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ABSTRACT

Six skilled typists were studied while they transcribed English text. The typists showed stable patterns of performance, but with significant individual differences among themselves. Inter-keypress latencies for two-finger digraphs (typed by two fingers on the same hand) were particularly variable among typists. Two typists showed large differences in two-finger digraph latencies, but similar overall typing speeds. Finger movement trajectories, determined from analysis of videotapes of these typists, indicated that the differences in two-finger digraph latencies correspond to differences in the independence of within-hand finger movements. A high-speed film of one typist showed that finger movements of this typist almost always overlapped. The starting times of movements were six times as variable as the ending times, suggesting that it is the completion rather than the initiation of the movements that is controlled in skilled typing. These studies demonstrate the importance of considering individual differences in constructing a theory of skilled human performance, even in a highly automatized task such as transcription typing. (Author)

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SKILLED FINGER MOVEMENTS IN TYPING

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CENTER FOR HUMAN INFORMATION PROCESSING

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Skilled Finger Movements in Typing

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Abstract

Six skilled typists were studied while they transcribed English text. The typists showed stable patterns of performance, but with significant individual differences among the typists. Inter-keypress latencies for 2-finger digraphs (typed by two fingers on the same hand) were particularly variable among typists. Two typists showed large differences in 2-finger digraph latencies, but similar overall typing speeds. Finger movement trajectories, determined from analysis of videotapes of these typists, indicated that the differences in 2-finger digraph latencies correspond to differences in the independence of within-hand finger movements. A high-speed film of one typist showed that finger movements of this typist almost always overlapped. The starting times of movements were six times as variable as the ending times, suggesting that it is the completion rather than the initiation of the movements that is controlled in skilled typing. These studies demonstrate the importance of considering individual differences in constructing a theory of skilled human performance, even in a highly automatized task such as transcription typing.

Skilled Finger Movements in Typing

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Rapid, precise, malleable motor activity as demonstrated in speech and manual tasks is an important human characteristic. Because it is an extremely rapid skill and has a well defined output, typewriting has been the subject of speculation and some investigation (Lashley, 1959; Shaffer, 1973; Sternberg, Monsell, Knoll, & Wright, 1973; Terzuolo & Viviani, 1980). Typing has typically been thought of as a sequential, automatic process, and the corresponding models of performance involve a series of motor commands, often one for each letter, which are placed in a buffer and then sequentially executed. These models have been based primarily on records of the inter-keypress latencies (Sternberg et al., 1973; Shaffer, 1976).

This paper presents several studies of the transcription of normal English prose by expert typists. In addition to collecting inter-keypress latencies, high-speed film and videotapes were analyzed to determine the actual finger movements used by skilled typists.

Inter-Keypress Latencies

Although the keypresses of skilled typists are remarkably rapid and regular, there is still considerable variation in the inter-keypress latencies. The primary determinant of the inter-keypress latency for typing a given letter is the previously typed letter. This section examines the systematic variation in inter-keypress latencies as a function of the previous letter: the digraph latencies.

Eileen Conway assisted with the experimental studies and data analysis reported here. Jonathan Grudin collaborated in the high-speed film study and was a participant in many helpful discussions. The simulation model of typing was developed by David E. Rumelhart. I thank Donald A. Norman for his insightful comments on the manuscript.

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Method

Six professional typists transcribed normal English prose, typing on a high-quality electronic keyboard (Microswitch model 51SD12-4) with "tactile feel" and a keyboard layout identical to that of the normal IBM Selectric typewriter. All typists frequently typed on a Selectric typewriter. The typed letters were displayed on a CRT in front of the typist.

The text was adapted from a Reader's Digest article on diets (Bayrd, 1979); it will be referred to as the "diet text." The text was approximately 12,000 characters long and was presented as double-spaced, typewritten copy. After a 10 minute warmup with another text, the typists were asked to type the diet text at their normal, rapid rate, without correcting errors.

Keypresses and the corresponding times were recorded by a microcomputer. The typists' hands were videotaped during the experimental session. Analysis of the videotapes is reported later in this paper.

Digraph Latencies

The digraphs can be divided into three groups: 1-finger digraphs such as de, where two successive letters are typed by the same finger and there is no possibility of overlapping the movements to strike the first and second keys; 2-finger digraphs such as re, that involve movements by two fingers on the same hand; and 2-hand digraphs such as le, that involve movements on two different hands. Table 1 gives the median latencies of 1-finger, 2-finger, and 2-hand digraphs for the six typists. For every typist, 1-finger digraphs were typed slowest, 2-finger digraphs were intermediate, and 2-hand digraphs were typed fastest. As shown by the standard deviations in Table 1, latencies for 2-finger digraphs were most variable among typists. This finding is in accord with a study of individual differences in keystroke timing (Gaines, Lisowski, Press, & Shapiro, 1980) reporting that people were best differentiated by the digraphs in, io, no, on, and ul, all 2-finger digraphs. The typists also differ significantly when the latency for 2-finger digraphs is compared to the latencies for 1-finger and 2-hand digraphs. If the difference between 1-finger and 2-hand latencies is taken to represent 100% of the savings resulting from the possibility of overlapping movements, the percent of savings seen in the 2-finger latencies ranges from 28% for typist 3 and 30% for typist 5 to 90% for typist 1 and 97% for typist 6. Because typist 3 and typist 6 represent the extremes in the amount of savings for 2-finger digraphs but had similar overall typing rates (76 words/min for typist 3 and 82 words/min for typist 6), I will concentrate the remaining analysis on these two typists. On most measures, the other typists show intermediate performance.

