Chapter 9

Determinants of Interkey Times in Typing

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Typewriting, musical instrument playing, spoken language, and dance involve sophisticated motor skills and associated symbol schemes. Researchers in cognition have been interested in these abilities because they enable the study of relations between the structure of motor behavior and the organization of the associated formal system. Typewriting, in particular, is of interest because of the remarkable rate and complexity of finger and hand movements involved and because its performance is readily quantifiable. However, if typewriting is to be used to study either cognitive or motor organization, the factors contributing to its temporal structure must be identified.

In this chapter I present the findings of several studies that examine variables that influence the pattern of interkey times in typing. In addition to providing evidence on the constituents of control in typing, the studies provide a basis for the examination of proposals by Ostry (1980) and Sternberg, Monsell, Knoll, and Wright (1978) that certain aspects of typing control are inherently tied to the execution of the sequence. The suggestions arise from observations that patterns of initial latency and interkey time are not changed by the introduction of a delay between stimulus presentation and a response signal. The inability to take advantage of a preparation interval seems to indicate that the programming of typing movements is intimately linked to their execution.

Hand Movements

A common experience for both the novice and the expert is that it is easier to type words such as *for*, in which successive characters involve the fingers of opposite hands, than words such as *was* or *wed*, in which successive characters involve the repeated use of the fingers of a single hand and sometimes the repetition of the same finger. The phenomenon

W. E. Cooper (ed.), *Cognitive Aspects of Skilled Typewriting*

raises the question how much of the timing of typing is due to motor coordination between the fingers of the two hands as opposed to the lexical and orthographic structure of the material being copied.

The issue is relevant in the context of recent claims by Terzuolo and Viviani (1980) that the timing of typing reflects an underlying "engram" for the word as a whole. Terzuolo and Viviani found that on repeated typing of a single word, the duration of intervals from one keystroke to the next was scaled in proportion to changes in speed. The scaling of interval durations resulted in a characteristic interkey time profile for the word as a whole. This was interpreted as evidence for a central program for a word.

The interkey time patterns in typing are known to differ substantially between words (Harding, 1933; Shaffer, 1978: Terzuolo & Viviani, 1980). Part of the difference may be due to the particular hand movements involved, independent of the words that are actually typed. For example, on the repetition of isolated letter pairs, performance is more rapid when successive characters involve fingers of opposite hands than when two fingers of the same hand are used (Coover, 1923; Dvorak, Merrick, Dealey, & Ford, 1936). Similarly, with sentences, alternating between hands for successive characters is more rapid than repeating the use of a single hand (Lahy, 1924).

The first study was undertaken to examine the effects of hand movement on typing, independent of differences between words. In describing the study, the term *hand alternation* will be used when successive letters are typed with fingers of opposite hands; *hand repetition* will be used when two fingers of a single hand are used for successive letters. Because it was desirable to examine all possible combinations of hand alternation and repetition movements at a given word length, the study was restricted to five-letter words. For example, the same sequence of hand movements was represented by each of *right*, *blame*, *chair*, and *laugh*. A different sequence was represented by *grape*, *lunch*, *scale*, and *brake*. In total, there are 16 different patterns of hand alternation and repetition possible for five-letter words. Fifteen different monosyllabic words were tested for each of the 16 different movement sequences, with order of presentation randomized.

Subjects in the study were 15 students whose speeds on prose ranged from 37 to 89 words per minute (wpm). (The wide range of speeds enabled tests of performance change with differences in skill.) The words were presented in uppercase on a video screen, at a rate of one word every 5 sec. A brief audio signal was synchronized with the onset of each word. An IBM Selectric was used for testing; the interkey times were recorded with 1-msec accuracy by means of a PDP-11/20 computer. Subjects were instructed to start typing when the stimulus was presented and to type rapidly while maintaining as low an error rate as possible. (The effects of different instructions to subjects are reported later in the section on single-word strategies.) The data are based on words that were typed without error. Error rates in the study ranged from .02 to .11 with an average of .053.

Initial latencies and interkey times were examined separately. Initial latencies were greater than interkey times and also varied with the movement composition of the word. Initial latencies were longer when the first movement within the word (letter 1 to 2) involved alternation as opposed to repetition of hands, $F(1, 15) = 32.39$, $p < .01$, $SE = 2.41$ msec. Latencies preceding a hand alternation averaged 756 msec, while latencies preceding a repetition averaged 739 msec. In contrast, the total number of repetitions or alternations in a word did not affect initial latency in any systematic manner.

Interkey time patterns, excluding initial latencies, are shown in Figure 9.1 for the 16 different movement patterns that were tested. Each of the panels shows interkey times averaged over typists and over the 15 different words used for a particular movement sequence. In general, hand alternation movements were more rapid than hand repetitions, but the extent of the difference seemed to depend on the particular sequence of hand repetitions and alternations involved.

The data on movements within a word were also partitioned in order to examine differences in interkey time between hand alternations and repetitions, without regard to the actual movement sequence. Analysis of variance across typists found alternations reliably faster than repetitions, $F(1, 14) = 265.49$, $p < .01$, $SE = 1.38$ msec. In this study, the mean interkey time for hand alternation was 147 msec and that for repetition was 192 msec, a difference of 45 msec. The analysis was repeated for each of the 15 subjects individually. In all cases interkey times for hand alternations were reliably less than for hand repetitions.

A further analysis examined differences in interkey times for hand alternation and repetition movements as a function of typing speed. As shown in Figure 9.2, timing differences between hand repetition and hand alternation movements were relatively constant over differences in speed.

The constant difference between interkey times for hand alternation and repetition cannot be accounted for strictly in terms of a biomechanical constraint on the repeated use of one hand. This interpretation would require the assumption that slow typists were performing as near to their biomechanical limit for hand repetition as fast typists. Alternatively, the constancy of the delay brought about by the repeated use of a single hand may be associated with the motor organization of movements whose constituents are repeated or overlap. Delays brought about by movement repetition have been reported for both handwriting (Wing, Lewis, & Baddeley, 1979) and speech (Sternberg et al., 1978). The repetition of letters in handwriting causes a slowing relative to sequences in which different letters are produced. The slowing depends on the over-

