Timing of Skilled Motor Performance: Tests of the Proportional Duration Model

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Historically, theories of motor control have been based on either central or peripheral mechanisms. This article examines a current, explicit, central theory accounting for the observed flexibility in motor performance: the generalized motor program with a multiplicative rate parameter. Reanalysis of data from a variety of motor skills reported in the literature and a detailed study of skilled typing show that a generalized motor program with a multiplicative rate parameter generally does not fit observed performance. Instead, the data support a composite model of motor control in which performance is determined by both central and peripheral mechanisms.

Skilled motor performance is based on a combination of innate capabilities and learning. Actions such as walking, for which relatively little learning is required to produce competent behavior (Dennis & Dennis, 1940), lie at one extreme of a continuum. At the other extreme of the continuum are activities such as playing a violin or flying an airplane, which, although capitalizing on existing motor capabilities, require hundreds or thousands of hours of learning to reach expert performance. In all cases, however, flexibility is a striking characteristic of expert performance. Experts are able to modify their actions to accommodate their intentions and the changing task demands. For example, a skilled basketball player is able to shoot baskets not from just a few locations but from anywhere near the basket, from standing and jumping positions, around defending players, and so forth. Thus, the skills that a basketball player acquires can be flexibly applied in varied and novel situations. Any theory of motor skills must account for this flexibility in performance.

Historically, theories of motor control can be divided according to whether they are based primarily on central or peripheral mechanisms. For example, when describing locomotion, theories based on central mechanisms propose central (spinal) pattern generators that function with little or no sensory input, whereas theories based on peripheral mechanisms emphasize the role of stimulus–response chaining (see Delcomyn, 1980, for a review of this controversy). The timing of keystrokes in typing provides another example of this dichotomy. Terzuolo and Viviani (1980) proposed that the observed keystroke timing was based primarily on centrally stored patterns, whereas Rumelhart and Norman (1982) proposed that keystroke timing was based primarily on peripheral constraints of the fingers and hands.

Central theories of motor skills are often based on the concept of a motor program, but this concept has been given widely differing meanings over the past 50 years. Motor programs were originally used to describe action sequences as centrally controlled patterns that functioned with only minor involvement of sensory input, in contrast with the prevailing view of action sequences as stimulus–response reflex chains (Keele, 1968; Lashley, 1951). The view that motor programs made little use of sensory input was given support by the finding that animals could make the coordinated rhythmic leg movements typical of locomotion even when their spinal cords and sensory nerves were cut (see Grillner, 1985, for a review). It is now generally recognized, however, that normal motor behavior is based on a collaboration of perceptual, cognitive, and memory processes in the brain, reflexes and pattern generators in the spinal cord, and sensory input (see, for example, Bernstein, 1967; Keele & Summers, 1976; Pearson, 1976; Prinz & Sanders, 1984; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). For the purposes of this discussion, the concept of a motor program will refer to the centrally stored representations used in the performance of action sequences.

The simple concept of a central motor program, however, is not sufficient to account for the observed flexibility of motor performance. It seems implausible and grossly inefficient that a separate motor program would be stored for every variation of the action that can be performed. Further, with a separate motor program for each variation, there would also be no direct way to perform novel variations of an action. The generalized motor program provides a direct account of flexibility in performance.

The Generalized Motor Program

The generalized motor program model was originally proposed by Schmidt (1975) and has since been discussed by nu-
merous authors (Carter & Shapiro, 1984; Frohlich & Elliott, 1984; Klein, Levy, & McCabe, 1984; Schmidt, 1982; Shapiro & Schmidt, 1982). A generalized motor program is roughly analogous to a computer program. Just as a computer program can produce different outputs when it is invoked with different parameter values, a generalized motor program also has variable parameters, and motor performance will vary depending on the parameter values. It is generally assumed that there is a direct relation between a parameter of the motor program and a feature of the observed behavior. Evidence for a generalized motor program can be obtained, therefore, by observing behavior under a variety of conditions and searching for patterns that can be related to an underlying parameter in the motor program. An alternative strategy is to search for invariances in behavior that would indicate those aspects of a movement that are not the product of variable parameters.

Common candidates for parameters to the generalized motor program are overall duration (or rate) and force (Schmidt, 1984). For example, Carter and Shapiro (1984) trained subjects to perform a series of four wrist movements with a total duration of about 600 ms. Then they asked the subjects to perform the movements as fast as possible. They reported that the overall duration for the four movements decreased by about 100 ms for the fast trials and that the durations of the individual movements all decreased by the same ratio. The finding that the individual movement durations maintained a constant ratio with the overall duration was cited as evidence for a generalized motor program with a multiplicative rate parameter. There are fewer reports in the literature of force as a parameter in a generalized motor program, but as one example Hollerbach (1981) found that when one subject wrote the word hell in either large or small script, the timing of vertical accelerations was similar, suggesting that force of movement could be varied as a parameter, independent of timing.

The most widely cited evidence for a generalized motor program comes from studies of how action sequences change with changes in overall duration (Schmidt, 1982, p. 311). A number of authors have concluded that the evidence supports a generalized motor program with a multiplicative rate parameter (for example, Kelso, Putnam, & Goodman, 1983; Schmidt, 1982; Shapiro & Schmidt, 1982; Shapiro, Zernicke, Gregor, & Dies tel, 1981; Terzuolo & Viviani, 1980). The generalized motor program with a multiplicative rate parameter is now the most widely accepted model of timing in the field of motor control. The attraction of this model is that it potentially offers a unified view of seemingly divergent timing data from many different areas of motor behavior. Although this remains the dominant view in motor control, some recent studies have concluded that the timing of movements cannot always be described by a multiplicative rate parameter (Gentner, 1982; Zelaznik, Schmidt, & Gielen, in press).

This article is intended to be a critical review of the evidence for a generalized motor program with a multiplicative rate parameter. First, I present two statistical tests for the presence of a multiplicative rate parameter. These tests are then used to examine evidence cited in the literature and to test a large body of performance data collected from expert typists.

