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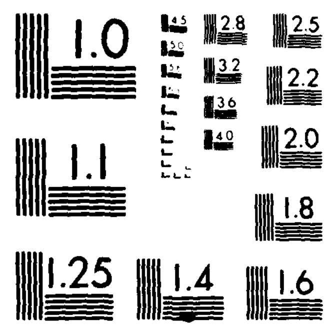

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Evidence Against a Central Control Model of Timing in Typing

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Abstract

Terzuolo and Viviani, in widely cited research, propose a central control model of timing in typing, in which keystroke times are generated in parallel from centrally stored, word-specific timing patterns. Differences in overall time to type a given word are attributed to a multiplicative rate parameter, constant for a given typing of the word, but varying from one typing to another. Three major lines of evidence are cited for this model: (a) keystroke times expand or contract proportionally when words are typed slower or faster; (b) the variances of keystroke times do not increase for successive letters in a word; (c) the times to type a given digraph exhibit word-specific differences. My analyses show that (a) keystroke times do not expand proportionally; (b) the apparent constancy of variances is an artifact of the method that Terzuolo and Viviani used to transform the keystroke times; (c) the effects of surrounding character context are sufficient to explain differences in digraph latencies and these effects cross word boundaries, showing that they are not word-specific.

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Eileen Conway assisted with the experimental studies and data analysis reported here. I have enjoyed many discussions of these issues with Jonathan Grudin, Donald A. Norman and David E. Rumelhart and they also made detailed comments on the manuscript.

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Evidence Against Timing Patterns in Typing

A large part of our daily activity is based on highly practiced motor movements. Examination of the detailed timing characteristics of these motor movements can provide insight into how the mind learns, stores, plans, and carries out actions. Typing is a particularly interesting skill from this vantage point because people are readily available with skills ranging from that of the complete novice to the professional typist with thousands of hours of practice. The sequence of keystrokes in typing provides a set of well defined events with easily measured times. In contrast with tasks such as playing a musical instrument, the control of timing in typing is not an explicit constraint of the task, and therefore the timing in typing should more clearly reflect the timing structure of the motor system.

Terzuolo and Viviani (Terzuolo & Viviani, 1979; Viviani & Terzuolo, 1980; Terzuolo & Viviani, 1980) have argued strongly and consistently for a model of the control of timing in typing that postulates an invariant timing pattern, or "motor engram," for each common word and some common letter sequences. These timing patterns may vary from one typist to another. They propose that keystroke times are generated in parallel from these centrally stored, word-specific timing patterns. Differences in overall time to type a given word are attributed to a multiplicative rate parameter, constant for a given typing of the word, but varying from one typing to another. They cite three lines of evidence for their model of timing: (a) although the overall time to type a given word may vary from one typing to another, the letter-to-letter intervals within the word expand or contract proportionally, maintaining fixed ratios and indicating a multiplicative rate parameter; the observed interstroke intervals for a word are "characterized by an abstract invariant, namely the set of ratios of time intervals between successive key presses" (Terzuolo & Viviani, 1980, p. 1098); (b) the variability in keystroke times does not increase with the position of the letter in a word, indicating that the times are generated in parallel, rather than sequentially; (c) the interstroke interval for a given digraph is sometimes significantly different when the digraph occurs in different words, indicating a word-specific timing pattern.

The TV Model

Although Terzuolo and Viviani never present an explicit model for timing in typing, the following model, which I will call the "TV model," is in accord with their view of timing control. In the TV model, the keystroke times are generated in parallel by multiplying a stored timing pattern by a rate parameter. Let the observed keystroke times for a word be given by the expression

$$t_{wn} = r_w T_n + e_{wn} \qquad (1)$$

The expression for the corresponding interstroke intervals is

$$i_{wn} = r_w I_n + e_{wn} - e_{w(n-1)} \tag{2}$$

where

e_{wn} is a random error term for the nth letter in the wth typing of the word. It is a random normal variate with mean = 0.

I_n is the stored timing pattern interval for the nth letter. ($I_n = T_n - T_{(n-1)}$).

i_{wn} is the observed interstroke interval for the nth letter in the wth typing of the word.

r_w is a rate parameter, constant for the wth typing of the word. It is a random normal variate with mean = 1.

T_n is the stored pattern time for the nth letter.

t_{wn} is the time for the nth keystroke in the wth instance of the word.

In this paper I question the evidence for the Terzuolo and Viviani model of timing, using data that I have collected from skilled typists as well as data published by Terzuolo and Viviani. I discuss the three aspects of the model in turn: (a) the multiplicative rate parameter; (b) the parallel generation of keystroke times; (c) the word-specific timing patterns.

Is There a Multiplicative Rate Parameter?

Although Terzuolo and Viviani (1980) argue for the presence of a multiplicative rate parameter and present suggestive data, they do not report any statistical evidence for this aspect of the model. The presence of a rate parameter in the model makes two predictions that can be tested. First, the rate parameter makes the weak prediction that the interstroke intervals within a word should be positively correlated over repeated typings of the word. Second, the multiplicative rate parameter makes the strong prediction that the ratio of the intervals should remain constant as the overall duration of the word changes. In the next two sections, I test these predictions of the rate parameter model.

Intervals Should Be Positively Correlated

Because the rate parameter is constant for a given typing of a word, if one interval is, for example, longer in a given instance of the word, the other intervals in that instance should tend to be longer also. That is, if several instances of a word are examined, the interstroke intervals within the word should be positively correlated. I therefore analyzed data from typists to see if the intervals within a word were positively correlated.

Method. In Study 1, five professional typists transcribed normal English prose, typing at a Hazeltine 1500 computer terminal. All five typists were very familiar with this terminal, using it as part of their normal employment in conjunction with the campus word processing system. The keystrokes were displayed on the screen of the terminal. Keypresses and the corresponding times were recorded by a minicomputer.

The text to be typed consisted of six prose articles adapted from Reader's Digest. The articles were edited to eliminate Arabic numerals and quotation marks. Other punctuation and capital letters were preserved from the original articles. The text was approximately 55,000 characters long and was presented as double-spaced, typewritten copy. After a 10 minute warmup with another text, the typists were asked to type the experimental text at their normal, rapid rate, without correcting errors. The typists transcribed the text in from one to three experimental sessions, taking occasional rest breaks at their own choosing.

Study 2 was conducted about one year after Study 1. In Study 2, six professional typists, including the five typists who participated in Study 1, transcribed normal English prose, typing on a high-quality electronic keyboard (Microswitch model 51SD12-4 with "tactile feel") with a keyboard layout identical to that of the normal IBM Selectric typewriter (Figure 1 shows the keyboard layout.) All typists frequently typed on a Selectric typewriter. The typed letters were displayed on a CRT in front of the typist. Keypresses and the corresponding times were recorded by a microcomputer.