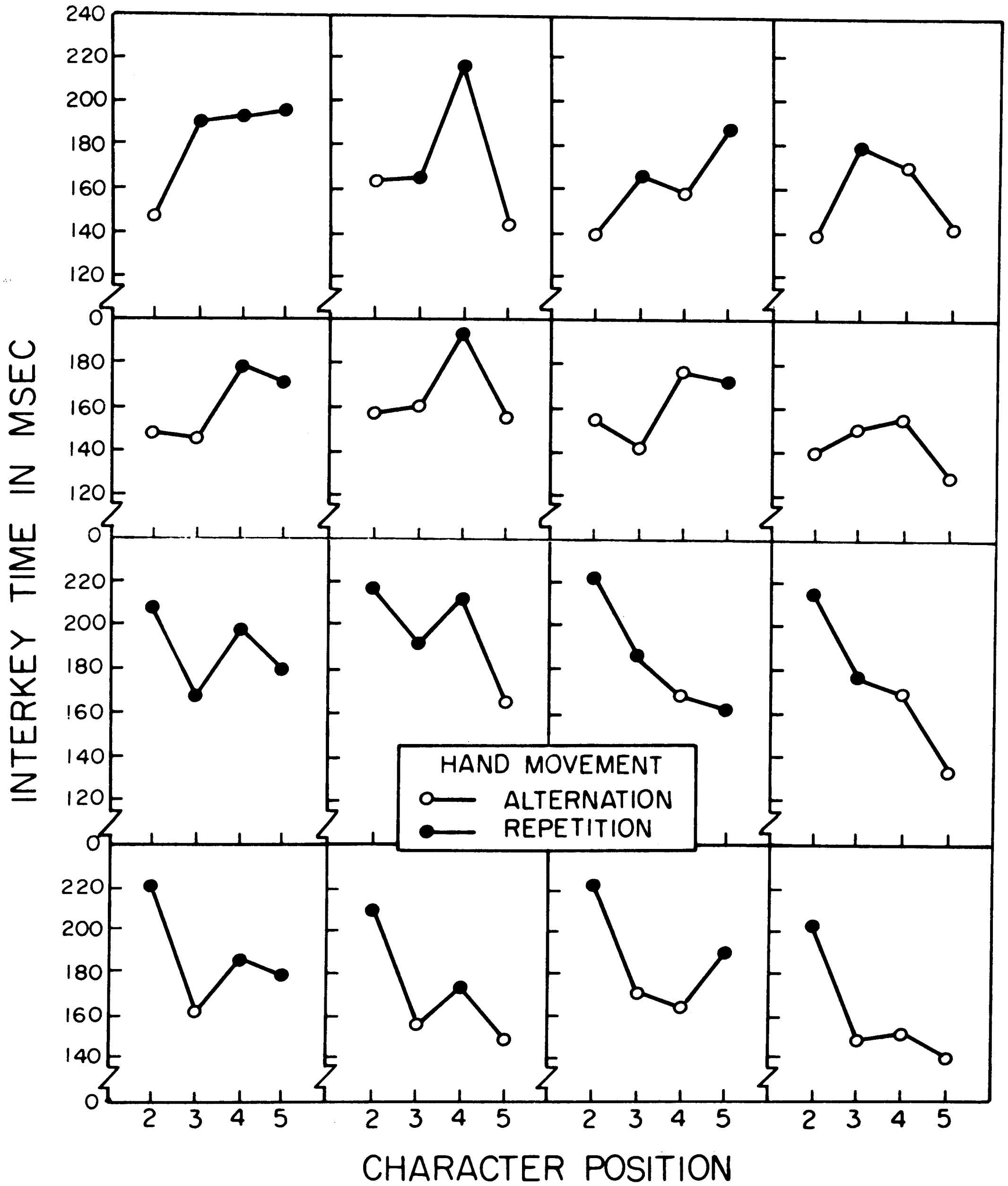

Fig. 9.1. Average interkey times for all sequences of hand alternation and repetition in five-letter words. Times shown at any character position represent average interkey time between character *n* - 1 and character *n*.

lap of movements rather than the actual repetition of the letters; the production of handwritten sequences involving both upper- and lowercase forms of a letter does not produce a comparable slowing of performance. Similarly, when subjects are instructed to say a particular word repeatedly, the production rate is slower than when subjects repeat a sequence of different words.

In contrast to the greater interkey times observed for hand repetition movements, initial latencies were greater prior to initial hand alternation. The finding is consistent with reports by Larochelle (Chapter 4) and

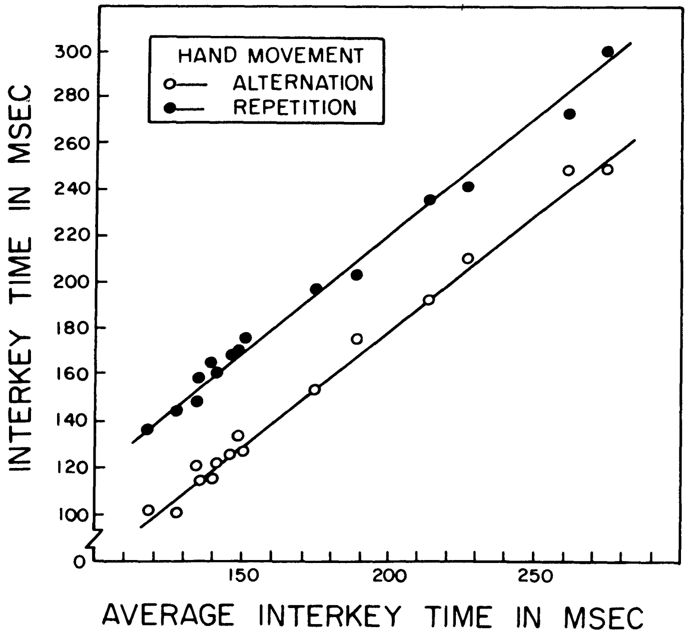

Fig 9.2. Average interkey times for each subject for hand alternation and hand repetition in five-letter words. Times for alternation and repetition are shown for each subject as a function of average typing speed.

Sternberg et al. (1978) as well as with demonstrations of movement timing within words. Both Ostry (1977) and Shaffer (1978) have observed that there is a slowing of movement in the interval preceding a hand alternation. Thus, although alternation of hands seems to improve interkey times in typing, the time occupied prior to response initiation may indicate that bimanual activity actually involves greater underlying complexity than unimanual control.

In summary, the pattern of hand alternation and repetition movements produces substantial differences in the timing of typing. Attempts to assess lexical or orthographic components of typing must account for differences due to movements alone. The delay in interkey times brought about by the repeated use of a single hand suggests that organization at the level of the movements themselves must extend at least to character pairs. Differences in initial latency dependent on the movement from letter 1 to letter 2 likewise implicate a motor organization that extends at least to adjacent movements.

Word Length

Interkey time functions in typing characteristically display a nonmonotonic inverted U-shaped pattern over successive characters. The pattern has been reported for sets of both words (Ostry, 1980; Shaffer & Hardwick, 1970) and nonwords (Ostry, 1980; Sternberg et al., 1978) and is obtained both when subjects start typing immediately on presentation of the stimulus and when performance is delayed for 1 sec. In single words the pattern is masked by substantial differences in timing due to movements between the hands (see the preceding section).

Several writers have interpreted initial latencies and interkey times as indicators of the underlying organization of typing (e.g., Shaffer & Hardwick, 1970; Sternberg et al., 1978). Initial latency and average interkey time have been shown to increase with sequence length when the stimuli are words or letter strings of five letters or less. Except for short sequences, however, the influences of length have not been explored systematically. To the extent that organization in typing is applied to the sequence as a whole, it should be evident over differences in sequence length. The results of several studies in which words of various lengths are typed either alone or in sentences are reported below. The stimuli have been balanced to eliminate differences due to hand alternation and repetition movements.

