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Perceptual, Cognitive, and Motoric Aspects of Transcription Typing

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Recent research findings in the domain of transcription typing are reviewed in the context of a four-component heuristic model. The four components consist of an input phase in which to-be-typed text is grouped into familiar chunks, a parsing phase in which the chunks are decomposed into discrete characters, a translation phase in which characters are converted into movement specifications, and finally an execution phase in which the actual movements are produced. This framework was used to integrate 29 distinct empirical phenomena related to transcription typing, including the multiple units of typing, the existence of four major categories of errors, and differences associated with increasing skill. The review concludes with a brief discussion of several issues that appear to provide promising directions for future research.

Transcription typing has many advantages over alternative forms of activity for the purpose of analyzing human skilled behavior. First, the number of practitioners is extremely large, making it relatively easy to locate moderately sized samples of individuals at many levels of expertise. Second, although the performance of skilled typists appears continuous, typing behavior is naturally partitioned into discrete and easily measured keystroke responses. Third, despite its seeming simplicity, transcription typing involves an intricate and complex interaction of perceptual, cognitive, and motoric processes. Not only does verbal material have to be registered and perceived, but it has to be appropriately partitioned, accurately translated into physical movements, and then those movements executed at rates exceeding several hundred keystrokes per minute. A thorough understanding of a task involving such precise and rapid coordination of diverse processes will surely contribute to greater knowledge about the nature of highly skilled performance in a wide range of cognitive activities.

In an earlier article (Salthouse, 1984a), a composite model of transcription typing was briefly outlined to provide a framework for localizing the effects associated with the age and skill level of the typist. Most of the properties of the model were derived from ideas introduced by earlier theorists (e.g., Cooper, 1983; Logan, 1983; Rumelhart & Norman, 1982; Shaffer, 1973, 1975a, 1976; Shaffer & Hardwick, 1970; Thomas & Jones, 1970), and thus it can be viewed as a synthesis of many previous proposals. The goal of the present article is to use that model as a heuristic device to help organize a review of the empirical literature concerned with transcription typing. Figure 1 illustrates the major components of the model, and the primary operations presumed to be performed by each. It can be seen that the model is based on four basic processing operations, each responsible for a specific type of information transformation.

The to-be-typed text is initially perceived and coded into easily remembered chunks using processes similar, but not identical, to those involved in reading. For lack of a better term, I label this initial processing component *input* because although it is more than mere registration or perception, it is not isomorphic with reading.

The second phase of processing is responsible for decomposing the multicharacter chunks into discrete characters. This type of parsing operation is necessary because the ultimate responses are in the form of separate keystrokes, each representing a distinct character, and therefore some means of isolating characters is required.

Once discrete characters are identified, it is necessary to translate them into the specifications or commands for the movements involved in pressing the proper key on the keyboard. These translation operations convert whatever code is used to represent individual characters into movement specifications for the hand, finger, and direction of reach. For example, the specification for the letter *p* might be "hand: right, finger: 4, reach: up." (For convenience, the fingers are labeled 1–4 from the index out to the little finger, respectively) It is also possible that the movement specification includes reference to the orientation of the hand as determined by the angle of the wrist; such as, the letter *q* might be represented as "hand: left, wrist: 20° clockwise, finger: 4, reach: up." Because of the reliance in the touch-typing system of "home-row" positions, the movement specifications are assumed to be expressed more in relative rather than absolute coordinates. It is unclear whether fast typists not using the touch system also rely on some form of home position and hence could also use relative movement specifications, or whether absolute specifications (e.g., "Press second key on top row") are necessary.

The final processing operation is execution, in which the specifications supplied by the translation processes are actually implemented as overt movements of the fingers and hands. It is assumed that the execution mechanism consists of the trans-

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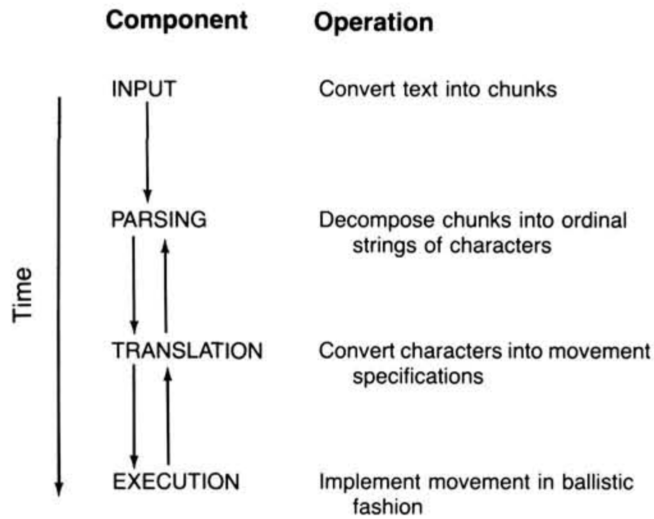

Figure 1. Diagram of the four proposed typing components and the nature of the processing presumed to be carried out in each.

mission of signals to the peripheral muscles, and therefore the contents of the execution stage are movement parameters that are largely ballistically implemented and no longer subject to control or modification. The end product of this phase is the overt keystroke, but most of the preparatory adjustments of the hand and finger would also be considered part of the execution phase.

Although somewhat vague and still incomplete, this four-component framework can serve a valuable heuristic function in helping organize the coverage of the research literature concerned with transcription typing. Moreover, listing the major phenomena in need of explanation, and then providing an account of how proposed theoretical systems might handle these phenomena is an effective way of describing the properties of those systems. Ideally, this should be done for several alternative models simultaneously to provide a basis for comparative evaluation, but this is not yet practical, either because competing models have not yet been specified in sufficient detail to derive explanations or because the other models were intended to apply to only a limited set of typing processes. For example, recent models by Rumelhart and Norman (1982) and Sternberg, Knoll, and Wright (1978) were deliberately restricted to what I here term translation and execution processes. Rumelhart and Norman (1982) explicitly stated that their model did not cover

> mechanisms involved in learning . . . mechanisms involved in perception or the encoding of the strings to be typed [or], in monitoring the accuracy of the typing . . . [or] . . . the deterioration of typing rate that occurs as the text is modified from normal prose to non-language or random letters. (p. 6)

By concentrating on discrete bursts of typing, Sternberg and his colleagues acknowledge that they are deliberately considering typing as a primarily motor skill because "the perception of the material to be typed has presumably all occurred early in the trial, and the subject has plenty of time to rehearse or prepare in other ways for what he or she has to type" (p. 4). Therefore, whereas these models make substantial contributions in attempting to formalize some of the mechanisms involved in skilled typing, they are not yet complete enough to allow comparisons across the entire domain of typing phenomena.

The preceding discussion suggests that another advantage of identifying well-established phenomena in the domain of typing is that it defines the criteria by which alternative models in this area may be evaluated. To the extent that these phenomena are judged relevant and important, then they must be explained by any adequate model of transcription typing. Because some intriguing theoretical speculations are based on very sparse amounts of data (e.g., results from a single typist or derived from the existence of errors with extremely low frequencies of occurrence), they will not be discussed in this review. Although this omission may lead to an erroneous impression that empirical research on typing has not been accompanied by considerable theoretical development, it seems premature to attempt to assess the validity of speculations without an adequate empirical data base. My approach therefore, is first to identify phenomena for which convincing empirical support is available, and only then to venture possible explanations. In this manner one can at least be assured that the phenomena being explained by various theoretical models are genuine, and do in fact require explanation.

Typing Phenomena in Need of Explanation

Basic Phenomena

1. People can type very quickly, with interkey intervals averaging only a fraction of the typical choice reaction time. For example, a recent study (Salthouse, 1984a) reported that the median interkey interval in normal transcription typing was 177 ms, whereas the median interkey interval for the same individuals in a serial two-alternative choice reaction time task was 560 ms. Even an average professional typist operating at a rate of 60 gross words per minute produces five keystrokes per second or 200 ms per response—an extraordinarily fast time in the context of choice reaction time activities.

The most plausible explanation for typing performance considerably exceeding the limits of choice reaction time is that the various processing operations in typing overlap in time, whereas those in a choice reaction time task are necessarily serial because the following stimulus does not appear until the occurrence of the preceding response. That is, in normal typing it is assumed that the typist is executing one keystroke while simultaneously preparing the movement patterns for the next keystroke, decomposing the characters from multicharacter chunks, and forming new chunks from the input text. These parallel operations are not possible in typical reaction time tasks and therefore the latencies in such tasks are the sum of the durations of all component processes instead of merely reflecting the durations of the last one or two processes, as in typing. Figure 2 illustrates the advantage of parallel processing in normal typing compared with the serial processing assumed to be characteristic of reaction time tasks.

2. Although typing is faster than reaction time, it is much slower than reading. Salthouse (1984a) found that two samples of typists averaged 246 and 259 words per minute when reading, but only 60 and 55 net words per minute, respectively, when typing. Butsch (1932) and Fuller (1943) also reported that the

SERIAL PROCESSES

	time —)			
INPUT	w		o	
PARSING	w		o	
TRANSLATION	H-L, F-2, R-U		H-R, F-3, R-U	
EXECUTION		PRESS		PRESS

PARALLEL PROCESSES

	time —)			
INPUT	w o r d			
PARSING	w-o-r-d			
TRANSLATION	H-L, F-2, R-U...H-R, F-3, R-U...H-L, F-2, R-U...			
EXECUTION		PRESS	PRESS	PRESS

Figure 2. Illustration of possible component contents with sequential and parallel processing. (In both cases the task is to type *word.* Movement specifications are expressed as L [left] or R [right] for hand, 1 [index] to 4 [little] for finger, and U [up], D [down], or 0 [no reach] for direction.)

eye movement patterns when typing were different from those when reading, with the former containing more, and longer, eye fixations than the latter.

