Effects of Age and Skill in Typing

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What are the factors responsible for skilled typing performance, and do they change with the age of the typist? These questions were addressed in two studies by examining time and accuracy of keystrokes in a variety of typinglike activities among typists ranging in speed from 17 to 104 net words per minute and ranging in age from 19 to 72 years old. Typing skill was related to (a) the temporal consistency of making the same keystroke, (b) the efficiency of overlapping successive keystrokes, (c) the speed of alternate-hand tapping, and (d) the number of characters of to-be-typed text required to maintain a normal rate of typing. Older typists were slower in tapping rate and in choice reaction time but were not slower in speed of typing, apparently because they were more sensitive to characters farther in advance of the currently typed character than young typists.

Although there has been considerable research on typing processes, only a small fraction has addressed the question of what skilled typists are doing that less skilled ones are not. The present article focuses on determinants of typing skill by examining correlates of typing proficiency in typists whose net rates (subtracting five characters for each error) ranged from 17 to 104 words per minute (wpm). Variables included in the analysis were selected on the basis of results from earlier studies investigating basic typing phenomena.

Skill Effects

One of the most dramatic findings from previous research is that the speed of typing is markedly slowed by reducing the number of characters visible in the to-be-typed material. Coover (1923) was apparently the first to report this effect, and it has subsequently been confirmed by Hershman and Hillix (1965), Shaffer (1973, 1976), Shaffer and French (1971), and Shaffer and Hardwick (1970). Shaffer's (1976) results with a single skilled typist are typical. The median interkey interval was 101 ms (approximately 118 gross wpm) for typing with unlimited preview and for typing with 8 characters visible to the right of the to-be-typed character, but was 446 ms (approximately 27 gross wpm) with only 1 character visible prior to each keystroke. Clearly, proficient typing is dependent on the ability to view characters in advance of the one currently being typed. Butsch (1932) and Fuller (1943) reached this same conclusion in an analysis of eye movements recorded while subjects were typing. Butsch (1932) also demonstrated that the span between the character being typed and the character currently being fixated was positively related to typing skill. On the average, typists performing at a rate of 40 wpm had an eye–hand span of 3.96 characters, while 70-wpm typists had an eye–hand span of 5.93 characters. Across 19 typists with typing speeds from 35 to 100 wpm, the correlation between eye–hand span and typing rate was +.68.

The preceding results, particularly those of Butsch (1932), suggest that one determinant of skilled typing is the ability to process characters in advance of the character whose key is currently being pressed. I examined this possibility by manipulating the number of

characters visible in the to-be-typed material and by defining the eye–hand span as the minimum preview window at which typing rate first differs from that of normal typing with unlimited preview. If rate of typing is disrupted, one can infer that the typist normally relies on the viewing of more than the presented number of characters; therefore, the preview at which typing rate is disrupted can serve as an estimate of eye–hand span in normal typing. It is worth noting that the present method probably produces an underestimate of the actual eye–hand span in that the disruption is evident only after the normal span is prevented.

Another well-documented finding is that familiar, meaningful material is typed faster than unfamiliar, nonsense material (e.g., Fendrick, 1937; Hershman & Hillix, 1965; Larochelle, 1983; Olsen & Murray, 1976; Shaffer, 1973, 1976; Shaffer & Hardwick, 1968, 1969a, 1970; Terzuolo & Viviani, 1980; Thomas & Jones, 1970; West & Sabban, 1982). The redundancy of familiar text evidently allows predictable sequences of characters (keystrokes) to be primed in some fashion, thereby facilitating their speed of execution. If a mechanism such as this is responsible for the meaningfulness effect, one may expect typing skill to be related to sensitivity to linguistic redundancy. In other words, fast typists may be fast in part because they are better able to predict and behave appropriately in response to lengthy sequences of characters. I examined this hypothesis by contrasting typing performance on normal text and on text in which the order of characters had been reversed in a letter-by-letter fashion. The reversal preserves the letter frequencies, punctuation, capitalization, and letter groupings of natural language while destroying its meaningfulness. A second manipulation of material meaningfulness was carried out in Study 2 by requiring subjects to type a continuous series of random letters. Although this material shared few structural properties with normal text, it provided a greater range of letter digram frequencies than was otherwise available.

A result obvious even by casual observation is that all keystrokes are not executed at the same rate. In order to achieve the high rates characteristic of skilled typing, fast typists may be more consistent in their keying speed than

less competent typists may be (Gentner, 1982a; Long, Nimmo-Smith, & Whitefield, 1983), having somehow managed to reduce the time of what are initially slow keystrokes to nearly the rate of the fastest keystrokes. (Interestingly, however, Harding, 1933, suggested just the opposite and claimed that faster typists exhibit more extreme variation among keystrokes than slower typists.)

There are actually two distinct classes of typing variability (Gentner, 1982a, 1982b), interkeystroke and intrakeystroke, and two plausible sources of the variability, mechanical and experiential. Interkeystroke variability can be easily assessed by means of the interquartile range encompassing the middle 50% of the intervals across all keystrokes. However, in order to determine the consistency of typing the same character, the context in which the character appears should be constant across character repetitions. This was achieved by requiring subjects to type the same sentence 10 times, and then by determining the interquartile range of interkey intervals across the 10 repetitions of the same character. The median of these interquartile ranges across all characters thus served as the measure of intrakeystroke variability.

Mechanical sources of interkeystroke variability include physical constraints such as keyboard location, finger dexterity, and repetition or alternation of finger and hand. For example, Coover (1923), Fox and Stansfield (1964), Gentner (1981, 1982a), Grudin and Larochelle (1982), Kinkead (1975), Lahy (1924), Larochelle (1983), Ostry (1983), Rumelhart and Norman (1982), Shaffer (1976, 1978), and Terzuolo and Viviani (1980) all demonstrated that the interkey interval is about 30–60 ms shorter when the two keystrokes come from opposite hands rather than from the same hand. Kinkead (1975) conducted one of the most complete analyses and reported that keys struck with alternate hands averaged 136 ms; those with the same hand, 168 ms; and those with the same finger, 218 ms. These mechanical factors may extend over sequences of three or more characters (Gentner, 1982b; Gentner, Grudin, & Conway, 1980; Rumelhart & Norman, 1982; Shaffer, 1978), and therefore physical constraints could be an important source of variability in interkeystroke timing. The difference between digrams

typed with alternate hands and with the same finger is the largest mechanical factor evident in previous studies; thus, skill effects were primarily examined on this variable.

Experiential factors refer to alterations in keying efficiency produced by differential amounts of experience typing specific character sequences. Perhaps the best illustration of this type of influence is the negative relation between interkey interval and frequency of the letter digrams in written language (e.g., Dvorak, Merrick, Dealey, & Ford, 1936; Grudin & Larochelle, 1982; Shaffer & Hardwick, 1969b; 1970; Terzuolo & Viviani, 1980). Because the transition time between two keystrokes is inversely related to the frequency of occurrence of the two-letter sequence, it is likely that at least some of the variability across keystrokes is attributable to frequency effects of this type. I investigated skill effects by computing the slope of the function relating digram frequency to interkey interval and then determining whether typing skill is related to the slope parameter, that is, whether faster typists exhibit differential amounts of timing shifts across digrams of varying frequencies than do slower typists.

A second experiential factor that may account for some of the interkeystroke variability is what may be called the *word initiation effect*. If words are stored in memory as integral units, one may expect the latency of the first keystroke in the word to reflect the time required to retrieve the word from memory. Because the magnitude of the word initiation effect may be related to typing skill (Ostry, 1980, 1983), I examined the ratio of the intervals of first keystrokes to all keystrokes in a word for typists of varying levels of skill.

Several investigators also reported that the length of the word being typed is positively related to the latency of either the first or of all keystrokes in the word (e.g., Larochelle, 1983; Ostry, 1980; Shaffer & French, 1971; Shaffer & Hardwick, 1968, 1969b, 1970; Sternberg, Monsell, Knoll, & Wright, 1978). I therefore examined the slope of the function relating typing interval to number of characters in words of different lengths in both initial latencies and median interkey intervals.

In addition, I included a number of other variables in the hope that they might contribute to the differentiation of typists of varying

skill levels. Among these were assessments of the type and the frequency of errors, and the level of comprehension of the typed material. Because it is possible that typists of varying skill levels exhibit different patterns in the types of errors committed, I contrasted the frequencies of four categories of errors: substitutions, omissions, intrusions, and transpositions. It has also been reported that competent typists detect their error responses immediately, as reflected either in weaker keystrokes on errors (e.g., Rabbitt, 1978; Wells, 1916) or in delayed posterror responses (e.g., Shaffer, 1973, 1975, 1976), and it is conceivable that typing skill is correlated with the ability to accurately monitor finger movements and to immediately detect keying errors (Shaffer & Hardwick, 1969a; West, 1967). Because the delay of posterror responses can be considered a manifestation of error detection, I therefore used the proportion of keystrokes immediately following an error that are slower than the median for all keystrokes as an index of error detectability.

Comprehension of the material being typed was assessed to determine whether some of the efficiency of skilled typists is due to their superior comprehension of the material, thereby allowing potentially greater predictability of forthcoming character sequences. This reasoning is an extension of the argument applied to explain the advantage of typing meaningful material compared with nonsense material—if the mere presence of predictable material is beneficial, then reading and comprehension of the passage should be even more helpful in developing expectations about the content of subsequent material. Because subjects are likely to exhibit considerable variability in comprehension even while merely reading, comprehension was assessed both after typing and after normal reading, with the difference between the two serving as the index of relative typing comprehension.

It should be emphasized that the present analyses do not always provide "pure" assessments of the contribution of each factor. For example, word length is likely to be confounded with word frequency and possibly with digram frequency; digram frequency may be correlated with finger or hand alternation; and so forth. Such confoundings are generally unavoidable when using natural material, and

for the present studies, the advantages of such material far outweigh the disadvantages. In the current studies, the primary focus is on individual differences associated with skill and age. Therefore, because all typists received similar kinds of material, the values across individuals can be compared, even if they are not precise with respect to the absolute contribution of each factor considered in isolation.

Age Effects

A second major goal of the present study was to investigate the effects of adult age on the mechanisms affecting typing skill. The numerous age-related declines in many aspects of cognitive functioning (see Salthouse, 1982a, for a review), and the general tendency for most behavioral activities to become slower with increased age (e.g., Salthouse, in press) lead to the expectation that the rate of typing also should slow down with increased age. In fact, if one extrapolates from the choice reaction time (RT) findings that adults in their 60s require about 100 ms more time per keystroke response than adults in their 20s, typists in their 60s may be expected to type at a rate of only 40 wpm compared with 60 wpm for typists in their 20s. Or expressed differently, 4 hr of continuous typing at a rate of 60 wpm and 5 keystrokes per word yields 72,000 total keystrokes, which at 100 ms extra per keystroke may require the older typist an additional 2 hr to complete. It seems unlikely that differences of this magnitude exist among typists of varying ages, and yet the reasons for this apparent discrepancy from laboratory findings are still not well understood.

