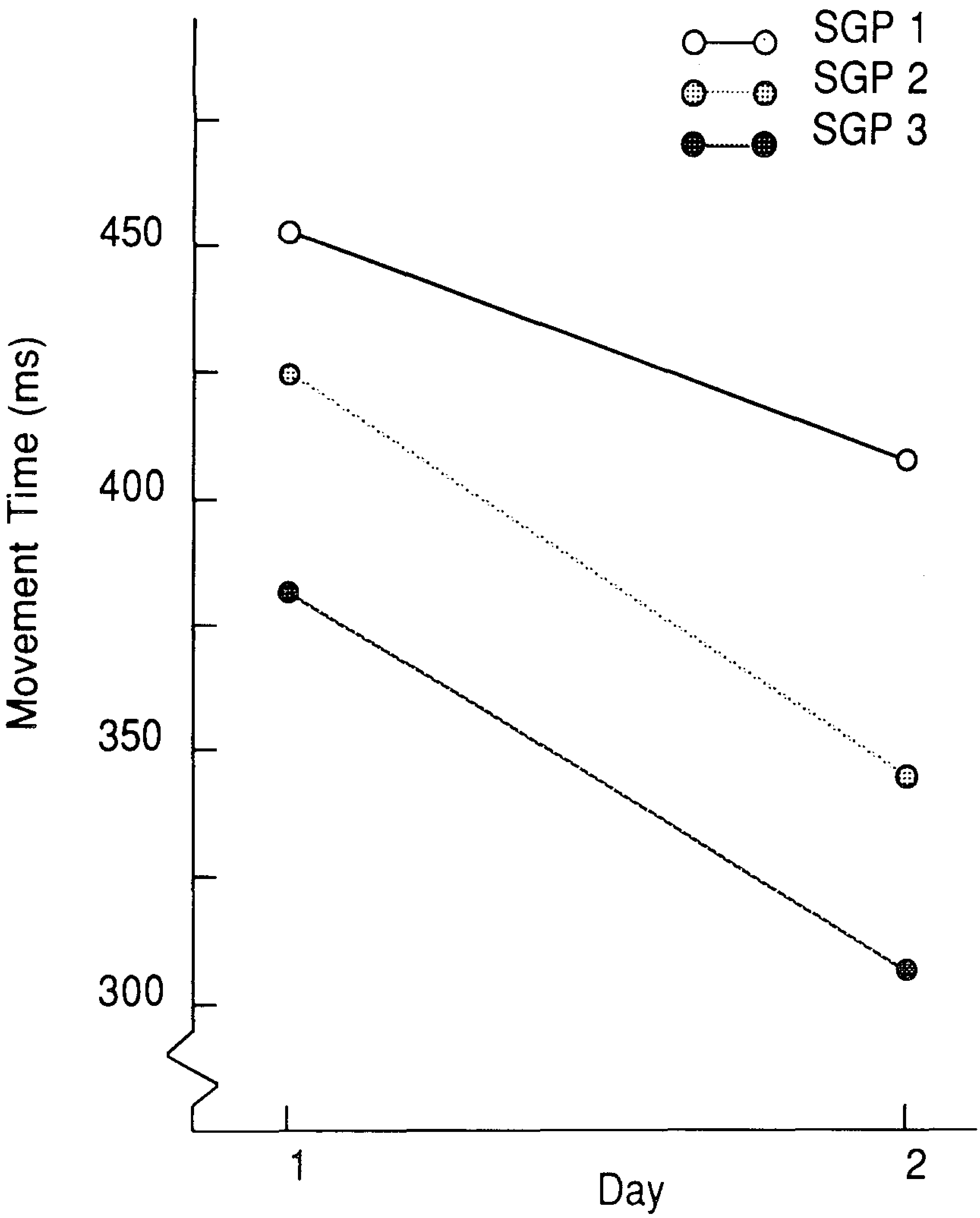

Figure 3. Mean movement time for each segment position as a function of practice.