This finding is simply interpreted as indicating that input processes are generally not responsible for limiting the maximum rate of typing. It is clear that at least the registration and perception of to-be-typed material can proceed at a much faster rate than that actually achieved in typing.

3. Across typists, there is no relation between typing skill and degree of comprehension of material that has been typed. Again, this result has been clearly demonstrated by Salthouse (1984a), where nonsignificant correlations were reported between net typing speed and comprehension scores obtained when typing (i.e., $r = -.169$, $p > .15$), and between net typing speed and the difference in comprehension when typing and when merely reading to take individual differences in reading ability into account (i.e., $r = -.214$, $p > .05$). The seemingly optional involvement of comprehension processes while typing was also confirmed by Marton and Sandqvist (1972). No differences in typing performance were found between typists instructed to type normally and those also instructed to think about what they were typing, despite significantly higher scores on a subsequent comprehension test by the "type-and-think" group compared with the "type-only" group.

An implication of these results is that reading and typing do not involve the same goals, and hence it is not necessary that they involve the same processes. That is, the purpose of reading is to comprehend the material, and consequently words or idea units must be fused or integrated to determine meaning. In typing, however, the goal is just the opposite of integration in that the words must be decomposed into discrete characters. Viewed in this context, it is not surprising that there is very little relation between typing speed and comprehension of what one has typed because typing ultimately requires parsing of words into individual letters, whereas reading requires integration of words into larger units of comprehension.

4. The rate of typing is nearly the same for random words as it is for meaningful text. This is an extremely robust phenomenon and has been reported many times over the past 50 years (e.g., Fendrick, 1937; Grudin & Larochelle, 1982; Hershman & Hillix, 1965; Larochelle, 1983; Olsen & Murray, 1976; Salthouse, 1984a; Shaffer, 1973, 1978; Shaffer & Hardwick, 1968; Shulansky & Herrmann, 1977; Terzuolo & Viviani, 1980; Thomas & Jones, 1970; West & Sabban, 1982). Perhaps the most convincing demonstration was by West and Sabban (1982) who examined typing rates for various kinds of material in 190 typists ranging in speed from 10 to 114 gross (uncorrected for errors) words per minute. They found that the mean gain for meaningful text over randomly arranged words was only 2.8%, and that there was little or no relation between the effect of coherent text and typists' skill. Salthouse (1985) also found that typing rates for normal text and randomly arranged words were correlated .99 across 29

typists of varying skill levels, with median interkey intervals of 174 and 178 ms for normal prose and random words, respectively.

As with the previous results, this finding can also be considered evidence that reading and typing involve fundamentally different processes. The fact that typing proceeds normally if the material has no syntactic or semantic relations implies that these properties are not important in typing. Cooper (1983) has also cited unpublished research that failed to find effects of phrase and clause boundaries on interkeystroke intervals, again suggesting that many linguistic factors are unimportant in normal typing. As stated earlier, it is plausible to assume that the input operation merely supplies the parsing mechanism with coded chunks of character sequences, and therefore the relation between successive chunks may be largely irrelevant for subsequent processing.

5. The rate of typing is slowed as the material approaches random sequences of letters. A variety of different techniques have been used to degrade the linguistic structure of material, but it is nearly always found that the average interkey interval in typing increases as the to-be-typed material becomes less structured or more random (e.g., Fendrick, 1937; Grundin & Larochelle, 1982; Hershman, & Hillix, 1965; Larochelle, 1984; Olsen & Murray, 1976; Salthouse, 1984a; Shaffer, 1973; Shaffer & French, 1971; Shaffer & Hardwick, 1968, 1969a; Terzuolo & Viviani, 1980; Thomas & Jones, 1970; West & Sabban, 1982). Material effects up to the word level may be partially attributable to the greater difficulty of perceiving and coding unfamiliar letter strings. The rate of typing could therefore be subject to limitations of input when, because of its unfamiliarity, the material has to be coded into very small and inefficient chunks. It is noteworthy that typing speed is slower with meaningless material even when digram frequency is controlled (Salthouse, 1984a), and when exactly the same digrams are contrasted in normal and random text (Terzuolo & Viviani, 1980). Larochelle (1984) has also reported that the time to initiate a keystroke is slower with meaningless material than with familiar words. These findings suggest that the component responsible for the effect of stimulus meaningfulness is different, and presumably occurs earlier in the processing sequence, than that responsible for the influence of digram frequency or for the initiation of overt movements.

6. The rate of typing is severely impaired by restricted preview of the to-be-typed material. This phenomenon was first noted by Coover (1923) who reported that

> If copy is presented one letter at a time, so that as soon as the letter is typed another automatically appears, the expert's performance is reduced to a series of reaction times to the letters, and his rate is greatly reduced. (p. 563)

This preview phenomenon has since been replicated and extended in reports by Hershman and Hillix (1965), Salthouse (1984a, 1984b, 1985), Salthouse and Saults (1985), and Shaffer and his colleagues (Shaffer, 1973; Shaffer & French, 1971; Shaffer & Hardwick, 1970).

The preview effect is generally interpreted as evidence of the necessity of overlapping processing operations in order to achieve the rapid rates characteristic of skilled typing. When overlap is prevented by restricting the preview of to-be-typed text, the rate of typing deteriorates because more and more of the processing has to be executed in a discrete, sequential mode. Figure 3 illustrates that there is a very systematic transition between performance characteristic of typing and performance characteristic of serial reaction time as the amount of preview is progressively decreased.

An alternative interpretation of the preview effect discussed by Shaffer (e.g., 1973; Shaffer & Hardwick, 1970) and Thomas and Jones (1970) is that typing proceeds by encoding the text into familiar chunks, and that restricting the preview impairs the ability to form meaningful input groups (see also Salthouse, 1984b). This argument is plausible when the text is normal prose, but it leads to the expectation that there should be no preview effect with random or otherwise meaningless material not amenable to chunking. In fact, however, sizable preview effects have been reported for random letters (Salthouse, 1984a; Shaffer, 1973; Shaffer & Hardwick, 1970), reversed text (Salthouse, 1984a), a foreign language unknown to the typist (Shaffer, 1973), and statistical approximations to English (Hershman & Hillix, 1965). It therefore seems reasonable to assume that the to-be-typed material is normally grouped into meaningful chunks, but that the consequences of restricted preview are more potent on reducing overlapped processing than on impairing chunk formation.

7. Successive keystrokes from fingers on alternate hands are faster than successive keystrokes from fingers on the same hand. This is another very well-documented phenomenon, one that has been confirmed in numerous reports (e.g., Coover, 1923; Fox & Stansfield, 1964; Gentner, 1981, 1982, 1983b; Grudin & Larochelle, 1982; Kinkead, 1975; Lahy, 1924; Larochelle, 1983, 1984; Ostry, 1983; Rumelhart & Norman, 1982; Salthouse, 1984a; Shaffer, 1978; Terzuolo & Viviani, 1980). Typists of average ability are generally between 30 and 60 ms faster when the preceding keystroke was on the opposite hand than when the preceding keystroke was on the same hand.

Many observers (e.g., Dvorak, Merrick, Dealey, & Ford, 1936; Gentner, 1981, 1983b; Larochelle, 1984; Olsen & Murray, 1976; Rumelhart & Norman, 1982; Terzuolo & Viviani, 1980) have interpreted this alternate-hand advantage by suggesting that with successive keystrokes on the same hand, there is little opportunity for advance preparation of following keystrokes, whereas when the opposite hand is involved in the preceding keystoke, the relevant finger can begin its motion toward the next key at the same time that the preceding key is being struck. Direct support for this view has been provided by Larochelle (1984) who found from analyses of videotape records that the initiation of a keystroke occurred 32 ms before the termination of the preceding keystroke for alternate-hand sequences but 39 ms after the prior keystroke for same-hand sequences.

8. Letter pairs that occur more frequently in normal language are typed faster than less frequent pairs. This diagram frequency effect has been reported many times (e.g., Dvorak et al., 1936; Grudin & Larochelle, 1982; Salthouse, 1984a, 1984b; Terzuolo & Viviani, 1980), although Grudin and Larochelle (1982) have pointed out that digram frequency may often be confounded with type of keystroke transition such that higher frequency digrams are more likely to involve fingers from alternate hands than fingers of the same hand. However, Grudin and Larochelle conducted an elegant analysis contrasting high- and low-frequency orderings of the same letter pair and found that frequency effects were evident even when type of transition was controlled. (See also Salthouse, 1984b, for a similar demonstration of a frequency effect unconfounded by type of finger or hand transition.)

The basic phenomenon therefore appears genuine even though prior estimates of its magnitude may be somewhat misleading.