Tests for a Multiplicative Rate Parameter
If the timing of an action sequence is determined by a generalized motor program with a multiplicative rate parameter, then the durations of all the components of the sequence should maintain a constant proportion of the overall duration, as the overall duration of the sequence changes (Schmidt, 1982, p. 308). For convenience, I will refer to this model of a generalized motor program with a multiplicative rate parameter as the proportional duration model.

To make the model more concrete, consider an action sequence that can be decomposed into a set of components. For example, the movement of a leg during one walking cycle can be decomposed into a support component (when the foot is touching the ground) and a swing component (when the leg is swinging forward). As the total duration of the step cycle increases, the duration of the support and swing components will probably change also. The prediction of the proportional duration model is that, even though the absolute durations may change, the duration of each component will remain a constant proportion of the total duration. For example, if the swing component occupies 0.4 s when the total cycle duration is 1.2 s, the swing component should occupy 0.5 s when the total cycle duration is 1.5 s. Specifically, the proportional duration model states that the ratio \( \frac{d_i}{T} \) should be constant over all instances of the action sequence, where \( d_i \) is the duration of the \( i \)th component and \( T \) is the total duration of the sequence.

Problems With Existing Tests of Multiplicative Rate Parameter
Although a number of published reports have attempted to examine behavior in relation to the proportional duration model, a critical test of the theory has not emerged thus far. There are two main weaknesses in published reports.

First, the data examined are often first averaged over instances and over subjects. For example, in an experiment with fast, medium, and slow conditions, the mean durations for each condition rather than the observed durations would be analyzed. The proportional duration model describes the timing of individual action sequences. It is true that if the proportional duration model holds for all the individual instances, it will also hold for the averaged data, but the reverse case is not necessarily true. Therefore it is necessary to analyze the raw data without first averaging it. The practice of averaging over subjects is even more problematical. The generalized motor program is necessarily specific to an individual, and data that have been averaged over subjects cannot be directly related to the model.

Second, in the cases where individual performances were examined, the papers present only a limited number of examples. What is needed is a statistical method that permits analysis of individual sequences and allows summary of these analyses over many different sequences and subjects.

The Constant Proportion Test
The constant proportion test is a simple and direct test of the proportional duration model. The test implements the basic statement of the proportional duration model: Although the total duration for an action sequence may change, the proportion of time occupied by a given component should remain constant. In more mathematical terms, if \( d_i \) is the duration of the \( i \)th component of an action sequence and \( T \) is the total duration of the sequence, then the relative proportion of \( d_i \) with respect
to $T$ should remain constant over changes in $T$. That is, when $d_i/T$ is plotted against $T$, the points should fall on a horizontal line. The constant proportion test thus simply consists of determining whether the slope of the linear regression line is significantly different from 0, when $d_i/T$ is plotted against $T$. When a large number of intervals are being examined, the results of the test can be conveniently summarized over many such linear regression analyses. Specifically, if the criterion of significance is taken to be $p < .05$, then in a large series of such analyses, we would expect only about 5% of the linear regression slopes to be significantly different from 0 if the proportional duration model is valid.

The primary virtue of the constant proportion test is that it is a direct test of the basic statement of the proportional duration model. However, the test does have some potential problems. First, the test is inherently conservative because it is based on linear regression and will be sensitive only to monotone deviations from constant proportion. Second, and more seriously, in a proper linear regression the errors in the two variates should be independent. The constant proportion test calculates the regression of $d_i/T$ against $T$. Because the total duration is the sum of the component durations, and because the total duration enters into both variates, the requirement of independent errors is violated for the constant proportion test. The next section examines the seriousness of this problem.

**Test Results With Simulated Data**

Because of the potential problem with correlated errors in the constant proportion test, the performance of the test was examined by using it to analyze simulated data generated according to two simple models of timing. Data for the proportional duration model were generated by the equation

$$d_{in} = r_nD_i + e_{in},$$

(1)

where $d_{in}$ is the observed duration of the $i$th component in the $n$th instance of the sequence; $r_n$ is a normally distributed rate parameter with a mean of 1, varying for each instance but constant for all components within an instance; $D_i$ is the mean duration of the $i$th component; and $e_{in}$ is a normally distributed random error with a mean of 0, differing for each component and instance of the sequence. Each simulated instance consisted of five intervals, and groups of 20 instances at a time were analyzed with the constant proportion test. The sample sizes and standard deviations were chosen to be comparable with experimental data to be analyzed later.

For purposes of comparison, data were also generated according to an alternative model with an additive rate parameter. Data for the additive rate parameter model were generated by the equation

$$d_{in} = D_i + r_n + e_{in}.$$  

(2)

For the additive rate parameter model, $r_n$ is a normally distributed rate parameter with a mean of 0. Note that for the simulated data it was assumed that the rate parameter does not vary across different components of the same instance and that the error variance is independent of the size of the component. These assumptions are fairly arbitrary, but no single model will be appropriate for all applications. For example, for typing data the variability of interstroke intervals is greatest for the shortest intervals, but in other domains the variability might be proportional to the size of the component.

One example of the constant proportion test with a data set generated by the additive model (Equation 2) is shown in Figure 1. The observed variability in duration results from both the changing rate parameter, $r_n$, and the random error term, $e_{in}$, but as expected the relative duration changes significantly with changes in the overall duration. The results of the constant proportion test on the simulated data are summarized in Table 1. Each value in the table is based on a total of 500 tests (the constant proportion test was applied to five intervals in 100 sets of 20 instances each). Table 1 shows how the relative contribution of the rate parameter term, varying from 99% to 0%, affects the test rejection rate. With the multiplicative model (Equation 1), the rejection rates are all near the expected level of 5%. With the additive model (Equation 2), the rejection rates are very high when most of the variability comes from the rate parameter term, but the rejection rates approach the 5% chance level when most of the variability comes from the random error term. Note, for example, that when 50% of the variance in the durations is contributed by the rate parameter, the rejection rate for the additive model is only 34%. This illustrates the fact that in the presence of noise, the proportional duration model cannot always be rejected, even though the data were generated by another timing model. As more of the variance in the observations comes from random error, it becomes harder to distinguish among various models.