The text was one of those used in Study 1: an article adapted from Reader's Digest about diets. It will be referred to as the "diet text." The text was approximately 12,000 characters long and was presented as double-spaced, typewritten copy. After a 10 minute warmup with another text, the typists were asked to type the diet text at their normal, rapid rate, without correcting errors.

All words of four or more letters which occurred at least ten times in either Study 1 or Study 2 were examined. Data from the two studies were treated separately. Since correlations can be strongly affected by outlying data, instances of words with aberrant intervals were eliminated by two procedures. First, words containing an interval greater than 400 msec (about 4% of the words) were eliminated. Next, words containing a interval more than 3 standard deviations away from the mean for that interval (another 2% of the words) were eliminated. The correlation coefficient was calculated for all pairs of intervals within each word. In all, 1517 correlations were calculated, involving 51 different words and 6 typists.

Results. Most of the correlations between interstroke intervals were very small. Overall, 82% of the correlations were not significantly different from zero. 3% of the correlations were significantly less than zero and 15% were significantly greater than zero. The average correlation was +0.162. For the individual typists, the average correlations ranged from +0.11 to +0.25. It is interesting to note that the average correlation between intervals for a given subject was significantly correlated with their median interstroke intervals: $r = +0.92$. That is, the slower typists had more highly correlated intervals. These values for the average correlation are strongly weighted toward the longer words, because all possible pairs of intervals within a word were used: for example, a four letter word has 3 different pairs of intervals but an eight letter word has 21 different pairs. However, when the correlations within each word are collapsed, thus weighting each word equally, the average correlation changed only slightly, to +0.176.

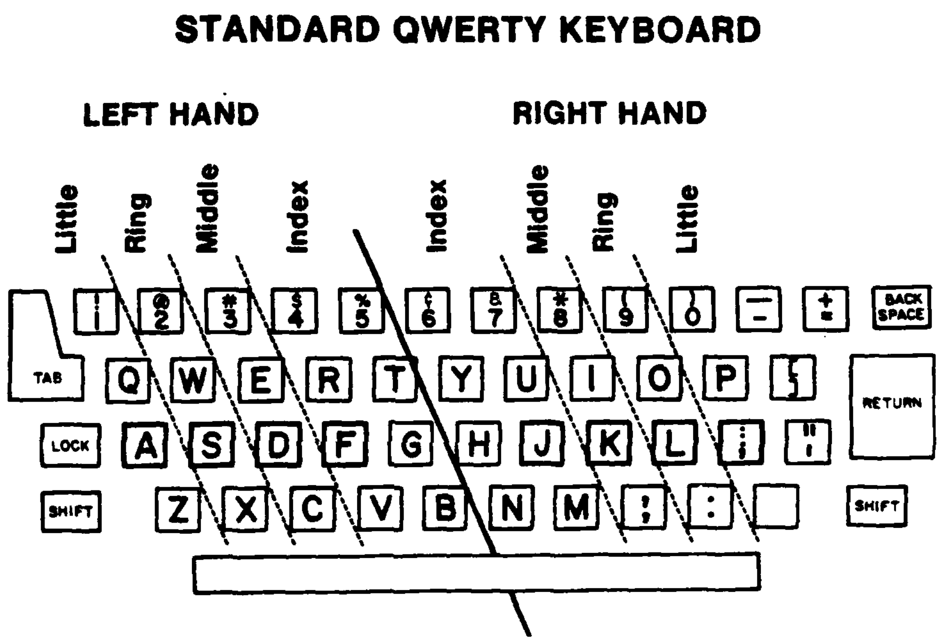

Figure 1. The layout of the keyboard used in Study 2. This is the standard "qwerty" keyboard and is identical to the keyboard layout of the IBM Selectric typewriter.

The TV model predicts a possible negative correlation for successive interstroke intervals. This can be seen by noticing in Equation 1 that the error term $e_{w(n-1)}$ enters into i_{wn} with a negative sign, but would enter into $i_{w(n-1)}$ with a positive sign. (For further discussion of the negative correlations in parallel timing models, see Wing, 1980.) These negative correlations are confined to adjacent intervals. Therefore, I also summarized the correlations with adjacent intervals omitted. The results are much the same. With adjacent intervals omitted, 86% of the correlations are not significantly different from zero, and only 12% are significantly positive. The average correlations were +0.139 (all intervals) and +0.205 (correlations collapsed within words). These results indicate that if there is a proportional expansion of intervals, the effect is extremely small. Overall, it would account for, at most, 4% of the variance observed in interstroke intervals.

The Ratio of Intervals Within a Word Should Be Constant

Even though the data fail the weak prediction of the rate parameter model, it is useful to test the stronger, quantitative prediction: if the interstroke intervals for two digraphs within a word are compared over instances of the word, the ratio of the two intervals should remain approximately constant. If the ratio of two intervals was exactly constant (which would be true if the error terms in Equation 2 were equal to zero), a scatter plot of the intervals over repeated instances of the word would fall on a straight line passing through the origin with a slope equal to the ratio of the intervals. I call this line the "constant ratio line." Even if both intervals contain a normally varying random error, as in Equation 2, the scatter plot will still form an ellipse whose principal axis is the constant ratio line.

Method. Of the 1517 pairs of intervals examined in the previous study, 234 of them had a significantly positive correlation. The 39 pairs of intervals with significantly negative correlations violate the rate parameter model and were not studied further. The 1243 pairs of intervals with insignificant correlations also do not support the model; since they do not have a well defined principal axis, they were not studied further. For each of the 234 pairs of positively correlated intervals, the slope of the principal axis of the corresponding scatter plot was determined along with its 95% confidence limits, using the method of Sokal and Rohlf (1969) for a bivariate normal distribution. The slope of the principal axis was then compared with the slope of the constant ratio line.

Results. Figure 2 shows a typical result. Note that the slope of the constant ratio line falls outside of the confidence limits for the principal axis slope. In the 234 comparisons made, the constant ratio slope was outside the 95% confidence interval for the observed slope 140 times. If a multiplicative rate parameter model underlies the observed data, the constant ratio slope should be rejected only 5% of the time. (A study of simulated data generated according to the TV model, Equation 1, confirmed the expected 5% rejection rate.) Instead the constant ratio slope was rejected 60% of the time. Separated by typist, the rejection rate varied from 50% to 67%. When adjacent intervals are excluded, out of 97 comparisons the constant ratio slope was rejected 59% of the time. Surprisingly, there appears to be no relation between constant ratio slope and the observed slope. The correlation coefficient between the constant ratio slope and the observed slope was +0.02.