One problem with the preceding argument is that typing is much faster than choice RT, and therefore it cannot be based on exactly the same set of processes. Nevertheless, there is considerable agreement among gerontological researchers that many, and perhaps all, perceptual and cognitive processes exhibit age-related declines in speed. Among the processes that appear most relevant to typing, correlations between adult age and rate of performance of +.22 to +.52 have been reported in choice RT tasks (e.g., Borkan & Norris, 1980; Clark, 1960; Dirken, 1972; Jalavisto, 1965; also see Salthouse, in press, for a summary of

other similar studies); correlations of +.18 to +.44, in tapping tasks (e.g., Borkan & Norris, 1980; Dirken, 1972; Furukawa et al., 1975; Jalavisto, 1965); and correlations of .42 to .53, in other visual–manual transcription tasks such as the digit–symbol substitution task (see Salthouse, 1982b, for a review). Several studies have reported that one or more of these measures is related to speed of typing (e.g., Ackerson, 1926; Book, 1924; Cleaver & O'Connor, 1982; Flanagan & Fivars, 1964; Flanagan, Fivars, & Tuska, 1959; Hayes, 1978; Hayes, Wilson, & Schafer, 1977; Leonard & Carpenter, 1964; Muscio & Sowton, 1923; Tuttle, 1923), although there are some contradictory results (e.g., Hansen, 1922). The RT analogy, therefore, still seems relevant, even though the quantitative estimates should not be taken too seriously.

Several years ago, Rabbitt (1977) posed a question with important implications both for the domain of skill and for the applicability of laboratory findings in aging to "real-world" tasks. His question was the following:

In view of the deterioration of memory and perceptual-motor performance with advancing age, the right kind of question may well be not "why are old people so bad at cognitive tasks," but rather, "how, in spite of growing disabilities, do old people preserve such relatively good performance?" (p. 623)

A research strategy introduced by Charness (1981a, 1981b, 1981c) in his studies of the relation between age and components of chess skill represents one approach to answering Rabbitt's question. This strategy can be termed the molar equivalence–molecular decomposition procedure in that it involves the following two steps. First, a sample of individuals is obtained that varies widely on both the skill and age dimensions, but in which the overall correlation between age and skill (molar behavior) is near zero. Next, the effects of age and skill are independently determined in a number of component (molecular) processes thought to be important in developing or maintaining skilled performance.

This strategy of equating age groups on molar performance and then investigating the effects of age on molecular processes is not designed to address the basic issue of whether there are age relations in the overall population in proficiency of the global activity. This nor-

mative question is always difficult to answer with small samples, and it is even more complicated with real-life activities because of the problem of differential representativeness of members in various age groups owing to "selective survival" of the best-performing individuals in successive age groups.

However, an interesting issue that can be investigated with the molar equivalence–molecular decomposition research strategy is to determine whether age trends similar to those often reported in laboratory studies are evident in the efficiency of (molecular) component processes, despite the equivalence of global (molar) achievement across age groups. Two distinct types of age trends in the component processes are possible. First, the component processes may exhibit age declines typical of those found in many laboratory studies of basic processes, implying that special mechanisms of compensation have been developed for preserving overall performance. This type of outcome would lead to questions about the specific nature of the compensatory mechanisms.

A second possibility is that the years or decades of performance of the molar activity along with its component processes have maintained the efficiency of processes that would have otherwise deteriorated. The potential magnitude of the practice effect with activities that are performed daily is difficult to overestimate, as indicated by a contrast with a recent laboratory experiment. Salthouse and Somberg (1982) had groups of young and old adults perform a variety of perceptual–motor tasks for what seemed to be a long period: 50 hr over approximately 10 weeks. Although performance increased with practice in both groups on all measures that were examined, age differences remained throughout all stages of practice. But now consider the amount of experience that a typist may be expected to receive in the course of normal employment. Fifty hours of typing performance could be completed in less than 2 weeks. The contrast of individual keystrokes is even more dramatic. Subjects in the Salthouse and Somberg (1982) study received 5,000 choice RT trials over the 50 experimental sessions, but a 60-wpm typist would execute that many keystrokes in about 17 min! A rough estimate of the number of keystrokes executed in a year of typing 30 hr

per week is 2.7 million. Because increased age is generally positively correlated with increased experience, it is reasonable to expect that if practice can ever prevent the age-related deterioration of perceptual–motor or cognitive efficiency, then effects of such practice would be evident in the components of typing.

The numerous measures included in the present study also provide an ideal environment for investigating the nature of any compensatory mechanisms employed by older typists. Because typists ranged from 19 to 72 years of age, both age and skill level could be considered independent variables in the analyses. Three tests of perceptual–motor efficiency—choice RT, tapping rate, and rate of digit–symbol substitution—were included to investigate the question of maintained or declining component processes, and also to reexamine the relation between these variables and rate of typing.

Two independent studies were conducted, but both involved very similar procedures and hence are described together. The concurrent presentation of the results from the two studies also allows a direct evaluation of the replicability of the major findings.

Method

Subjects

Study 1. Thirty-four female typists between 19 and 68 years old participated without monetary compensation in a single session of 1.5 hr. All subjects were electric-typewriter touch typists, but the amount of typing experience over the last 6 months ranged from 0 to 49 hr per week, with a mean of 11.2 hr. The total number of months employed with typing activities required for 10 or more hr per week ranged from 0 to 552 months, with a mean of 113.4 months.

Study 2. Forty typists between 20 and 72 years old, 9 males and 31 females, each received $10 to participate in a single session of 1.5 hr. All were experienced electric-typewriter touch typists with a mean of 13.0 hr of typing per week over the last 6 months, and a range of 0 to 40 hr. The mean number of months employed with at least 10 hr per week of typing activities was 126.9 months, with a range of 0 to 600 months.

Apparatus

All typing was performed on an Apple II+ computer with a Videx Keyboard Enhancer to allow recording and display of both uppercase and lowercase characters. The

computer also contained a Mountain Hardware programmable real-time clock that provided temporal measurement to a precision of 10 ms.

Procedure

Study 1. Seven different tasks were performed. Task 1, preceded by several minutes of practice to become familiar with the keyboard and typing in the manner requested, was normal typing from printed copy. The typing was to be performed as rapidly and as accurately as possible, but the (carriage) return key was not to be pressed because the typed copy, which was visible on the display monitor, would automatically wrap around to the next line; no attempt was made to correct errors. The typing selections were Paragraph 2 (for half of the subjects) or paragraph 3 (for the remaining subjects) from Form B of the Nelson–Denny Reading Test. These passages (and similar ones presented later in the session) contained between 1,149 and 1,258 characters, including normal punctuation and capitalization, and were accompanied by four 5-alternative comprehension questions. Subjects were informed that comprehension questions would be asked after typing the passage, but they were encouraged to try to type as normally as possible. A response was required to each comprehension question even if it was only a guess.

In order to provide a basis for evaluating the accuracy of answers to the comprehension questions concerning typed material, Task 2 was to read a similar passage (either Paragraph 6 or 7) from Form B of the Nelson–Denny Reading Test and to answer four 5-alternative comprehension questions about the passage. Subjects indicated when they began and finished reading the passage, so that the reading rate could be timed with a stopwatch.

Task 3 was to type material displayed on a single line of the video monitor and arranged such that each keystroke caused the display to move one space to the left. No visible copy was produced in this task. In successive conditions, the display contained 19, 11, 9, 7, 5, 3, or 1 character of a 60- to 83-character sentence. The sentences were movie descriptions taken from *TV GUIDE* magazine and were randomly assigned to preview conditions. One half of the subjects received one order of sentences; the remaining subjects received a different order.

Task 4 consisted of typing sentences in which the sequence of characters had been reversed in a letter-by-letter fashion, beginning with the final period and ending with the capital letter that initiated the first word of the sentence. This material was presented with preview windows of 19 characters and 1 character, using the leftward-moving display described earlier.

Task 5 was a serial choice RT task. Stimuli were uppercase and lowercase versions of the letters *L* and *R*, and responses were presses of the leftmost and rightmost keys on the lowest row on the keyboard, Z (for l and L) and/(for r and R). Subjects were instructed to respond as rapidly and as accurately as possible. Each keystroke caused the immediate display of the next stimulus until a total of 50 randomly arranged stimuli had been presented.

Task 6 was a tapping task in which the subjects, using left and right index fingers, alternately tapped the *f* and *j* keys on the keyboard as rapidly as possible for 15 s. The letters appeared on the video monitor as they were typed, but only speed and not accuracy was stressed in this task.

Finally, Task 7 was to type a standard sentence ("The quick brown fox jumps over the lazy dog.") 10 separate times, always striving for maximum speed and accuracy. The typed material appeared on the display monitor as it was entered by the typist.

Following Task 7, the first five tasks were repeated in the opposite order to provide a counterbalanced sequence. New sentences were presented in the preview conditions, and different paragraphs were presented in the normal typing task (i.e., Nelson–Denny Form B, Paragraph 4 or 8) and reading task (i.e., Nelson–Denny Form B, Paragraph 6 or 7). (No systematic performance differences were observed across the two sets of material; therefore, this control variable is ignored in discussing the results.)

Study 2. Many of the tasks from Study 1 were repeated in Study 2, including the following: (a) normal typing followed by comprehension questions, (b) reading with subsequent comprehension questions, (c) typing normal text with varying number of preview characters, (d) choice RT, and (e) alternate-hand tapping. The initial typing selections were Paragraph 2 (for half of the subjects) and Paragraph 6 (for the remaining subjects) from Form B of the Nelson–Denny Reading Test. The final typing selections were Paragraphs 7 or 5. The reading selections were similarly balanced; the subjects who typed Paragraphs 2 and 7 read Paragraphs 5 and 6, and vice versa. Two *TV GUIDE* movie description sentences were presented together with preview windows of 11, 9, 7, 5, 3, and 1 character. The length of the material was twice that of Study 1 because only a single test was used with each preview condition. The choice RT and alternate-hand tapping tests were identical to Study 1 except that the tapping test was performed twice instead of only once, and the first choice RT test was preceded by a practice block of 50 trials in an attempt to increase reliability.

New tasks introduced in Study 2 consisted of the following: (a) typing random letters with varying numbers of preview characters, (b) repetitive tapping with only the left index finger on the *f* key, (c) repetitive tapping with only the right index finger on the *j* key, (d) a conventional memory span assessment with randomly selected consonants, and (e) the Digit Symbol Substitution Test from the Wechsler Adult Intelligence Scale.