Effects of Practice Upon the Distribution of Writing Size (WS) Across Segments

Figure 4 depicts the effects of practice on the mean WS of the first, second, and third segment of all six graphemes. It shows an overall decrease of WS as a result of practice, $F(1, 15) = 7.80, p < .05$. Furthermore, the effect appears to be of equal size across the three grapheme segments. The interaction between practice and the serial position of the segments was not significant, $F(2, 30) = 0.03, p > .10$. The latter finding means that the differential effects of practice on the distribution of MT, as described above, can not be attributed to a changing distribution of the WS across the segment trajectories.

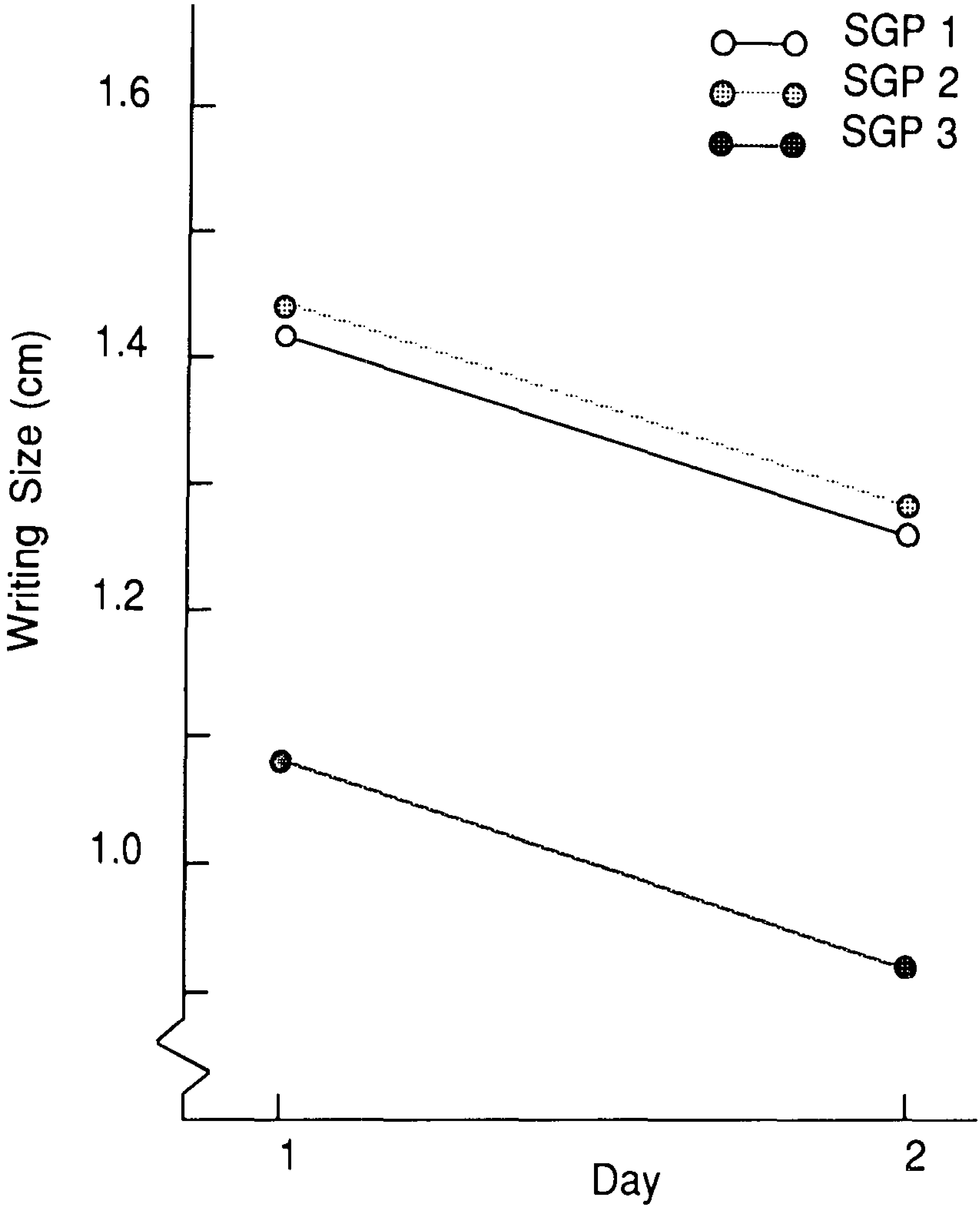

Figure 4. Mean writing size for each segment position as a function of practice.