There are two technical issues that should be mentioned with respect to the constant proportion test. First, as shown in Table 1, when the variability in durations is entirely due to the random error term, the rejection rate is approximately 10% rather than the expected 5%. (The rejection rates should of course be identical for the two models when all the variability comes from the random error term. The different values found in this simulation, 11.0% and 8.2%, reflect the range of variability in these simulation tests.) The increased rejection rate above the 5% level is due to the correlation of the errors in the relative duration and total duration that was discussed earlier. Depending on the relative standard deviations of the error terms for each component, the slope of the linear regression line may not be exactly 0, even when all the variability is due to the error terms. To take an extreme example, imagine that a single component in the sequence had a large error term but that for the other components in the sequence the error terms were negligible. In that case, all the variability in the total duration will be due to the variability in the single component, and the relative duration of that single component will be small when the total duration is small and large when the total duration is large, thus producing a nonzero slope. The exact rejection rate obtained with the constant proportion test depends on the mean durations of the component intervals, the standard deviations of their error terms, and the number of instances sampled. The mean durations (100, 150, 200, 75, 130), variabilities (standard deviations of 12), and sample size (20) used for the results in Table 1 were chosen to be representative of the typing data presented later in this paper. In the light of these results, it seems reasonable that, when conducting a large number of constant proportion tests and using .05 significance level for rejections, a rejection rate of at least 10% should be required before concluding that the proportional duration model does not hold.
The second technical issue concerns whether the constant proportion test should be applied to the intervals between components or to times measured from the start of the sequence. The constant proportion test will work with either intervals or times because the proportional duration model predicts a constant proportion in either case. The choice between using intervals or times should depend on whether intervals or times are controlled in the timing model being tested. A serial model of timing, in which timing is based on the time of the previous component, would indicate use of intervals, whereas a parallel model, in which timing is based on the start of the sequence, would indicate use of times in the test. The typing data discussed later were tested using both intervals and times. The rejection rate was slightly higher with times than with intervals. This probably reflects an earlier finding that typing data fit a serial model of timing better than a parallel model of timing (Gentner, 1982).

### The Interaction Test

As was described earlier, the constant proportion test has a potential problem stemming from the fact that errors in the relative duration of a component are correlated with errors in the total duration. In studies where the variations in total duration result from different experimental conditions, such as slow, normal, and fast conditions in a typing study, there is another test that avoids the problems of the constant proportion test. This test will be called the interaction test because it looks for an interaction between the component and the rate parameter in an analysis of variance (ANOVA).

To understand the interaction test, consider the additive rate parameter model described by Equation 2. In this model, an observed duration, $d_i$, is equal to the sum of the mean duration for the $i$th component, a rate parameter that is constant for the whole instance, and an error term. Therefore, if an experiment has several conditions that affect the rate parameter (such as slow, normal, and fast conditions), an ANOVA should show main

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<th>Proportion of variance from rate parameter (%)</th>
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*Note. Simulated data were generated for 20 instances of a five-component sequence. Each test was repeated 100 times.*
effects of the component and the experimental condition but no interaction between the component and condition factors. An interaction between the component and condition factors would indicate that the rate parameter was not constant for all components in the instance. Thus, if an ANOVA of the component durations shows a significant interaction between the component and condition factors, the additive rate parameter model of Equation 2 can be rejected.

In addition to applying the interaction test directly to the component durations in order to test the additive rate parameter model, the interaction test can be applied to the logarithms of the component durations to test the proportional duration model. Assume that the underlying model is the proportional duration model of Equation 1, but add the plausible assumption that the error in a duration is proportional to the size of the duration.

\[ d_{in} = r_n D_i + r_n D_i e_{in} \]  

As before, the standard deviation of \( e_{in} \) is equal for all durations, and thus the standard deviation of the error term in Equation 3, \( r_n D_i e_{in} \), will be proportional to the size of the duration, \( r_n D_i \).

Grouping the terms, and taking logarithms, we obtain

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In this section, I analyzed Armstrong's data to determine their applicability to the proportional duration model. Armstrong had subjects move a lever with a series of elbow flexions and extensions, while attempting to match a target pattern of displacement versus time. After 4 days of practice, subjects became fairly good at this task, but the interesting finding was that timing errors within an individual trial appeared to be related. In particular, Armstrong found that when individual instances of movements were compared across trials, the time from the start of the movement to the second displacement peak was highly correlated with the time from the start of the movement to the third displacement peak. The correlation was .88 in the first experiment with a 3-s movement (Figure 8 in Armstrong, 1970, p. 25) and .79 in a second experiment with a 4-s movement (Figure 13 in Armstrong, 1970, p. 34). Of course, some correlation between these two times is expected, because the time to reach the second peak is included in the time to reach the third peak. I analyzed Armstrong's data to determine if these positive correlations reflected more than the common time interval. In the first approach I assumed that the time to the third peak represented a total duration and used the...
constant proportion test to determine if the relative time to the second peak is constant. In Armstrong's first experiment, the relative time to the second peak increased from 53% of a 1.8-s total duration to 60% of a 3.3-s total duration, \( t(62) \) [for slope \( b \neq 0 \) - 2.18, \( p < .05 \). In the second experiment, the change in the relative time to the second peak was not significant, decreasing from 69% of a 2.3-s total duration to 66% of a 3.7-s total duration, \( t(191) = -1.83, \) ns. Thus, the proportional duration model does not fit the data from the first experiment, but it is consistent with the data from the second experiment.