Six sequences of 120 randomly selected lowercase letters served as the stimulus material in the variable preview task with meaningless material. All subjects were presented preview conditions in the order 1, 3, 5, 7, 9, and 11 characters, but two different pairings of the letter sequences and preview conditions were used, with one half of the subjects receiving each pairing.

In the one-finger tapping tests, the typist simply attempted to tap as rapidly as possible with the appropriate finger for 15 s. The memory span procedure was introduced to investigate a hypothesis about the nature of the eye–hand span (to be discussed later). It involved the 3-s presentation of a random series of consonants with the number of items increased by one after two correct reproductions of the series. A failure to achieve two correct reproductions in five attempts terminated the procedure and the memory span was then identified as one less than the terminal series length, that is, the largest sequence correctly recalled two times.

The order of tasks in Study 2 was as follows: (a) normal typing followed by comprehension questions; (b) reading

followed by comprehension questions; (c) normal text with preview windows of 11, 9, 7, 5, 3, and 1 character; (d) choice RT; (e) memory span; (f) alternate-hand tapping; (g) left-hand tapping (right-hand tapping for half the subjects); (h) digit symbol; (i) right-hand tapping (or left-hand tapping for half the subjects); (j) alternate-hand tapping; (k) memory span; (l) choice RT; (m) random letters with preview windows of 1, 3, 5, 7, 9, and 11 characters; (n) reading followed by comprehension questions; and (o) normal typing followed by comprehension questions. In all cases where the same task was presented twice, the mean of the two values was used in all analyses.

Results

Each of the variables is initially considered separately, and the effects of skill level (in net words per minute) and age (in years) are assessed independently by means of correlation and hierarchical multiple regression analyses (see Table 1). In none of the hierarchical regression analyses was the Skill × Age interaction significant, and except where noted, the significant main effects were not altered by varying the order of entry, that is, removing the effects of one variable by entering it before the second variable in the regression equation, and thus only the results when the variable was entered first are reported. Because of the large number of analyses across the two studies, a .01 level of significance was adopted. The statistical results of the regression analyses are summarized in Table 1; only the simple correlations are reported in the following text.

Normal Typing

Gross typing speeds in Study 1 ranged from 30.2 wpm to 117.0 wpm with a mean of 61.4 wpm; those in Study 2 ranged from 24.0 wpm to 109.6 wpm, with a mean of 64.4 wpm. However, because the error rate also varied considerably across subjects, a measure of net typing rate was used as the index of skill. Net typing rate in wpm was computed by subtracting five characters (one word) for each error, dividing the net keystrokes by 5 to yield net words, and then dividing this quantity by the number of minutes required to type the entire passage. The mean net wpm across the 34 typists in Study 1 was 54.8, with a range of 17 to 104. The 40 typists in Study 2 averaged 60.0 net wpm, with a range of 23 to 98. Net typing speed was positively, although not always significantly, correlated with recent typing

experience (Study 1, $r = .291$; Study 2, $r = .503$) and with the number of months employed with at least 10 hr typing per week (Study 1, $r = .335$; Study 2, $r = .285$). The correlations between recent experience and age were small and were not statistically significant (Study 1, $r = .215$; Study 2, $r = -.041$), but those between total number of months of relevant employment and age were significant and were positive (Study 1, $r = .505$; Study 2, $r = .551$). As expected, because of the way it was computed, net typing speed was highly correlated with median interkey interval (Study 1, $r = -.941$; Study 2, $r = -.897$), and to a lesser extent, with percentage of errors (Study 1, $r = -.581$; Study 2, $r = -.438$). The ranges of these latter two variables across typists in Study 1 were 85–270 ms for median interkey interval, and 0.5–8.3 for percentage of errors. Ranges in Study 2 were 100–340 ms for median interkey interval, and 0.3–8.0 for percentage of errors.

A more detailed method of expressing typing performance is to report the percentage of errors and summary statistics reflecting the intervals between successive keystrokes. Because the interkey intervals are often skewed, I followed the convention of reporting these data in terms of the first (Q1), second (Q2, or median), and third (Q3) quartiles, and the percentage of intervals in excess of 1,000 ms (% > 1,000). The means for each parameter are displayed in Table 2 for Study 1 and in Table 3 for Study 2.

In Study 1, the typing rates were nearly identical in the normal typing, 19-character preview, and repeated-sentence tasks. Median intervals in the three tasks were also highly correlated (i.e., normal: 19-character preview, $r = .948$; normal: repetitive sentence, $r = .911$; 19-character preview: repetitive sentence, $r = .906$). The convergent estimates from these different procedures and the high reliability of the measurements add credibility to the claim that the present study is assessing the typists' normal levels of typing performance. The nearly equivalent rates in the initial and final normal typing tasks (i.e., 184 ms and 177 ms per keystroke, respectively), which were the first and last performed in the session, and in the 1st and 10th typing of the repeated sentence (i.e., 189 ms and 179 ms per keystroke, respectively), also indicate that fairly stable

Table 1

Means, Standard Deviations, and Hierarchical Analysis Statistics for All Variables in Studies 1 and 2

Measure	M		SD		MS error		Skill		Age	
	1	2	1	2	1	2	1	2	1	2
Interkeystroke variability	76.76	80.13	35.59	45.37	694.39	1,042.20	28.19*	40.28*	3.11	0.05
Recent experience	11.35	12.95	11.39	10.36	124.35	81.83	2.92	12.95*	1.59	0.09
Relevant employment	96.44	126.85	129.92	161.01	11,430.90	15,650.66	5.46	5.24	12.43*	19.61*
Eye-hand span	3.35	3.45	1.67	1.72	1.72	1.68	13.33*	19.18*	11.02*	5.84
Meaning	1.60	2.01	0.29	0.38	0.08	0.13	2.42	2.76	1.81	2.32
Intrakeystroke variability	32.94	—	13.26	—	85.11	—	34.84*	—	0.27	—
Ratio of slowest: fastest keystroke	1.78	1.73	0.39	0.30	0.14	0.08	1.95	1.30	0.32	1.47
Ratio of one-finger: two-hand digrams	1.48	1.59	0.23	0.26	0.03	0.04	15.48*	25.14*	2.10	0.06
Ratio of digram frequency slope: median interkey interval	0.25	0.27	0.16	0.15	0.02	0.02	0.12	0.05	2.87	1.23
Ratio of first letter latency: median interkey interval of all letters	1.16	1.25	0.18	0.23	0.02	0.05	7.95*	7.58*	3.93	0.00
% substitutions	21.12	22.38	13.71	11.89	189.22	118.44	1.74	4.09	0.83	2.05
% intrusions	36.03	35.93	19.54	13.81	331.59	185.54	0.10	0.17	6.48	4.03
% omissions	34.92	34.53	15.22	16.15	218.68	258.90	2.93	0.79	0.99	0.14
% transpositions	8.03	7.18	6.78	6.85	38.26	37.98	0.06	4.52	9.70*	8.56*
% slow substitutions	74.68	82.05	26.20	23.88	582.47	561.33	0.08	1.21	5.78	1.46
Reading rate	259.06	245.65	68.02	67.27	4,513.53	4,768.14	0.60	0.58	0.71	0.50
Reading comprehension – typing comprehension	11.40	15.40	25.26	26.01	583.73	674.58	5.93	0.06	0.00	2.92
Choice RT	567.35	553.38	62.25	83.27	3,091.60	3,973.47	1.37	8.82*	8.74*	25.94*
Alternate-hand tapping	125.59	125.25	29.04	35.54	566.20	792.27	9.14*	11.48*	7.79*	16.78*
Left-hand tapping	—	169.00	—	26.39	—	341.32	—	10.20*	—	32.00*
Right-hand tapping	—	156.25	—	22.04	—	222.45	—	7.10	—	44.73*
Eye-hand span with random material	—	1.75	—	1.17	—	1.19	—	7.57*	—	0.61
Memory span	—	5.81	—	0.68	—	0.43	—	2.78	—	2.64
Digit symbol	—	62.60	—	14.30	—	102.21	—	21.84*	—	23.46*

Note.— = data not applicable.
* p < .01.

Table 2
Study 1: Summary Statistics in Typing Conditions

Condition	Correlation[a]	Q1	Q2	Q3	% > 1,000[d]	% errors
Normal typing	.966	148	181	225	1.1	2.4
Repeated sentence	.892[b]	151	183	227	1.4	1.5
Preview: Normal text						
19	.889	148	179	227	2.8	5.3
11	.890	147	183	236	3.1	4.6
9	.901	147	180	231	2.4	3.1
7	.834	152	185	235	2.5	3.7
5	.773	168	205	267	2.7	2.3
3	.646	220	293	425	5.7	6.5
1	.830	554	645	761	13.5	6.4
Preview: Reversed text						
1	.922	602	665	793	15.0	5.8
19	.888	228	285	383	5.3	6.8
Choice RT	.770	510	567	658	8.2	3.7
Tapping	c	110	126	143	0.9	NA

Note. Q = quartile. NA = not applicable.
[a] Correlation between medians of 1st and 2nd tests. [b] Correlation between medians of 1st and 10th tests. [c] Only one test was administered in this task. [d] % > 1,000 refers to the percentage of interkey intervals exceeding 1,000 ms.

aspects of typing behavior are being assessed. Study 2 exhibited similar consistency in the measures of normal typing; the initial and final values correlated .961, with means of 172 ms and 173 ms per keystroke, respectively.

Age Relations

Figure 1 illustrates the relation in Study 1 between typist's age and the median interkey interval in normal typing and choice RT; Fig-

Table 3
Study 2: Summary Statistics in Typing Conditions

Condition	Q1	Q2	Q3	% > 1000[b]	% errors
Normal typing					
(r = .961)[a]	138	172	219	0.9	1.6
Preview: Normal text					
11	151	190	248	2.6	4.9
9	149	188	250	2.3	5.5
7	153	193	253	2.0	3.6
5	162	206	279	2.4	4.7
3	199	266	411	5.3	6.8
1	604	703	867	18.7	5.7
Preview: Random letters					
11	291	374	516	6.8	5.5
9	291	369	501	6.7	5.0
7	286	362	490	6.5	5.7
5	282	358	488	5.9	5.9
3	317	404	609	9.5	8.3
1	623	677	777	12.9	3.8
Choice RT					
(r = .910)	501	553	639	7.7	4.1
Tapping:					
Two hand					
(r = .899)	108	125	145	0.9	NA
Left hand	159	169	180	1.1	NA
Right hand	146	156	166	1.1	NA

Note. Q = quartile. NA = not applicable.
[a] Correlations in the first column relate performance across the two tests with that variable. [b] % > 1,000 refers to the percentage of interkey intervals exceeding 1,000 ms.

ure 2 illustrates comparable data from Study 2. Two important points highlight major goals of the present research. The first is the dramatic difference in speed between the typing and choice RT tasks, which ostensibly should involve very similar processes. One goal of the current research is to explain the discrepancy between the temporal performance of these two types of tasks. The second point is that choice RT increases with increased age, whereas typing time remains stable. Linear regression parameters (in ms) were as follows: Study 1, choice RT = 483.3 + 2.02 years, r = .460; Study 2, choice RT = 393.4 + 3.74 years, r = .617; and Study 1, typing time = 187.8 − 0.17 years, r = −.057; Study 2, typing time = 161.0 + 0.25 years, r = .069. Typing performance, therefore, appears to be maintained across the adult life span in these individuals, whereas "typical" age-related declines are exhibited in choice RT and rate of alternate-hand tapping (i.e., Study 1, tapping time =

91.6 + 0.82 years, r = .398; Study 2, tapping time = 67.8 + 1.34 years, r = .520). Explaining how stability in the molar performance is achieved despite age-related declines in the hypothetical molecular components is the second major goal of the present work.