A mechanism that may be responsible for many of the facilitative effects of frequency is more efficient overlapping and integration of translation and execution processes for highly practiced letter pairs. Grudin and Larochelle (1982) have described one example of this type of adjustment revealed by an analysis of videotapes of finger movements during typing. They focused on the retraction of finger movements, reasoning that

> If successive keys are being typed by the same hand, then when the hand pulls up from the keyboard after the first keystroke, the finger descending for the second must work against the upward movement of the hand . . . [and consequently the] finger travels a greater distance than it would have had the hand not retracted. (p. 17)

Grudin and Larochelle found that the *i* key was held down longer in the sequence *ion* than in the sequence *iet*, presumably because early retraction in the former case would delay subsequent keystrokes on the same hand (i.e., *o* and *n*), but not on the opposite hand (i.e., *e* and *t*).

High- and low-frequency digrams are therefore postulated to be different in the integration and coordination of the finger movements for the two keystokes in the letter pair. Higher frequency pairs are expected to have a smooth transition with the preparation for the next keystroke occurring during, and possibly even before, the execution of the present keystroke. In contrast, the keystrokes in low-frequency pairs are expected to be relatively independent of one another, with little or no adjustment of the fingers for the second keystroke during the preparation and execution of the first keystroke. At least part of this smoother and quicker transition between keystrokes may be attributable to a shift toward movement specifications expressed relative to the current finger positions rather than in terms of the home-row positions. That is, with experience the typists may be able to make direct movements from one key to another without a return to the home-row positions, such as moving from *r* to *t* without first pausing above *f*. Videotape analyses of novice and expert typists would allow an examination of this speculation, but the relevant data have apparently not yet been collected.

9. There is no systematic effect of word length on either the interkey interval between the space and the first letter in the

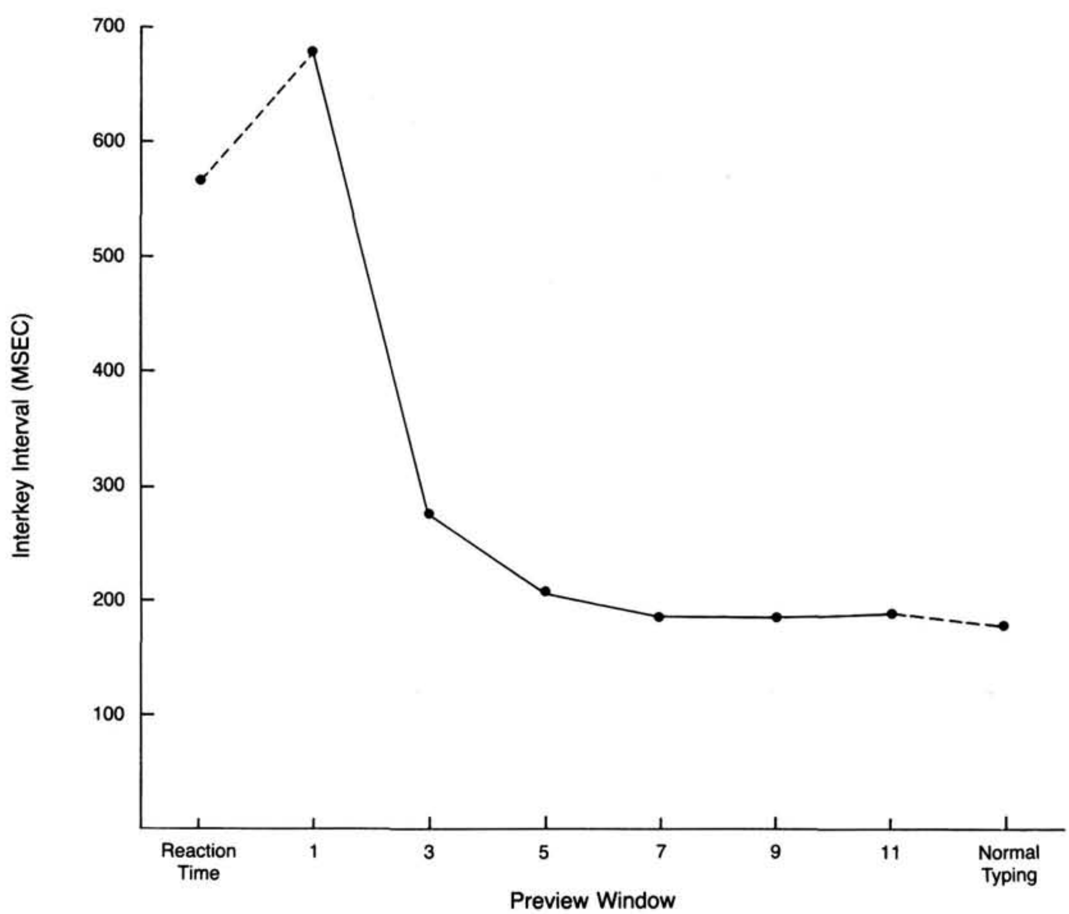

Figure 3 Median interkey interval as a function of number of visible characters during transcription typing. (The leftmost point represents choice reaction time [*Z* key for "*L*", / key for "*R*"], and the rightmost point represents typing from printed text. The remaining points derive from typing material displayed on a video monitor with the designated number of characters. Average results across the 74 typists in the Salthouse, 1984a, studies.)

word, or on the interkey interval between letters within the word. Although null effects are often not reported, the absence of a word-length effect in normal typing has been noted several times (e.g., Allen, 1981; Salthouse, 1984a, 1984b; Shaffer, 1978; Shaffer & Hardwick, 1968, 1969a; but see Ostry, 1983, for an exception).

The lack of an effect of word length is important because the presence of such an effect would constitute impressive evidence for the existence of motor programs corresponding to words. For example, Sternberg et al. (1978) have proposed a model in which the time of the initial keystroke and the time between successive keystrokes within the word are both predicted to increase with the length of the word. Their reasoning is that the retrieval time of the overall sequence, and possibly the time to execute units of that sequence, should be greater the greater the number of units in the sequence. In fact, data consistent with these predictions were obtained in discontinuous or burst typing tasks in which a string of characters or a word is presented and the typist is instructed to type the character string as rapidly as possible. However, somewhat different processes are apparently involved in continuous typing because the studies cited above indicate that no word-length effect is evident in transcription typing of normal prose.

10. The first keystroke in a word in normal continuous typing is generally slower than subsequent keystrokes in the word. This word-initiation effect has been reported by Ostry (1983), Sternberg et al. (1978), and Terzuolo and Viviani (1980), and was clearly documented by Salthouse (1984a, 1984b), where the interval before the first keystroke in a word was found to be approximately 20% longer than the interval between later keystrokes in the word. MacNeilage (1964) has also reported that the first keystroke in a word has a higher probability of several types of error than subsequent keystrokes in the word, suggesting that the word-initiation effect may be manifested in reduced accuracy as well as increased time.

This phenomenon may be attributable to either the parsing operation or the execution operation. The parsing influence could occur because the chunks produced by the input operation are probably grouped on the basis of words, and therefore the speed of isolating characters may be faster within, as opposed to between, these naturally occurring units. Execution processes might also be somewhat slower for the transition from the space character to the first letter of a word because the space bar is unique in being pressed by the thumb rather than by one of the fingers. That is, the space–letter transition may be slower than the letter–letter transition because of physical factors related to the musculature of the thumb relative to the fingers, or to the location and shape of the space bar compared with the letter keys.

Evidence against this latter interpretation, and in favor of a locus at higher levels of processing, comes from a study by Thomas and Jones (1970). They found that the first keystroke in a word was longer than the average interval for within-word keystrokes even when the typists were instructed not to reproduce spaces in their typing of the passage. Furthermore, in another condition they found that the first keystroke in the word was longer when the text did not contain any spaces between words but was instead presented as a continuous stream of letters with typists instructed not to produce spaces in their typed output. These findings suggest that the existence of words is apparently a sufficient condition for the word-initiation effect, and that the pressing of the space bar is not necessary for its occurrence.

11. The time needed to produce a keystroke is dependent on the specific context in which the character appears. Basically this statement means that the interkey interval for a given character is not constant, but varies systematically as a function of the characters that precede it, and possibly those that follow it. Specific examples have been provided by Salthouse (1984b), Shaffer (1973, 1978), and Terzuolo and Viviani (1980).

This context phenomenon can be at least partially explained by means of the same mechanisms discussed earlier in connection with the alternate-hand advantage, the digram-frequency effect, and the word-initiation effect. That is, the time for a specific character will vary in different contexts because the character: (a) is sometimes preceded by a keystroke on the alternate hand and sometimes by a keystroke on the same hand, (b) is sometimes preceded by a letter that produces a high-frequency digram and sometimes preceded by one that produces a low-frequency digram, and (c) is sometimes the first character in a word and other times is in an interior or terminal position within the word. Although distinctive latency profiles for particular words have sometimes been interpreted as evidence for word-length motor programs (e.g., Harding, 1933; Terzuolo & Viviani, 1980), Gentner (1982, 1983b), Rumelhart and Norman (1982), and Shaffer (1973, 1978) have maintained that these profiles can be explained on the basis of local context effects primarily involving the structure of the hand and topography of the keyboard interacting with prior and subsequent keystrokes.

Of greater theoretical interest than the mere existence of the context effect is the length of the keystroke sequence over which such an influence is found to operate. Because these context effects can be presumed to originate primarily in the translation and execution operations, they can be interpreted as a reflection of the amount of advance preparation carried out for forthcoming keystrokes. That is, if there is an effect of context n characters in advance of a given character, then at least $n + 1$ characters (the current one and the preceding n characters) must be simultaneously available for processing in the translation and/or execution mechanisms. The maximum sequence at which contextual effects are observed thus provides an estimate of the buffer size of either the translation or execution processing operations.