The constant proportion test is inherently conservative, and the lack of a significant change in proportion for the data from Armstrong's second experiment could result if the data was too noisy to distinguish the true model from the proportional duration model. Therefore, the second approach to analyzing the data was to compare the time interval from the start of movement to the second peak (0-2 interval) with the time interval from the second to third peaks (2-3 interval). The proportional duration model makes two predictions: First, these intervals should be positively correlated across trials, and second—and more important—the intervals should maintain a constant ratio across trials. These intervals had a significant correlation \( (r = .31, p < .05) \) in the first experiment (Figure 8 in Armstrong, 1970, p. 25), but their ratio decreased from 1.07 to .50 as the 0-2 interval changed from .8 to 1.9 s, \( t(62) = -7.5, p < .001 \). The results were even more negative for the second experiment (Figure 13 in Armstrong, 1970, p. 34); the intervals had an insignificant negative correlation \( (r = -.07, \) ns) and their ratio decreased from .61 to .26 as the 0-2 interval changed from 1.4 to 2.7 s, \( t(191) = -8.6, p < .001 \). Thus, contrary to the prediction of the proportional duration model, the ratio of the two intervals varies widely.

In sum, then, the studies of Armstrong (1970) do not support a proportional duration model. The basic flaw in Armstrong's analyses was that the correlation Armstrong observed, between the time from the start of movement to the second peak and the time from the start of movement to the third displacement peak, is primarily due to their shared component (the time from start of movement to the second peak) rather than any consistent change in movement rate. In other words, for two variables \( a \) and \( b \), \( a \) and \( a + b \) will be positively correlated, even if \( a \) and \( b \) are completely independent, as was the case for Armstrong's second experiment (for more discussion of this part-whole artifact, see Munhall, 1985).

This reanalysis of Armstrong's data also illustrates the conservative nature of the constant proportion test. The constant proportion test can only reject data that have a consistent, linear change in proportion with overall duration. Because the time from the start of movement to the second peak and the time from the second to third peaks was completely uncorrelated in the second experiment, there was no consistent trend in the relative time to the second peak, and the constant proportion test did not detect a violation of the proportional duration model.

Zelaznik et al. (in press) examined simple horizontal arm movements to a target, with varying movement distances and movement times. In their first study, subjects were given about 500 practice trials at each time and distance condition. The movements were 10, 20, and 30 cm long, with movement times of 150, 200, and 250 ms. Data from individual subjects and instances were analyzed. Zelaznik et al. (in press) found that although the durations of the positive and negative accelerations were linearly related to the movement's duration, the times of peak acceleration and deceleration were not. In fact, they found that the time of peak acceleration was constant and independent of the movement duration, and the same was true of the time of peak deceleration with respect to the end of the movement. A second experiment that focused on the effect of movement times confirmed these results. Zelaznik et al. (in press) conclude that "the maintenance of relative timing is not an invariant feature of motor control" (p. 22) in this task.

In a similar study, Gielen, van den Oosten, and Pull ter Gunne (1985) analyzed short (22.5 cm) arm movements with movement times ranging from 125 to 250 ms. They found no significant differences in time to peak acceleration as the overall movement time changed. Conversely, the ratio of the time to peak acceleration to the overall movement duration decreased significantly as the overall duration increased. These results are in agreement with the previous results of Zelaznik et al. (in press) that, for short rapid arm movements, the time to peak acceleration is constant and does not scale with overall movement time as is predicted by the proportional duration model.

Wrist twist. Shapiro (1976) had subjects learn a timed sequence of seven wrist twists in 265 trials over 3 days. A pattern group attempted to match a given pattern of time and angle targets with a total movement time of 1.6 s. There was also a control group that made the same movements, attempting only to match the total time. After completion of the learning trials, there were 15 trials of the movement from memory and 15 sped-up trials in which subjects were instructed to make the movements as fast as possible while disregarding any learned timing pattern. The data were averaged over subjects and trials. In a combined analysis of pattern and control groups, Shapiro found no significant difference between the memory and sped-up trials but did find significant differences in the duration proportions for several of the components. The author concluded that the results supported a proportional duration model but was able to hold this view only by combining the pattern and control groups and proposing that "the first part of the movement sequence is programmed and the second half is programmed separately" (Shapiro, 1976, p. 23). The entire movement sequence did not maintain relative timing, and this is especially evident when the pattern and control group are analyzed separately.

Carter and Shapiro (1984) reported a similar experiment in which subjects learned a sequence of four wrist twists. After 600 trials in 3 days, subjects were asked to ignore the timing they had learned and to make the response as rapidly as possible while maintaining spatial accuracy. Data from the last 10 learning trials were compared with data from the 10 sped-up trials. The data were averaged over trials and subjects. The average total duration was 570 ms for the final learning trials, compared with 461 ms for the sped-up trials, and the proportional durations of the components were not significantly different in the two conditions. However, it should be noted that none of the subjects were able to learn the original target movement. The target durations varied by a factor of almost 2 (200 ms for the first component and 110 ms for the second component), but subjects made all movements with approximately equal durations (e.g., 135 ± 16 ms for the first component and 150 ± 8 ms for the second component). The sped-up trials also had approx-
imately equal durations for all components. This suggests that the timing was determined by some simple physical constraint rather than a central motor program, or that subjects adopted a pattern of equal timing for all movements. In either case, there is little evidence for the proportional duration model.

**Key press.** Summers (1975) trained subjects to make a series of nine keypresses with a specified timing pattern and then asked them to make the keypress sequence as fast as possible while ignoring the previously learned timing. The training consisted of 423 repetitions of the sequence over 3 days. Flashing lights above the keys indicated the target timing, which was a repeating sequence of intervals: 500-500-100 ms for one group of subjects and 500-100-100 ms for another group of subjects. At the end of training, there was a test condition in which subjects pressed the same sequence of keys as rapidly as possible for a total of 110 repetitions. Data were combined across subjects and instances for analysis. Although subjects were told that maintenance of the previous timing was no longer important or necessary in the test condition, some remnant of the previous timing was apparent, at least at the beginning of the test condition. By the end of the test condition, subjects in the 500-500-100 group had completely lost the previous timing pattern, but subjects in the 500-100-100 group still showed remnants of the previous timing pattern. Although Summers's (1975) results are often cited in support of the proportional duration model, the results actually strongly contradict such a model. The ratio of slow to fast interkeypress intervals in the final block of training for the 500-500-100 group was 579/252 = 2.3, but the corresponding ratio in the test block was 292/246 = 1.2. Similarly, the ratio of slow to fast intervals for the 500-100-100 group was 421/184 = 2.3 in the final block of training, and 283/185 = 1.5 in the test block. It appears that the fast intervals were at a floor, and the only effect of speeding up was to speed up the slow intervals. Proportional durations were not preserved in the test condition, as required by the proportional duration model.