One set of studies was conducted with words from five to eight letters in length. At each word length, 80 words were selected, such that between any two successive characters the total number of hand alternations and repetitions was approximately equal. For example, approximately half of the 80 words at length 5 required hand alternation from letter 1 to letter 2. Likewise, half (40) required alternation from letter 2 to letter 3, and so on for all character positions and word lengths. All but 5 of the 320 words tested were bisyllabic.

The actual frequencies of hand alternation at word length 5 were 35 alternations between letters 1 and 2; 45 alternations between letters 2 and 3; 38 between letters 3 and 4; and 44 between letters 4 and 5. Corresponding letter pairs at length 6 had hand alternation frequencies of 35, 37, 41, 40, and 41, respectively. Alternation frequencies at length 7 were 43, 36, 40, 42, and 32, and at length B the frequencies were 44, 37, 39, 42, 46, 42, and 30. Proportions of high-frequency words (AA and A, respectively, in Thorndike & Lorge, 1944) were likewise similar at the four word lengths. The proportions of AA-frequency words were .21, .20, .20, and .15 for word lengths 5 to 8, respectively. Proportions of A-frequency words were .21, .25, .21, and .23. The aim of these procedures was to ensure that the patterns of performance described below would not be accounted for by either by the linguistic frequency of the test words or the sequence of hand movements involved in their typing.

In an initial study with these stimuli, the words were presented in uppercase on a video screen at a rate of one word every 5 sec. The order of presentation was randomized with respect to word length. A brief audio signal was synchronized with the onset of each stimulus. Fifteen different subjects, whose speeds on prose were 30 to 82 wpm, were tested. Subjects were screened prior to the experiment for standard finger-key assignments, including spacing with the right-hand thumb. An IBM Selectric was used for testing, and as in the first study, interkey times were measured with 1-msec accuracy by a PDP-11/20 computer.

Subjects were instructed to type rapidly while maintaining as low an error rate as possible. Each subject provided mean interkey times for correctly typed words at each character position and all word lengths. Error rates ranged from .02 to .13, with an average of .07.

The data were partitioned with respect to initial latency and interkey time. Initial latencies were evaluated as a function of word length in characters. Initial latencies were longer than interkey times as a result of the single-word format but they were not otherwise affected by differences in word length, $F(3, 42) < 1$, $SE = 4.51$ msec. Average latencies were 836, 834, 833, and 839 msec for word lengths 5 to 8, respectively. Initial latency also varied with differences in skill, where shorter initial latencies were associated with greater average typing speeds, $r(13) = .64$, $p < .01$.

Interkey times were likewise assessed with respect to word length. The obtained patterns, averaged over typists, with initial latencies excluded, are summarized in Figure 9.3 (the times shown at any character position represent the average interkey time between character $n - 1$ and character n). The initial latency was followed by a relatively short interval from character 1 to character 2. Interkey time increased in the interval from character 2 to character 3 and, with the exception of word length 5, again from character 3 to character 4. Interkey time then decreased toward the end of the word, with performance tending toward an asymptote at word lengths 7 and 8. The maximum interkey time at midword and the times toward the end of the word both increased with word length.

Except at word length 5, the pattern of short interkey times at the beginning and the end of a word and slower performance in the middle

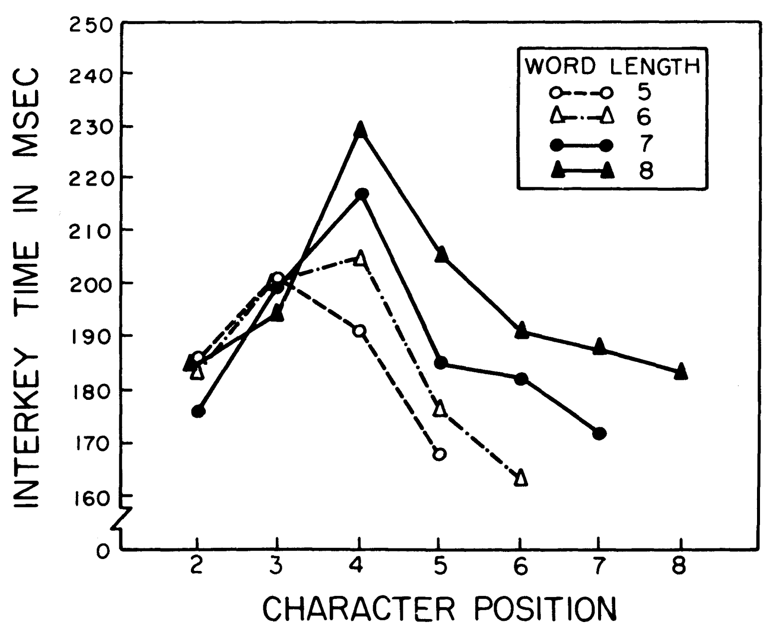

Fig 9.3. Average interkey times over successive character positions for five- to eight-letter words.

was obtained for all typists and word lengths. For five-character words, 6 of the 15 typists produced functions in which interkey time monotonically decreased from the first to the last interval in the word.

Differences in the set of interkey times at each word length were tested by analysis of variance. These analyses were reliable in all cases, indicating that performance varies over word length: $F(3, 42) = 10.99$, $p < .01$, $SE = 4.16$ msec; $F(4, 56) = 20.03$, $p < .01$, $SE = 3.89$ msec; $F(5, 70) = 13.52$, $p < .01$, $SE = 4.58$ msec; $F(6, 84) = 12.12$, $p < .01$, $SE = 4.68$ msec, respectively. Differences between interkey times for character 1 to character 2 and times for the longest interval at midword were tested by using Scheffé contrasts. At all word lengths, the character 1 to character 2 interkey times were found to be reliably less than the interkey times at midword: $F(3, 42) = 13.68$, $p < .01$; $F(4,56) = 28.04$, $p < .01$; $F(5, 70) = 80.07$, $p < .01$; $F(6, 84) = 88.49$, $p < .01$, respectively. Differences between the interkey time preceding the final character and the longest time at midword were also tested. Differences were again reliable in all cases, indicating a significant increase in speed toward the end of a word: $F(3, 42) = 62.83$, $p < .01$; $F(4, 56) = 116.96$, $p < .01$; $F(5, 70) = 98.21$, $p < .01$; $F(6, 84) = 99.79$, $p < .01$, respectively.

Tests for differences among the four functions were also carried out, in order to assess the reliability of the observed divergence among the functions beyond the third character position in the word. The analysis of variance compared performance at all word lengths up to character position 5 (the part common to all test items). The patterns were found to differ at the four word lengths, $F(9, 126) = 13.66$, $p < .01$, $SE = 2.94$ msec. Tests for simple main effects showed no differences among the curves at character positions 2 and 3—$F(3, 168) = 2.31$ and $F(3, 168) = 1.02$, respectively—and reliable differences at both character position 4, $F(3, 168) = 29.35$, $p < .01$; and 5, $F(3, 168) = 27.97$, $p < .01$.

The contribution of typing skill to this pattern was assessed by examining, for each subject, the difference between the maximum interkey time at midword and the shortest time at word end. Estimates averaged over the four word lengths ranged from approximately 20 msec for rapid typists to about 75 msec for slow typists. The average difference between the times at midword and those at word end decreases with increases in typing speed, $r(13) = .61$, $p < .01$. As typists become more skilled, there is a less pronounced slowing at midword.