The range of context effects is also interesting from the perspective of models proposing that typing proceeds via the retrieval and execution of motor programs for familiar letter sequences such as words (e.g., Leonard & Newman, 1965; Terzuolo & Viviani, 1980). The motor-program view maintains that the spatiotemporal parameters of the finger movements required for a specific character sequence are stored in memory as an integrated unit rather than being generated on-line during execution. However, the sequence length over which context effects are evident is still informative about the maximum size of the relevant units, which in this case would be motor programs.

Several studies have indicated that the maximum length over which context effects are evident in skilled typists is only two to three characters. Shaffer (1978) reported that the interkey interval for a given character was different when the character two keystrokes before the character was varied and the intervening characters were constant, suggesting that there was a context effect extending over at least three characters. However, his data were based on a single highly skilled typist and therefore the generality of this finding was unclear. Gentner (1982, 1983b) considered a greater number of typists and more alternative contexts. He reported that the variability of interkey intervals appeared to decrease as the amount of prior context was increased from zero to two characters, implying that the context effect may extend to three keystrokes. Very similar results were obtained by Salthouse (1985), in which typists ranging in skill from 18 to 113 net words per minute were found to be sensitive to prior context only up to an average of 1.76 characters in advance of the keystroke.

12. With highly skilled typists, a concurrent activity can often be performed with little or no effect on speed or accuracy of typing. This phenomenon has been described in many anecdotal reports, including the claims that some expert typists can converse in one language while typing technical material in another language, or can add 10 numbers while typing at championship speed (Dvorak et al., 1936, p. 128). Shaffer (1975b) provided the most detailed descriptions of this phenomenon by reporting that the distribution of interkey intervals for typing visually presented prose was only slightly displaced when the typist simultaneously recited nursery rhymes or shadowed auditorily presented prose. Salthouse and Saults (1985) have recently demonstrated that this phenomenon is generalizable throughout a large range of skill levels by measuring reaction time performance alone and while simultaneously typing. As might be expected, the amount of interference in reaction time was negatively correlated with typing skill (i.e., $r = -.34$ for the difference in reaction times and $r = -.38$ for the ratio of the two reaction times), indicating that higher skill was associated with less dual-task interference.

There are apparently some limits on the types of activities that may be performed while concurrently typing because Shaffer (1975b) reported sizable disruption of typing from auditorily presented text if the typist was attempting to read aloud a different, visually presented text. Factors responsible for determining exactly when interference occurs have not yet been precisely identified, however, and the generality of this qualification is unknown because Shaffer's (1975b) data were derived from only one highly skilled typist.

The explanation for the concurrent-task phenomenon seems to be based on the well-accepted principle that tasks become automatic and less demanding of cognitive resources as they are extensively practiced. Further research of the type begun by Shaffer (1975b) is necessary to explore the limits of this automaticity, and to determine exactly which component processes are independent of attention demands. However, the basic finding that a highly overlearned perceptual-motor task can be performed with little or no decrement from other concurrent activities should not be considered surprising from the perspective of any model of skilled typing.

Units of Typing

There is no single unit of typing because each processing component is presumed to operate with different levels or types of information. The bottom panel of Figure 2 illustrates the nature of the information assumed to be transmitted from each hypothesized component to the next. The input phase holds the text in several easily remembered chunks, and thus the unit here might be the word or phrase. However, words are presumed to be decomposed into discrete characters by the parsing process, and therefore the individual letter might be considered the functional unit in this component. Because the translation and execution components are postulated to deal with the specification and performance of movements in as smooth and integrated a fashion as possible, it would be arbitrary and misleading to isolate a single unit in what appears to be a continuous flow of movement activity. In this section I describe the major empirical phenomena supporting this characterization of the multiple units of typing.

13. The copying span, defined as the amount of material that can be typed accurately after a single inspection of the copy, ranges from about two to eight words, or 7–40 characters. Rothkopf (1980) measured copying span by determining the number of characters typed between successive glances at the to-be-typed copy. He found that the copying span for 5 highly skilled typists averaged about 40 characters, or nearly eight words. However, because Rothkopf's typists were required to commit the to-be-typed material to memory before beginning to type, it is likely that the mode of input processing was not typical of that used in transcription typing, where the source material is continuously available. A related procedure, although generally yielding smaller estimates, involves determining the number of characters that can be typed correctly after an unexpected disappearance of the copy. Salthouse (1985) found that an average of 13.2 characters could be typed under these conditions, and that in nearly 87% of the cases the copying span terminated in a complete word. Still smaller copying spans, averaging 6.6 characters, were obtained in a study by Salthouse and Saults (1985) in which randomly arranged words were used as the source material.

It seems reasonable to conjecture that the copying span has its origins in the input operations in that it reflects the chunked output of the initial stage of input processing. This span may correspond to the approximate working memory capacity of the typist, expressed in discrete chunks generally corresponding to separate words. Just as is the case with memory tasks, however, the size of the chunks appears to be dependent on the familiarity of meaningfulness of the material.

14. The stopping span, defined as the amount of material to which the typist is irrevocably committed to typing (Logan, 1982), averages only one or two keystrokes. Stopping span can be measured in one of two ways, and both yield nearly identical results. Logan (1982) and Salthouse and Saults (1985) have conducted a direct assessment of the stopping span by requesting typists to terminate their typing immediately after perceiving a stop signal. Several different types of stop signals were used in Logan's experiments, but in all cases the typist was able to stop within about two keystrokes of the signal. Moreover, the stopping span was found to be the same for early, middle, and late positions in the word and for words of varying length, indicating that the units of response commitment are generally smaller than a word. Stopping span was also assessed in a recent study by Salthouse and Saults (1985), where it was found to average 1.4 characters, a value quite consistent with Logan's findings.

A similar inference about the number of units of response commitment is reached when typists are asked to correct their errors (Long, 1976; Shaffer & Hardwick, 1969b), or to type a special symbol when an error is noticed (Rabbitt, 1978). In the large majority of the cases, the error is noticed and responded to within one or two keystrokes. Moreover, error detection may sometimes be almost instantaneous because Rabbitt (1978) and Wells (1916) have reported that erroneous keystrokes are frequently weaker than correct keystrokes, implying that the keystroke is partially inhibited while still in progress.

Examination of the timing of keystrokes preceding and following errors also leads to the same conclusion about the magnitude of the stopping span. Very often the keystroke immediately after an error is much slower than keystrokes preceding the error or than the average keystroke (e.g., Grudin, 1982; Salthouse, 1984a, 1984b; Shaffer, 1973, 1975a; Wells, 1916; see also Table 3). This posterror slowing has been interpreted as an indication that the typist is aware of the error, and pauses momentarily before resuming normal typing. The important point for the present argument is that the lengthier interval after an error is nearly always on the immediately following keystroke, and seldom occurs on keystrokes more than two removed from the error. Detection of an error can therefore be considered equivalent to a pause signal, and the finding that the hesitation response is evident within one or two keystrokes is thus consistent with the results obtained with the stop-signal technique.

A probable locus of the stopping span is in the execution operation. The translation process is postulated to supply the movement specifications to the execution process and also to monitor the successful implementation of those specifications. If an error is detected or an overt stop signal is presented, the translation operation may be temporarily interrupted and no more material delivered to the execution phase. The stopping span can therefore be interpreted as a reflection of the size of the execution buffer, which probably contains detailed parameters of movements that are no longer subject to much control or modification. It is noteworthy that the two measures presumed to indicate the capacity of the execution buffer, the maximum sequence exhibiting sensitivity to prior context and the stopping span, both average between one and two characters.

The small size of the stopping span presents obvious problems for models postulating the existence of word-length motor programs because typists appear to have precise control over single, or perhaps double, keystrokes. Either the motor programs must involve fewer than three keystrokes, or they must be easily interruptible, and not autonomous and ballistically executed, as sometimes proposed.

15. The eye–hand span, defined as the amount of material intervening between the character receiving the attention of the eyes and the character whose key is currently being pressed, ranges between three and seven characters for average to excellent typists. As with the copying and stopping spans, two different procedures have been used for determining eye–hand span. The most direct technique has been to record eye movements when a person is typing and then to synchronize the eye movement and typing records to determine the position of the eye at the time of each keystroke. Butsch (1932) used this technique and reported that the eyes average about five characters ahead of the finger for moderately skilled typists.

The second technique for determining eye–hand span makes use of the restricted preview procedure in which the rate of typing is examined with systematically varied amounts of preview of the to-be-typed material. An estimate of the eye–hand span can be derived from the smallest preview size at which the typing rate first reaches its asymptotic speed. The reasoning is that if the rate of typing is disrupted with less than this number of characters visible on the display, then the typist must rely on the availability of at least that many characters in normal typing. Hershman and Hillix (1965), Salthouse (1984a, 1984b, 1985), and Shaffer (1973) have all reported that between three and eight characters were needed for moderately skilled typists to achieve a typing rate equivalent to that produced with unlimited preview (cf. Figure 3).