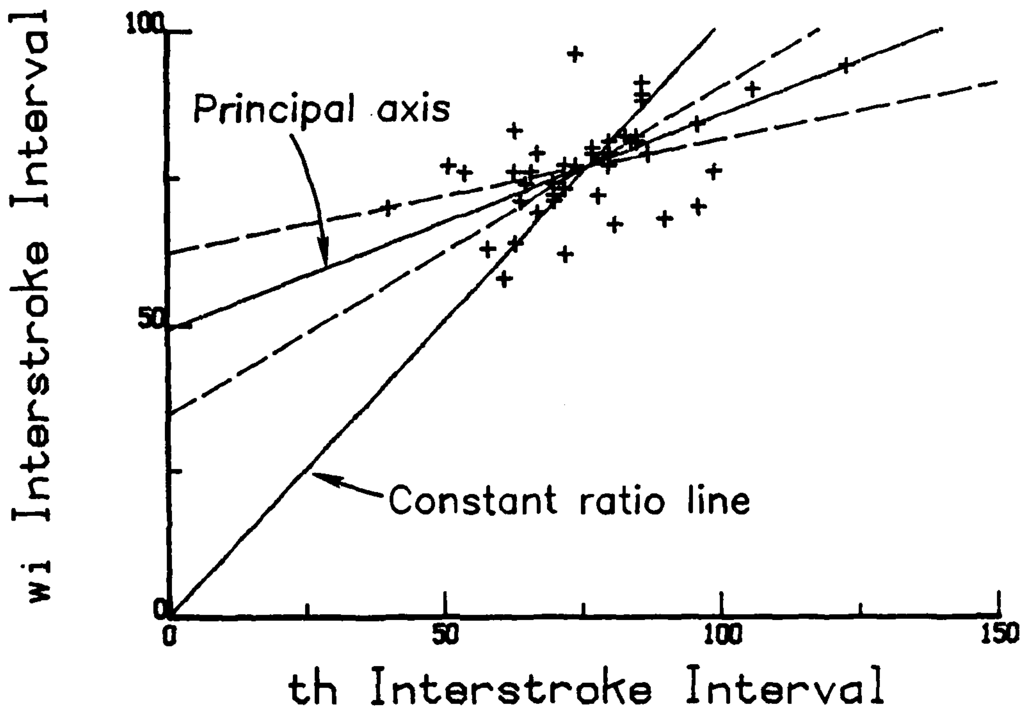

Figure 2. Scatter plot of the wi versus th interstroke intervals in instances of the word with as typed by Typist 3. The observed principal axis of the bivariate distribution is shown, along with the 95% confidence limits for its slope. The constant ratio line was calculated from the ratio of the mean interstroke intervals. Its slope falls outside the confidence limits for the observed principal axis. In an analysis of 234 such interval pairs, the constant ratio line had a slope significantly different from the observed axis 60% of the time, indicating that the interstroke intervals within a word do not expand proportionally.

Summary

An examination of interstroke intervals in repeated words did not support the presence of a multiplicative rate parameter--the first feature of the TV model of timing. The multiplicative rate parameter makes the weak prediction that intervals within a word should be positively correlated. 82% of the correlations found were not significantly different from zero, 3% were significantly negative, and only 15% were significantly positive. The multiplicative rate parameter also makes the strong prediction that intervals within a word should tend to have a constant ratio. Even when the analysis was restricted to the intervals that were positively correlated, the scatter plots of interval pairs had principal axes significantly different from the constant ratio line 60% of the time.

Are Keystroke Times Generated in Parallel?

The second line of evidence cited by Terzuolo and Viviani for the TV model is that the variances of the keystroke times do not increase for successive letters in a word. They state:

> The variance across instances of the time of occurrence of each event of the sequence does not increase with the rank order of the event within the sequence. . . . This implies that the operations which specify the time of occurrence of each event are not serially arranged for, otherwise, the variability inherent to each event would summate. . . . The events of the pattern are represented within the engram by using a (functionally) parallel arrangement. (Terzuolo & Viviani, 1980, pp. 1101-1102)

The contrast here is between a parallel model, such as the TV model, in which the time of each keystroke is independently specified, and a serial model in which the time of each keystroke is based on the time of the previous keystroke. It is important to note that when Terzuolo and Viviani refer to "the variance across instances of the time of occurrence of each event of the sequence," they do not mean the observed times of the events. The variance in the observed times does increase along the sequence, as can be easily seen in Terzuolo and Viviani's data. Instead they are referring to the variances after the observed times have been altered by a transformation which I will call the "TV transformation." Most of this section will be devoted to the nature of this transformation and its effects on simulated and observed times.

In the simple parallel model, without a rate parameter,

$$t_{wn} = T_n + e_{wn} \tag{3}$$

The variance in both the time for each keystroke and the interstroke intervals is constant. In the corresponding serial model,

$$t_{wn} = t_{w(n-1)} + I_n + e_{wn} \tag{4}$$

$$= T_n + \sum_{s=1}^{n} e_{ws} \tag{5}$$

The variance in the time for each keystroke with the serial model equals the variance in the error term plus the variance in the previous time. Thus, assuming the error terms are independent, the variance will tend to increase linearly for successive times. (Note, however, that this distinction only applies to the times; the variance of the interstroke intervals is constant with both models.)

It would be easy to distinguish between the simple parallel and serial models on the basis of this difference in variances. The addition of a multiplicative rate parameter, however, complicates the analysis. With the rate parameter, r_w, the simple parallel model becomes the TV model discussed in the previous section:

$$t_{wn} = r_w T_n + e_{wn} \tag{6}$$

The corresponding expression for the serial model is:

$$t_{wn} = r_w T_n + \sum_{s=1}^{n} e_{ws} \tag{7}$$

Because the rate parameter is constant for a given typing of the word, it leads to a positive correlation between intervals and hence the variance of the times increases for successive keystrokes with both models. Figure 3 compares the typical pattern of standard deviations of keystroke times produced by the serial and parallel models with and without a multiplicative rate parameter.