The finding that the extent of the midword slowing varies with the skill of the typist is consistent with the suggestion that sequence level aspects of typing organization take place while the response is actually in progress. In this context, the midword slowing can be viewed as a loading effect due both to the efficiency of organization and to sequence length.

Delayed Response

Because of the possibility that the interkey time patterns just reported resulted from an insufficient opportunity to complete the perceptual processing of the stimulus or the organization of its response, the single-word procedure was repeated with varying delays introduced between the presentation of an item and an audio signal to respond. Greater delays should enable the completion of perceptual processing, and to the extent that the observed interkey time pattern results from the immediate response condition, an advantage to the delayed condition should be seen in the timing of the subsequent motor sequence.

The stimuli were the same items tested above (80 items at each of word lengths 5-8). They were presented one at a time in uppercase and were followed, after a delay of 0, 50, 100, 200, 400, or 800 msec, by a brief audio signal to respond. The trials were blocked on response delay, with the order of test items differently randomized for each block.

Ten subjects, none of whom participated in the first studies, were tested. Their speeds on prose ranged from 35 to 80 wpm. A Cybernex electronic keyboard and PDP-11/20 were used for the test. The subjects were instructed to prepare their response when an item appeared on the screen and to begin typing as soon as possible after the audio signal. The results are based on correctly typed items. Error rates ranged from .01 to .09, with an average of .048. Similar error rates were observed at all six delays.

The data indicated that the benefits of greater preparation time extended only to the first character in a word (Figure 9.4), and that, at least for longer words, the nonmonotonic interkey time pattern was obtained after an 800-msec delay. Thus, the interkey time pattern reported in the preceding section does not seem to have resulted from the immediate response condition.

The initial latency decreased from an average of 615 msec at a response delay of 0 msec to a value of 310 msec at the 800-msec delay, but the benefit of greater preparation time did not appear to extend beyond the first character in the word. A monotonically decreasing interkey time pattern was observed at word lengths 5 and 6; the nonmonotonic pattern of Figure 9.3 was obtained at word lengths 7 and 8. However, with the exception of the initial latency, none of the actual output patterns was altered, even at delays of 800 msec.

Initial latencies were independent of word length at all response delays. The initial latencies decreased from values of 619, 610, 609, and 617 msec at delay 0 msec to values of 305, 305, 313, and 311 msec at the 800-msec delay. At all delays the initial latencies varied in a nonsystematic manner as a function of word length.

The analysis of variance tested differences in performance as a function of response delay for each word length separately. With initial

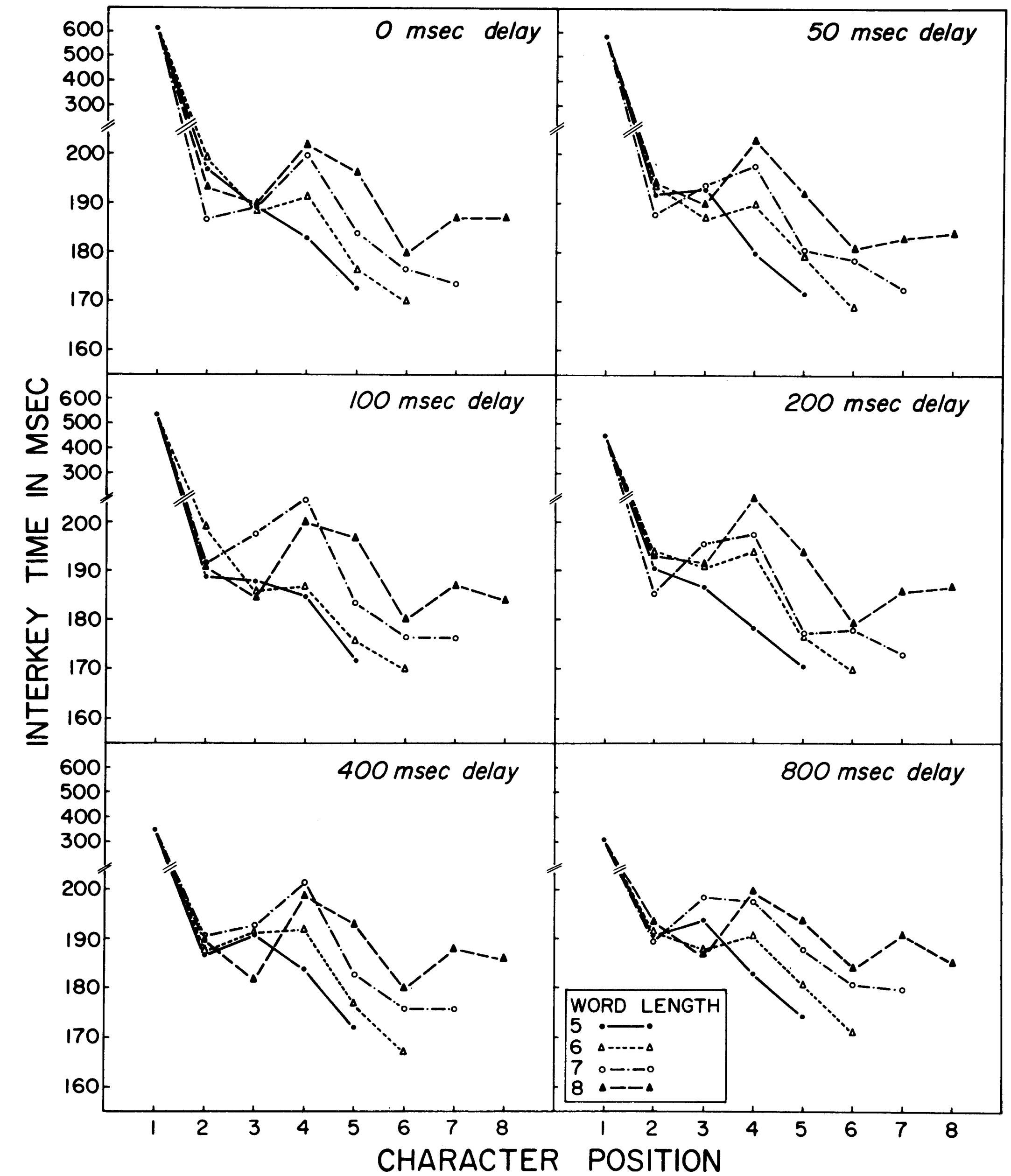

Fig. 9.4. Average interkey times over successive character positions in five- to eight-letter words as a function of response delay.

latencies included in the analysis, interactions between interkey times and response delay were obtained at each of word lengths 5-8: $F(20, 180) = 256.31$, $p < .01$, $SE = 3.52$ msec; $F(25, 225) = 240.74$, $p < .01$, $SE = 3.25$ msec; $F(30, 270) = 229.21$, $p < .01$, $SE = 3.04$ msec; $F(35, 315) = 218.68$, $p < .01$, $SE = 2.97$ msec, respectively. The interactions were all due to a decrease in the initial latency as a function of increased response delay. The patterns of interkey time were not otherwise affected by the delay manipulation, and in fact, at any specified word length and character position, there was little variation in the values obtained at the different response delays. The interkey times were within 6 msec of one another for over 80% of the data points at any character position, and in all cases the range of interkey times was no greater than 10 msec.