Although most researchers have agreed with Butsch (1932) that the eye–hand span emerges because the eye "keeps far enough ahead to provide copy for the hand as it is needed" (p. 113), the locus of the eye–hand span is still a source of controversy. One possibility, explicitly advocated by Salthouse (1984a), is that it originates in the parsing process as a consequence of the need for a continuous flow of information to the translation and execution operations. From this perspective, therefore, the eye–hand span is considered an adaptive mechanism whose purpose is to ensure efficient, uninterrupted processing concerned with the specification and execution of movement sequences. Although some theorists (e.g., Logan, 1983) have speculated that the eye–hand span may simply be a reflection of a disparity in the buffer capacities of different stages of processing, this view would not account for the finding that typing rate is impaired when preview is restricted below the critical span amount. That is, a mere mismatch in the size of buffer memories in different processes would not explain the apparent necessity of having at least the span amount of material visible while typing.

An alternative view shared by Logan (1983) and Shaffer (e.g., 1973, 1978; Shaffer & French, 1971; Shaffer & Hardwick, 1970) is that the eye–hand span has a locus after the translation component. However, a difficulty with the proposal that the contents of the eye–hand span are translated response codes is the existence of a stopping span distinct from the eye–hand span. The stopping span seems to involve character codes translated into movement specifications, and thus to assert that the eye–hand span also involves similar forms of representation necessitates a separate explanation of the discrepancy between the magnitudes of the eye–hand span and the stopping span.

16. The eye–hand span is smaller for unfamiliar or meaningless material than for normal text. Hershman and Hillix (1965) and Salthouse (1984a) have both demonstrated this phenomenon with comparisons of normal text and random sequences of letters. The 40 typists in the Salthouse study for whom spans were determined with both kinds of material had an average eye–hand span of 3.45 characters with normal text, and an average eye–hand span of only 1.75 characters with random text.

This phenomenon is interesting from a theoretical perspective because whereas unfamiliar material would be presumed to be coded in smaller sized chunks, the eye–hand span is postulated to reflect operations of the parsing, translation, and execution mechanisms and not the input mechanism. According to this view, smaller eye–hand spans with unfamiliar material must therefore be due to one or more of the following: (a) slower parsing of the unusual chunks, (b) less efficient translation of individual characters into movement specifications, or (c) poorly coordinated sequences of finger motion. Slower parsing might occur because unfamiliar letter groupings, by definition, do not have the predictability or redundancy of meaningful words, and it is possible that the partitioning of multicharacter groups into individual characters is facilitated when these properties are present. Translation and execution processes may be less efficient with unfamiliar material because the movements or their specifications extend beyond the single keystroke. If the degree to which the transition between successive keystrokes approaches optimality is related to the frequency of typing those keystrokes in the past, less familiar material might be translated and executed slower than more familiar material simply because there are fewer high-frequency sequences in unfamiliar material.

17. Typists appear to commit themselves to a particular character approximately three characters in advance of the current keystroke. This inference is based on the results of a replacement span procedure introduced by Salthouse and Saults (1985). Subjects are instructed to type exactly what appears on a video display, but at unpredictable intervals one of the characters is replaced by a different character. The probability of typing the second (replaced) character systematically decreases as the replacement occurs closer to the keystroke, and the replacement span is defined as the keystroke-replacement interval corresponding to a .5 probability of typing the second character. Because typists are apparently insensitive to display changes within the replacement span, the replacement span can be assumed to reflect the point at which typists commit themselves to particular characters. Salthouse and Saults (1985) found the replacement spans to average 2.8 and 3.0 characters in two studies involving 45 and 40 typists, respectively.

One plausible interpretation of the replacement span is that it represents how far in advance of the keystroke information is passed out of the parsing component. The fact that its average value is intermediate between the eye–hand span and the stopping span is consistent with this view in that the former value may reflect when information enters the parsing component, whereas the latter value corresponds to the contents of the subsequent execution, and possibly translation, buffers.

Errors

The vast majority of typing errors can be classified into four categories originally proposed by Wells (1916): substitutions, intrusions, omissions, and transpositions. The frequencies of each type of error from several studies are tabulated in Table 1. Because these categories include most of the classifiable errors, I focus the present discussion on only these four categories. However, other types of errors almost certainly exist and may be mistakenly classified into one of the above categories. For example, Lashley (1951) claimed that a frequent typing error is an anticipation of a character that actually occurs later in the to-be-typed sequence. Depending on the extent of the anticipation and the typists' adjustment to the initial mistake, the resulting keystrokes could be classified as any of several types of error. That is, the error would be identified as an intrusion if the anticipated keystroke is the only erroneous keystroke, whereas it would be classified as a transposition error if the anticipated character is the immediately following character and the typist then attempts to remedy the wrong sequence by typing the omitted character. The four categories of errors should therefore not be considered exhaustive, but rather as representing classifiable patterns of keystrokes that, when taken together, encompass a large proportion of misstrokes in transcription typing.

Table 1
Percentages of Single Errors

			Error category			
Source	GWPM	Overall error	Subs	Intr	Omis	Trans
Grudin (1983a)	20	3.2	75	9	4	4
	75	1.0	23	43	14	7
Salthouse (1984a)	61	2.4	21	36	35	8
	64	1.6	22	36	35	7
Salthouse (1985a)	68	1.7	32	41	18	10

Note. GWPM = gross number of words typed per minute. Subs = substitution (e.g., wor*k* for word). Intr = intrusion (e.g., wor*r*d for word). Omis = omission (e.g., *wrd* for word). Trans = transposition (e.g., w*ro*d for word).

18. Only from 40% to 70% of typing errors are detected without reference to the typed copy. This finding has been reported by Long (1976), Rabbitt (1978), and West (1967). The results of the West study are particularly impressive because they were obtained from a large number of typists with a wide range of skill levels. Although there was a slight increase in the percentage of detected errors among typists with speeds from 9 to 30 words per minute, it remained relatively constant at 45% in the skill range from 30 to 108 gross words per minute.

The fact that all errors are not detected without looking at the typed copy suggests either that different mechanisms are responsible for producing errors, or that the mechanism that detects errors is itself faulty. Although there are apparently no data pertinent to the reliability of a mechanism specialized for error detection, it seems likely that different processes contribute to typing errors. Specifically, because error detection is probably handled by the translation mechanism monitoring the correspondence between afferent movement specifications and efferent response feedback, undetected errors can be postulated to originate at earlier levels of processing.

Table 2 illustrates possible determinants for each type of error, with potential origins within or between each of the four processing components. Of course, one conceivable source of errors is in the input phase, in which misperceptions could result in incorrect material being coded for further processing. Substitutions of entire words, particularly when the erroneous word is a synonym of the original word, are especially likely to originate in the input phase of processing because confusion at the semantic level seems plausible only in the input component of processing.

Another possible source of errors is in the parsing and translation processes, where multicharacter chunks are decomposed into discrete characters and then converted into movement spec-

Table 2
Proposed Causes of Errors

Component	Error type			
	Subs	Intr	Omis	Trans
Input	Perceptual confusion	Perceptual confusion	Perceptual confusion	Perceptual confusion
Parsing	Capture by high-frequency digram	—	—	—
	Failure to preserve sequence	Failure to preserve sequence	Failure to preserve sequence	Failure to preserve sequence
Translation	Faulty assignment of movement specification	Failure to deactivate prior character	Inhibition of code by recent deactivation	—
	Failure to preserve sequence	Failure to preserve sequence	Failure to preserve sequence	Failure to preserve sequence
Execution	Misplaced finger positions	Simultaneous depression of two adjacent keys	Inadequate force or reach on keystroke	Keystroke preparation out of sequence
	Inaccurate movement trajectory	—	—	—

Note. Subs = substitution (e.g., wor*k* for word). Intr = intrusion (e.g., wor*r*d for word). Omis = omission (e.g., *wrd* for word). Trans = transposition (e.g., w*ro*d for word).

ifications. Because the information in these operations consists of an ordered sequence, it is conceivable that some errors occur because of a failure to preserve the proper ordinal positions as the character information is passed from one processing operation to the next. Also, following Lashley (1951), both Shaffer (1975a; Shaffer & Hardwick, 1968) and Rumelhart and Norman (1982, 1983) have pointed out that repetition of the incorrect letter in a string (e.g., *aat* instead of *att*) "suggests that double letters are stored as a single letter together with a repeat label which . . . may get displaced" (Shaffer & Hardwick, 1968, p. 368). In addition to doubling errors, reversals of an alternating sequence (e.g., *thses* instead of *these*) and transposition errors (e.g., *wrod* instead of *word*) are particularly likely to originate as sequence failures, although substitution, intrusion, and omission errors might also be produced in this manner.

In the following paragraphs I describe an empirical phenomenon associated with each category of error, and in offering an explanation of the phenomenon, discuss a dominant cause of that type of error. For purposes of illustration, I report analyses of the isolated errors (i.e., an error preceded and followed by correct keystrokes) committed by typists during transcription typing from printed text in the Salthouse (1984a, 1985) studies. These 103 typists ranged from 20 to 120 gross words per minute, and between 0.1% and 8.0% of their total keystrokes were errors.

Before discussing the causes of specific types of errors, it is instructive to consider why an error of any type would be committed. One possibility, often mentioned in the typists' introspective reports, is that the speed of typing increased beyond the rate at which proper control could be exerted. An implication of this interpretation is that the intervals for keystrokes preceding an error should be shorter than the median interval across all keystrokes. Data relevant to this hypothesis are presented in Table 3, which contains averages of the interval for a given keystroke relative to the median interval across all keystrokes. (Expressing the values in ratios of this form serves to normalize the data and thereby facilitate comparisons across typists of different speeds.)