Effects of Practice Upon Writing Pressure and Writing Disfluency

Practice had no significant effect on WP. WD, however, decreased for all three segments, $F(1, 15) = 32.15$, $p < .001$. This decrease was not similar for all segments, as appeared from the significant interaction between practice and segment position, $F(2, 30) = 4.77$, $p < .05$. WD decreased less, as a result of practice, in the first segment than it did in the second and third segment.

Effects of Degree of Familiarity on the Movement Time and Writing Size Across Segments

The means and standard deviations of MT and WS as a function of segment position and familiarity are summarized in Table 4. As a main

TABLE 4
Means and Standard Deviations of Movement Time and Writing Size, as a Function of Segment Position and Familiarity

	MT(ms)		WS(cm)	
SGP	*M*	*SD*	*M*	*SD*
		Familiar graphemes		
1	430	147	1.34	.45
2	383	119	1.37	.48
3	336	104	.99	.30
		Unfamiliar graphemes		
1	429	144	1.33	.44
2	388	118	1.36	.46
3	349	107	1.01	.31

factor, familiarity of the grapheme segments also significantly affected performance. MT was shorter in graphemes composed of familiar segments than in graphemes composed of unfamiliar segments, $F(1, 15) = 6.73$, $p < .05$. As with the effects of practice, it appeared that this finding was more pronounced in the second and third segment. The interaction between familiarity and segment position was significant, $F(2, 30) = 6.05$, $p < .01$. The MT of the first segment was even slightly longer in graphemes composed of familiar segments than in graphemes composed of unfamiliar segments. There was no significant difference in WS as a result of the familiarity factor. The third-order interaction between practice, familiarity, and segment position appeared to be nonsignificant, $F(2, 30) = 0.12$, $p > .10$.

Effects of Degree of Similarity on the Movement Time and Writing Size Across Segments

The means and standard deviations of MT and WS as a function of segment position and degree of similarity are presented in Table 5. The structure of the graphemes, in terms of the degree of similarity between the initial and final segments, had as a main factor a significant effect upon MT, $F(2, 30) = 5.46$, $p < .01$. The Newman-Keuls tests revealed that, for each of the three segments, mirroring led to the longest MT, followed with increasing significant gaps by geometrical repetition and alteration, respectively, $p < .05$ and $p < .05$.

This outcome may be considered equally valid for all three segments because neither the interaction between similarity and segment position, $F(4, 60) = 1.71$, $p > .10$, nor the third-order interaction be-

TABLE 5
Means and Standard Deviations of Movement Time and Writing Size as a Function of Practice and the Three Levels of Similarity

	MT(ms)		WS(cm)	
SGP	*M*	*SD*	*M*	*SD*
		Alteration		
1	415	142	1.30	.44
2	375	108	1.34	.45
3	336	98	1.00	.31
		Repetition		
1	432	148	1.33	.44
2	384	122	1.36	.47
3	339	107	.98	.30
		Mirroring		
1	440	148	1.38	.47
2	398	125	1.39	.49
3	353	111	1.03	.32

tween practice, similarity, and segment position, $F(4, 60) = 2.23$, $p = .08$ were significant.

The Student-Newman-Keuls test showed a similar result for WS, which was found to be significantly larger in graphemes containing a geometrical repetition or a mirroring than in graphemes containing an alteration ($p < .05$).

Discussion

The main findings of our experiment can be summarized as follows: The distribution of movement time, across the consecutive segments of handwritten graphemes, appeared to be a sensitive measure of practice effects. Although the general effect of a decrease of movement time was found for the first as well as for the second and third segment of a grapheme, it turned out that, for the first stroke, the decrease significantly lagged behind the decrease of movement time of the other two strokes. Analysis of the size of the drawing trajectories showed that the interaction of practice and segment position with respect to movement time could not be attributed to spontaneous fluctuations of writing size. If we assume that movement time of a grapheme segment relatively increases as a result of concurrent preparation of upcoming grapheme segments, we can justifiably conclude that a shift of the locus of programming toward the initial part of a drawing task is present during the learning process. The more a subject masters the task, the more unpacking activities of the composing segments occur concurrently with the execution of the first segment.