The slowing that was observed at midword in the previous study was not obtained at word length 5 or 6. This may be a result of the introduction of an electronic keyboard. However, differences in the interkey time pattern are more likely a reflection of the subjects themselves; patterns such as this were observed for 40% of the subjects tested at word length 5 in the single-word study of the preceding section. The nonmonotonic interkey time patterns of Figure 9.3 were obtained for word lengths 7 and 8, where Tukey contrasts verified a reliable slowing between character position 2 and the point of slowest performance, at two of six and five of six response delays, at word lengths 7 and 8, respectively. This increase in interkey times was also tested with planned contrasts, which showed reliable midword slowing at all response delays for both seven- and eight-letter words.

The finding that the nonmonotonic interkey time pattern reported above cannot be eliminated by extending the period before response initiation is consistent with the notion that aspects of motor organization at the level of the sequence or perhaps the word take place while the movement is in progress.

Typing Sentences

In a final study with this stimulus set, words were embedded in sentences and presented to subjects one sentence at a time. While there is little evidence that typing organization extends to the phrase or the sentence, the subject may adopt different strategies for single words than for continuous typing. Shaffer and Hardwick (1970), for example, have demonstrated that when visual preview is restricted, performance is not degraded until fewer than eight characters are available. Similarly, Butsch (1932) showed that even with extremely rapid typists the eyes rarely lead the hands by more than two words. Further, Fendrick (1937) and West (1969) have shown that performance is only slightly more rapid for prose than for the same words randomly ordered and that the advantage to prose is unrelated to skill.

Fifteen subjects (speeds on prose from 32 to 94 wpm right-hand thumb for spacing) copied sentences one at a time. A brief audio signal synchronized with the presentation of each sentence served as a starting tone. The sentences were from 7 to 10 words in length, and the words were no more than eight letters each. The sentences were constructed to include all of the words used earlier (these will be referred to as test words) and as many others as necessary for meaning and continuity.

The sentences were presented to subjects on double-spaced 22- by 28-cm pages. The subjects read all sentences before the experiment began. An IBM Selectric was used for testing. For each sentence, all interkey times, including times to move to and from the space bar, were recorded. For purposes of analyses, the first and last words in each sentence were excluded to eliminate overall start-up and ending effects. All words with errors were likewise removed.

Initial latencies for test words were evaluated as a function of word length and, as in the single-word condition of the preceding section, they were not found to differ, $F(3, 42) = 1.92$, $SE = 3.52$ msec. The obtained values were 220, 228, 227 and 231 msec for word lengths 5-8, respectively. The initial latencies were considerably shorter than those observed when single words were tested, but they were similar to values obtained at the points of slowest performance in the middle of the word (longest interkey times at midword for word lengths 5-8 were 222, 212, 227, and 229 msec, respectively).

The interkey times for test words were partitioned with respect to word length (Figure 9.5). The obtained patterns were similar to those reported above. The initial latency was followed by a short interkey time preceding character 2, and a maximum interkey time between characters 2 and 3 for word lengths 5 and 6 and between characters 3 and 4 at word lengths 7 and 8. Unlike the single-word condition, there was little evidence that interkey times reached an asymptote at the ends of longer words. As in the previous studies, however, interkey times beyond midword were greater at longer word lengths. Each word was terminated by striking the space bar. The interval from the final character to the space averaged 186 msec, and its duration was uninfluenced by word length. Similar patterns were observed for all typists.

Differences in interkey times at each word length were tested by analysis of variance and were found to be reliable in all cases, which indicates that performance varied over word length: $F(5, 70) = 9.30$, $p < .01$, $SE = 5.40$ msec; $F(6, 84) = 12.72$, $p < .01$, $SE = 4.75$ msec; $F(7, 98) = 10.84$, $p < .01$, $SE = 5.52$ msec; $F(8, 112) = 9.97$, $p < .01$, $SE = 5.24$ msec, for word lengths 5-8, respectively. Scheffé contrasts confirmed that interkey times from character 1 to character 2 were reliably less than values at the point of slowest performance in the middle of the word: $F(5, 70) = 30.79$, $p < .01$; $F(6,84) = 17.93$, $p < .05$; $F(7, 98) = 60.45$, $p < .01$; $F(8, 112) = 57.13$, $p < .01$, again for word lengths 5-8; and that differences between the final interkey time in the word (excluding the space) and the point of slowest performance at midword were likewise reliable: $F(5, 70) = 42.75$, $p < .01$; $F(6, 84) = 28.33$, $p < .01$; $F(7, 98) = 45.71$, $p < .01$; $F(8, 112) = 21.46$, $p < .01$, respectively.

The movement between the final character and the space generally produced short interkey times. Further tests of the spacing sequence

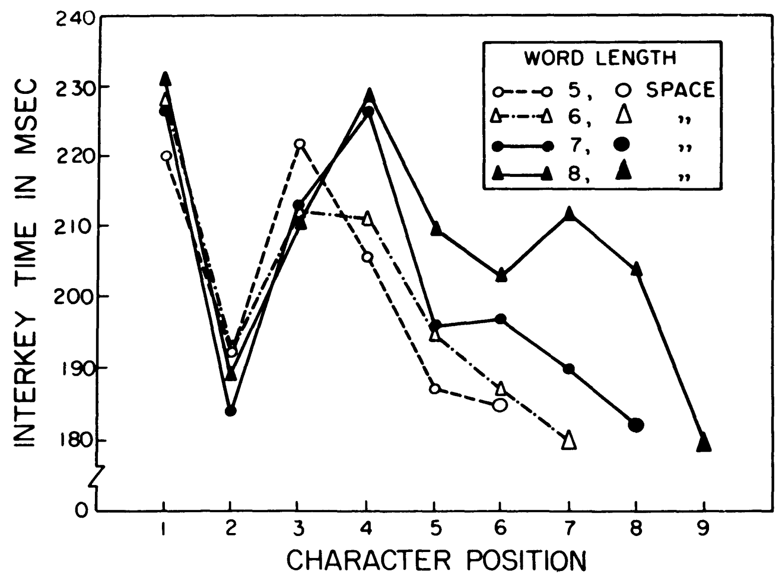

Fig. 9.5. Words in sentences. Mean interkey times over successive character positions as a function of word length.

studied its relations to hand alternation and repetition (all typists used the right-hand thumb for the space bar; thus a word ending in a *d* required a hand alternation, whereas one ending in a *k* required a repetition). The analysis of variance found reliable time differences between spacing movements involving hand alternation and those involving hand repetition, $F(1, 14) = 13.28$, $p < .01$, $SE = 3.31$ msec. Alternating hands to move to the space bar was faster than using the same hand for both the last character of a word and the space. Average times were 177 msec for hand alternation and 194 msec for repetition. The duration of the spacing movement was not related to word length, $F(3, 42) < 1.00$, $SE = 2.39$ msec; the average time for spacing was 186 msec at all word lengths tested.