Table 1

Letter-Letter Digraphs

Typist	Median Latency (msec) Overall	1-finger	2-finger	2-hand	Savings[a]
1	114	180	103	94	90%
2	160	225	176	132	52%
3	128	164	147	103	28%
4	135	167	132	115	67%
5	181	209	190	145	30%
6	129	176	119	117	97%
s.d.	24.7	24.6	33.5	18.6	

[a]savings = $\frac{\text{1-finger latency} - \text{2-finger latency}}{\text{1-finger latency} - \text{2-hand latency}}$

The differences in median latencies of the digraph types are reflected in the distributions of individual latencies. The distributions of digraph latencies for typist 3 and typist 6 are shown in Figures 1 and 2. For typist 3, the 2-finger digraphs were most similar to the 1-finger digraphs. Typist 6 shows a completely different pattern; the 2-finger digraphs were almost identical to 2-hand digraphs. Figure 3 presents a more detailed comparison of the 77 highest frequency digraphs for typists 3 and 6. Typist 3 was faster on 1-finger and 2-hand digraphs and typist 6 was faster on 2-finger digraphs.

Comparison with Simulation Model

Rumelhart and Norman (1981) have developed a computer model of a typist that simulates the finger movements during typing. In the simulation model several letters in the text and their corresponding fingers are simultaneously activated. Depending on the geometry of the keyboard and the physical constraints of the fingers and hands, the movement to type one letter may be aided or hindered by movements to type other letters. The inter-keypress latencies are determined by the resolution of these interactions. Figure 4 compares the digraph latencies produced by the simulation model with the average digraph latencies for all six typists. Although the correspondence between the simulation model and typists is fairly good (correlation coefficient = 0.78), a major discrepancy stands out. The typists have a wide range of latencies for 2-finger digraphs, but the simulation model types all 2-finger digraphs at essentially the same rate. The basis for this variation in digraph latencies on the part of our typists is not clear at this point, although the simulation results indicate that a simple competition between letters to be typed is not sufficient.

Comparison of Finger Movements for Typists 3 and 6

All six typists were faster when typing 2-hand digraphs than when typing 1-finger digraphs. Because there is no possibility of overlapping the successive keystrokes in 1-finger digraphs and because typists have been observed to overlap keystrokes with 2-hand digraphs (Olsen & Murray, 1976; Gentner, Grudin, & Conway, 1980), the shorter latency of 2-hand digraphs has been attributed to overlapped movements. This perspective suggests that the variation in relative latency of 2-finger digraphs could be caused by a variation in different typists' ability to overlap movements within a hand. To examine this hypothesis, I compared keystrokes of typists 3 and 6 for 2-finger digraphs with their keystrokes for 2-hand digraphs.

Method

While the typists were transcribing the diet text in the previous experiment, their finger movements were recorded on videotape using a Sony RSC 1050 Rotary Shutter Camera. A mirror mounted at the top of the keyboard at a 45-degree angle allowed simultaneous recording of two views of the typist's fingers (normal and parallel to the plane of the keyboard). The video fields, recorded every 16.7 msec, were serially