The important point to be noted from these data is that only with the omission and transposition errors are the ratios for the intervals preceding the errors (E − 1, E − 2, and E − 3) consistently less than 1.0, suggesting that the occurrence of an error may be associated with unusually short intervals in the immediately preceding keystrokes. As will be discussed later (Phenomena 21 and 22), the "out-of-control" interpretation has some plausibility for both the omission and transposition errors because the dominant cause of each could be produced by an attempt to perform faster than one's capabilities. However, some other mechanism is apparently necessary to explain the occurrence of substitution and intrusion errors because there is no evidence that the keystrokes preceding these types of errors are any faster than the average keystroke.

19. Many substitution errors involve adjacent keys. Grudin (1983a, 1983b) demonstrated this phenomenon convincingly in analyses of his own data and reanalyses of confusion matrix data reported by Lessenberry (and reproduced in Grudin, 1983a). Results from highly skilled typists indicated that from 31% to 59% of substitution errors involved horizontally adjacent keys, and between 8% and 16% involved vertically adjacent keys. Values from the typists in the Salthouse studies were that 35% of all substitution errors involved a horizontally adjacent key, and 17% involved a vertically adjacent key.

Shaffer (1975a, 1976) and Grudin (1983a) proposed that many substitution errors occurred because of a faulty assignment of the movement specifications at the finger level. Grudin argued that the error originated in the assignment rather than execution phase because an analysis of videotapes revealed that the incorrect keys were pressed by the fingers that normally struck them rather than by the "correct" finger with an inappropriate movement trajectory. In other words, his evidence suggests that many substitution errors are caused by proper motion of the wrong finger instead of improper motion of the correct finger. Many years ago, Wells (1916) also noted that "the false strokes are generally effective strokes at wrong keys; inaccurate fumbling strokes at right keys play an insignificant part" (p. 59). The errors are therefore consistent with a mistake in finger assignment and not with a mistake in the execution of the finger movement. Hence, their locus is probably in the translation phase of processing because of an error in specifying the parameters of the movements.

The faulty-assignment interpretation of substitution errors also predicts the existence of errors in which the hand was mis-

Table 3
Median Interval Ratios for Keystrokes Surrounding Errors

Error	*n*	Keystroke E − 3	E − 2	E − 1	E1	E2	E + 1
Substitution	506	1.00	1.00	0.97	1.11	—	1.10
Intrusion	730	1.00	1.00	1.00	0.68	—	0.87
Omission	600	0.94	0.96	0.96	—	—	1.54
Transposition	177	0.95	0.96	1.00	1.15	0.77	1.33

Note. Values are medians of the ratio of the interval for a particular keystroke relative to the median interkey interval across all keystrokes for that typist. A value of 1.00 therefore signifies that the median interval for that keystroke was exactly the same as the median interval across all keystrokes. The erroneous keystroke is designated E1 (and E2 in the case of transposition errors) with preceding keystrokes designated E − 1, E − 2, and so on.

specified, and Book (1925), Grudin (1983a, 1983b), Munhall and Ostry (1983), and Wells (1916) have all reported that errors with the corresponding finger of the opposite hand do occur more frequently than might be expected by chance (estimated by Grudin, 1983a, 1983b, to be 3%). Approximately 15% of the total substitution errors by the typists in the Salthouse studies involved homologous fingers on the opposite hand.

Another probable source of substitution errors, particularly among novice typists, is mispositioning of the hands and fingers above the keys. Indeed, Long (1976) found that the frequency of substitution errors increased when typists were prevented from seeing the keyboard during typing, thereby directly implicating inappropriate positioning as a cause of substitution errors. It has also been suggested (e.g., Dvorak et al., 1936; Grudin, 1983a) that more frequent digrams occasionally disrupt or displace less frequent digrams such that a character forming a digram of higher frequency is substituted for the original character, which is a member of a lower frequency digram. In support of this speculation is the finding that over 67% of the substitution errors in the Salthouse studies resulted in a digram of higher frequency than that which would have resulted from the original character. The origin of this type of substitution error is most likely in the parsing component because frequency effects are assumed to be primarily operative in this phase of processing.

20. Many intrusion errors involve extremely short interkey intervals in the immediate vicinity of the error. This phenomenon is reflected in Table 3 in the median ratios considerably less than 1.0 for the error keystrokes (E1) and the immediately following keystroke (E + 1).

The fact that a large proportion of the intervals around an intrusion error are much shorter than average is interpreted as being caused by the nearly simultaneous contact of two adjacent keys by a finger imprecisely positioned above the target key. In support of this interpretation are the findings in the Salthouse data that nearly 38% of the intrusion error keystrokes had ratios less than 0.1, and that over 54% of all letter intrusion errors involved an adjacent key in the same row or column as either the preceding or following key. Further, 60% of the adjacent intrusions had interval ratios of less than 0.1. More direct evidence, although based on rather small amounts of data, is available in Grudin's (1983a) report that most intrusion errors examined in his videotape analyses involved two keys struck by the same finger. The likely locus of this phenomenon is therefore in the execution component because it is assumed to be the result of faulty implementation of the keypress (i.e., movement trajectory).

Another possible source of intrusion errors is inadequate deactivation of the prior keystroke. This is inferred from the finding in the Salthouse studies that nearly 16% of all intrusion errors, and over 34% of all nonadjacent intrusion errors, consist of the repetition of the immediately preceding character. Only a very small number of these repetition errors had interval ratios less than 0.1, and hence the percentages for which keyboard bounce or finger tremor can be ruled out are 14% and 30% for all intrusion errors and nonadjacent intrusion errors, respectively. Failure to deactivate the prior keystroke probably occurs in either the translation or execution component of processing.

21. Many omission errors are followed by a keystroke with an interval approximately twice the overall median. This phenomenon has been described by Shaffer (1975a), and is evident in the median ratio of 1.54 for the E + 1 interval in Table 3. Shaffer (1975a) suggested that the longer posterror interval is consistent with insufficient depression of the keystroke for the omitted character such that its latency is incorporated into the interval for the following keystroke. In keeping with this interpretation, Dvorak et al. (1936) claimed that omission errors are more frequent on keys that are difficult to reach, like *m* and *n*. Figure 4 confirms this suggestion in demonstrating that the relative frequency of an omission varies with the location of the key. In particular, characters involving the little finger of each hand have a much greater likelihood of being omitted than characters struck by the index finger of each hand. Although not indicated in the figure, the space character was also omitted over twice as frequently as its occurrence probability would lead one to expect. This may also be due to inadequate reach or pressure on the key.

In addition, it has been suggested by Grudin (1983b) and MacNeilage (1964) that some omissions might occur because the character recently occurred in the text and was somehow inhibited from being repeated. In fact, Grudin (1983b) claimed that 60% of all omissions had the omitted letter in the immediate context, and that for 42% of the omissions of the first letter of a word, the omitted letter was one of the three preceding letters. However, analyses of the omission errors committed by the typists in the Salthouse studies failed to confirm this finding. Of the 370 total omissions excluding the space bar, only 24, 25, and 21 had the omitted character in the E − 1, E − 2, and E − 3 positions, respectively. The cumulative percentage of the omitted letter in one of the preceding three character positions was therefore only 19%, substantially less than the figure reported by Grudin and probably not much different than the percentage of letters expected to reappear within four character spaces. Inhibition of the keystroke because of recent activation of the character code therefore cannot be considered well established on the basis of the currently available evidence.

22. Most transposition errors are cross-hand rather than within-hand. Shaffer (1975a) and Grudin (1982, 1983b) have both reported this phenomenon. Shaffer (1975a) found that in all but 3 of 128 transposition errors the transposed letters were

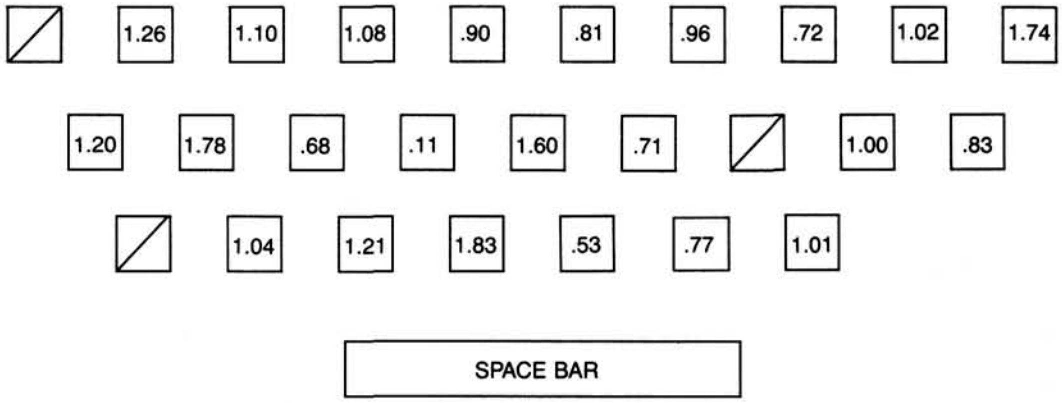

Figure 4. Relative omission frequency (i.e., number of errors per number of letter occurrences) for all lowercase letters with more than five occurrences in the source text. (Data collapsed across all subjects in the Salthouse, 1984a, 1985, studies.)

on different hands. The percentage of total transposition errors that involve fingers on opposite hands reported by Grudin was 78%, compared with a chance value (based on the frequency of cross-hand vs. within-hand digrams) of approximately 53%. The corresponding percentage from the Salthouse studies was 80%.