Because of its advantage in speed, the space stroke was presumed to reflect characteristics of skilled performance. A test was conducted to examine the time difference in spacing movements as a function of typing speed for hand alternation as opposed to hand repetition. The analysis suggested that the time difference between repetition and alternation in spacing may increase as typists increase in speed, $r(13) = .43$, $p \cong .05$. Alternations in spacing were about 10 msec faster than repetitions for slower typists, whereas for faster typists the difference increased to approximately 30 msec.

There is a parallel between the difference in interkey times observed in spacing and the time difference between hand alternation and repetition movements within words (see the section on hand movements at the beginning of the chapter). In both, with increases in speed, there are proportionately larger deviations from uniformity in successive interkey times. In effect, for both spacing movements and movements within words, improvements in skill seem to result in relatively greater departures from temporal uniformity (see Harding, 1933, for a related demonstration of departure from temporal uniformity with increases in typing skill). The finding is not at odds with the reported decrease in midword slowing for faster typists (see the section on word length), since the data presented earlier in the word-length section are based on performance averaged over differences in hand alternation and repetition. Thus, although performance is generally streamlined with increases in skill, the timing of the individual typing movements becomes less periodic relative to their average speed.

Longer Words

A final assessment of the effects of word length involved the examination of typing performance for longer words, from 8 to 11 letters. The stimuli were four sets of 60 words each, all two to four syllables in length. Hand movement pattern and digraph frequency were balanced at each word length separately (see below). The proportion of high-frequency words was low in all conditions, with 3 of 60 words at word length 8, 4 of 60 at length 9, 3 at length 10, and 0 at length 11 having frequencies of occurrence of 100 per million or greater (Thorndike & Lorge, 1944).

As in the foregoing studies, the set of 60 words at each word length was balanced for the total number of hand alternations and repetitions between any two successive characters. The balancing never departed by more than 10% from equal numbers of alternation and repetition movements at a given word length and character position, with stimulus sets at word lengths 8, 9, and 10 being perfectly balanced. The proportion of high-frequency digraphs (frequencies greater then 750 per 20,000 words; Mayzner & Tresselt, 1965) was likewise similar at all character positions and word lengths. The overall proportion of high-frequency digraphs was .17 with obtained proportions within .05 of this value at all character positions at each word length.

The stimuli were presented one at a time in uppercase with order of presentation randomized. As earlier, an audio signal was synchronized with the onset of each stimulus and served as a starting tone. An IBM 2741 terminal was used for testing. Sixteen subjects whose speeds on prose ranged from 39 to 84 wpm participated in the study. Subjects were instructed to begin typing when a word appeared on the screen, to type rapidly, and to maintain as low an error rate as possible. Both initial latency and interkey times were measured. Error rates ranged from .005 to .07, averaging .04.

The interkey times were examined at each word length separately (there were no systematic differences due to initial latency; values of

635, 652, 625, and 632 msec were obtained for word lengths 8-11, respectively). Interkey times followed a pattern similar to that obtained at shorter word lengths (Figure 9.6). After a relatively short interval preceding character 2, performance slowed, reaching a maximum interkey time at character position 4 at word lengths 8, 9, and 11 and at position 5 for word length 10. Interkey times then progressively decreased until the final interval in the word, where an increase of about 10 msec was observed.

Differences in interkey times at each word length were tested with analysis of variance. These analyses were reliable in all cases, indicating an overall difference in speed across the word: $F(6, 84) = 9.41, p < .01$, $SE = 3.88$ msec; $F(7, 98) = 11.91, p < .01, SE = 4.41$ msec; $F(8, 112) = 14.54, p < .01, SE = 4.34$ msec; $F(9, 126) = 12.05, p < .01, SE = 4.83$ msec, respectively. Differences between interkey times at character position 2 and the maximum values observed at midword were reliable by planned comparisons. The slowing that is seen in the final interval was not reliable by Tukey tests at any word length.

Similar patterns of interkey times have been observed in the studies described here. In these studies, word length in characters has been varied from 5 to 11 letters. In general, interkey times display a nonmonotonic inverted U-shaped pattern over successive letter positions. More specifically, interkey times are relatively short at the beginning of a word, progressively increase to reach a maximum at about position 4, and then decrease monotonically over the remainder of the word. The magnitude of the maximum interkey time may increase with word length; however, its location in the word is relatively constant. Interkey

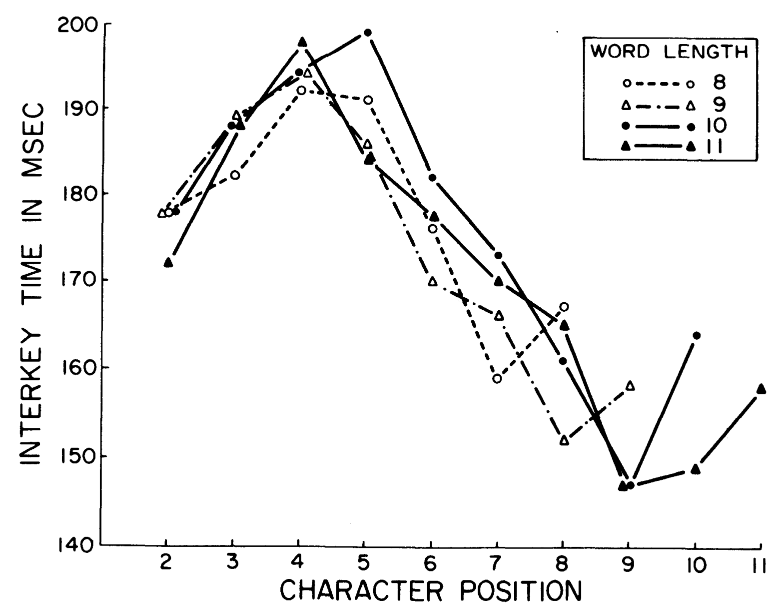

Fig. 9.6. Average interkey times over successive character positions for words from 8 to 11 letters in length.

times at a given character position are similar for different word lengths prior to the slowest point at midword. Beyond midword, interkey times are greater for longer words (exceptions are discussed in the last section of this chapter). Initial latencies are not found to vary as a function of word length in the range from 5 to 11 letters.

An organization extending to the sequence as a whole may be indicated by the finding that beyond the maximum interkey time near position 4, times at any character position are greater for longer words. The pattern observed here cannot be attributed to hand movement, digraph or word frequency, or differences in typing skill. It does not result from the presentation of the stimuli one word at a time, incomplete perceptual processing, or an inadequate period for motor organization prior to movement. Possible influences on interkey times that were not controlled in these studies are syllabification, the use of words as stimuli, and the implicit strategies the subject might adopt in typing.

Syllabification does seem to account somewhat for the form of the interkey time function in typing. Ostry and Munhall (Note 1) tested subjects with mono-, bi-, and trisyllabic words that were otherwise balanced for differences in word length, hand movement, and digraph and word frequency. They obtained patterns similar to those reported here for both bi- and trisyllabic stimuli. With monosyllabic words a somewhat different nonmonotonic pattern was obtained. Specifically, an initial decrease in interkey times was followed by a slowing of performance later in the word and a subsequent increase in speed for the final characters.