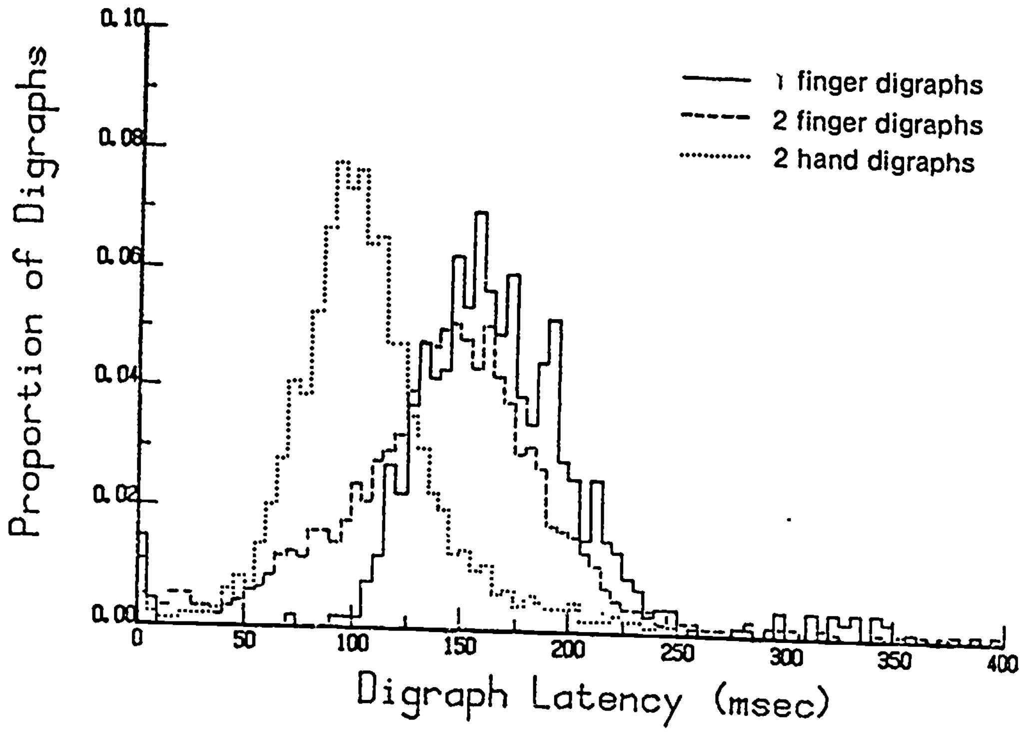

Figure 1. The distributions of all lower case letter-letter digraph latencies for typist 3. The latencies for 1-finger digraphs (n = 669, median = 164 msec) were generally longer than for 2-hand digraphs (n = 3926, median = 103). The latency distribution for 2-finger digraphs (n = 3029, median = 147) was most similar to that for 1-finger digraphs.

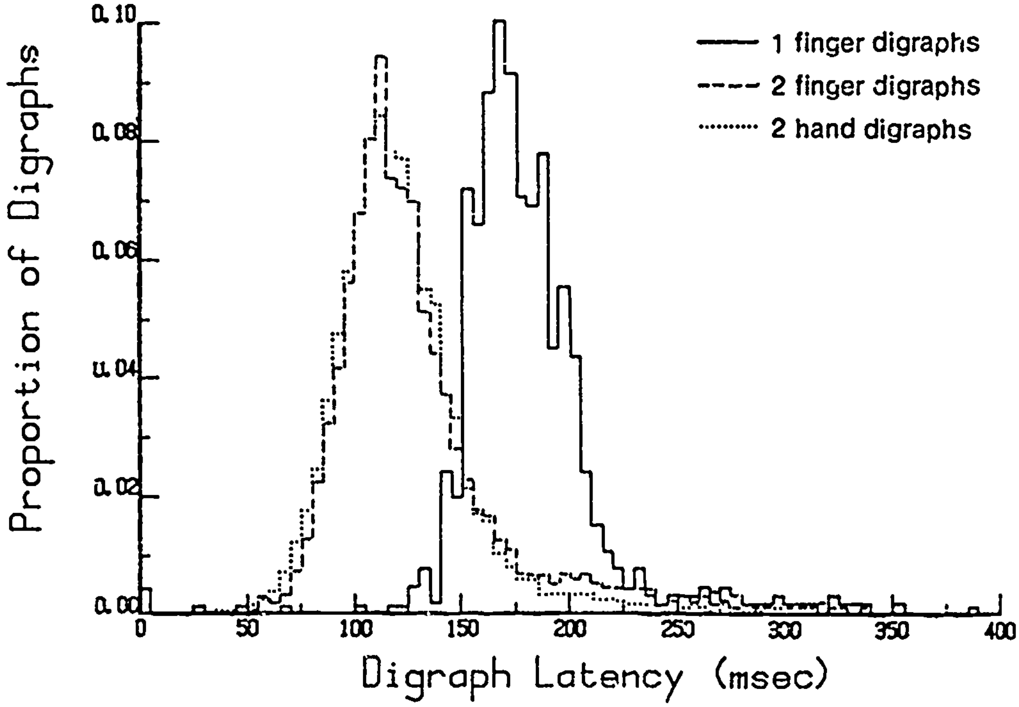

Figure 2. The distributions of all lower case letter-letter digraph latencies for typist 6. The latencies for 1-finger digraphs (n = 668, median = 176 msec) were generally longer than for 2-hand digraphs (n = 3875, median = 117). In contrast to typist 3, however, the latency distribution for 2-finger digraphs (n = 2960, median = 119) was almost identical to that for 2-hand digraphs.