Preview

Data from the different preview conditions were analyzed in terms of the percentage of errors and the three quartile measures. The median interkey intervals from the fastest and slowest typists in Study 1 are illustrated in Figure 3. Both sets of data are typical in that each subject performed at a rate similar to that of normal typing with previews of more than seven characters, but typing rate was much slower with smaller previews.

The eye–hand span in Study 1 was defined as the smallest window at which the first quartile was greater than the second quartile of
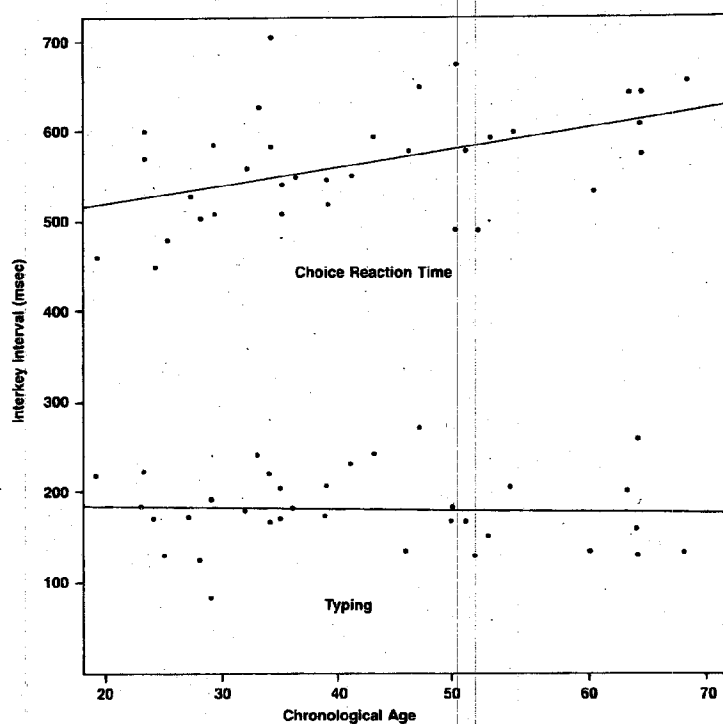

Figure 1. Median interkey interval in milliseconds for the normal typing and choice reaction time tasks as a function of typist age in Study 1. (Each point represents a single typist, and the solid lines illustrate the regression equations relating interkey interval to age.)

normal typing. This procedure effectively identified the span as the number of display characters at which 75% of the interkey intervals exceeded the median interval from normal typing. In order to allow direct comparisons across the normal and random-letter material, the eye–hand span in Study 2 was defined as the smallest window at which the first quartile was greater than the smaller of the second quartiles from window sizes 11 or 9. Several alternative operational definitions of the eye–hand span were examined, but they were either highly correlated with the current measures (e.g., span defined as the largest window at which the third quartile first fell below the median of normal typing) or yielded unstable estimates with a high proportion of discrepancies between ascending (starting from the smallest window) and descending (starting from the largest window) procedures (e.g., span defined as the window at which the inter-

quartile range first exceeded the interquartile range of normal typing).

Both studies were consistent in exhibiting significant positive relations between skill and eye–hand span (Study 1, $r = .500$; Study 2, $r = .527$). The age effect was significant in $r = .455$) but not in Study 2 ($r = .291$). However, the age variable in Study 2 was significant when entered second in the hierarchical regression model, after controlling for the effects of skill, that is, $F(1, 36) = 8.23$, $p < .01$. Similarly, the correlation between age and eye–hand span after partialing out skill was significant in this study ($r = .406$).

The discovery that the age effects were stronger in Study 2 after controlling for the level of skill prompted a further analysis in which typists below 45 net wpm were excluded. The reasoning was that the fairest test of age relations would be among subjects who were all at least moderately competent typists. De-
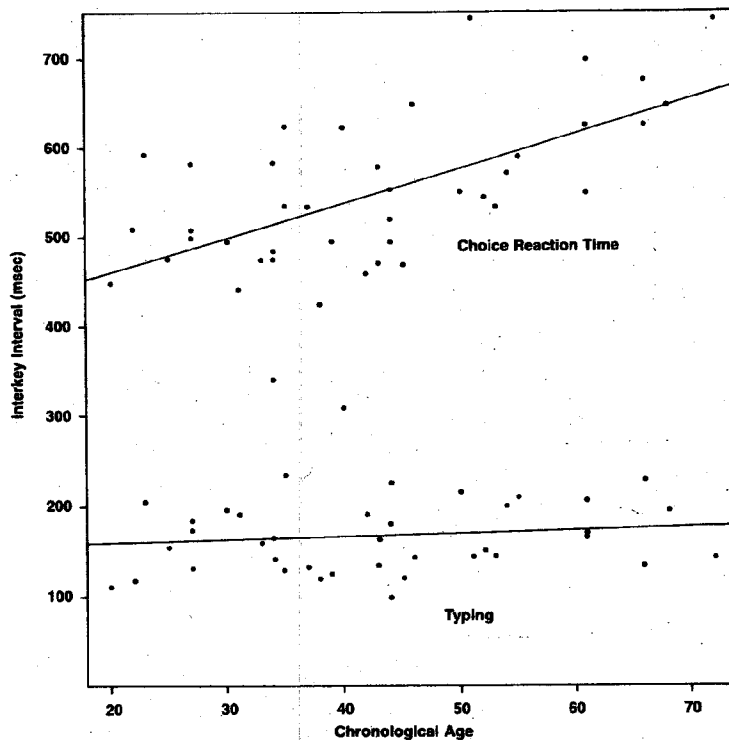

Figure 2. Median interkey interval in milliseconds for the normal typing and choice reaction time tasks as a function of typist age in Study 2. (Each point represents a single typist, and the solid lines illustrate the regression equations relating interkey interval to age.)

spite the reduction in sample sizes (i.e., to 23 and 33 in Studies 1 and 2, respectively), the age effects on eye–hand span were highly significant, that is, Study 1: $r = .522$, $F(1, 19) = 12.93$; Study 2: $r = .497$, $F(1, 29) = 11.58$, $ps < .01$.

Multiplying the eye–hand span by the median interkey interval during normal typing yields a measure that can be termed the *time span*, in that it reflects the gap between the eye and the hand in units of time. The mean time span across all subjects was 574.7 ms in Study 1 and 550.0 ms in Study 2, with standard deviations of 265.1 ms and 243.3 ms, respectively. The regression parameters relating age to time span were as follows: Study 1, time span = 195.3 + 9.12 years, $r = .487$; and Study 2, time span = 278.48 + 6.34 years, $r = .359$. These values indicate that on the average, typists in their 60s effectively have between 254 and 365 additional ms of preparation time relative to typists in their 20s.

The significant effect of age on the eye–hand span suggests that one mechanism used to compensate for declining perceptual–motor speed with increased age is more extensive an-
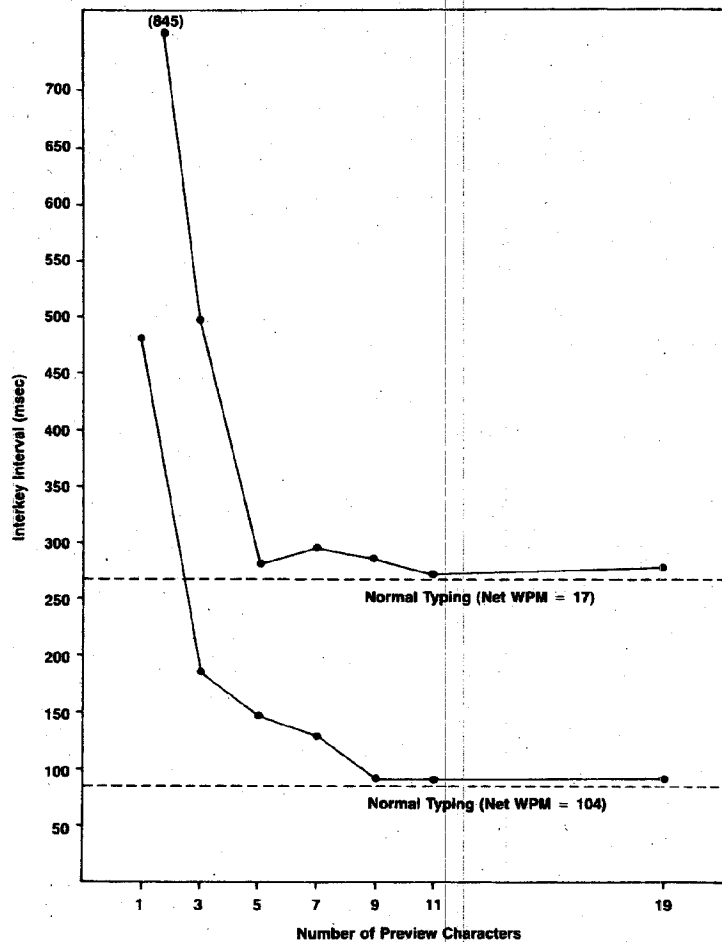

Figure 3. Median interkey interval as a function of preview window size for the slowest (net words per minute [WPM] = 17) and fastest (net WPM = 104) typists in Study 1. (The dotted lines indicate the median interkey interval during normal typing with unlimited preview.)

ticipation of impending keystrokes. Additional evidence for this interpretation are the correlations between age and median interkey interval across the various preview conditions. Figure 4 illustrates these correlations across all preview window sizes and the choice RT and typing tasks. Observe that the correlations systematically decrease as the window size increases, eventually reaching the near-zero correlation of normal typing at a window of nine characters. This pattern indicates that age ceases to be an important predictor of the interkey interval when the typist is able to view simultaneously more than seven characters of the to-be-typed material.