In contrast, the overall form of the interkey time function does not appear to depend on the use of words as stimuli. Larochelle (Chapter 4) has demonstrated that when words and nonwords are balanced for digraph frequency, the interkey time patterns and the extent of midword slowing at a given sequence length are similar in the two conditions.

The form of the interkey time function—a single slowing of performance early in the word followed by a monotonic increase in speed that continues to the final characters—raises the possibility that the nonmonotonic pattern is the reflection of a strategy used for typing. The following study examined this possibility.

Single-Word Strategies

The nonmonotonic pattern of interkey times may reflect a strategy, presumably implicit, that subjects adopt for typing. Alternatively, it may be a relatively rigid characteristic of the structure of typing, a "rise time" effect associated with rapid seriation. If the initial slowing in the interkey time function results from a start-up or rise time effect, it would be expected only at the beginning of the word and should not be modifiable by instructions to subjects.

A final study was conducted with the aim of explicitly manipulating the strategies subjects use in typing. The effects of three instructions on the typing of single words were examined. One instruction was to start typing as soon as possible after a word appeared on the video screen and to continue at a normal rate after starting. A second instruction was to be fully prepared before starting to type, and to finish as soon as possible once started. A third instruction was simply to type each word as it appeared on the screen. These instructions were combined either with the information that errors were unimportant or that errors were to be minimized. Subjects were tested in all six conditions with order of conditions balanced according to a Williams square (Cochran & Cox, 1957) in order to eliminate first-order carry-over effects.

The stimuli were 64 words at each of word lengths 4-7. The stimuli were selected in order to balance for differences in hand movement, and digraph and word frequency. All possible combinations of hand alternation and repetition were tested at each word length. At length 4 there are eight possible combinations of hand alternation and repetition; at length 5 there are 16 combinations; at length 6 there are 32 combinations; and at length 7 there are 64. The complete set of 64 words was obtained by using eight different words for each of the eight hand alternation-repetition combinations at length 4, four different words for each of the 16 combinations at length 5, and so on. The proportion of high-frequency words (frequencies greater than 100 per million; Kucera & Francis, 1967) was .25 at all word lengths. The proportion of high-frequency digraphs (frequencies greater than 750 per 20,000 words; Mayzner & Tresselt, 1965) was .15 ± .07 at all character positions and word lengths.

Eighteen subjects, whose speeds ranged from 27 to 74 wpm, participated. The stimuli were presented one at a time in uppercase on a video screen, with a brief audio signal simultaneous with the stimulus onset. The testing was carried out on an IBM 2741 terminal. Each subject was tested over a period of six sessions, with a different set of instructions at each session. Items that were typed incorrectly were re-presented at random later in the session.

Initial latencies and interkey times were examined separately. Initial latencies varied systematically with instructions to the subject. Latencies increased in conditions in which errors were to be minimized (753 vs. 730 msec). They were shortest when subjects were instructed to start typing as soon as possible (660 msec) and longest when subjects were to prepare fully before starting to type (825 msec). Initial latency did not vary systematically as a function of word length (736, 736, 736, and 756 msec for lengths 4-7, respectively).

Interkey times for each of the six conditions are shown in Figure 9.7. The three main instructions each resulted in different interkey time patterns. The instruction to begin typing as soon as possible produced an increase in interkey time at character position 2 that accompanied

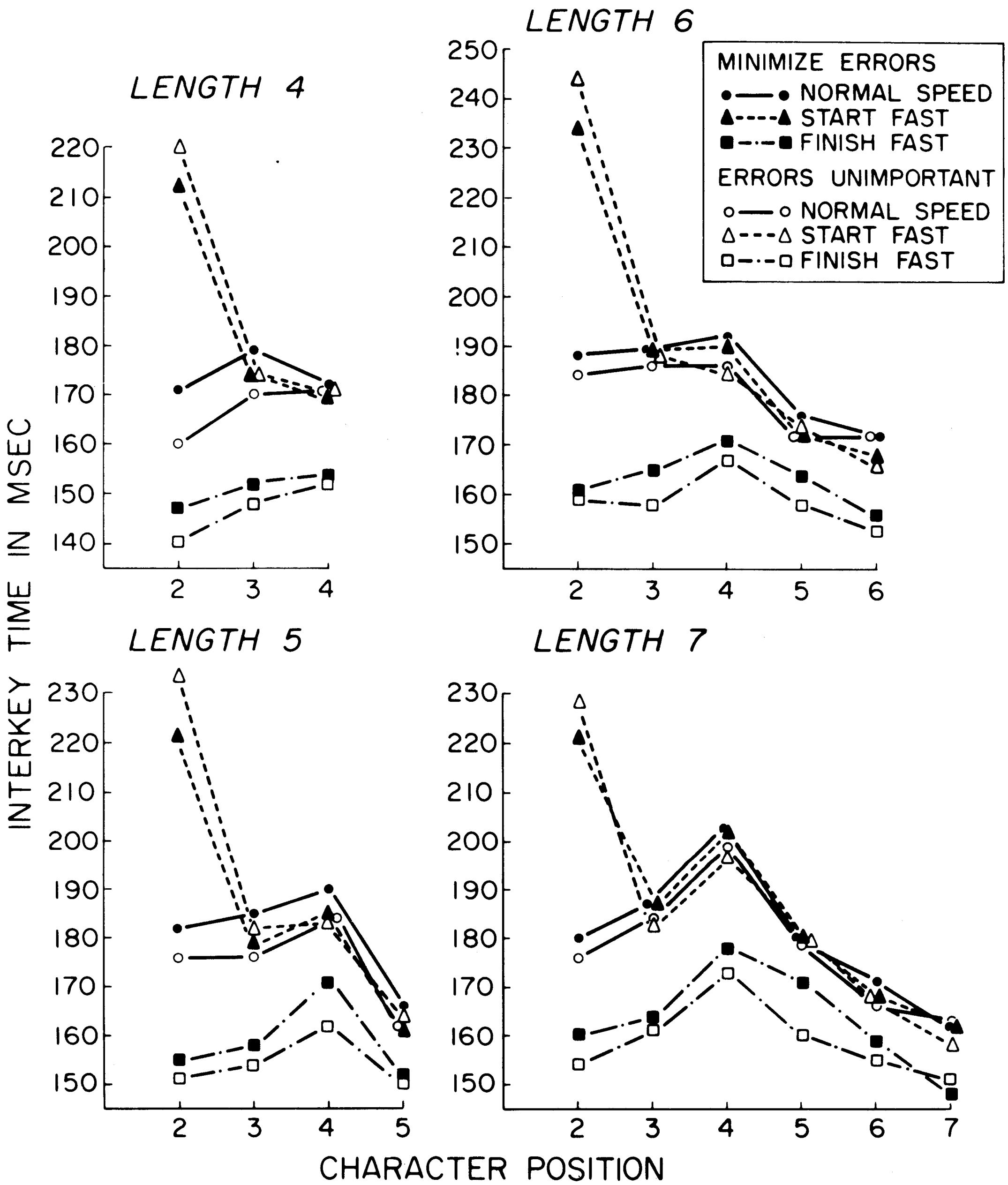

Fig. 9.7. Average interkey times over successive character positions for four- to seven-letter words. Subjects were instructed either to start typing as soon as possible, to be fully prepared before starting and then finish as soon as possible, or to type each word as it appeared on the screen. They were also told either that errors were unimportant or that errors should be minimized.

the reduction in initial latency described above. The interkey time pattern was otherwise similar to that produced by the instruction to type each word as it appeared on the screen. The instruction to start only when fully prepared and then finish as soon as possible produced a reduction in interkey times but no change in the form of the overall function.