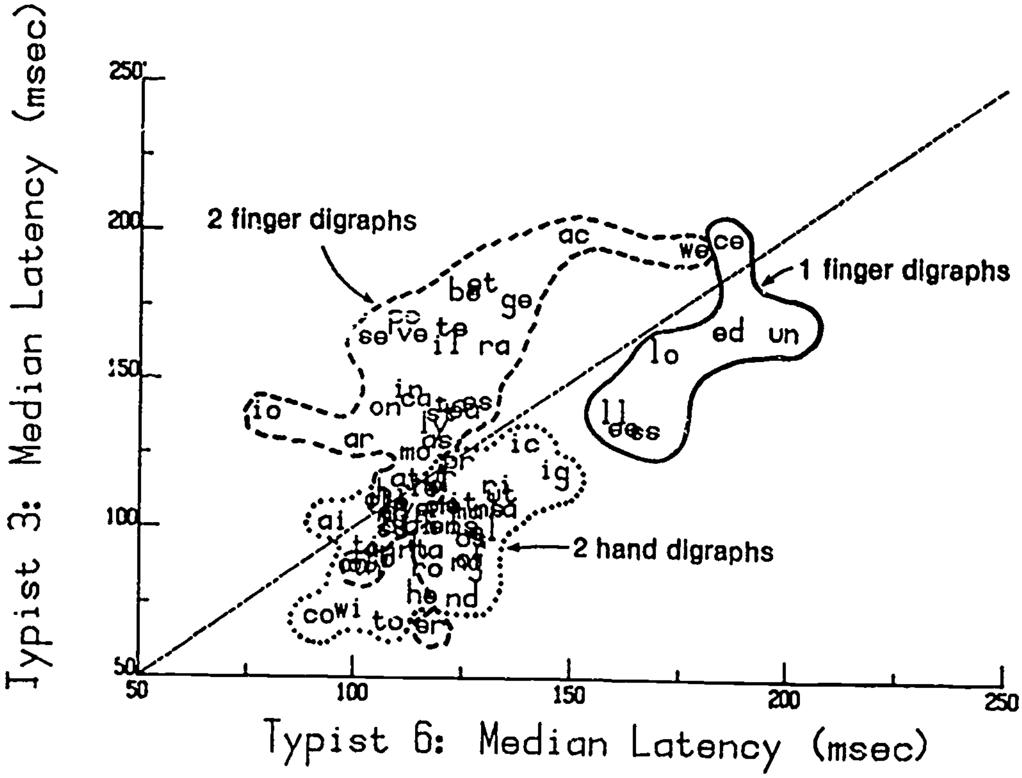

Figure 3. Comparison of the median latencies of the 77 highest frequency digraphs for typists 3 and 6. Digraphs plotted below the diagonal line were typed faster by typist 3, while those above the diagonal were typed faster by typist 6. Although typist 3 was faster with 1-finger and 2-hand digraphs, typist 6 was faster with 2-finger digraphs. Their overall typing rates were similar.

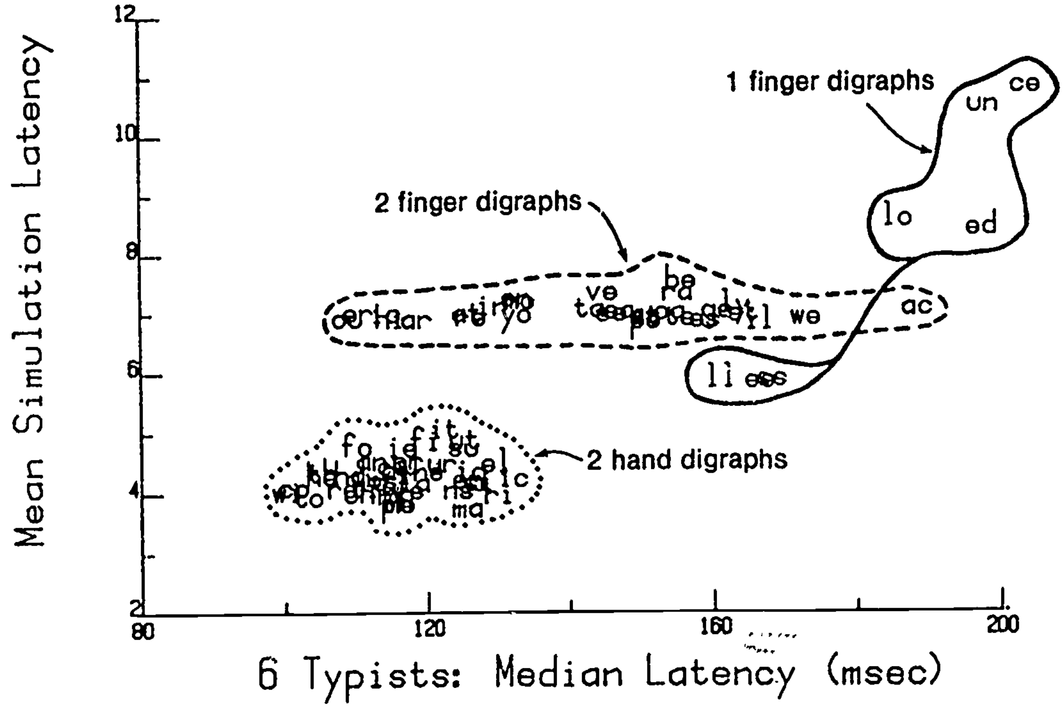

Figure 4. Comparison of digraph latencies produced by a computer simulation model of a typist and the average of the median digraph latencies of six skilled typists. The latencies for the simulation are plotted in arbitrary time units.

numbered with an electronic video counter enabling them to be individually analyzed, field-by-field, with a Sony SVM 1010 Video Motion Analyzer. Finger coordinates were digitized from a video monitor with the aid of a light pen. These coordinates were used to calculate the successive positions of the fingertip in 3-dimensional space.

Four digraphs were selected for detailed analysis. Examples were chosen to contrast 2-finger and 2-hand digraphs in identical contexts. For example, the finger trajectories while typing in in things (a 2-finger digraph) were compared with the trajectories while typing en in calisthenics (a 2-hand digraph). The observed latencies for the examples chosen were within seven msec of the median latency for that digraph and typist.