Meaningfulness

Table 2 illustrates the interkey interval statistics for 1- and 19-character preview conditions with normal and reversed text. It is obvious that typing efficiency is impaired with reversed text, particularly when the display allows simultaneous examination of many characters. Comparable impairment is evident in the contrast between normal text and random letters illustrated in Table 3.

Because the reversed and random-letter texts disrupt the normal ordering of letter sequences, it may be expected that some of the slower performance with meaningless material is attributable to a lower average digram frequency. Analyses conducted on normal typing, typing the reversed text with the 19-character window, and typing the random letters with the 11-character window assessed this possibility. Each letter pair was categorized according to the logarithm of its frequency in written English, as reported by Solso, Barbuto, and Juel (1979), and then the median interkey interval for each category was determined. The means across subjects of these medians are displayed in Figure 5, along with histograms confirming the expected difference in digram frequencies between normal and meaningless text. The most important aspect of Figure 5 is that the meaningless text is slower than normal text at nearly all digram frequencies. The meaningfulness effect, therefore, cannot be simply attributed to a lower average digram frequency with nonmeaningful material.
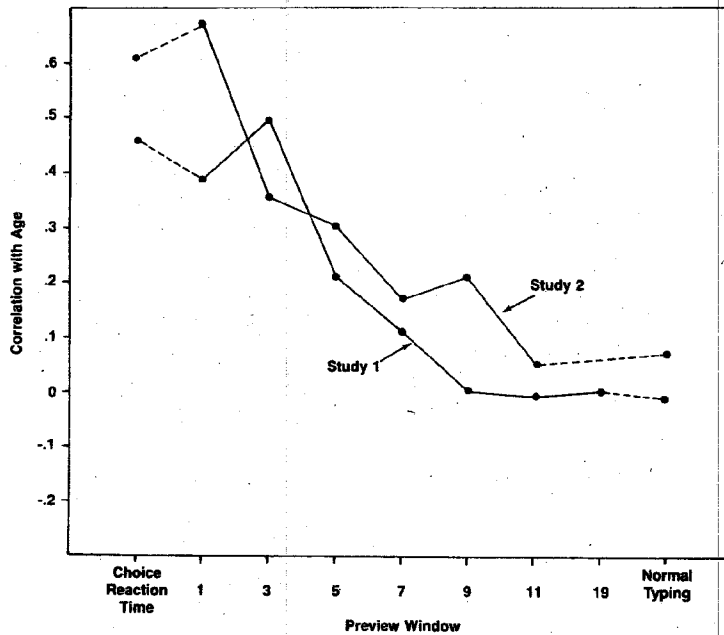

Figure 4. Correlation coefficients between interkey interval and typist age across preview window conditions and the choice reaction time and normal typing tasks.

A meaningfulness index was established in Study 1 by dividing the median interval of typing reversed text with a 19-character preview by that of typing normal text with a 19-character preview. The index in Study 2 was obtained by dividing the median interval of typing random letters with an 11-character preview by that of typing normal text with an 11-character preview. Neither index was significantly related to skill (Study 1, r = .267; Study 2, r = .257) or age (Study 1, r = .230; Study 2, r = .236) in either study.

As noted earlier, the eye–hand span for typing the random-letter material in Study 2 was identified as the smallest window at which the first quartile was greater than the smaller of the second quartiles from window sizes 11 or 9. The mean of this eye–hand span (1.75) was only about half the magnitude of that derived from the same subjects with normal text (3.45).

Faster typists had larger eye–hand spans with this meaningless material than did slower typists (r = .410), but there was no relation between age and eye–hand span with random letters (r = .117).

Intrakeystroke Variability

Temporal analyses of the keystroke intervals in the repetitively typed sentence were conducted after first deleting error responses and responses immediately following errors. The median intervals for each character and the median intrakey interquartile range for the fastest and slowest typists in Study 1 are illustrated in Figure 6. An index of intrakey variability was derived by computing the median, across characters, of the interquartile range of the intervals for the same keystroke over the 10 repetitions of the sentence. Faster
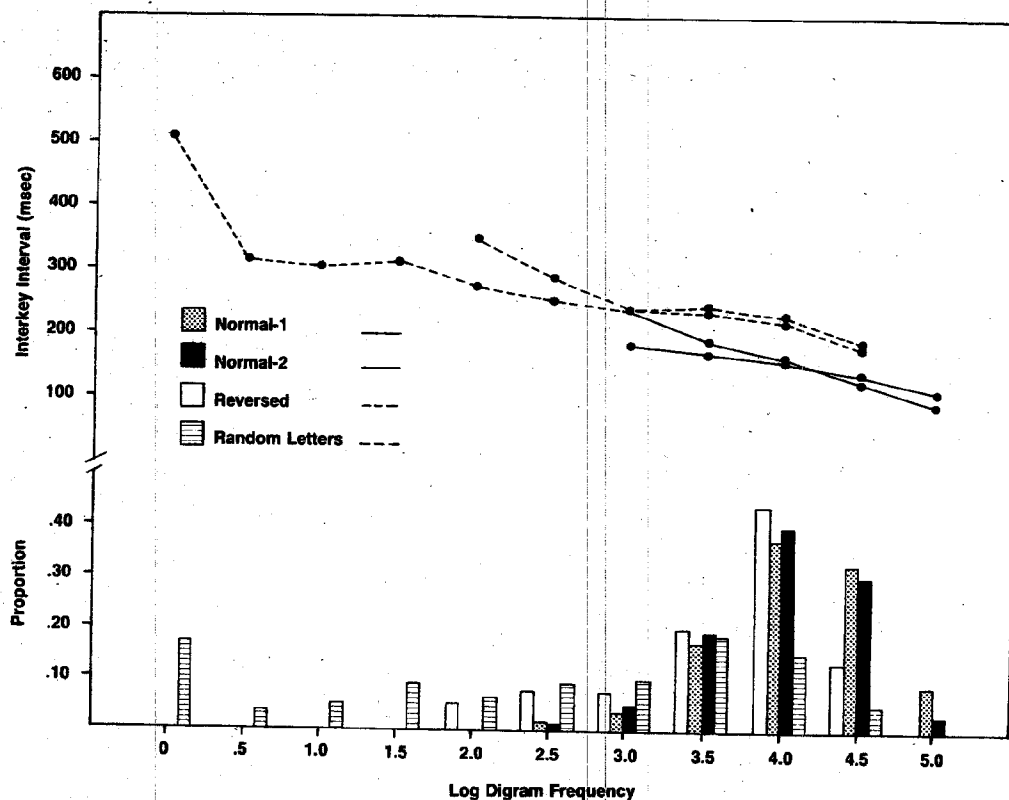

Figure 5. Median interkey interval and frequency proportion for normal and reversed text in Study 1 and normal and random-letter material in Study 2 as a function of log digram frequency.

typists were significantly less variable than slow typists ($r = -.715$), but there was no age relation ($r = -.062$) on this measure of within-keystroke consistency.

Interkeystroke Variability

The remaining analyses of timing variability were based on data from normal copy typing. The first variable was simply the interquartile range of the interkey intervals. Skill was a significant determinant of interkey variability in both studies (Study 1, $r = -.684$; Study 2, $r =$ $-.723$), with faster typists exhibiting lower variability, but the relation between age and interkey variability was not significant in either study (Study 1, $r = -.227$; Study 2, $r = -.024$).

Next, the median interkey interval for each lowercase character with a frequency of more than 10 occurrences in the two normal typing passages was determined. The ratio of the slowest character to that of the fastest character, reflecting the range of timing of separate keystrokes, served as the consistency index for each subject. Neither the skill effect (Study 1, $r = -.239$; Study 2, $r = -.170$) nor age effect
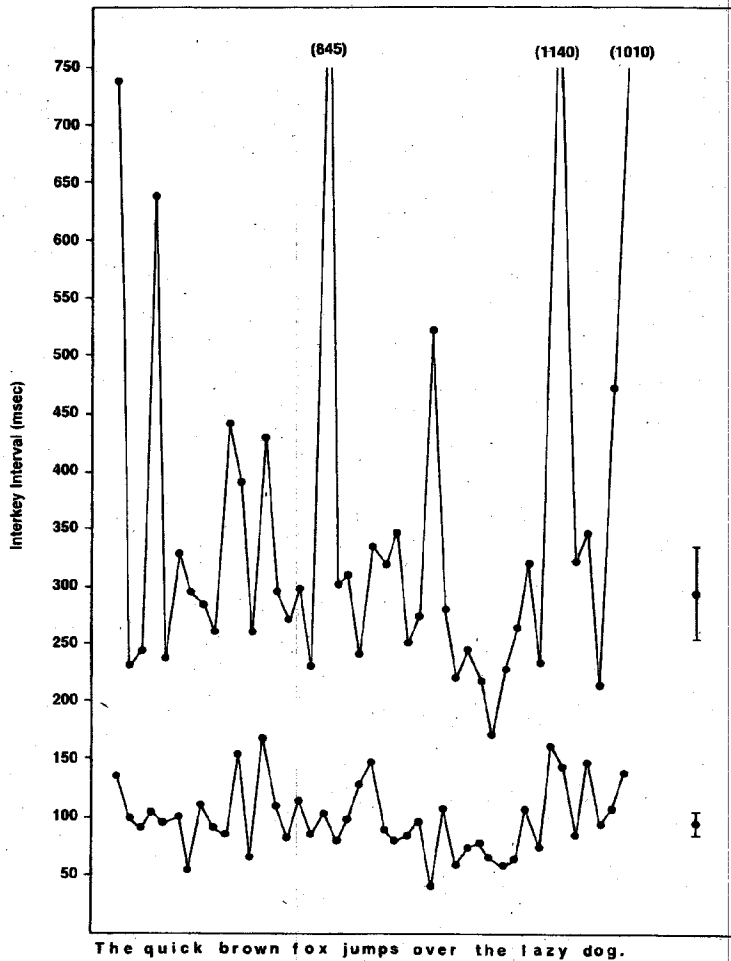

Figure 6. Median interkey interval for the slowest (top) and fastest (bottom) typists in Study 1 across characters in the repetitively typed sentence. (The points and bars at the far right illustrate the overall median interkey interval and interquartile range across all keystrokes in the sentence.)

Table 4
Means and Standard Deviations Across Typists of Medians and Interquartile Ranges for the Four Digram Categories

| | Median | | | | Interquartile range | | | |
| | Study 1 | | Study 2 | | Study 1 | | Study 2 | |
Category	M	SD	M	SD	M	SD	M	SD
Two hand	155	43	144	46	74	76	64	44
Two finger	194	45	185	51	87	102	70	31
One finger	223	41	221	42	64	60	52	43
Same letter	176	26	168	22	45	69	36	43

Note. For medians: Study 1, $F(3, 99) = 98.54$; Study 2, $F(3, 117) = 96.59$, both $ps < .01$. For interquartile ranges: Study 1, $F(3, 99) = 8.25$; Study 2, $F(3, 117) = 17.71$, both $ps < .01$.