This interpretation is corroborated by the results of the familiarity factor. We found that, apart from a general speeding up of drawing tasks composed of familiar stroking patterns, a significant interaction with segment position was present. As with the effects of practice in general, it appeared that the interaction originated from a significantly smaller profit from training for the first segment. Both practice and familiarity effects can be explained by the same shift of programming load toward initial segments of the graphemes. The drawing of a familiar grapheme possibly allows for a greater amount of concurrent programming during the execution of the initial segment in an earlier phase of the learning process than is the case with graphemes composed of unfamiliar segments.

Both above-mentioned findings form confirming evidence in favor of the view that an increased load leads to a slowing down of the real-time execution process of those parts of a multisegmented grapheme in which the concurrent programming of oncoming segments is concentrated (Van Galen et al., 1986). Because of the chunking of a longer sequence of segments, as a result of practice, the initial segments of the pattern become more heavily loaded by concurrent programming and unpacking activities than the later segments. This means that with an increase of the amount of practice, on-line programming during execution of initial segments is directed at greater chunks. This view is in parallel with the Rosenbaum, Hindorff, and Munro (1987) theory of movement organization. They also argue for a chunking theory and for the view that, under certain conditions, movement preparation of subsequent movements occurs during the execution of previous movements. A corresponding line of argument is presented by Logan (1985), who elaborates on forms of executive control during the execution of a movement strategy in order to explain the complexity of movement coordination and control. The essential view that is defended in this paper is that, with practice and familiarity, there is a shift from a more serial form of programming of subsequent segments to a form of concurrent programming in which the preparation of future segments can occur simultaneously with the execution of the current segment. It might be expected, therefore, that early in practice more signs of serial programming can be found than later in practice. It might be argued that an analysis of the incidence and duration of movement pauses is specifically appropriate to establish the degree of seriality in movement execution. Our segmentation strategy, in its original form, did not allow for a detailed analysis of movement pauses. We therefore conducted a post hoc analysis of the duration of the pauses between Segment 1 and Segment 2 of Grapheme C as a function of practice. This analysis was performed on the data of 2 subjects, the slowest and fastest performers (Subjects A and B, respectively).

We chose to analyze the pauses between Segment 1 and Segment 2 of Grapheme C because, in this grapheme, subjects were forced to stop at the end of Segment 1 before they could start the execution of Segment 2. A pause was defined to be present when the minimum value of the writing velocity at the boundary of two consecutive segments was continuously observed for at least two subsequent sampling periods (1 sampling period = 10 ms) of the digitizer tablet. The results for Subject A showed that, as a function of practice, the proportion of pauses decreased from 72.5% to 67.5%. The mean duration of these pauses also decreased, from 87 ms to 65 ms. For Subject B, we found a decrease in the amount of pauses from 32.5% to 12.5%, and a decrease in duration from 13 ms to 3 ms. The duration as well as the prevalence of pauses decreased for both subjects. The decrease in the duration was more pronounced in the fast writer than in the slow writer. These results support the view that longer pause durations occur early in practice. This strengthens our theory of a shift from a more serial form of programming to a more concurrent form of preparation, as a result of practice.

Similarity, as defined by the pattern relation between initial and final parts of the task figures, appeared to have a quite different relation to the learning and programming processes. Although the general effect was again significant, the direction and the pattern of interactions seemed completely different. Instead of speeding up, similarity slowed down the writing process. This was true for similarity in the sense of mirroring as well as for a completely geometrical repetition of the first segment. An explanation for this finding has been suggested in an earlier study by Van Galen (1984), which concluded that the retrieval of figure elements from the short-term motor buffer is hindered by the similarity of the figure elements. This explanation was further corroborated in a study by Van Galen et al. (1989), which found that clearing the short-term motor buffer was especially hindered in the case of repetitive stroking patterns and in the absence of visual control. Interestingly, the present study showed that the repetition effect is not restricted to geometrical repetition only. The representation of motor patterns in short-term motor memory might be of a more abstract nature, as sometimes has been proposed.