**Summary.** Laboratory tasks involving several hours of training do not support the proportional duration model. Armstrong's (1970) promising study of arm movement has a fatal flaw in the data analysis. Zelaznik et al. (in press) and Gielen et al. (1985) found that simple arm movements did not preserve relative timing. Shapiro (1976) did not find relative timing for wrist twists. Carter and Shapiro (1984) did find relative timing preserved in another study of wrist twists, but it appears likely that these results were obtained only because the subjects were unable to perform the task properly. Finally, Summers (1975) found that relative timing was not preserved in a keypress task.

**Locomotion**

In contrast to laboratory tasks practiced for a few hours, there are many motor skills that are used in the course of normal living, and individuals can accumulate thousands of hours of practice in these skills. There can be dramatic changes in performance between the point when a skill has been practiced for tens of hours and when it has been practiced thousands of hours (Gentner, 1983). Perhaps the control of timing is one of the things that changes with extensive practice. Therefore, it is also worthwhile to examine highly practiced, real-world tasks. Locomotion is a largely innate skill (Dennis & Dennis, 1940), but individuals also come to the laboratory with a background of thousands of hours of practice in locomotion. In addition, locomotion is an interesting task because it has been studied in a wide variety of species.

**Cockroach.** Most of the studies of movement in the literature report behavioral data because it is the easiest data to collect. A few investigators, however, have examined data from neural recordings. Pearson (1972) presents an impressive study based on single motor-neuron recordings in cockroaches. Pearson measured the burst durations in levator and depressor motor axons. The depressor motor neuron fires during the support phase of the walking cycle, while the cockroach's foot is on the ground and supporting the cockroach. The levator motor neuron fires during the swing phase, while the leg is lifted and swung forward for the next step. Figure 2 shows the burst duration of the depressor motor axon from a remarkable cockroach that varied its total step cycle from 84 ms to 1,265 ms. (The sum of the depressor and levator burst durations is approximately equal to the total cycle duration.) The observed depressor burst durations clearly do not maintain a constant proportion of the total cycle duration. The constant proportion test indicated that the proportion of the total cycle occupied by the depressor bursts increased significantly as the total duration increased, \( t(196) = 22.3, p < .001 \). The depressor bursts occupied 42% of an 84-ms step cycle, but this proportion increased to 87% of a 1,265-ms step cycle. In fact, for cycle times greater than 400 ms, changes in the depressor durations accounted for almost the entire increase in cycle time, and the duration of the levator bursts remained approximately fixed.

When the constant proportion test was applied to data from another cockroach (Figure 5 in Pearson, 1972, p. 181), none of the durations showed evidence of a multiplicative rate parameter. The burst duration of levator axon 5 decreased from 46% of a 150-ms step cycle to 34% at a 500-ms step cycle, \( t(33) = -7.8, p < .001 \). The duration of levator axon 6 decreased from 29% of a 86-ms step cycle to 19% at a 500-ms step cycle, \( t(41) = -6.8, p < .001 \). And the duration of depressor axon \( D_i \) increased from 40% of a 98-ms step cycle to 68% of a 530-ms step cycle, \( t(37) = -14.4, p < .001 \).

In terms of absolute times, most of the increase in step-cycle time came from the increase in depressor burst duration; the levator burst duration changed very little. For the cockroach in Pearson's Figure 5, as the total cycle time increased from 200 to 500 ms, the burst duration for depressor axon \( D_i \) increased from 103 to 333 ms, whereas the burst durations for levator axons 5 and 6 only increased from 78 to 101 and 96 to 175 ms, respectively. As we will see, this pattern holds generally for animals from cockroaches to humans: Most of the increase in duration of step cycles comes from an increase in duration of the support component, whereas the duration of the swing component is relatively constant.

Pearson's observations of motor-neuron activity correspond nicely to the behavioral observations of cockroach walking by Delcomyn (1971). Delcomyn recorded the walking movements of cockroaches with a high-speed motion picture camera. He found that cockroaches used a single, alternating triangle gait at all speeds of locomotion from 5 to 80 cm/s, corresponding to step cycles of 400 to 45 ms. Delcomyn found that, on average, the support phase occupied about 51% of the step cycle when the cycle time was 50 ms, but increased to 71% of the cycle when the cycle time was 400 ms. The data presented in Delco-
Figure 2. Variation in the burst duration of motor axon D, with cycle time for a cockroach. (The dashed line is an example of how the data might look if the depressor burst duration occupied a constant proportion of the total cycle time. From “Central Programming and Reflex Control of Walking in the Cockroach” by K. G. Pearson, 1972, Journal of Experimental Biology, 56, p. 182. Copyright 1972 by the Company of Biologists Limited. Reprinted by permission.)

Donals (1971) article are for individual instances of step cycles; it is unclear whether the data is for one or several cockroaches. Data for individual instances of step cycles (from Figures 5A and 5B in Delcomyn, 1971, p. 449) were analyzed with the constant proportion test. The support phase duration of leg R1 increased from 47% of a 52-ms step cycle to 70% at a 440-ms step cycle, t(59) = 8.3, p < .001. The support phase duration of leg R2 increased from 51% of a 53-ms step cycle to 78% at a 465-ms step cycle, t(55) = 9.5, p < .001. These analyses support Delcomyn’s conclusion that “both forward [swing] and rearward [support] movements of the legs relative to the body decreased in duration as the insect’s rate of forward progression increased, but at different rates” (p. 452).