(Study 1, $r = -.096$; Study 2, $r = -.181$) was significant with this measure.

Digram Analyses

Although measures for single keystrokes are interesting, it is probably more meaningful to consider at least the immediately preceding keystroke when attempting to partition the variability in interkey intervals. One analysis of this type contrasted the intervals of letter pairs involving the same letter, the same finger but different letters, different fingers on the same hand, and different hands. The means and standard deviations across typists of the quartile statistics for the last interkey interval for these four categories of two-letter sequences are illustrated in Table 4. Notice that the letter pairs differ significantly across two-hand, two-finger, one-finger, and one-letter pairs in both the median and interquartile range of keystroke intervals.

Both studies revealed significant effects of skill on the ratio of one-finger:two-hand digrams (Study 1, $r = .551$; Study 2, $r = .638$), indicating that faster typists had greater relative differences between one-finger and two-hand digrams than did slower typists. Very similar results were obtained with the ratio of one-finger:two-finger digrams serving as the index of finger overlapping, but this ratio was highly correlated (i.e., Study 1, $r = .648$; Study 2, $r = .656$) with the one-finger:two-hand ratio, and therefore only the latter was included in the analyses. Age was not a significant factor in the ratio of one-finger:two-hand digrams in either study (Study 1, $r = -.203$; Study 2, $r = .030$).

A second digram analysis was based on the negative relation between digram frequency and interkey interval illustrated in Figure 5. The digram frequencies were incorporated into a computer program that computed the regression parameters relating the logarithm of digram frequency to the interval between the appropriate keystrokes. The mean values (in ms) of the parameters across the 34 subjects of Study 1 were as follows: interval = 394 − 44 (log digram frequency), $r = -.167$. Values for the 40 subjects of Study 2 were nearly identical: interval = 384 − 45 (log digram frequency), $r = -.166$. Although the low correlations indicate that the relation was rather weak, the slope of 44–45 ms/log digram frequency indicates that the interkey interval was shorter with more frequently occurring letter sequences. Analyses on the slope parameter after dividing it by the median interkey interval to convert to a relative score indicated nonsignificant effects of skill (Study 1, $r = .058$; Study 2, $r = -.035$) and age (Study 1, $r = -.279$; Study 2, $r = .180$).

Word Effects

The mean intervals for initial keystrokes and for the median of all keystrokes in words of one to eight characters are displayed in Figure 7. The functions are quite flat, with the slopes across word lengths of three to eight characters averaging 4.4 ms for all interkey intervals and 7.5 ms for initial latencies.

The word initiation effect was quantified by dividing the latency of the initial character in four-letter words by the median interkey interval for all characters in the same four-letter
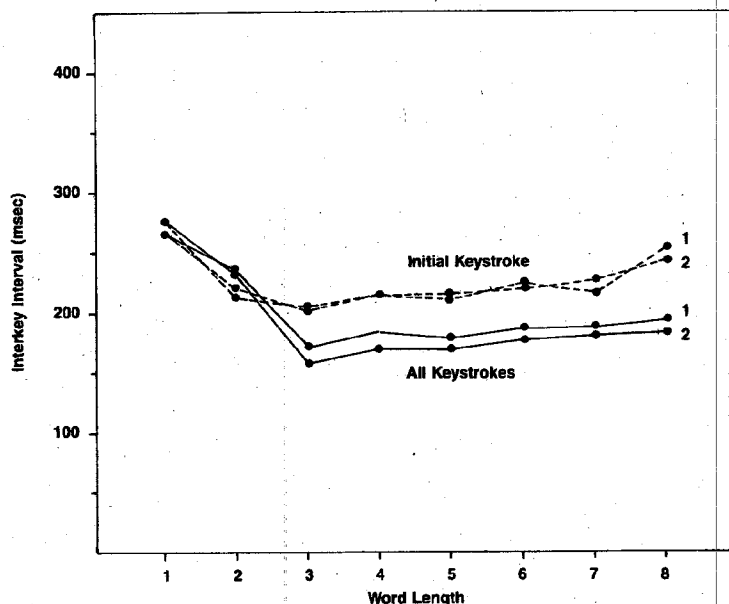
Figure 7. Mean interkey interval for initial keystrokes and for the median of all keystrokes in words of one to eight characters in Studies 1 and 2.

words. Only four-letter words were examined because they were among the most frequent, and other word lengths yielded comparable differences (see Figure 7). The skill effect was significant in both studies (Study 1, $r = -.437$; Study 2, $r = -.413$), indicating that faster typists had smaller word initiation effects than did slower typists. The age effect was not significant in either study (Study 1, $r = -.307$; Study 2, $r = .010$).

Errors

Isolated incorrect responses during normal typing were classified into four categories, and the median interkey intervals were determined for the error responses, for the preceding response, and for the first and second responses following the error. (Because of the difficulty of interpretation with series of two or more consecutive errors, which accounted for 55.6% of all errors in Study 1 and 29.5% of all errors in Study 2, only isolated errors were included in these analyses, although all errors were used in the computation of net wpm and the average accuracies that are summarized in Tables 2 and 3.) In substitution errors, the correct character was replaced with an inappropriate char-

acter (e.g., *work* for *word*); in omission errors, a character was deleted (e.g., *wod* for *word*); in intrusion errors, a character was added (e.g., *wored* for *word*); and in transposition errors, a letter sequence was reversed (e.g., *wrod* for *word*). Skill was not a significant predictor of any type of error in either study ($-.296 <$ $r < .306$), but age was negatively correlated (Study 1, $r = -.494$; Study 2, $r = -.422$) with the relative proportion of transposition errors. The correlations between age and the absolute number of transposition errors were $-.332$ and $-.225$ for Studies 1 and 2, respectively. Although both were in the same direction as the proportion results, neither value was statistically significant, indicating that it is not simply the total number of transpositions but their number relative to the total number of errors that exhibits the significant age relation. Correlations between age and the proportions of other types of error were not significant in either study ($-.210 < r < .413$), although there was a tendency in both studies for age to be positively correlated with the proportion of intrusion errors.

Figure 8 illustrates the median intervals of keystrokes surrounding single error responses

for each type of error. The posterror intervals are difficult to interpret in the case of omission errors because the omitted keystroke might have been too weak to have activated the key, and its interval may thus be incorporated into the interval of the posterror response. The data from intrusion errors are also complicated because many of the intrusions were a consequence of the nearly simultaneous (i.e., latencies less than 20 ms) activation of two keystrokes. The data from substitution and transposition errors are unambiguous, how-

ever, and clearly indicate that the responses following errors are much slower than the average response. The percentages of subjects in Study 1 with interkey intervals greater than their median interval for all keystrokes were as follows: 51.5% and 53.6% for keystrokes preceding substitution and transposition errors, respectively, and 87.9% and 96.4% for keystrokes immediately following substitution and transposition errors, respectively. Comparable percentages in Study 2 were 48.7% and 46.7% for keystrokes preceding errors, and
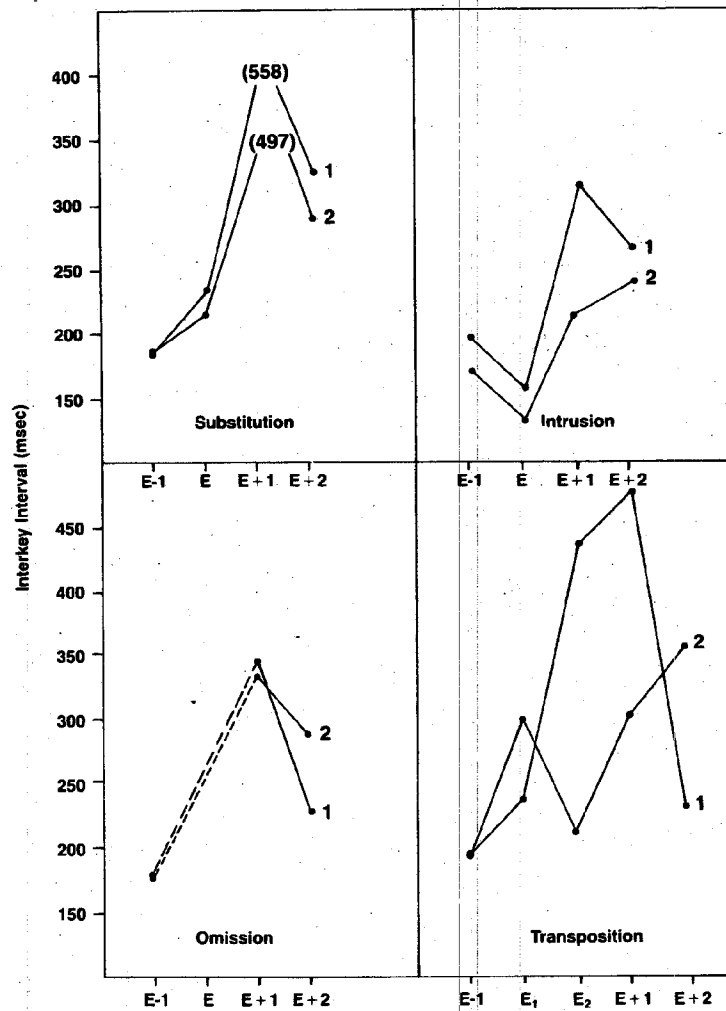

Figure 8. Mean interkey interval for keystrokes preceding and following isolated errors (E) in Studies 1 and 2.

89.7% and 83.3% for keystrokes following errors.

Skill and age analyses were conducted on the percentage of posterror substitution responses greater than the subject's median interval across all keystrokes. The other error categories were not analyzed in this fashion because of the interpretation problems with the omission and intrusion data, and the low frequencies of transposition errors. Neither the skill effect (Study 1, $r = -.045$; Study 2, $r = .175$) nor the age effect (Study 1, $r = -.385$; Study 2, $r = -.192$) was significant in either study.

Typing and Reading Comprehension

Across subjects, mean accuracy on questions assessing comprehension of typed material was 45.6% in Study 1 and 43.7% in Study 2, and that on questions assessing comprehension of similar material that was only read was 57.0% in Study 1 and 59.1% in Study 2. A comprehension differential score was derived for each subject by subtracting typing comprehension from reading comprehension. Neither study exhibited a significant skill effect (Study 1, $r = .406$; Study 2, $r = .038$) or age effect (Study 1, $r = -.007$; Study 2, $r = .273$) on this variable. Reading rate was not related to skill (Study 1, $r = .133$; Study 2, $r = .126$) or age (Study 1, $r = .145$; Study 2, $r = -.116$) in either study.