The present results also showed an increase of writing size, due to similarity of the drawing segments. This result is in accordance with a study by Van der Plaats and Van Galen (1990), which found that complex movements lead to a slowing down of movement time together with an increase of writing size. Similarity, as a structural stimulus variable, does not seem to have a relation to the long-term learning process because, contrary to the earlier mentioned results concerning practice and familiarity, it does not interact with any of the main factors.

Furthermore, the distribution of writing disfluency appeared to be sensitive to practice, in the sense that the general effect of a decrease of writing disfluency was found for all three segments. Again, this decrease was less in the first segment than it was in the second and third segment. This change in the distribution of writing disfluency is remarkably similar to the change in the distribution of movement time described above. This result can be related to a study reported by Meulenbroek and Van Galen (1989), which showed that connecting strokes were written more disfluently than within-letter strokes. These results were considered as supporting evidence for greater motoric demands of connecting strokes. The finding of a differential effect of practice on writing disfluency of the first three segments can therefore be considered additional evidence in favor of an explanation in terms of a shift of programming load toward initial segments. A possible objection to the present interpretation of practice effects might be that the results are based upon the comparison of two complete sessions. If the performance of Segment 1 improved in Session 1 but not in Session 2 and the performance of the Segments 2 and 3 improved in Session 2 but not in Session 1, then the present differential MT effects would be found when the improvement of the performance of the first segment was less than that of the subsequent segments. This situation would not be compatible with the concurrency hypothesis. In order to investigate this alternative explanation, a control analysis was performed, in which each session was subdivided into two equally large subsessions. This control analysis, however, showed that the differential MT effects of practice could be found not only between sessions but within sessions as well.

Finally, we considered the possibility that the results might be explained by differences of curvature between the grapheme segments. From Figure 1, it can be seen that the first segment of each of the six graphemes was generally more curved than the second and third segments. As an alternative explanation, it could be argued that the difference in curvature was responsible for the differential practice effects. We therefore analyzed, post hoc, the curvature of each produced grapheme segment (see Teulings & Maarse, 1984) and related the change in mean curvature from Day 1 to Day 2 to the change in writing velocity from Day 1 to Day 2. According to the isogony principle (Lacquaniti, Terzuolo & Viviani, 1983), a constant relationship between these measurements should exist. We found, however, that the differential MT effects could not be accounted for by differential changes in curvature.

The view of cognitive control in motor learning has recently been corroborated by Shea and Zimny (1988). Motor learning would be highly influenced by people's goals, by their knowledge, and by the incorporation of new knowledge with old. Evidence was found that verbal reports could provide valuable insights into subjects' strategic and heuristic processes in motor learning.

A further important issue of theories on motor programming concerns the linear versus the continuous character of programming activities. Whereas in some of the theories each programming element is handled within a serially organized architecture of subprocesses

(Sternberg et al., 1978), other models advocate simultaneous processing at different levels (Rosenbaum, 1980). Especially for handwriting, Van Galen et al. (1986) developed the view that parallel processing is possible within a serially organized structure of processing stages. According to their model, phonological codes are delivered to a graphemic buffer after going through a semantic stage. Subsequently, this buffer is read by the allographic processor. The latter substitutes the graphemes for allographic motor programs that are still quite abstract. These allographic motor programs are stored in a short-term motor buffer and are followed by initiation and execution of the writing movement. In their study, evidence was found for a mixed linear and parallel character of the model, in which the (more abstract) intentional, linguistic and lexical processors handle bigger and more abstract representations of a message. These processors deliver their output with an increasingly smaller grain size (Miller, 1988) to the lower, motoric levels of the system that prepare the final, concrete muscle initiations. Processing goes on continuously in all stages of the system, but, at the same time, output from each of the subsystems is passed in a strictly linear fashion toward the subsystems of the hierarchy. A further characteristic of the model is that in realistic tasks like handwriting, hardly any discrimination is made, as far as time is concerned, between movement preparation and movement execution phases. Once task execution has started, preparation and execution go on hand in hand. Forthcoming elements of the message are prepared during the execution of earlier segments. Empirical evidence for the model has been provided in studies of the systematic variation of movement time in handwriting tasks (Van Galen et al., 1986; Van Galen, in press; Van Galen et al., 1989) and the spectral power density function of drawing movements (Van Galen, Van Doorn, and Schomaker, 1988).

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