Terzuolo and Viviani's approach was to try to remove the effects of the rate parameter by a "homothetic" (proportional) transformation (the TV transformation), and then look at the variances in the transformed times. Their transformation method is to proportionally adjust the observed keystroke times for a particular instance of a word by multiplying each time by a constant. The set of constants, one constant for each instance of the word, is chosen to minimize the variance of the transformed times while keeping the average duration for the words the same before and after the transformation (Terzuolo & Viviani, 1980; Viviani, 1981). The TV transformation does indeed remove the effects of the rate parameter. Unfortunately, it also introduces an artifact into the transformed times. In particular, the TV transformation causes systematic distortions of the random error component in the observed times. The consequence is that with the parallel model, although the variances should be constant in the absence of the rate parameter, the variances of the transformed times tend to decrease for successive keystrokes. Surprisingly, the variances of the transformed times do not increase for successive keystrokes with the serial model either. Instead they form a distinctive pattern, but one different from that based on the parallel model. In both cases, the pattern of variances depends on the number of letters in the word (or more precisely, on the number of successive times included in the transformation). Figure 3 shows how the TV transformation reduces the variance in the keystroke

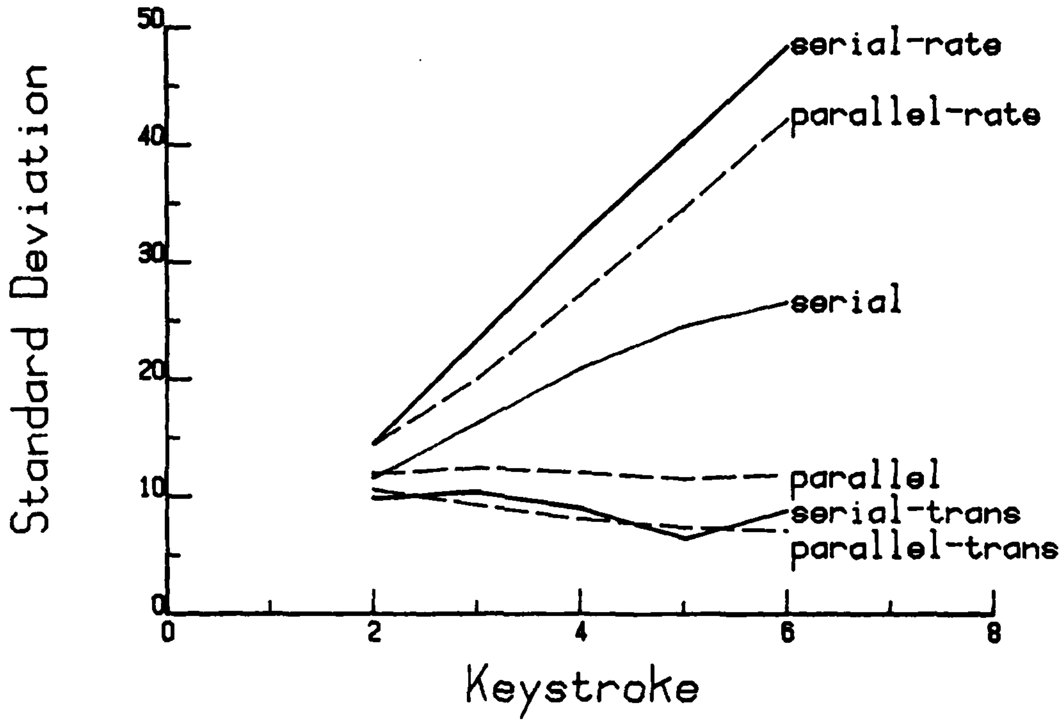

Figure 3. The standard deviations of simulated keystroke times produced by (starting at the top) parallel and serial models with a multiplicative rate parameter, parallel and serial models without a multiplicative rate parameter, and TV transformed times produced by the parallel and serial models. In the case of the TV transformed times, the standard deviations are the same whether or not model includes a rate parameter. Each curve is based on simulated data for 1000 repetitions of a six letter word.

times. Note in particular that the variances are reduced below that for parallel and serial models without a rate parameter, indicating that the TV transformation is also reducing variance due to the random error term, e_{wn}. The basis of the artifact produced by the TV transformation is that it reduces the variance due to the random error term in a systematically biased fashion.

Much of the following discussion will center on the pattern obtained by plotting the standard deviations of the TV transformed times as a function of letter position. I will call this pattern of standard deviations the transform pattern. To investigate the effects of the TV transformation on keystroke times, I generated simulated times according to the parallel and serial models as given in equations 6 and 7. These simulated times were then transformed according to the method of Terzuolo and Viviani. Figure 4 shows the resulting transform patterns for sequences of length three to ten keystrokes. For three and four keystroke sequences, the transform patterns decrease for successive keystrokes with both models, and the models cannot be qualitatively distinguished. For sequences of five or more keystrokes, however, the transform patterns are qualitatively different for the serial and parallel models.

Two important conclusions can be drawn from these simulation results. First, the absence of increasing variance in the transformed times, which Terzuolo and Viviani found, does not indicate an underlying parallel model, since the variances of transformed times do not increase with the serial model either. Second, since the parallel and serial models produce different transform patterns, it still might be possible to distinguish between parallel and serial control of timing by comparing experimental keystroke times with those simulated according to the two models.

Comparison of Data with Parallel and Serial Models

In Figure 5 the transform patterns for the words father and during, as reported by Terzuolo and Viviani, are compared with the simulation results for a 6 keystroke sequence. The experimental data fit a serial model of timing much better than a parallel model. To make a more complete evaluation, I compared the transform patterns published by Terzuolo and Viviani with the corresponding patterns for the parallel and serial models.

Method. Terzuolo and Viviani report transform patterns for 27 words of length 5 or more letters. The pattern for each word was compared with the parallel and serial model by scaling the model pattern with a multiplicative constant until the sum of the squared deviations from the corresponding points of the word pattern was minimized. The model pattern which produced the lowest minimum sum was declared the best fit.

Results. 70% of the 27 words reported by Terzuolo and Viviani fit the serial model better than the parallel model. I repeated this analysis using my own data (the repeated words from Studies 1 and 2, described previously) and found similar results. The analysis covered six typists and a total of 97 words (5 letters or longer). 75% of the words fit the serial model better than the parallel model. Additional evidence is presented in Figure 6, taken from Terzuolo and Viviani (1980), which shows the transform patterns for the ends of various words. These patterns all show the striking increase in standard deviations for the last letter that is typical of the serial model and