The error rate manipulation did not affect interkey times to the same extent as the other instructions. It did, however, result in the anticipated changes in error rates. Error rates averaged .049 in conditions where errors were to be minimized and .086 in conditions where errors were unimportant. The average error rate was .047 for the normal speed condition, .066 in the condition where the typist was to start as rapidly as possible, and .090 in the condition where the typist was to finish as rapidly as possible.

The increase in interkey times over successive character positions at word length 4 has been reported previously for three- and four-letter words (Chapter 4, this volume; Ostry, 1980). A similar increase in interkey times, from character position 2 to approximately 4, is also observed at longer word lengths. It is possible that interkey time functions at all word lengths may be similar in this range.

The overall form of the interkey time pattern was not substantially affected by the different instructions. The instruction to start typing as soon as possible seemed to result in a one-character slowing after the first keypress and then a return to the nonmonotonic pattern that is otherwise observed. The instruction to finish as soon as possible shifted the entire curve as if a gain setting had been changed, but the overall form of the function did not appear to be altered. Therefore, the characteristic interkey pattern does not appear to be the result of a flexible strategy that subjects adopt for typing. The slowing that occurs over the first characters in the word may be a rise time or start-up effect accompanying the initiation of each movement sequence.

General Discussion

Determinants of interkey times in typing were examined in a series of studies in which movements, word length, and instructions to subjects were manipulated. Effects were obtained both for movements between letter pairs and for the sequence as a whole. The interkey time pattern in typing was relatively insensitive to attempts to manipulate strategies.

In a study of movement patterns, timing differences were assessed between letter pairs that involved the successive use of two fingers of one hand and movements in which letters were typed with two fingers of alternate hands. Three main findings were described. First, sets of words requiring different sequences of hand alternation and repetition resulted in different interkey time patterns. Second, the average time difference between hand alternation and hand repetition movements was constant, independent of differences in typing speed. Finally, interkey times were reliably less for hand alternation movements, but initial latencies were less preceding initial hand repetitions.

The first finding suggests that the sequence of movements between hands is a main contributor to the pattern of interkey times for a given word. The Terzuolo and Viviani (1980) observation that each word has a distinctive pattern is perhaps a reflection of this fact, rather than a reflection of a motor engram per se.

The constant difference between interkey times for hand alternation and repetition was interpreted as a property of motor organization associated with the repetition or overlap of successive movements. Repetition of letters in handwriting and words in speech produces similar delays (Wing et al., 1979; Sternberg et al., 1978). The difference between alternation and repetition movements is in part the result of a mechanical advantage in hand alternation. However, the constant difference, independent of typing speed, makes it unlikely that the effect can be accounted for strictly in biomechanical terms.

The longer interkey times for movements involving the repetition of a hand can be contrasted with their shorter initial latencies. The latency pattern suggests differences in the organizational complexity of bimanual and unimanual control. The differences in initial latency dependent on the movement from letter 1 to letter 2 along with delays in interkey times brought about by the repeated use of a single hand both suggest that organization at the level of the movements themselves extends at least to character pairs.

The study of movement patterns also led to the observation of proportionately greater departures from temporal uniformity with increases in typing speed, both within words and in spacing. (The constant difference between interkey times for alternation and repetition within words necessarily produces proportionately larger deviations from uniformity with increases in speed.) The observation is not consistent with the notion of exact periodicity in movement timing. Indeed, Shaffer (1982) has suggested recently that there is little evidence that the control of typing movements is based on a strictly periodic timing mechanism.

The pattern of interkey times was also examined as a function of word length. In general, performance could be described by a nonmonotonic inverted U-shaped function in which interkey times were short in the interval from letter 1 to letter 2, lengthened over the next several letters to reach a maximum at about character position 4, and then decreased over the remainder of the word. The first part of this function, approximately to character 4, was similar in form at most word lengths (including length 4). (Some exceptions are discussed below.) The second part of the function, from the position of maximum interkey time onward, involved a progressive increase in speed, with the average interkey time at a given character position being somewhat greater for longer words. The sets of stimuli used in these studies were balanced with respect to hand movement, digraph frequency, and word frequency. Thus, the observed pattern of interkey times cannot be attributed to these factors. The pattern did not depend on whether the words were typed in sentences or alone, or whether the typist was to start immediately on presentation of the stimulus or after a delay. Instructions aimed at changing the strategy the subject adopts for typing did not alter the overall form of the interkey function.

The slowing of performance that was observed over the first four letters in a word may be a rise time effect associated with the initiation of a sequence. If so, it seems to be sufficiently basic to rapid seriation that it is not modifiable by instructions to induce strategy shifts. It should be noted, however, that the slowing was not observed for every subject, particularly at shorter word lengths. A tempting possibility was that faster subjects produced the monotonically decreasing interkey time functions whereas slower subjects showed the nonmonotonic pattern present in the averaged displays. An examination of the data was not consistent with this suggestion. For example, in the manipulation reported earlier in the section on word length, 6 of 15 subjects tested produced monotonically decreasing interkey times over successive character positions at word length 5. The average interkey time for this group was 190 msec, while the average for subjects who produced the more common nonmonotonic pattern was 197 msec. The slowest typist in the study was one of the subjects whose pattern was monotonic.

The divergence of interkey time functions beyond the position of slowest performance suggests an effect on organization at the level of sequence length. However, there is little evidence that this should be interpreted as organization at the level of words. West (1969), for example, found only a modest advantage in speed in typing words rather than high-frequency letter pairs and likewise showed that the advantage to words was unrelated to skill. Lexicality per se does not seem to be entirely responsible for interkey time effects either, since functions similar to those reported above have been obtained for both words and nonwords (Chapter 4, this volume; Ostry, 1980; Shaffer & Hardwick, 1970).

Manipulations of word length also indicate that certain sequence level aspects of control in typing occur after the initiation of the response. Even if an extended period is provided for response preparation, an initial increase in interkey times is observed, followed by a decrease whose rate varies with both sequence length and skill. The dependence on length and skill suggests that output timing reflects both the overall load and the efficiency of organization of movement after response initiation. The insensitivity of the pattern of interkey times to response delays and strategies suggests that the function depends on properties of a relatively rigid system that is activated at the initiation of movement.

Acknowledgments

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Reference Note

1. Ostry, D. J., & Munhall, K. G. *Syllabic influences on the timing of typing.* Unpublished manuscript, McGill University, 1981.

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