Finger Trajectories

Table 2 summarizes the results of the videotape analysis comparing the digraphs en and in. Note that the finger of typist 3 traveled further than the finger of typist 6 between the time the e and n were struck, but this was more than compensated for by the higher speed of typist 3. The difference in path lengths was even greater with the digraph in, but the ratio of speeds did not change and the net effect is that typist 3 had a longer latency than typist 6 for the 2-finger digraph.

Typical trajectories are shown in Figure 5 for the sequences hen and hin. The critical difference between the two typists was in the independence of their finger movements. Consider the two sequences hen and hin. The h and n are both typed with the right index finger (h is on the home row, n is on the bottom row); e is typed by the left hand; i is typed by the right middle finger on the top row. When typing hen both typists struck the h on the home row with their right index finger and then moved that same finger down to the lower row to type the n while the e was being struck by the other hand. When typist 3 typed hin, however, the right index finger moved up towards the top row along with the right middle finger, while the middle finger struck the i key. Typist 6 was quite different, in that the index finger hardly moved while the middle finger pressed the i on the top row. This contrast was observed in all cases of en and in digraphs that were analyzed. Thus typist 3 coupled the finger movements within a hand, whereas typist 6 kept them relatively independent.

On the basis of this analysis one would expect that typist 3 would not be at a disadvantage when typing 2-finger digraphs such as te, in which both letters occur on the same row. Table 3 compares the trajectories of the left middle finger while typing the digraphs le and te. The major factor related to the longer latencies of typist 3 when typing te was the slow speed of the index finger (45 cm/sec with le versus 70 cm/sec with te). This somewhat puzzling result becomes clear upon examining the typical trajectories shown in Figure 6, which compares the trajectories of the left middle finger while typing the sequences roble and e te.

Table 2

Comparison of typical typings of en and in

Context	Typist 3			Typist 6			
	Latency (msec)	Path Length (cm)	Average Speed (cm/sec)	Latency (msec)	Path Length (cm)	Average Speed (cm/sec)	Path Length Ratio
Interval between striking e and n							
calisthenics	106	5.4	51	117	4.1	35	1.3
arguments	96	4.9	51	124	3.4	28	1.4
most beneficial	98	3.9	40	116	2.1	18	1.8
deterrent	108	4.4	41	121	2.5	20	1.8
your entire	101	4.4	44	121	2.8	23	1.6
Average	102	4.6	45	120	3.0	25	1.6
Overall[a]	102			121			
Interval between striking i and n							
thing	145	6.5	45	109	3.3	30	2.0
things	146	6.6	45	107	3.4	32	1.9
lengthening	148	8.4	57	112	2.7	24	3.1
taking	146	7.5	52	110	3.7	34	2.0
contains	149	9.3	62	113	3.7	33	2.5
but inefficient	152	7.9	52	116	3.4	29	2.3
Average	148	7.7	52	111	3.4	30	2.3
Overall[a]	148			112			

[a]Median latency for this digraph for entire session.

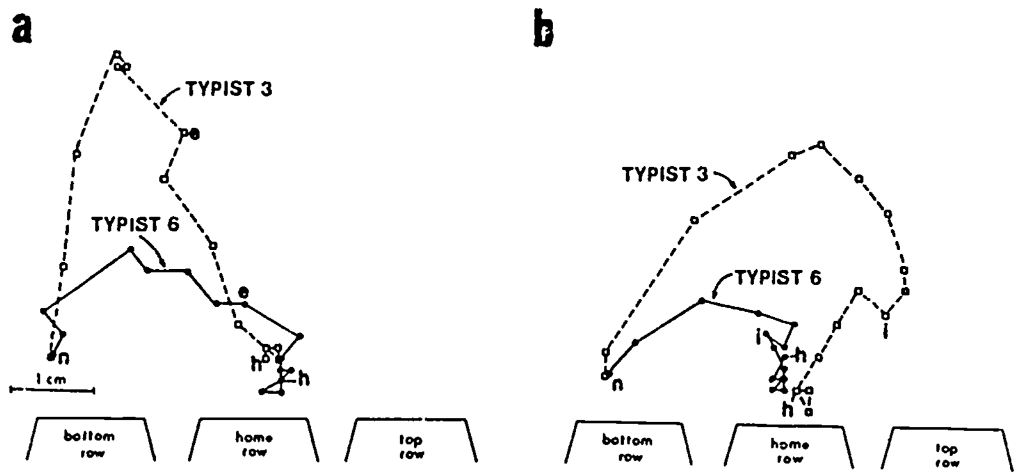

Figure 5. Trajectories of the right index fingertip while typing hen (a) in the word calisthenics and hin (b) in the word things. The successive points along the paths are 16.7 msec apart. The letters next to some points indicate when the corresponding key was pressed. In the sequence hen, the right index finger presses the h on the home row and then moves down to press the n on the bottom while the e is typed by the left hand. Although typist 3's fingertip traveled a longer path, its speed was greater and the latency for the 2-hand digraph en was shorter than for typist 6. When typist 3 typed hin, however, the right index finger moved up toward the top row along with the right middle finger, while the middle finger struck the i key. Typist 6 was quite different, in that the index finger hardly moved while the middle finger pressed the i on the top row. For typist 3, the coupled movements of the fingers on the left hand resulted in a much longer path length which was not fully compensated for by typist 3's higher finger speed. Thus typist 3 had a longer latency than typist 6 for the 2-finger digraph in.