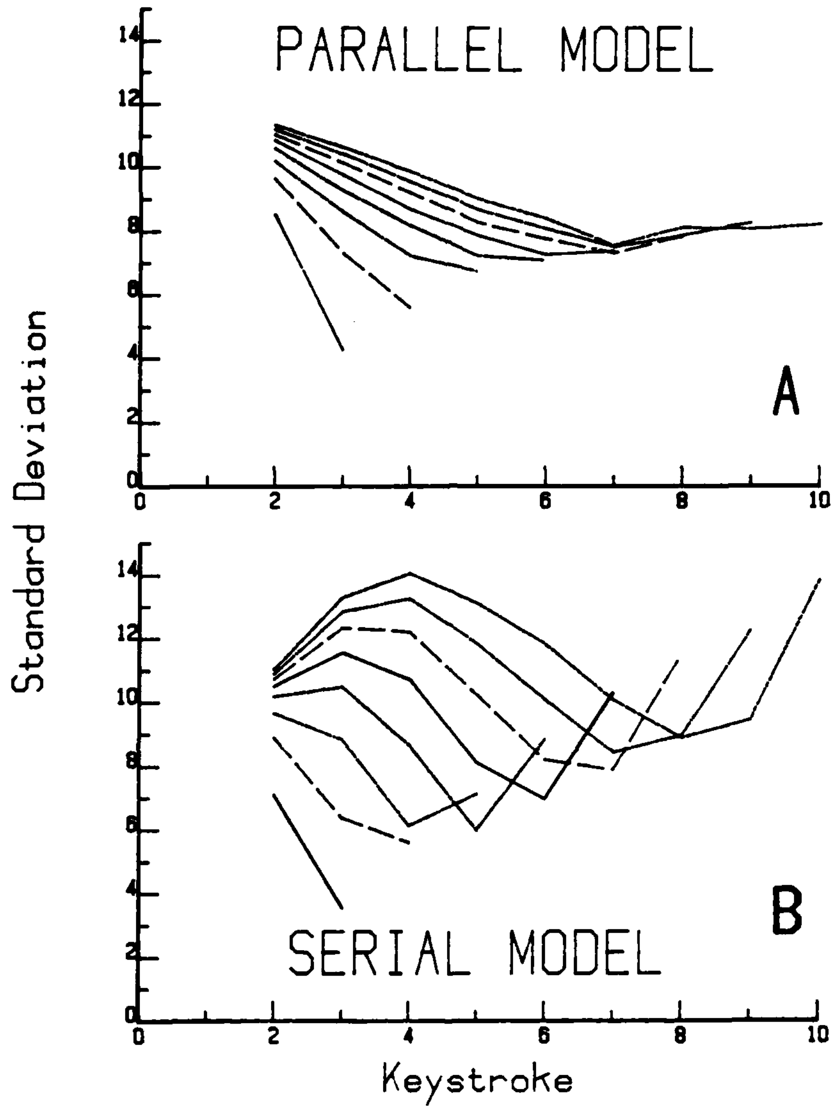

Figure 4.

A. Transform patterns obtained when simulated keystroke times generated by a parallel model (equation 6) were subjected to the proportional transformation of Terzuolo and Viviani. For each curve, simulated keystroke times for 1000 sequences were transformed. The original interstroke intervals had a standard deviation of approximately 17.

B. Identical to A, except that the simulated keystroke times were generated by a serial model (equation 7).

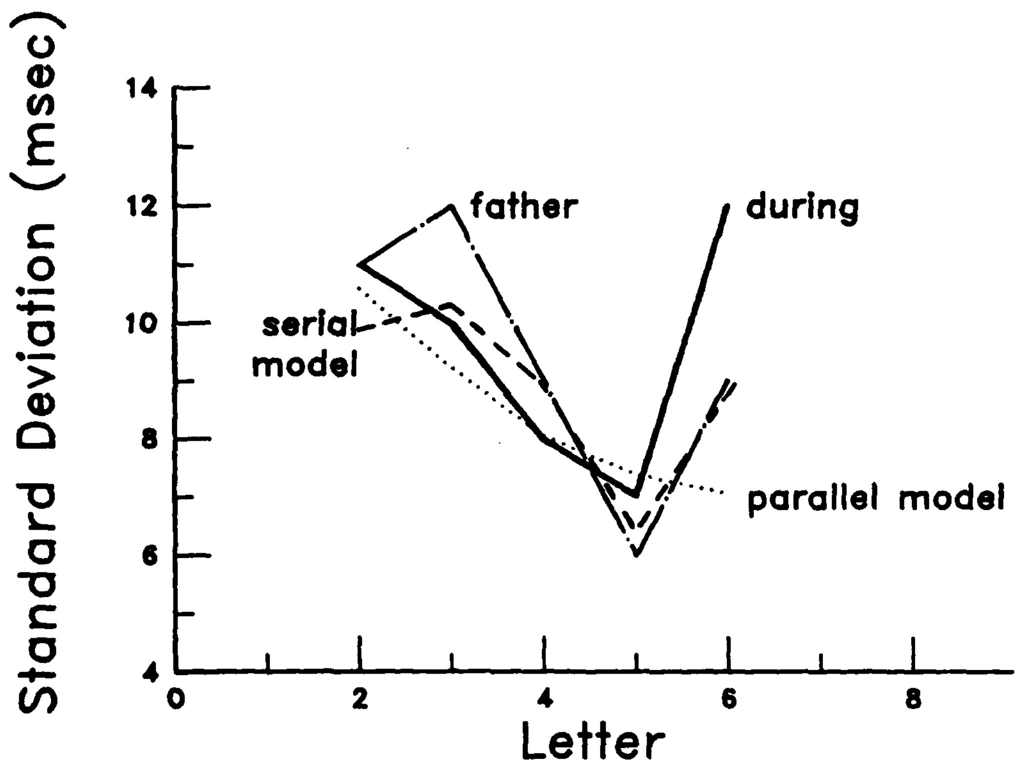

Figure 5. Comparison of transform patterns based on typist's data with the transform patterns obtained from simulated data generated by parallel and serial timing models. The typist's data are for the words <u>during</u> and <u>father</u> as reported by Terzuolo and Viviani (1980). The simulated data are the parallel and serial transform patterns for six keystroke sequences from Figure 4. The transform patterns for the experimental data fit the pattern for the serial model better than for the parallel model.