Lobster. Macmillan (1975) examined walking in the American lobster, recording movements on videotape and also recording electromyograms from selected muscles. Two of Macmillan’s figures report data from individual instances of movement that could be analyzed with the constant proportion test. Both sets of data were consistent with the proportional duration model. The proportional duration of the swing phase measured from the videotape record (Figure 21a in Macmillan, 1975, p. 31) did not change significantly from 44% of the step cycle as the step-cycle time increased from 1,000 ms to 1,800 ms, t(63) = 1.31, ns. Similarly, the proportional duration of the depressor bursts measured from the electromyograph record (Figure 29 in Macmillan, 1975, p. 31) did not change significantly from 66% of the step cycle as the step-cycle time increased from 600 ms to 1,200 ms, t(65) = -.18, ns.

Cat. Goslow, Reinking, and Stuart (1973) analyzed high-speed motion pictures of cats moving freely at speeds from 1 to 16 miles/hr (0.4 to 7 m/s). Cats use three gaits over these speeds: walk (up to 0.7 m/s), trot (0.7 to 2.7 m/s), and gallop (above 2.7 m/s). Across this range of speeds and gaits, Goslow et al. (1973) found that the duration of the support phase remained approximately constant at 200 ms, whereas the duration of the swing phase decreased from about 500 ms at the slowest speeds to less than 100 ms at the highest speeds (Figure 3 in Goslow et al., 1973, p. 12). They also reported the durations of the four phases of the Phillipson step cycle (Figure 4 in Goslow et al., 1973, p. 13; for a description of the Phillipson step cycle and other terms used to describe the step cycle, see Grillner, 1975). The data were for individual instances, combined over nine cats. There were insufficient data from the walking gait, but it was possible to analyze the data from the trot and gallop gaits with
The net results, then, are somewhat consistent with the general finding that the proportional duration model does not fit Goslow et al.'s (1973) data for the trot gait, but the relative durations of the step-cycle phases are remarkably constant for the gallop gait.

These results on cat locomotion are complemented by Miller and Van der Meche (1975), who report the duration of flexion and extension at four joints in the cat forelimb while walking at two different speeds. Miller and Van der Meche measured joint angles from film, television, and X-ray cineradiography records of cats walking on a treadmill. They report mean data for one cat walking at two speeds. The step cycle is divided into two parts: flexion and extension. The flexion phase corresponds to the early part of the swing phase when the foot is being flexed (phase F in the Philippson cycle). The extension phase corresponds to the latter part of the swing phase when the foot is being extended (phase E1 in the Philippson cycle) plus the entire support phase (phases E2 and E3 in the Philippson cycle). Because there are only two data points reported with no indication of uncertainty, it was not possible to apply the constant proportion test. However, the data (listed in Table 3) showed the usual pattern: Almost all the change in step-cycle duration was reflected in the change in extension durations, whereas the flexion durations remained essentially constant in duration.

**Dog.** Arshavskii, Kots, Orlovskii, Rodionov, and Shik (1965) measured the leg joint angles of dogs running on a treadmill. The joint angle records were used to calculate the durations of the support and swing phases of the step cycle (Figure 3A in Arshavskii et al., 1965, p. 741). The data presented were individual instances from one dog. Analysis with the constant proportion test did not support the proportional duration model. The support-phase duration increased from 45% of a 420-ms step cycle to 69% of a 765-ms step cycle, \( t(4) = 5.9, p < .001 \). Once again, almost the entire change in step-cycle duration was reflected in the change in support-cycle duration: The support-phase duration increased from 191 to 513 ms, whereas the swing-phase duration only increased from 232 to 251 ms.

**Human.** Shapiro et al. (1981) filmed experienced runners while running and walking on a motor-driven treadmill. They measured the duration of the four phases of the Philippson step cycle at four walking speeds and four running speeds. (Recall that the swing phase = Philippson F + E1; the support phase = Philippson E2 + E3). Data were combined over subjects and instances before analysis. The authors report that there was a significant effect of speed on the proportion of the step cycle occupied by the components, but most of the change was between gaits, and they did not find a significant difference in relative durations within the walking or running gaits. These results are not immediately relevant to the proportional duration model, however, because Shapiro et al. (1981) examined proportions as a function of speed of locomotion on the treadmill rather than as a function of total step-cycle duration. Although the average step-cycle durations for their walking speeds have a reasonable range of about 33%, the range of step-cycle durations that they report for running is only 4%, and three of the four durations are within 1% (the mean cycle durations for running from Figure 3A in their paper are 822, 798, 791, and 790 ms). Thus the running data cannot provide any information about how the components of the step-cycle change with changes in the total duration, which is the basic concern of the proportional duration model. When the data for walking (from Figures 3 and 4 in Shapiro et al., 1981, pp. 41-42) were analyzed with the constant proportion test, the mean relative duration of three of the components of the Philippson step cycle did not change significantly with total cycle duration, but the fourth component, E3, increased from 48% of a 954-ms cycle to 54% of a 1,320-ms cycle, \( t(3) = 6.9, p < .01 \). Obviously, one component cannot change while the other three components remain the same. The proportion for some of the other components must have changed also, but the changes were not large enough compared with the variability in the data to be statistically significant. When the walking data (Figure 3 in Shapiro et al., 1981, p. 41) were analyzed in terms of swing and support phases, there was no change in the relative duration of the support phase, \( t(3) = 2.4, \text{ns} \). The net results, then, are somewhat mixed. Several measures of the walking cycle fit the proportional duration model, but the E3 phase in walking did not maintain a constant proportion, and the running data do not span a significant range of cycle durations. Note that E3 is part of the support phase, so this is consistent with the general find-

### Table 2

**Duration of Two Step-Cycle Phases in the Cat**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Short duration</th>
<th>Long duration</th>
<th>( t(\text{slope} \neq 0) )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trot</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>22</td>
<td>16</td>
<td>-1.51</td>
<td>ns</td>
</tr>
<tr>
<td>E2</td>
<td>19</td>
<td>12</td>
<td>-2.74</td>
<td>&lt;.02</td>
</tr>
<tr>
<td>E3</td>
<td>27</td>
<td>53</td>
<td>4.63</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>F</td>
<td>31</td>
<td>18</td>
<td>-3.24</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Gallop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>28</td>
<td>29</td>
<td>.10</td>
<td>ns</td>
</tr>
<tr>
<td>E2</td>
<td>14</td>
<td>13</td>
<td>-.30</td>
<td>ns</td>
</tr>
<tr>
<td>E3</td>
<td>18</td>
<td>18</td>
<td>-.13</td>
<td>ns</td>
</tr>
<tr>
<td>F</td>
<td>39</td>
<td>41</td>
<td>.15</td>
<td>ns</td>
</tr>
</tbody>
</table>

Note. Data are from Goslow, Reinking, and Stuart (1973), Figure 4.