Table 3

Comparison of typical typings of le and te

Context	Typist 3 Latency (msec)	Typist 3 Path Length (cm)	Typist 3 Average Speed (cm/sec)	Typist 6 Latency (msec)	Typist 6 Path Length (cm)	Typist 6 Average Speed (cm/sec)	Path Length Ratio
Interval between striking l and e							
clearly	116	9.5	82	102	4.2	41	2.3
vegetables	112	7.4	66	113	3.2	28	2.3
detailed	109	6.1	56	116	2.5	22	2.4
problems.	106	9.6	91	111	1.5	13	6.4
motionless	110	6.3	57	110	2.6	24	2.4
Average	111	7.8	70	110	2.8	26	3.2
Overall[a]	110			109			
Interval between striking t and e							
counter,	170	8.9	53	122	3.0	24	3.0
the tempting	165	6.6	40	117	2.5	22	2.6
plate,	164	6.6	40	124	2.3	19	2.9
plate.	171	8.0	47	118	2.0	17	4.0
weight steadily	171	7.3	43	121	2.2	18	3.3
Average	164	7.5	45	120	2.4	19	3.2
Overall[a]	169			122			

[a] Median latency for this digraph for entire session.

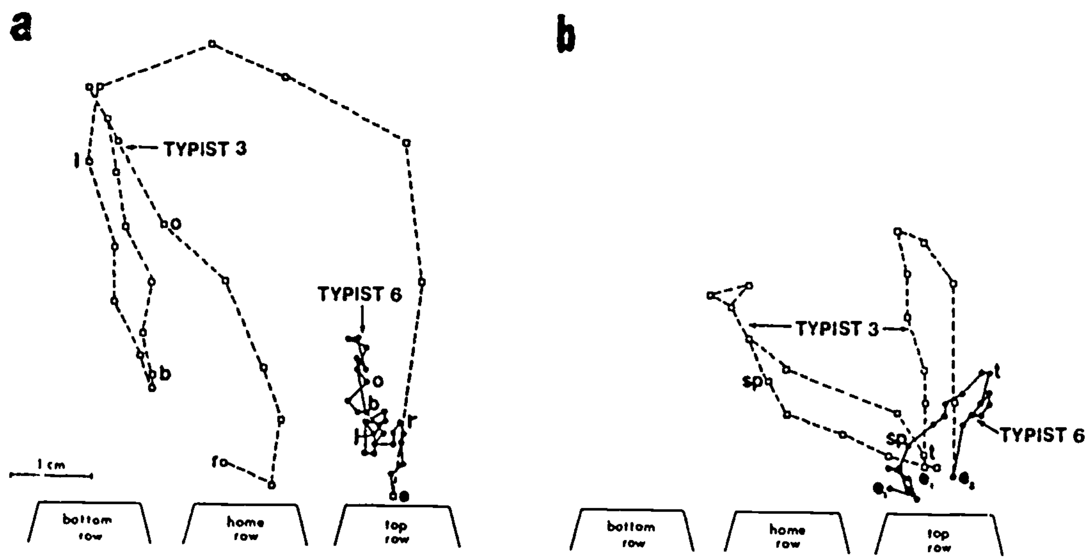

Figure 6. Trajectories of the left middle fingertip while typing roble (a) in the word problems and e te (b) in the words the tempting. The successive points along the paths are 16.7 msec apart. The letters next to some points indicate when the corresponding key was pressed. As in Figure 5, the striking difference was that typist 3's finger movements within a hand were strongly coupled, but typist 6's movements were not. Typist 3's middle finger made large vertical and horizontal movements as the r, b, and t keys were struck by the index finger. Although typist 3's middle finger moved to the bottom row while b was typed, it was moving back to the top row at full speed while l was typed by the right hand and the le latency was similar to that for typist 6. In the sequence e te, however, typist 3's middle finger moved down and up as the index finger struck the t and the much longer path length led to a longer latency for the 2-finger digraph te than for typist 6.

In the sequence roble the left index finger typed the r on the top row, the b on the bottom row, and finally the e is typed on the top row by the left middle finger. The o and l are typed by the right hand. Note that typist 3's left middle finger moved in conjunction with the movements of the index finger on the left hand, moving all the way to the bottom row when the index finger typed the b. The le latency was still short, however, since the middle finger was already moving rapidly towards the e key while the l was being typed by the other hand. The performance of typist 6 provides a striking contrast: the middle finger never left the top row while the b was typed.

Although typist 3 did not suffer a latency penalty from the lack of independent movement while typing le, that was not the case for the 2-finger digraph te. In the sequence e te the left middle finger types the e on the top row, the space bar is pressed by the right thumb, then the left index finger types the t on the top row, and finally the left middle finger types the second e. Notice in Figure 6 how typist 3's middle finger moved down to the keyboard as the t was struck by the left index finger. The middle finger then moved up before moving down again to strike the e. In contrast, the middle finger of typist 6 was poised at the top of its arc as the t was struck, and only a short movement was required to strike the e (2.5 cm for typist 6 versus 6.6 cm for typist 3).