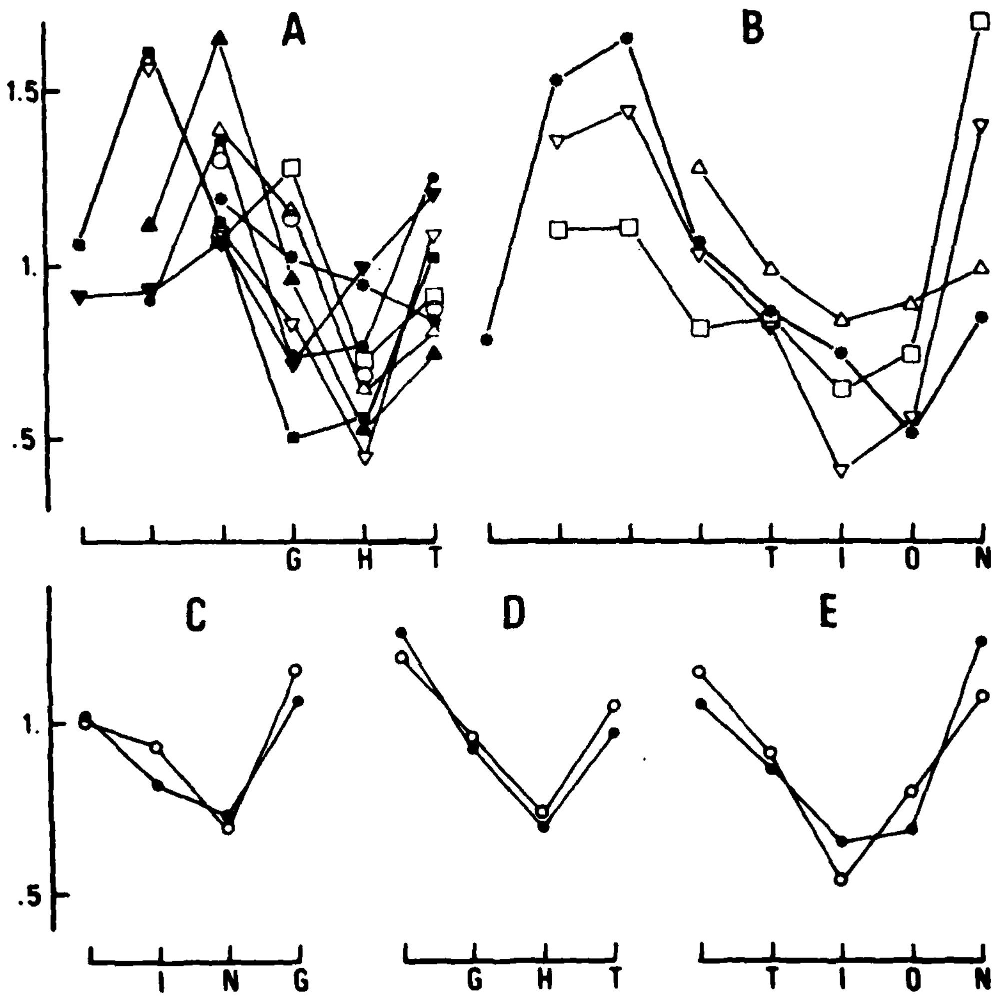

Figure 6. Transform patterns for the end of various words, as reported by Terzuolo and Viviani. Note the striking increase in the pattern for the last letter in the word. This behavior is characteristic of transform patterns based on serial models, and once again indicates the the experimentally observed keystroke times are more indicative of an underlying serial control of timing than of a parallel control of timing. (From "Determinants and Characteristics of Motor Patterns Used for Typing" by C. A. Terzuolo and P. Viviani Neuroscience, 1980, 5, 1085-1103. Copyright 1980 by IBRO. Reprinted by permission.)

is not seen with the parallel model.

Summary

Terzuolo and Viviani found that TV transformed keystroke times do not exhibit a general increase in variance for successive letters in a word, and cite this as evidence for a parallel rather than a serial model of timing. It turns out, however, that the lack of increase in variances was an artifact of the TV transformation. For sequences of five or more keystrokes, however, the TV transform does produce a qualitatively different pattern of variances for parallel and serial models. I showed that the data of Terzuolo and Viviani, as well as my data, fit a serial model better than a parallel model 70% to 75% of the time. Thus the experimental data do not support the second feature of the TV model--that keystroke times are determined in a parallel fashion.

Are There Word-Specific Timing Patterns?

Terzuolo and Viviani (1980) showed that, in a number of cases, the interstroke interval for a given digraph differed significantly depending on the word in which it was embedded. For example, they report that for one typist, the *an* interstroke interval (the time between the *a* and *n* keystrokes) was 147 msec in the word *thank*, but 94 msec in the word *ran*. They cite these differences as evidence for a word-specific timing pattern. An alternative explanation, however, is that the interstroke interval could be modulated at the time of execution by wider context beyond the digraph. In the word *thank*, for instance, it could be that the right index finger which types the *n* is later than usual because it was recently occupied with typing the *h*. (Figure 1 shows the standard typewriter keyboard layout.) There would be no comparable delay in the word *ran* because the previous letters are typed by the opposite hand. In my data, I found differences in interstroke intervals for a given digraph in different contexts, similar to those found by Terzuolo and Viviani. In this section I describe a study of the effects of context on interstroke intervals, and of whether these effects are word-specific.

The interstroke intervals in typing have almost always been categorized in terms of the digraphs being typed. Some authors have subdivided the digraphs, based on the type of finger movements required to type the digraph (Coover, 1923; Kinkead, 1975; Terzuolo & Viviani, 1980; Gentner, 1981), but the digraph has remained the unit of description. One study which considered wider context beyond the digraph was reported by Shaffer (1978). Shaffer found that the interstroke interval for a given digraph was affected by context both to the left and right of the digraph. I conducted a systematic study of how interstroke intervals are affected by the surrounding character context.

Method

The data were interstroke intervals from Study 2, in which six typists transcribed normal English prose. The analyses reported here are based on all six-character sequences made up of the 26 lower case letters along with period, comma, and space. Approximately 10,000 overlapping sequences were examined for each typist.

Because interstroke interval distributions are highly skewed, I have followed Shaffer (1973) in characterizing them by medians and quartiles. The spread of an interval distribution was measured in terms of the half-width: the difference between the third and first quartile (the 75th and 25th percentile). I also repeated these analyses using the standard deviation rather than the half-width as a measure of the spread of the distribution. To eliminate the effect of very long intervals on the standard deviation, intervals greater than 400 msec were discarded (1.8% of the intervals). All results reported in this paper were unaffected by the choice of standard deviation or half-width as a measure of spread.

Half-Widths of Interstroke Interval Distributions

Figure 7 shows the distribution of all interstroke intervals for a typical typist. The half-width of the overall distribution is 63 msec. On analysis it became clear, however, that this distribution was a composite of many narrower distributions. When the context of the interstroke interval was highly constrained by fixing the six character string containing the interval (the three characters before and after the interval), the interval distributions had a median half-width of 18 msec. Two such narrower distributions are also shown in Figure 7. Figure 7 illustrates the extremes of context effects, going from no context at all (the distribution of all intervals) to the highly controlled context provided by a string of six characters. I first explore the effects of context by measuring the half-width of interval distributions as context is sequentially added to the left and right of the interval. Then in the following section I address the question of whether these context effects are independent of words, or if controlling the context merely helps specify the word in which the digraph occurs.