Choice RTs

The RT data were analyzed in the same fashion as the typing data, and the mean values across all subjects are displayed in Tables 2 and 3. The skill effect was not significant in Study 1 ($r = -.182$) but was significant in Study 2 ($r = -.360$). Age was positively and significantly related to RT in both studies (Study 1, $r = .460$; Study 2, $r = .617$).

Tapping

Mean values of interkey intervals while tapping with alternate hands are displayed in Tables 2 and 3. The skill (Study 1, $r = -.431$; Study 2, $r = -.430$) and age (Study 1, $r = .398$; Study 2, $r = .520$) effects were significant in both studies, indicating that faster and younger typists were faster in tapping than

slower and older typists. Both left- and right-hand tapping rates in Study 2 exhibited significant age relations (left hand, $r = .634$; right hand, $r = .725$), with younger typists faster than older typists, but with weaker effects of skill (left hand, $r = -.358$; right hand, $r = -.289$).

Memory Span

No significant effects of skill ($r = .259$) or age ($r = -.253$) were evident on the measure of conventional memory span obtained in Study 2.

Digit Symbol

Younger typists ($r = -.548$) and faster typists ($r = .529$) had significantly higher scores on the Digit Symbol Substitution Test in Study 2 than did older or slower typists.

Predicting Typing Skill

A stepwise multiple regression analysis was conducted to determine the independent sources of variance related to typing skill. A forward selection procedure with a .05 significance level for variable entry was conducted with predictor variables consisting of all variables found to yield significant skill effects in each study. The variables with significant skill relations in Study 1 were as follows: eye–hand span, interkeystroke variability, intrakeystroke variability, ratio of one-finger:two-hand digrams, ratio of first keystrokes:all keystrokes in four-letter words, and alternate-hand tapping time. Four of these variables were found to make significant and independent contributions in the regression equation predicting net typing speed: eye–hand span, intrakeystroke variability, ratio of two-hand:one-finger digrams, and tapping time. The four-variable equation yielded an R^2 of .877, with successive increments of .511 for intrakeystroke variability, .161 for the ratio of two-hand:one-finger digrams, .091 for eye–hand span, and .114 for rate of alternate-hand tapping.

The variables entering into the equation for Study 2 were as follows: eye–hand span with normal text, eye–hand span with random letters, interkeystroke variability, ratio of one-finger:two-hand digrams, ratio of first keystrokes:all keystrokes in four-letter words,

choice RT, alternate-hand tapping time, left-hand tapping time, and digit–symbol substitution score. The variables making independent contributions to the prediction of net typing speed, and their respective proportions of variance, were as follows: interkeystroke variability, .523; ratio of one-finger:two-hand digrams, .193; and rate of left-hand tapping, .067. The cumulative R^2 for the three-variable equation was .783. Although the particular variables entering the equation differ somewhat across Studies 1 and 2, this is largely attributable to the existence of variables not available in the other study, for example, intrakeystroke variability in Study 1 but not in Study 2, left-hand tapping in Study 2 but not in Study 1.

Two additional analyses were conducted in which only variables common to the two studies were included, that is, eye–hand span with normal material, interkeystroke variability, ratio of one-finger:two-hand digrams, ratio of first keystrokes:all keystrokes in four-letter words, choice RT, and alternate-hand tapping rate. The cumulative R^2 after four variables (i.e., interkeystroke variability, ratio of one-finger:two-hand digrams, eye–hand span, and alternate-hand tapping rate) was .830 for Study 1 and .772 for Study 2.

Discussion

Before discussing the theoretical implications of the results, it is important to emphasize the close agreement of the data from the two studies. Despite different samples of typist subjects, with different forms of compensation and slightly different experimental procedures, the major results from the two studies were nearly identical. This correspondence is apparent in Figures 1, 2, 4, 7, and 8, and in all of the tables. Particularly impressive are the very similar patterns of relationships evident in the correlations reported in the preceding text and the summary of means and F ratios in Table 1. Given such consistency, there seems little reason to doubt the reliability of the current findings.

General Model of Typing

Two questions motivated the present research: What differentiates skilled typists from less-skilled ones, and how are older adults able to circumvent limitations of slower RT to achieve rapid typing speeds? Many of the current findings are relevant to these issues, but their interpretation requires a general model of typing behavior within which the effects of skill and age can be set. Most of the properties of the model I describe have been suggested by others, and therefore it is best considered a synthesis or a composite view of the activity of typing. Another caveat is that the model clearly does not provide a complete explanation of all aspects of typing, but focuses on the limited set of phenomena established or confirmed in this study.

It is useful to begin a description of the model by distinguishing among four categories of processing. The first is termed *input processes* because there has to be some way for the to-be-typed material to enter the processing system. The extensive experience typists have had with reading makes it likely that the input material is initially segmented into familiar, meaningful units such as words or phrases. The output of the system must eventually consist of discrete keystroke responses, however, and thus a second category of processing consists of *parsing* the large reading units into discrete characters. A third set of processes then *translates* characters into patterns of finger movements and also *monitors* the keystroke actions. The fourth and final category of processes is responsible for the actual *execution* of the finger movements that culminate in overt keystrokes.

A fundamental property of this model is that all of the processing steps are assumed to be capable of simultaneous operation (e.g., Book, 1908; Coover, 1923; Dvorak et al., 1936; Gentner, 1982a; Hershman & Hillix, 1965; Logan, 1983; Norman & Rumelhart, 1983; Olsen & Murray, 1976; Rabbitt, 1978; Rumelhart & Norman, 1982; Shaffer, 1971, 1973, 1976; Shaffer & Hardwick, 1968, 1969b). That is, the keystroke for one character may be executed while the immediately following character is being translated to patterns of finger motions, the character after that is being parsed from the input string, and still other characters are being registered and encoded by the input processes. It is this property that is postulated to be responsible for much of the speed of typing compared with serial reaction tasks because the interkey interval is assumed to rep-

resent only the time between the final processes of successive keystrokes, rather than the time between the initial and final processes of a single keystroke as in RT tasks. The dramatic reduction in typing speed produced by restricting the number of simultaneously visible characters found in these studies and others (e.g., Coover, 1923; Hershman & Hillix, 1965; Shaffer, 1973, 1976; Shaffer & French, 1971; Shaffer & Hardwick, 1970) is consistent with the parallel execution assumption because curtailing the preview reduces the possibility of overlapping in processing.

In fact, the notion of overlapping processing is so dominant in typing performance that I referred to each processing step as a category or set of processes to allow for the possibility of overlap in the subprocesses within each category. An example of this type of within-categories overlap was described by Gentner et al. (1980) in their analyses of high-speed films of skilled typing. (Also see Olsen & Murray, 1976, for a similar analysis.) These investigators reported that the average interval between the initiation of a finger movement and its completion was 261 ms, but that the average interval between successive keystrokes was 124 ms. Many cases of two or more fingers simultaneously in motion were also observed, and thus the overlapping of processing has been empirically documented at least within the set of processes responsible for keystroke execution.

Although overlapping of processing is assumed to be extensive, physical constraints imposed by the configuration of fingers and the layout of the keyboard set limits on the degree of overlap in at least the execution processes (e.g., Rumelhart & Norman, 1982). Specifically, overlap of finger movements is least likely when successive keystrokes involve the same finger, increases somewhat when the two characters involve different fingers on the same hand, and is most likely when the digram involves fingers on alternate hands. This is precisely the ordering of interkey intervals found in the current studies and in earlier reports by Dvorak et al. (1936), Gentner (1981, 1982a), Kinkead (1975), Rumelhart & Norman (1982), and Terzuolo and Viviani (1980).

Many experiential effects, such as the negative relation between digram frequency and interkey interval found here and elsewhere (e.g., Dvorak et al., 1936; Grudin & Larochelle, 1982; Terzuolo & Viviani, 1980) are probably due to extensive practice leading to the development of more efficient techniques of overlapping those particular keystrokes. Less frequent digrams have not had the benefit of such extensive practice and thus are still typed without overlapping or with inefficient modes of overlapping.

Other phenomena are not so easily explained by the concept of parallel activity of various processes but seem to be due to other properties of the typing model. For example, the robust effect of material meaningfulness appears to extend beyond the digram level because the reversed and random-letter texts were found to be typed slower than normal text even when the frequency of letter digrams was controlled (see Figure 4). Terzuolo and Viviani (1980) also reported that the same digrams were typed faster in meaningful text than in randomly arranged letters, thereby further confirming this observation. A likely candidate for the meaningfulness effect is the parsing process in which the input units are segmented into individual characters (Rumelhart & Norman, 1982; Shaffer, 1976). The decomposition of familiar words and phrases is likely to be facilitated by knowledge of orthographic rules governing the sequencing of letters in English and by the thousands of hours of viewing the intact units in reading. Meaningless material often violates orthographic rules and almost by definition is not as familiar as meaningful material. The meaningfulness effect could also be localized in the input processes, but if so, it is unlikely to extend beyond the level of the word because several investigators found that randomly arranged words are typed about as rapidly as normal text (e.g., Fendrick, 1937; Hershman & Hillix, 1965; Olsen & Murray, 1976; Shaffer, 1973; Shaffer & Hardwick, 1968; Shulansky & Herrmann, 1977; Terzuolo & Viviani, 1980; Thomas & Jones, 1970; West & Sabban, 1982).

The word initiation effect, that is, the tendency for the first keystroke in a word to have a longer interval than other keystrokes in the word (e.g., Larochelle, 1983; Ostry, 1980, 1983; Shaffer & Hardwick, 1970; Terzuolo & Viviani, 1980; Thomas & Jones, 1970), may have its primary origin in the input processes. Words appear to be natural units in reading

and therefore are presumed to correspond to the groupings received by the input processes. The parsing mechanism may also play a role in this phenomenon because the transition from space to letter found in the first character of a word is distinctive among primarily letter-to-letter sequences. Translation and execution processes seem unlikely candidates for the slower initial keystrokes in words because the space bar is pressed with the thumb and thus should allow considerable overlapping of subsequent finger movements.

The claim that errors are detected rapidly, often before the following keystroke is completed (e.g., Rabbitt, 1978; Shaffer, 1973, 1975, 1976; Shaffer & Hardwick, 1969a), is supported in the present study by the markedly slower posterror intervals with substitution and transposition errors (see Figure 7). This phenomenon seems to necessitate some type of monitoring mechanism at the level of the individual keystrokes but not involving the keystrokes themselves or no error would have resulted. The processes in the model responsible for translating characters to finger movements seem ideally suited for this kind of monitoring. If the feedback received from the completed finger movement does not correspond to the intended signal, a temporary blockage of communication channels may result (e.g., Logan, 1982, 1983) or the next keystroke could simply be inhibited while higher levels of processing become directed to the error.