It should be noted that typist 3 was faster than typist 6 for some 2-finger digraphs that occur on the same row, such as er and ou. In those cases, typist 3 combined the two keystrokes effectively and typed the two letters with a rolling motion of the hand.

Relative Amounts of Hand and Finger Movement

An important correlate of the observed differences between typists 3 and 6 was their different proportions of hand and finger movement in typing. The quantitative measures of finger movement reported above describe the movement of the fingertip relative to the keyboard. This movement can be decomposed into a movement of the hand relative to the keyboard and a movement of the fingertip relative to the hand. Comparing the movements in this way for the sequence hin in the word things showed significant differences between the two typists. For these measurements, the hand position was measured at the point where the right index finger joins the palm (the metacarpophalangeal joint). The position of the fingertip was then measured relative to that point on the hand.

When typist 3 typed the sequence hin, the ratio of finger movement to hand movement was 1.2. The corresponding ratio for typist 6 was 1.8. This contrast was even more striking if we examine the component of the movement in the Y direction (parallel to the keyboard, toward the top or bottom row). Here the ratio of typist 3's hand to finger movement was 1.0, while the ratio for typist 6 was 2.9.

Starting and Ending Times of Finger Movements

For a more detailed examination of the typing process, Grudin, Conway, and I made a high speed motion picture of typist 6 (see Gentner et al., 1980 for a more detailed presentation). The film has the advantage of greater temporal and spatial resolution than video. The emphasis in this analysis is on when each finger starts its movements.

Method

The data reported here are based on a high-speed (100 frames per second) 16mm film of typist 6. The typist transcribed English sentences on the typewriter-like keyboard of a Hazeltine 1500 computer terminal at approximately 90 words/minute. A mirror placed at an angle at the top of the keyboard allowed a second view of the hands to be recorded simultaneously. During the filming, the keypresses and inter-keypress latencies were recorded by the computer.

The film covers 310 keystrokes (about 40 seconds of typing). Because we were primarily interested in the possibility of overlapping keystrokes, this analysis does not include keystrokes where successive keys were typed by the same finger, since the finger movements were necessarily sequential; in addition, the initiation of a movement toward a home row key is ambiguous, as it may simply be a return of the finger to a home position. Therefore, the analysis was restricted to the 147 keystrokes for letters on the upper or lower rows of the keyboard, where the previous keystroke was not made by the same finger.

For each of these keystrokes, the starting and ending times of the keystroke were determined. The time of the keypress, as recorded by the computer, was taken as the ending time of the movement. To determine the starting time of the keystroke, two judges viewed the film frame-by-frame on a film editor. The starting time of the keystroke was determined as the time when the finger started a smooth movement toward the key that terminated in the keypress. In almost all cases, the judges were able to agree on the starting time of the finger movement. When there was disagreement, the later starting time was used. In two cases, the finger moved toward the key, paused, and then struck the key; the initial starting times were used in these cases. The determination of starting times was greatly aided by the mirror which provided a second view of the fingers in the same frame. This study was actually completed before the videotape study of all six typists reported earlier in this paper. In retrospect it seems that the small hand movements and relatively large independent finger movements of typist 6 made the determination of finger starting times much easier than it would have been for the other typists.

Overlapped Finger Movements

Of the cases studied (keypresses on the upper or lower rows when overlapped movements were possible), 96% of the finger movements were initiated before the previous key was pressed. The mean time for a complete finger movement was 261 msec, while the mean inter-keypress latency was 124 msec. Thus two or three fingers were often in motion simultaneously. Overlapped movements were frequent for both 2-hand digraphs (97% of the time) and 2-finger digraphs (91% of the time). Based on the studies of other typists reported earlier in this paper, however, typist 6 may represent an extreme in ability to overlap within-hand movements.

Variability of Starting and Ending Times

If the starting time and ending time of a keystroke are measured relative to the end of the previous keystroke (the keypress), the variability of the starting and ending times can be determined. The starting times of finger movements (standard deviation = 103 msec) were more variable than the ending times (standard deviation = 26 msec). This difference in variability remains even if the context provided by the neighboring letters is controlled. The film included two sentences which were typed twice. Comparing corresponding letters in the repeated sentences, the average difference in starting times was 78 msec, but the average difference in ending times was only 16 msec.

Figure 7 shows the timing of keystrokes for two typings of the phrase an epic. Contrast the irregularity of the initiations of finger movements with the regularity of the keypresses. Also note that keystrokes were sometimes initiated in an order different from the final keypresses. Overall, of the 103 cases where starting times had been determined for successive keystrokes, 21% of the movements were initiated out of order (although the movements always ended with keypresses in the correct order). This happened for sequences of letters occurring both across hands (24% of the time) and within hands (13% of the time). There were several cases where the finger movements were initiated out of order by 150 msec or more. One case of out-of-order initiation, shown in the top portion of Figure 7, extended over two words: in the sequence an epic, the movement to type the e was initiated before the movement to type the n.