The simplest explanation of this phenomenon is provided by Grudin (1983b), who stated, "The second letter has more freedom to reach its key early if it is on a different hand" (p. 136). That is, successive keystrokes made with opposite hands are faster than those made with the same hand, presumably because of more extensive overlapping of operations in the former case, and thus the preparation of the following character may be completed at or before the execution time of the current character.

One possible difficulty with this interpretation is that it leads to the expectation that the interkey intervals for transposition errors should be quite short. That is, if transposition errors are produced because of an occasional upset in the race for execution, one would predict that the out-of-order keystrokes should have a very short interkey interval. However, Grudin (1982) has claimed that the timing pattern of transposition errors is much like what would be produced with normally sequenced keystrokes, implying an origin at relatively early stages of processing. Unfortunately, the available data are inconsistent on this issue. Shaffer (1975a) found that the intervals for keystrokes in transposition errors were nearly the same magnitude as normal keystrokes for his single highly skilled typist, whereas the data from the Salthouse studies (cf. Table 2) indicate that the median interkey interval for the second keystroke in the transposed sequence is only about 77% the value of the overall median. It therefore seems reasonable to conclude that at least some of the transposition errors are due to out-of-sequence completion of keystroke preparation, although other factors are probably involved in a certain proportion of errors of this type.

Skill Effects

One of the most intriguing questions in any skilled activity is what are the experts doing differently than the novices that contributes to their superior performance? In this section I summarize some of the empirically established differences related to typing skill and how they might be interpreted in terms of the four hypothesized processing components.

23. Digrams typed with two hands or with two different fingers of the same hand exhibit greater changes with skill than do digrams typed with one finger. Gentner (e.g., 1983a, 1983b) has reported this phenomenon several times, and it has also been described by Salthouse (1984a). The slopes of the regression equations relating digram interval in milliseconds to net words per minute for the 74 typists in the Salthouse (1984a) studies were two-hand digrams: −2.08; two-finger digrams: −2.38; one-finger digrams: −1.91; and one-letter digrams: −0.85.

The explanation for this phenomenon seems to be that a large part of skill acquisition in typing consists of learning to overlap and coordinate the movements of successive keystrokes. Because overlapping is only possible with successive keystrokes made by different fingers, the absolute amount of improvement can be expected to be much greater for two-hand and two-finger digrams than for digrams made by the same finger.

24. The rate of repetitive tapping is greater among more skilled typists. Both same-finger and alternate-hand tapping rates were examined in the Salthouse (1984a) studies, and in each case faster typists had shorter interkey intervals in finger tapping. Correlations between tapping rate and net typing speed were −.42 ($p < .01$) for alternate-hand tapping, and −.32 ($p < .01$) for same-finger tapping. This phenomenon is also evident in an increase in the rate of executing one-letter digrams or letter doubles. The data reported above indicate that whereas the skill-digram interval slopes are larger for digrams typed with two different fingers, there is still a sizable relation between overall skill and typing rate for repeated letters. Greater typing skill is also associated with shorter interkey intervals under conditions of single-character preview. The correlation among the 74 typists in the Salthouse (1984a) studies was −.51 ($p < .01$), indicating that the more skilled typists were also much faster than less skilled typists at making keystrokes to individually presented characters.

Skill-related increases in the efficiency of repeating exactly the same finger movement or in making discrete keystrokes suggests that the precision and coordination of basic execution processes improve with increased skill. Shaffer and Hardwick (1968) therefore appear to have overstated the case in claiming that "finger dexterity and overlearned associations between letters and finger movements play only a small part in the typist's skill" (p. 360). Indeed, the faster speed of translation and execution might even be considered to drive or motivate the increase in eye–hand span associated with increased skill (cf. Salthouse, 1984a).

25. The variability of interkey intervals decreases with increased skill of the typist. At least two types of variability can be distinguished in typing, and both have been reported to be smaller among faster typists. One type is interkeystroke variability, in that it refers to the distribution of interkey intervals across different keystrokes and different contexts. The interquartile range of interkey intervals across all keystrokes typically averages between 70 and 80 ms for average typists, but correlates −.69 with net typing speed, and decreases about 1.5 ms for every net word per minute increase in speed (data from Salthouse, 1984a).

The second type of variability is intrakeystroke variability or repetition variability. This is the distribution of interkey intervals for the same keystroke in the same context, but across multiple repetitions. Average interquartile ranges for same-keystroke intervals are about 33 ms, correlate −.71 with typing skill, and decrease about 0.5 ms for every net word per minute increase in overall speed (data from Salthouse, 1984a).

It can be postulated that this reduced variability is partly attributable to greater precision of movement specifications with increased skill, partly to better coordination of movement execution, and at least partly to improved synchronization of all processing components. Movement specification and execution processes are presumably involved because the tapping and intrakeystroke results are unlikely to originate from higher levels. Hesitations and pauses evident in beginning typing are eliminated and interkeystroke variability consequently reduced by more precise synchronization of the content and timing of successive processing operations.

26. The eye–hand span is larger with increased skill. This phenomenon was first reported by Butsch (1932), and has subsequently been confirmed and extended by Salthouse (1984a, 1985), and Salthouse and Saults (1985). In the Salthouse (1984b) studies, the correlation between eye–hand span and net words per minute across 74 typists was .51 ($p < .01$). Parameters of the regression equation indicated that every 20 net words per minute of typing speed was associated with an increase of approximately one character in eye–hand span. These results have also been replicated by Salthouse (in press) and Salthouse and Saults (1985), where the regression slopes indicated an increase of between 0.5 and 1.2 characters with every 20 net words per minute increase in skill. Salthouse (in press) has also demonstrated in a longitudinal study that the size of the eye–hand span increases as individuals become more skilled in a sequential keying task designed to be similar to the activity of typing.

The increase in eye–hand span with increased typing speed is consistent with the assumption that the span originates in order to ensure a continuous supply of information to the translation and execution mechanisms. As these mechanisms increase in speed there will be an increased demand for an uninterrupted flow of information and therefore the eye–hand span will expand. The maximum size of the eye–hand span among the 103 typists in the Salthouse studies was only seven characters, however, and thus it can be inferred that structural factors related to memory capacity set upper limits on the amount of information that can be simultaneously held in any of the processing buffers.

27. The replacement span, indicating how far in advance of the current keystroke the typist commits to a particular character, is larger among more skilled typists. Correlations between net words per minute and replacement span in the Salthouse and Saults (1985) studies were .46 and .80 (both ps $< .01$), and the regression equations indicated that the replacement span increased by about one character with every 30 net words per minute increase in skill.

Interpretation of the skill effects on replacement span is similar to that with eye–hand span because both are assumed to correspond to processing in the parsing component. It seems indisputable that greater preparation for forthcoming keystrokes is an important concomitant of typing skill.

28. The copying span is moderately related to typing skill. Salthouse (1985a) found that his 29 typists exhibited a correlation of .35 between net words per minute and copying span, and Salthouse and Saults (1985) reported a correlation of .57 in a study with 40 typists.

Lack of a strong skill relation with the copying span might be expected if copying span is postulated to be more a reflection of reading habits than of typing processes per se, and therefore should not be related to typing speed. Fuller (1943) proposed an interpretation of this type in arguing that

> it is unfair . . . to assume that the typist develops the ability to absorb larger units of copy paralleling development of typewriting skill . . . because the typist already has the perceptual ability to absorb larger units of copy at a single glance than is necessary in the typewriting process. (p. 153)

However, because faster typists have developed greater automaticity of their component processes, they may be better able to divide their attention between typing and reading. Therefore some of the observed relation between skill and copying span might be attributable to this type of secondary, or indirect, mediation.

29. Fast typists have larger stopping spans than slow typists. This finding was reported by Logan (1983), who found a correlation of .20 between typing speed and number of characters typed after a stop signal, and Salthouse and Saults (1985), who found a correlation of .57 in a study involving a larger number of typists with a greater range of skill levels. However, Salthouse (1985) reported inconsistent results in an examination of the relation between typing skill and the maximum character sequence to which one exhibits sensitivity to preceding context. A very low ($r = -.21$) and statistically nonsignificant ($p > .25$) correlation was obtained, suggesting that faster typists had no more, and if anything had fewer, characters in the execution buffer than slower typists.

Because both the stopping span and the maximum contextual sensitivity are assumed to be a function of the number of characters in the execution buffer, these results do not yet allow a conclusion about the effects of typing skill on the capacity of the execution buffer.

Issues To Be Investigated

Although the preceding sections have documented the progress that has been made in understanding the nature of transcription typing, there is still much to be learned about how this activity is actually accomplished. It is obviously impractical (and probably impossible) to enumerate all of the questions that might be asked concerning transcription typing, but some indication of what remains to be resolved can be provided by briefly discussing several important issues that are current topics of controversy.