### Table 3

**Joint Movements in the Cat Forelimb During Walking**

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Scapula</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>412</td>
<td>488</td>
<td>495</td>
<td>483</td>
</tr>
<tr>
<td>1.3</td>
<td>294</td>
<td>318</td>
<td>318</td>
<td>316</td>
</tr>
<tr>
<td>Flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>202</td>
<td>123</td>
<td>121</td>
<td>127</td>
</tr>
<tr>
<td>1.3</td>
<td>185</td>
<td>112</td>
<td>112</td>
<td>115</td>
</tr>
</tbody>
</table>

Note. Data are from Miller and Van der Meche (1975), Figure 5.
ing that most of the changes in duration are concentrated in the support phase.

Grillner, Halbertsma, Nilsson, and Thorstensson (1979) studied humans walking and running on a treadmill at velocities from 1.7 to 8.3 m/s. They recorded joint movement with a knee goniometer, and mounted foot switches on the subjects' shoes to record the duration of foot contact with the ground. Cycle duration data are reported for seven individual subjects but are averaged over 10 instances at each speed (Figures 2A and 2B in Grillner et al., 1979, p. 179). The constant proportion test could not be applied to the data for individual subjects because data were plotted only for slowest and fastest running and walking speeds, but I did compare these extremes. The support phase occupied an average of 49% of a 630-ms cycle at the fastest walking speed, and 58% of a 915-ms cycle at the slowest walking speed. The within-subject difference in proportion was significant, t(6) = -8.1, p < .001. Similarly, the support phase occupied an average of 25% of a 530-ms cycle at the fastest running speed, and 45% of a 725-ms cycle at the slowest running speed. The within-subject difference in proportion was significant, t(6) = -8.6, p < .001.

Grillner et al. (1979) also present data for two of their eight subjects on the duration of the flexion phase at the knee joint during running and walking. The data are for individual subjects and step cycles. The duration of the flexion phase was linearly related to the step-cycle duration, but it was not proportional to step-cycle duration; that is, when flexion or extension duration is plotted against step-cycle duration, the fitted straight line cannot be extrapolated through the origin. These conclusions were confirmed when the data were analyzed with the constant proportion test. For one subject (Figure 1A in Grillner et al., 1979, p. 178), the relative duration of the flexion phase decreased significantly as the walking step cycle increased from 620 ms to 918 ms, t(16) = -3.56, p < .01, and the relative duration of the flexion phase also decreased significantly as the running step cycle increased from 519 ms to 758 ms, t(22) = -2.73, p < .01. For a second subject, one of two with different slopes for running and walking when flexion duration was plotted against step cycle (Figure 1B in Grillner et al., 1979, p. 178), the relative duration of the flexion phase did not change significantly as the walking step cycle increased from 553 ms to 897 ms, t(17) = 1.24, ns whereas the relative duration of the flexion phase decreased significantly as the running step cycle increased from 482 ms to 705 ms, t(24) = -5.14, p < .001.

Lee, Lishman, and Thomson (1982) measured the strides of skilled long jumpers during their run up to the takeoff board. They were primarily interested in how the jumpers adjusted their gait to land just in front of the takeoff board for the jump, but they report data from the individual step cycles that could be analyzed with the constant proportion test. The data reported were for individual jumpers for each stride before takeoff, but averaged over 12 runs (Figure 4 in Lee et al., 1982, p. 453). Data for the last stride before takeoff were not included in the constant proportion test because that was atypical. Subject MN's support-phase duration varied from 47% of a 218-ms step cycle to 60% of a 272-ms step cycle, t(15) = 5.0, p < .001. Subject VW's support-phase duration varied from 48% of a 225-ms step cycle to 63% of a 281-ms step cycle, t(15) = 4.7, p < .001. Subject FM's support-phase duration varied from 50% of a 220-ms step cycle to 60% of a 246-ms step cycle, t(16) = 2.0, ns. Thus, the step cycles of two of three jumpers are not consistent with the proportional duration model.

Winter (1983) presents a plot of ankle, knee, and hip joint angles during the step cycle for people walking at their natural pace (571-ms mean step cycle), as well as other groups walking at a slow pace (708 ms) or a fast pace (493 ms). The data were averaged over 14 to 16 subjects within each pace group and over an unstated number of step cycles for each subject. Plots of the average joint angles against the normalized stride cycles appear remarkably similar for the three pace groups, but there is insufficient information for any statistical test of the proportional duration model.

Summary. Most studies of locomotion do not support the proportional duration model, with the possible exception of walking in lobsters, galloping in cats, and some studies of walking in humans. The general finding from studies of EMG, joint movements, and foot movements is that changes in overall duration of the step cycle are almost entirely reflected in changes in duration of the support cycle, whereas the duration of the swing cycle remains relatively constant. Therefore, the proportion of the step cycle occupied by the support phase increases as the cycle duration increases, rather than remaining constant as the proportional duration model predicts. This finding is so well established that, in a recent paper on mathematical models of cat locomotion, Stafford and Barnwell (1985) use the relative constancy of flexor duration with changes in cycle duration as a criterion for evaluating their model.

Other Highly Practiced Skills

Although locomotion is the most widely studied real-world task, other tasks have been studied, particularly with human subjects. The final section of this review focuses on other highly practiced skills. Some are innate actions, such as breathing; others are learned skills in which the subjects have had thousands of hours of practice, such as handwriting.