Overall, comparing corresponding letters in the repeated sentences, earlier starting times for a movement were not correlated with shorter inter-keypress latencies ($r = 0.05$). An analysis of corresponding keystrokes in the repeated sentences showed that there can be significant variation in the finger's position at the start of the keystroke. In particular, keystrokes that start with the finger closer to the target key were initiated later than keystrokes starting farther away.

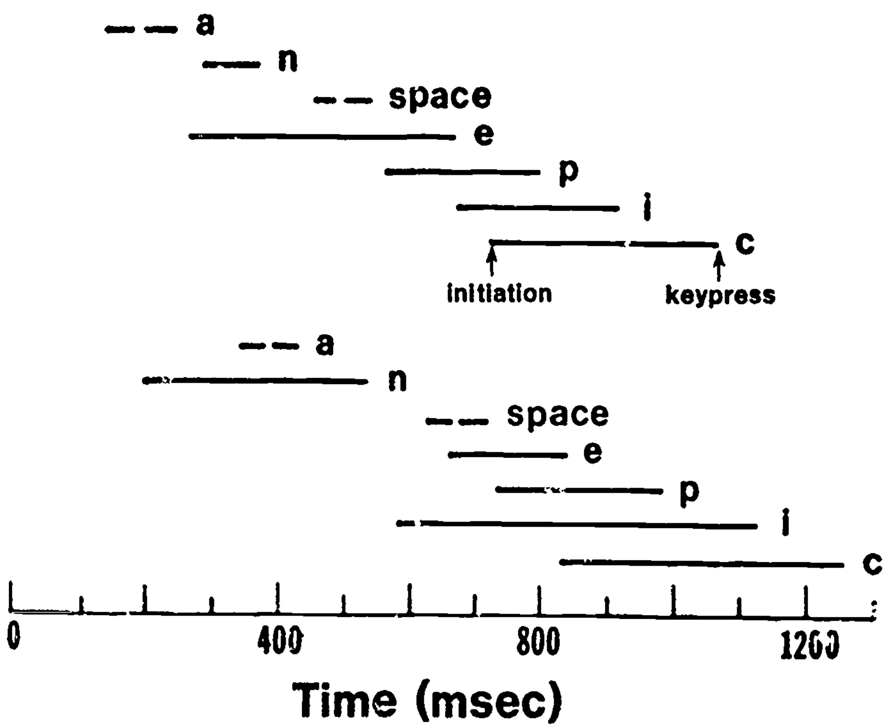

Figure 7. Relative timing of keystrokes for the phrase "... an epic tal lines represent the initiation time of the keystrokes, and the right ends of the lines represent the time of the keypresses. Initiation times were not measured for the letter a and the space bar; this is indicated by the dashed lines to the left of the keypress times. Note that successive keypresses were more regularly timed than the corresponding initiations. In two cases, although the keys were pressed in the proper order, the keystrokes were initiated out of order: in the first sentence the e keystroke was initiated before that of n in the previous word; in the second sentence the keystrokes for the word epic were initiated in the order i, e, p, c. (From Gentner, Grudin, & Conway, 1980.)

Summary

The inter-keypress latencies of skilled typists when transcribing normal prose were dependent on the digraphs being typed. In general, 1-finger digraphs (such as de, typed by a single finger) were slowest, 2-finger digraphs (such as fe, typed by two fingers on the same hand) were intermediate, and 2-hand digraphs (such as le, typed by fingers on different hands) were fastest. The latencies for 2-finger digraphs were the most variable among typists. For some typists they were like the rapid 2-hand digraphs; for other typists they were like the slow 1-finger digraphs; for the remaining typists, 2-finger digraphs were intermediate in speed. These differences were not always related to overall typing speed. Typists 3 and 6 had the slowest and fastest relative latencies for 2-finger digraphs, but similar overall typing rates.

Analysis of videotapes showed that typist 3 had longer movement trajectories than typist 6, but more than compensated for the longer path by higher finger velocities. When typing 2-finger digraphs, however, typist 3 tended to move all the fingers of a hand in concert, whereas typist 6's fingers moved independently. These independent within-hand movements of typist 6 were associated with shorter latencies for 2-finger digraphs.

Typist 6's finger movements were studied further in a high speed film. Finger movements for successive keypresses overlapped in 96% of the cases where overlap was possible. The timing of the keypresses (the end of the movement) was more regular than the starting times of finger movements, suggesting that the completion of the movement is being controlled rather than its initiation. This was true even when the context was controlled by repeated typing of the same sentence.

These results are in general accord with a computer simulation model of a typist based on distributed control and an interactive relaxation mechanism. To a first approximation, inter-keypress latencies in typing appear to be determined by the geometry of the keyboard and the physical constraints of the hands. There are important individual differences, however, which are not accounted for by these general factors.

There is more than one way to be a skilled typist. Skilled typists show patterns of behavior which were consistent across context and across time, but there were significant differences among typists. Studies of cognitive and motor skills which average across subjects run the risk of obscuring important features of performance.

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