One such issue concerns the details of the proposed processing components, and how the components are synchronized and coordinated with one another. Much of the contemporary research on typing has focused on output or motor processes, with processes of input, parsing, and translation largely neglected. This is unfortunate because transcription typing seems to involve a great many perceptual and cognitive aspects that may prove at least as interesting as those related to purely motoric characteristics. Specific questions to be resolved concerning these earlier phases of processing include the following. Exactly what is the function of the input component (as presumably indexed by the copying span), as the parsing process (which seems to be reflected in the eye–hand and replacement spans) apparently also relies on the source text? Are there really separate parsing and translation components, because whereas the components can be distinguished on theoretical grounds, there is not yet convincing empirical evidence to support the existence of separate components. An alternative possibility, proposed by Shaffer (1975a), is that there are only two separate components, but each has both a buffer store and a process register responsible for the conversion of information from one form into another. The question of the nature of the internal representation in each postulated processing component is also important. Of particular interest is whether there will be convergence of inferences about the size and type of units involved in each component based on error analyses, quantitative analyses of interval distributions (e.g., Shaffer, 1973; Shaffer & French, 1971; Shaffer & Hardwick, 1968, 1970; Thomas & Jones, 1970), and span-assessment procedures. Finally, what is the precise role of the spans or inferred buffer sizes in coordinating communication and transmission of information from one processing component to the next? Any buffer allows for some independence of the rates of different processes, but it is not yet clear whether the different spans are necessary to accomodate varying rates in different components, or are merely reflections of disparate capacities for different processes (cf. Logan, 1983).

Related to the role or function of the component buffers is the degree to which they reflect invariant temporal properties as opposed to skill-dependent structural capacities. That is, because skilled typists execute keystrokes at a faster rate than novice typists, it is possible that the larger spans on the part of skilled typists simply reflect greater output for the same temporal duration. This view was introduced in the typing literature by Butsch (1932), who claimed on the basis of his research on the eye–hand span that "the eye keeps at an average distance ahead of the hand such that the time interval between seeing a letter and writing it is approximately one second, no matter what the speed of the writing" (p. 114). In fact, Butsch (1932) did find that groups of typists with speeds ranging from 40 to 100 words per minute all had average time spans (i.e., the product of eye–hand span in characters and the average interkey interval in seconds) of about 1 s.

The notion that the spans represent different temporal constraints of the human information processing system implies: (a) That there should be relatively little variance across individuals in the time estimates; and (b) that the variance that does exist is not systematically related to skill. That is, if relatively invariant temporal factors are responsible for the various span magnitudes, then the distribution of time spans should be much smaller than the distribution of spans in terms of number of items, and the differences associated with level of skill should be eliminated. The data reported by Butsch are consistent with these implications, but two characteristics of that study should make one cautious about accepting the results at face value. One is that Butsch did not actually measure the speeds of his typists but apparently relied on reports (self-generated?) of the speeds at which they ordinarily typed. The other problem with the Butsch data is that only averages from different speed groups were presented, and thus the variability within the groups was ignored.

More recent and complete analyses of the two implications from the temporal perspective on the various spans are summarized in Table 4. All of the data were obtained from samples of typists with sample averages ranging between 55 and 62 net words per minute and between 172 to 182 ms per interkey interval (Salthouse, 1984a, 1985; Salthouse & Saults, 1985). The two comparisons most relevant to the current issue are Columns 5 versus 9 and Columns 6 versus 10. Columns 5 and 9 report the coefficient of variation for each measure, and if time is more fundamental than number of characters as the determinant of span, the values in Column 9 would be expected to be smaller than those in Column 5. In fact, however, the values were quite comparable, with means of 0.41 and 0.40. Entries in Columns 6 and 10 further indicate that not only was the relative variance not greatly reduced by expressing the spans in terms of time, but there were still systematic relations with skill in many of the measures.

The results summarized in Table 4 therefore do not provide much support for the idea that the spans are merely reflections of temporal constants in the processing system. This is admittedly indirect evidence, but at the very least it calls into question Butsch's claim that typists of all speeds have a buffer representing approximately 1 s worth of processing. Not only are the estimates from different span types quite distinct, ranging from averages of less than 0.25 s to more than 2 s, but the variability around these averages is also very large.

A second issue that should be the focus of additional research has to do with the nature and role of motor programs in typing. Introspective reports are quite consistent in suggesting that one need only intend to type a familiar word and it is automatically typed, as though under the control of an autonomous motor program. Several theorists (e.g., Leonard & Newman, 1965; Terzuolo & Viviani, 1980) have therefore incorporated the notion of a sequence of integrated keystrokes composed into a single unit that, when activated, can be ballistically executed with no further conscious control. However, the lack of evidence for response sequences extending across more than two or three char-

Table 4
Span Estimates Expressed in Number of Characters and in Milliseconds

Span type	Number of characters *M*	*SD*	*M/SD*	*r* (skill)	Milliseconds *M*	*SD*	*M/SD*	*r* (skill)
Coping	13.19[a]	4.41	0.33	.345	2158	941	0.44	−.528
	6.62[b]	2.42	0.37	.565	1132	346	0.31	−.179
Eye–hand	3.35[c]	1.67	0.50	.500	575	265	0.46	−.042
	3.45[d]	1.72	0.50	.527	550	243	0.44	.160
	3.97[a]	1.61	0.41	.851	598	164	0.27	.061
	4.89[b]	0.99	0.20	.470	868	249	0.29	−.628
Replacement	2.79[b]	1.16	0.42	.462	484	231	0.48	−.178
	3.04[e]	1.02	0.34	.798	509	102	0.20	−.280
Stopping	1.36[e]	0.64	0.47	.563	224	89	0.40	−.062
Contextual sensitivity	1.76[a]	0.95	0.54	−.211	313	213	0.68	−.661

Note. Superscripts on *M* values denote source of data for the whole row.
[a] Salthouse, 1985, Experiment 1. [b] Salthouse and Saults, 1985, Experiment 1. [c] Salthouse, 1984a, Experiment 1. [d] Salthouse, 1984a, Experiment 2. [e] Salthouse and Saults, 1985, Experiment 2.

acters (cf. the discussion of the stopping span and the sensitivity to prior context) argues against motor programs corresponding to entire words. Also, Shaffer and his colleagues (Shaffer & French, 1971; Shaffer & Hardwick, 1970) point out that the motor program concept "seems extravagant for typing since it requires a large amount of response learning in which the output system acquires distinct states for a large number of movement patterns" (p. 426). Finally, lack of conscious awareness of processing beyond the input phase may simply be a consequence of the growing automaticity of processing, and not a reflection of an absence of further processing.

It should be mentioned that there is currently little consensus about the defining attributes of a motor program, and therefore the use of this term is somewhat ambiguous. In the present context, a motor program can be considered to be a sequence of previously independent and discrete movements that have been integrated or compiled into a single unit such that once initiated, the entire sequence is executed without conscious control or awareness. Still unresolved in this definition is the degree of temporal or spatial flexibility in the program, and the specific level (e.g., muscular vs. mental, cf. MacKay, 1982; or intention vs. execution, cf. Shaffer, 1976) within the processing system at which it is presumed to operate. However, a critical property of the motor program concept is that the program exists in some form of memory and does not need to be assembled at the time of execution. It is in this respect that the motor program concept might be testable because it should be possible to determine whether on-line or real-time assembling of movement patterns is sufficient to account for the major phenomena of typing.

A third issue that should be addressed in future research concerns the role of a metronome or temporal pacer in transcription typing. Because there are wide within-typist variations in the rate of typing, several theorists (e.g., Cooper, 1983; Logan, 1983; Shaffer, 1973, 1978) have proposed that a central timing mechanism is involved in coordinating the activity of the various processing operations. Although intuitively attractive, this notion has seldom been specified explictly enough to allow many precise predictions in the domain of typing. Other questions left unresolved with metronome-based models are: (a) Why are there not higher correlations between successive keystroke intervals if the timing of keystrokes is controlled by a central pacer (e.g., Gentner, 1982, 1983b; Salthouse, 1984b; Shaffer, 1978, 1982)? (b) What happens to the metronome pace with increasing skill (e.g., does the rate of the metronome increase as the typist becomes faster?) (c) What is the nature of the metronome involvement in other speeded activities (e.g., is the same metronome also responsible for coordinating the operations involved in choice reaction time or alternate-hand tapping?)? Moreover, the demonstration by Rumelhart and Norman (1982) that a computer simulation relying only on local contextual determinants produces temporal patterns similar to many of those observed in normal typing seems to be persuasive evidence against the necessity of a central pacing mechanism in typing. It still remains to be determined whether a metronome or oscillator of any type is required to account for typing phenomena. Logan (1983), for one, argues in favor of a metronome, claiming that "the keyboard and the hands may determined the variance of interkeystroke intervals, but the metronome determines the mean" (p. 220). Cooper (1983) has also claimed that a pacing mechanism is necessary to account for speed–accuracy tradeoffs in typing and for regulating speed under conditions of degraded source material.

Summary

Transcription typing is an activity with fascinating potential for increasing understanding of complex perceptual, cognitive, and motoric processes. Much of the existing research in this area has been reviewed in the context of a four-component conceptualization of typing. The four components—input, parsing, translation, and execution—provided a useful framework for organizing the discussion of 29 empirical phenomena related to transcription typing. These phenomena characterize the current state of the field, and also define what needs to be explained by satisfactory theories in this domain. Finally, several issues were identified as warranting special investigation in future research.

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