The remaining general typing phenomenon that constrains the typing model is the eye–hand span. In the procedure followed here, the span is the minimum number of characters of preview necessary to achieve one's normal rate of typing. Because typing rate is slowed when fewer than the span number of characters is presented, the typist must normally be using that many characters in some fashion.

When analyzing a phenomenon such as the eye–hand span, it is important to think of it in both dynamic and functional terms. (See Logan, 1983, for a related discussion of this issue.) The span is dynamic because it is continuously being updated with new items as earlier items are typed, and its apparent function is to ensure an uninterrupted stream of input to later processing steps. These considerations suggest that the most plausible origin for the span is in the requirements of the pars-

ing processes for a steady flow of information from the input processes. Parsing processes do not operate in isolation, however, and it is likely that both translation and execution processes contribute to the driving of the parsing mechanism. A lag or span between the character being parsed and the character whose keystroke is being executed is therefore assumed to arise in response to the need for a continuous flow of information to all subsequent processes.

The origin of the span is assumed to be downstream, that is, later in the processing sequence, because performance is impaired when fewer than the span number of characters is available. A simple mismatch of capacities between early and late processes, with larger capacities in earlier processes, could produce a spanlike buffer, but in this case performance would not suffer with subspan previews. An analogy with a commonplace toilet may help illustrate this distinction between later (demand–deficit) and earlier (supply–surplus) interpretations. The amount of water in the toilet tank can be considered to represent a "span" in that it consists of an accumulation of water in some type of storage system. When the toilet is flushed, nearly all of that water is used, and if the tank was not full, the flushing might be incomplete. Because the performance of the system is impaired by subspan quantities, this is a case in which the span exists to prevent a deficit in response to the demand. Now consider what happens when a blockage forms in the plumbing below the toilet. A flush of the toilet will produce a considerable amount of water filling the toilet bowl, but when it cannot drain adequately, it will create a quantity (span) of water above the blockage. In this case, reducing the amount of water in the toilet bowl will not substantially affect the flow of water in the pipes below the blockage (i.e., performance is not impaired by subspan quantities), and thus the span is produced by a surplus of supply rather than an attempt to minimize deficit to demand.

My interpretation of the eye–hand span in typing is that it is more analogous to the toilet tank rather than the blockage-induced overflowing toilet bowl, or in more scholarly language, it is a span that is driven by demand rather than by surplus of supply. This view leads to several implications concerning the

eye–hand span measured here. One implication is that because the span is presumed to arise as a consequence of the rapid and efficient operation of parsing, translation, and execution processes, faster typists would be expected to have greater spans than would slower typists. This prediction is confirmed in the present results.

A second prediction is that the same typists should have smaller eye–hand spans when their rate of typing is slower, as is the case when typing unfamiliar, meaningless material. This hypothesis was confirmed in Study 2 in which the eye–hand span with random letters was substantially smaller than the eye–hand span with normal material. The span is therefore a characteristic of a momentary typing rate and not a fixed attribute of the typist. Fuller (1943) reached a similar conclusion on the basis of examinations of eye movements when typists were asked to type at normal and slow speeds, and when they were typing text in unfamiliar French rather than text in their native English.

A third implication of the current view of the eye–hand span is that it is unlikely to be correlated with conventional measures of memory span. The reason is that conventional estimates of memory span appear to be assessing the static (surplus) capacity of a particular memory structure, and not the dynamic (demand) requirements of later processes for continuous input as in the eye–hand span. The results of the traditional measure of memory span available in Study 2 confirm this prediction; there was no relation ($r = -.124$) between eye–hand span in typing and the conventional memory span for letter sequences. The correlation between the conventional memory span and the eye–hand span with random letter material was also low and nonsignificant ($r = .214$).

To summarize, a general model of typing is proposed with four categories of processing: input, parsing, translation, and execution. There is assumed to be considerable operational overlap or parallel processing among and within each processing category, and this feature is assumed to be responsible for many of the phenomena that have been observed in studies of typing. No single unit of typing can be identified in this model because different processes are presumed to operate with dif-

ferent segments of information, for example, the parser decomposes reading units into single characters, the translator converts character representations into motor patterns and monitors the individual movements, and so forth. Finally, typing performance is degraded by restricting the number of visible characters because the parsing, translation, and execution processes require a steady flow of information in order to obtain maximum efficiency.

Skill Effects

Assuming that typing proceeds in approximately the manner previously described, how do skilled typists differ from less skilled ones? At a purely descriptive level, skilled typists relative to less skilled typists are less variable both across keystrokes and in the execution of the same keystroke across repetitions; they tend to rely on more of the advance copy while typing; they have a smaller relative variation between two-hand and one-finger digrams; they have a smaller relative difference between the timing of initial keystrokes and subsequent keystrokes in words; they have higher rates of alternate-hand tapping; they are faster at manually writing symbols in place of digits; and they may be faster at choice RT.

The stepwise regression analyses were useful in reducing these variables to a minimum set of predictors with independent contributions to the variance in typing performance. Variables not included in these equations can be presumed to share substantial variance with the variables that were included (e.g., the ratio of initial keystrokes:all keystrokes in four-letter words is probably encompassed by the measure of interkeystroke variability). Four such unique predictors were identified as consistent across the two studies: interkeystroke variability, ratio of two-hand:one-finger digrams, eye–hand span, and speed of alternate-hand tapping.

Although both studies exhibited highly significant relations between skill and interkeystroke variability, the stepwise analysis in Study 1 indicated that most of this common variance was attributable to the measure of intrakeystroke variability. That is, once intrakeystroke variability was entered into the regression equation, the interkeystroke variability measure no longer made a significant contribution. The skill effect on the measure of intrakey-

stroke variability indicates that faster typists are more consistent than slower typists in executing the same keystroke. Because the context was identical across repetitions, mechanical and experiential factors were held constant in this procedure. The greater consistency of skilled typists must therefore be attributed to internal factors such as rhythm, finger coordination, and precision of finger placement. Faster tapping among skilled typists can also be interpreted as evidence that one concomitant of skill is more efficient coordination of elementary finger movements. A somewhat more complex correlate of skill, although still motoric in nature, is the ratio of one-finger:two-hand digrams. Faster typists were found to have larger ratios than slower typists, indicating that they had developed more efficient modes of overlapping two-hand sequences. One-finger letter digrams were also typed faster by skilled typists (Study 1, $r = -.876$; Study 2, $r = -.826$), but execution processes cannot overlap when the same finger must make two responses in succession, and therefore this variable provides a reasonable baseline for estimating the relative efficiency of two-hand overlapping.

The preceding three variables, although making independent contributions to the prediction of typing speed, can all be classified as primarily motoric, or in Book's (1908) terminology, "habits of manipulation." Their primary locus in the current typing model is therefore in the execution processes, with perhaps some influence on the translation processes. A variable that appears more cognitive in nature, or a habit of control in the words of Book, is the eye–hand span, which was found to be significantly larger in skilled typists than in unskilled ones. According to the interpretation previously proposed, the larger span among skilled typists arises because of a need for higher rates of transmission of information to the parsing, translation, and execution processes. These processes are apparently either more efficient or overlap more extensively among the skilled typists, such that there is a greater demand for information about forthcoming characters.

It is interesting to compare the present interpretation of the skill difference with that proposed by several earlier researchers (e.g., Book, 1908; Dvorak et al., 1936; Swift, 1904).

For many years the dominant explanation of skilled typing was that the fastest individuals typed in units of words or phrases, whereas beginners were limited to individual letters. Implicit in this perspective was a top-down view of the eye–hand span in which the acquisition of larger units was assumed to be responsible for the faster rates of typing. By contrast, a bottom-up view of typing is implied from the current perspective because the span is assumed to be a consequence, and not a cause, of the faster rate of typing. The skill relations observed in the motoric variables of same keystroke consistency, tapping speed, and two-hand digram efficiency are also consistent with the view that many of the skill effects arise because of increased efficiency of component processes. Although not pursued at the time, isolated references to a bottom-up interpretation of the eye–hand span can be found in the earlier literature. For example, Coover (1923) stated that, "The telescoping of preparation for sequences of letters leads to word units in copy-getting and in typing (p. 564)," and Butsch (1932) claimed, "It is probable that the eye simply keeps far enough ahead to provide copy for the hand as it is needed, and rapidly enough to prevent retarding the writing (p. 113)."

Age Effects

Three categories of variables are significantly related to the age of the typist: transposition errors, component process variables, and the eye–hand span. Older typists made relatively fewer transposition errors than did younger typists in both studies. This finding may be interpreted as suggesting that with increased age, and consequently experience, there is more precise control over the sequencing of keystrokes. No other evidence is available for this inference, however, and the low incidence of transposition errors among all typists (between 7% and 8% of all errors) should make one cautious about this result.

The discovery that several measures of perceptual–motor efficiency—choice RT, rate of tapping, and digit-symbol substitution rate—were all slower with increased age is consistent with the results of many previous studies in the aging literature (see Salthouse, in press). Assuming that such measures are components

of typing, this result provides no evidence that even millions of "trials" of experience can lead to the preservation of basic capacities. However, the samples are too small and variable to consider the present study a strong test of the maintenance-with-practice hypothesis. Nevertheless, the slower performance on these tasks was accompanied by virtually unchanged performance across the adult life span in the rate of typing. Individuals in the current samples could expect to differ by between 80 ms and 150 ms in choice RT between age 20 and age 60, and yet the average interkey interval in typing was found to be nearly identical for 60-year-old typists compared with 20-year-old typists. A dramatic discrepancy therefore clearly exists between the results of traditional laboratory tasks and the performance of the real-life activity of typing.

The existence of a significant relation between age and eye-hand span, independent of the relation between span and skill, suggests a possible mechanism that may allow older typists to compensate for lower perceptual-motor efficiency. Older typists were found to have larger eye-hand spans than did younger typists, and it is conceivable that this larger span is a reflection of more extensive overlapping and anticipation of impending characters developed in order to maintain relatively high speeds of typing in the face of declining basic capacities. That is, the span may be larger because the older typists have adapted to their slower rates of processing by planning further ahead, in effect, scheduling around the bottlenecks in the system as much as possible. The computations of time span, that is, the product of eye-hand span and median interkey interval, indicate that this mechanism may allow typists in their 60s an additional 254 ms to 365 ms of preparation for a given keystroke compared with typists in their 20s.

Although I tend to favor the compensation interpretation of the age-span relation, another interpretation cannot be rejected. This is the notion that the older typists were once much faster and that their larger eye-hand spans are merely a residual consequence of their former degree of skill. In other words, the larger spans of older typists may be a reflection of their previous higher levels of skill, but as the efficiency of component processes and speed of molar performance declined with increased

age, the span remained at the length appropriate for the former, more proficient, level of skill. This interpretation does not seem testable without extensive longitudinal investigations, and thus we cannot distinguish between this and the compensation interpretation previously offered.

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