The effects of specifying context are shown in Table 1. The line labeled "All" gives the half-width of the distribution of all interstroke intervals (the mean half-width across all typists is 56.7 msec). The median half-width of interval distributions for the individual characters, shown on line "C", is the median half-width of the distributions of interstroke intervals ending with a, b, c, etc. The median half-width for individual characters (55.2 msec) is essentially the same as for all characters combined, indicating that specifying the character being typed has little effect on the variability of interstroke intervals. In contrast, specifying one additional character to the left of the character being typed ("cC") reduces the half-width by almost half to 31.7 msec. This is the strongest context effect observed and is the basis for the common practice of describing intervals in terms of the corresponding digraphs. Table 1 also shows that the effect of context extends further than one character to the left of the character being typed. Specifying a second character to the left ("ccC") further decreases the half-width of the distributions to 25.7 msec. Specifying a third character to the left ("cccC") has little effect. Somewhat surprisingly, context to the right of the character being typed also affects the intervals. It appears from the data in Table 1 that specifying one character ("Cc") or two characters ("Ccc") to the right also reduces the half-width of the interval distributions.

The data in Table 1 are confounded, however. Because the data are based on normal English text, the distribution of letters in words is not balanced and, for example, specifying right context also puts constraints on the left context. To separate these factors, consider

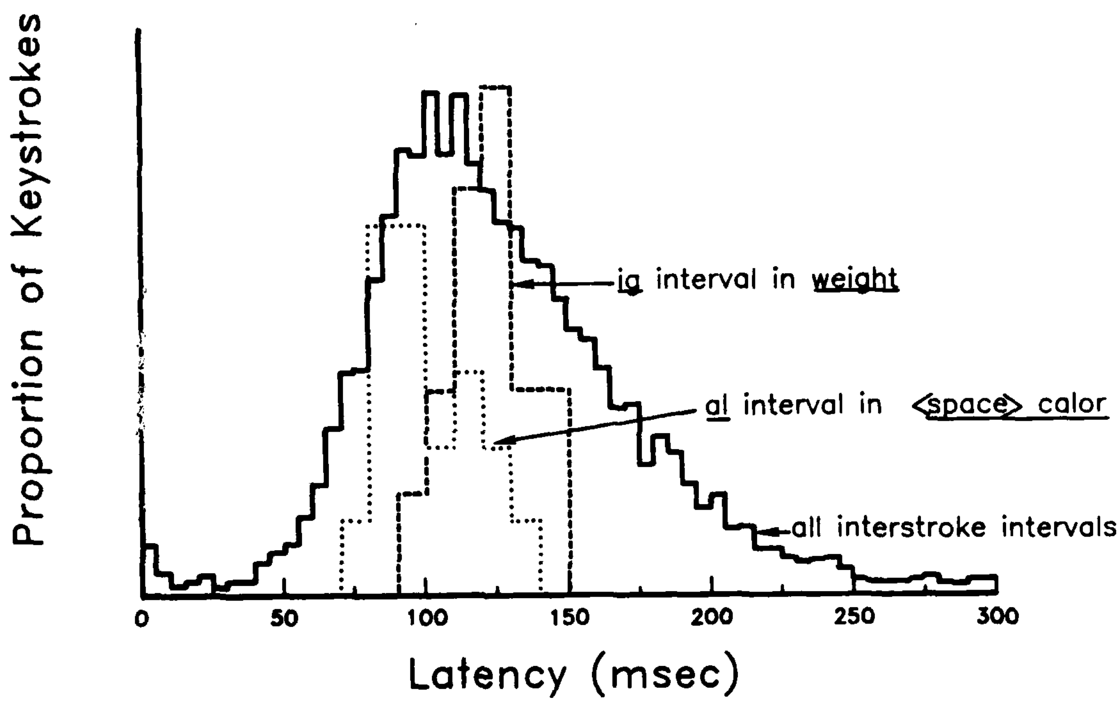

Figure 7. The distribution of all interstroke intervals for Typist 3. This distribution has a half-width of 63 msec. The figure also shows the distribution of intervals for the digraph al in the sequence <space>calor with a half-width of 30 msec, and the distribution of intervals for the digraph ig in the sequence weight with a half-width of 17 msec. The median half-width for all such interval distributions with six characters of context fixed is 18 msec, indicating that the distribution of all interstroke intervals is composed of many narrower distributions with varying medians.

Table 1

Median Half-Widths of Interval Distributions

Fixed String[a]	N[b]	Typist 1	2	3	4	5	6	Mean
All	1	56	73	63	51	57	40	56.7
C	26	57	76	59	50	52	37	55.2
cC	206	35	39	34	30	24	28	31.7
ccC	238	27	33	27	23	21	23	25.7
cccC	94	26	29	26	21	22	22	24.3
Cc	210	44	58	47	41	43	34	44.5
Ccc	237	34	40	42	35	38	29	36.3
ccCc	94	23	25	23	19	17	19	21.0
ccCcc	58	24	25	19	19	16	18	20.2
cccCc	59	23	25	21	19	17	19	20.7
cccCcc	20	25	22	18	20	16	21	20.3

Note. Based on all six-character strings composed of lower case letters, period, comma, and space occuring ten or more times in the diet text.

[a] The row labeled "All" is for the distribution of all characters combined. The labels for the other rows specify the fixed string with "C" indicating the character which terminates the interval and "c" indicating additional context characters. For example, the label "ccC" refers to a series of 238 distributions including the distribution of <u>an</u> intervals in the string <u>tan</u>.

[b] N is the number of distributions analyzed for each typist.

the case when the character being typed and two characters to the left are specified ("ccC"). A total of three characters are specified and the mean half-width is 25.7 msec. A fourth character can be added to the context either by specifying a third character to the left ("cccC") or one character to the right of the typed character ("ccCc"). Adding a character on the left to the context decreases the half-width by 1.4 msec, but adding a character on the right decreases the half-width by 4.7 msec. This effect holds for every individual typist, and indicates that adding context to the right does more than merely constrain left context. A similar argument shows that the second character of right context has little effect (compare line "ccCc" with line "cccCc" versus line "ccCcc"). In summary then, the interstroke interval for typing a given character is influenced by the neighboring two characters to the left and one character to the right.

Word Effect or Context Effect?

It could be argued that the interstroke interval for a given digraph is specific to the word, and in specifying the context we are merely limiting the set of words in which the digraph occurs. There are three major lines of evidence against this argument: first, context effects cross word boundaries; second, intervals in the same context, but in different words, do not differ; third, context effects can be produced without word-specific timing patterns.

First, context effects cross word boundaries. To determine whether context effects apply only within words or could also be found between two words, I compared cases in which the left context was within the word, with cases where it crossed a word boundary. As indicated in Table 2, the half-widths of distributions for intervals preceeding lower case letters narrows as the left context is further specified (compare line "C" with line "cC" and line "_C"). The character context is clearly more effective than the space context: reducing the half-width to an mean of 30.8 msec, compared to 42.7 msec for the space context. The important point for this analysis, however, is that specifying a second character of left context further reduces the half-width of the distributions by similar amounts whether the intervening character is a lower case letter or a space. When it is within-word context ("ccC"), the second character of context reduced the half-width by 6.5 msec on average, and when it is cross-word context ("c_C"), the second character of context reduced the half-width by 7.4 msec. Context effects cross word boundaries for all six typists.

In accord with this result, Shaffer (1978) found that the initial interval in a word could be affected by the previous word. For example, the mean <space>s interval was 91 msec in the phrase win supply but 121 msec in the phrase ratio supply. He found significant effects of the previous word in 12 of the 39 cases examined. Shaffer's results indicate not only that context effects can cross word boundaries, but that the pattern of intervals found in a given word is dependent on the previous word--additional evidence against a word-specific timing pattern.

Second, intervals in the same context, but in different words, do not differ. I examined all words in the diet text that shared a string of four or more letters to see if there would be any effect of the word being typed, once two letters of left context and one letter of right context were specified. For example I compared the er interval in the words permanent and supermarket. Since the text was not specially chosen for this test, the number of possible comparisons was small.

Table 2

Context Effects Within and Across Words
Median Half-Widths of Interval Distributions

Fixed String[a]	N[b]	Typist 1	2	3	4	5	6	Mean
C	23	57	74	56	50	51	37	55.2
cC	161	35	37	32	28	24	29	30.8
ccC	104	27	30	25	21	21	22	24.3
_C	20	45	50	53	50	32	26	42.7
c_C	36	33	41	50	37	28	23	35.3

Note. Based on all strings composed of six lower case letters occuring 10 or more times in the diet text. Some of the half-widths in this table are slightly different from the corresponding half-widths in Table 1 because "C" and "c" in Table 1 include lower case letters, period, comma, and space, but "C" and "c" in this table are restricted to lower case letters only.

[a] The labels specify the fixed string with "C" indicating the letter terminating the interval and "c" indicating additional context characters. For example, the label "c_C" refers to a series of 36 distributions including the distribution of <space>t intervals in the string e<space>t.

[b] N is the number of distributions analyzed for each typist.

Nonetheless, out of 77 pairs of intervals compared in the same context but different words, none of the means was significantly different at the 5% level. Although a null result is never very convincing, this finding supports the view that it is the surrounding character context, rather than the word, which determines the interstroke interval.

Third, context effects can be produced without word-specific timing patterns. Examination of the typewriter keyboard (Figure 1) suggests how these wider context effects can be accounted for without having to postulate word-specific timing patterns. Consider the it interval in the sequences bit and wit. The typing of the t by the index finger on the top row could be delayed in the sequence bit, relative to the sequence wit, because the index finger is pulled away from the top row to type the b on the bottom row (the w is typed by the left ring finger on the top row). Five of the six typists had a longer median it interval in the sequence bit (mean over typists = 130 msec) than in the sequence wit (mean = 112 msec). The means were significantly different by a t test.

It is less obvious how context to the right of the digraph could affect intervals. To see how this might come about, consider the sequences tin and tio. The i and o are typed by the right hand on the top row, but the n is typed by the right hand on the bottom row. If the attempts to type neighboring letters overlap somewhat in time, we could expect the ti interval to be longer in the sequence tin; a tendency to move to the bottom row to type the n would conflict with the movement to the top row to type the i. This conflict would not exist when typing the sequence tio. All six typists had a longer median ti interval in the sequence tin (mean over typists = 126 msec) than in the sequence tio (mean = 100 msec). The means were significantly different by a t test. Shaffer (1978) has also found effects of right context on interstroke intervals.

These data from typists are supported by results from the simulation model of typing developed by Rumelhart and Norman (1982). Their simulation model has no word-specific timing patterns. Instead, keystroke timing is determined by the layout of the keyboard and the physical constraints of the hands and fingers, which may be attempting to type several letters at once. Rumelhart and Norman report effects of right context very similar to those obtained by Shaffer. I did several experiments with their computer simulation model, having it type the diet text as well as specially controlled texts. I found context effects from characters two to the left and one to the right similar to those shown by typists. For instance, the mean it interval produced by the simulation model in the sequence bit was 1.6 times as long as in the sequence wit. The mean ti interval in the sequence tin was 1.3 times as long as in the sequence tio. In both cases the means were significantly different by a t test.

Summary

Terzuolo and Viviani argued that the fact that digraph intervals could vary from one word to another was evidence for a word-specific timing pattern. Although I also find that a given digraph interval can vary from one word to another, I show that this variation is part of a systematic pattern of context effects produced by the surrounding characters. The effects of local context at the time of planning or execution appear to be sufficient to account for all the observed results. Most importantly, the fact that context effects act similarly within words and across word boundaries indicates that word-specific timing patterns do not produce in these context effects. Thus, these analyses do not support the third feature of the TV model--word-specific timing patterns.

Discussion

The data and analyses presented in this paper are in conflict with the model of Terzuolo and Viviani in which keystroke times are generated in parallel from a word-specific timing pattern with a multiplicative rate parameter. This conflict is not based on differences between my data and theirs; instead, it is based on a different interpretation of the data.

My data show the same pattern of variances in keystroke times as reported by Terzuolo and Viviani after the times were "normalized" by their proportional transformation. However, the observation that variances do not increase for successive letters in a word is not evidence for a parallel timing model. Instead it is an artifact of their transformation. The pattern of variances in the transformed times is different for parallel and serial models, however, and data from typists fits a serial model of timing more closely than a parallel model.

My data confirm the finding by Terzuolo and Viviani that the interstroke interval for a digraph can depend upon the word in which it appears. However, the relevant context is the surrounding characters, not the word, as they claim. These context effects cross word boundaries, which argues against a word-specific basis.

Finally, on the issue of whether the interstroke intervals expand proportionally, some of my data are similar to those reported in various figures by Terzuolo and Viviani. However, Terzuolo and Viviani only report on selected words and, although some of my data look like theirs, most do not. Statistical techniques can be used in these cases to compare the entire body of experimental data with a theoretical model. This gives a better view of the typicality and range of the experimental data and helps guard against the tendency to select only those instances that support a particular theory. When that is done with my data, a model with proportionally expanding interstroke intervals is rejected by the data about 60% of the time.

My analyses argue against the control of timing in typing by a word-specific, stored, timing pattern which can be proportionally expanded or contracted to produce words of differing overall duration. This does not, however, rule out all models of timing based on central patterns. For example, a timing pattern could be generated in the course of preparing to execute the keystrokes, or might be based on digraphs or trigraphs rather than word units. Grudin (1981) has found that, in the case of transposition errors, the timing of the keystrokes is closer to what would be expected for the correct sequence, rather than what would be expected for the incorrect sequence that was actually typed. It is difficult to account his results without proposing some type of timing pattern to control the keystrokes.

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1. David M. Green and William J. McGill. On the equivalence of detection probabilities and well known statistical quantities. October, 1969.
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