Breathing. Clark and von Euler (1972) studied the relations between the duration of the inspiratory and expiratory phases of breathing in cats and humans. They found an approximately linear relation between the inspiration and expiration durations. Clark and von Euler also state that the durations were approximately proportional for humans, but the durations were not proportional for cats. Analyses of data from individual breaths for one human and one cat with the constant proportion test confirmed these findings. For the human (Figure 9a in Clark & von Euler, 1972, p. 286), the relative duration of the inspiration phase remained at 47% as the total duration changed from 1.2 to 3.7 s, t(133) = -0.04, ns. In contrast, for the cat (Figure 9b in Clark & von Euler, 1972, p. 286), the relative duration of the inspiration phase increased from 38% to 50% as the total duration changed from 1.4 to 2.4 s, t(89) = 18.1, p < .001.

Speech. Kozhevnikov and Chistovich (1965) studied how the components of speech varied as the overall speaking rate changed. They had subjects repeat phrases with overall durations ranging from 1 to 3 s and determined the duration of various components from measurements of speech articulator movement. They examined the relative duration of words, syllables, vowels, and consonants. The data were averaged over instances and subjects. When analyzed with the constant propor-
jaw movement during speech, paralleling their EMG studies, below the syllable level but does provide a good description of the relative duration of words (Figure 3.5 in Kozhevnikov & Chistovich, 1965, p. 83) changed significantly in two of nine cases. This rejection rate is within chance (binomial distribution, \( p = .23 \)). The relative duration of syllables in the word *topila* (Figure 3.7 in Kozhevnikov & Chistovich, 1965, p. 86) did not change significantly in any of nine cases. In contrast to behavior of words and syllables, however, the relative duration of consonants within a syllable (Figure 3.9 in Kozhevnikov & Chistovich, 1965, p. 88) decreased from 36% for a total phrase duration of 800 ms to 29% with a total phrase duration of 3,000 ms, \( t(6) = -12.7, p < .001 \). Thus, at least in Russian, the constant proportion test does not describe speech for components below the syllable level but does provide a good description of longer units of speech.

Tuller, Kelso, and Harris (1982) recorded EMG patterns associated with tongue, lip, and jaw movements while words were spoken with different speeds and stress. They searched for linear relationships between components of the EMG pattern and longer periods of activity by calculating correlations between times of onset, offset, and peak amplitude of EMG for muscles associated with vowel and consonant production. Data were averaged over instances before analysis. Eight of the nine relationships reported showed a wide variety of positive and negative correlations, which was taken to indicate a lack of linear relationship. Only one relationship showed a consistently high correlation: In the sequence \( V_1 C V_2 \), the time from onset of \( V_1 \) to onset of the consonant \( C \) was highly correlated with the time between onset of \( V_1 \) and \( V_2 \). But these analyses have the same problem that occurred in Armstrong’s (1970) report, discussed in the section on arm movement. Because the period (the time from onset of \( V_1 \) to onset of \( V_2 \)) is the vowel time (from onset of \( V_1 \) to onset of \( C \)) plus the consonant time (from onset of \( C \) to onset of \( V_2 \)), the vowel time and the period will be highly correlated even if the vowel time and consonant time are independent. For the 12 data sets reported by Tuller et al. (1982, Figure 4, p. 467), the correlations between vowel time and period were between .89 and .99 with a mean of .97, whereas the correlations between vowel time and consonant time ranged from -.53 to .97 with a mean of .37. Nonetheless, reanalysis of the data with the constant proportion test showed that the ratio of vowel time to consonant time did not change significantly for 10 of the 12 data sets, generally supporting the proportional duration model for this one relationship. However, it should be mentioned that each of the data sets contains only 4 points, so it might be difficult to reject any model on statistical grounds.

The Tuller et al. (1982) paper has since provoked considerable discussion in the literature, focusing on problems with part–whole correlation analyses (Barry, 1983; Munhall, 1985; Tuller, Kelso, & Harris, 1983). In more recent studies of lip and jaw movement during speech, paralleling their EMG studies, Tuller and Kelso (1984) found high correlations between vowel-to-consonant onset times and the vowel-to-vowel onset periods. In this report, however, they are quite explicit that “the changes that occur are not ratiomorphic; the calculated regression lines... do not intercept the \( y \) axis at the origin... Again, the changes were systematic but not ratiomorphic” (Tuller & Kelso, 1984, p. 1032). I believe they intend this to mean that their data do not fit the proportional duration model, although they nonetheless conclude that “speech production [can be] characterized by the temporal stability of movements relative to a cycle and the independence of the relative timing of movement from modulations in displacement or force” (p. 1035).

In other analyses of these EMG data, Tuller, Kelso, and Harris (1981) found that “no measured interval was found to vary systematically with changes in speaking rate” (p. 73), and that “the temporal relationships between these muscles were not systematically affected by changes in speaking rate” (p. 73).

In a related study, Tuller, Harris and Kelso (1981) found that, contrary to the proportional duration model, overlap between articulator muscle activities was independent of acoustic syllable duration (Figure 4 in Tuller, Harris, and Kelso, 1981, p. 48). The proportional duration model predicts that all aspects of speech production should scale proportionally in time. The results of Tuller et al. (1982) and Tuller, Harris, and Kelso (1981) are thus consistent with the finding by Kozhevnikov and Chistovich (1965) that speech events below the level of the syllable do not correspond to the proportional duration model.

Munhall (1985) reports a study of how changes in stress during speech affected the timing of tongue movements. Two subjects repeated the nonsense word *ka kak* with emphasis on either the first or second syllable, while the vertical movement of the tongue was recorded with an ultrasound transducer. The sequence was divided into three intervals with boundaries at the upper and lower extremes of tongue movement. Munhall found results similar to those of Tuller and Kelso (1984), with high correlations (\( r = .92 \) and \( .88 \)) between vowel–consonant onset latency and the vowel–vowel onset period. However, when Munhall calculated the expected correlations based solely on the part–whole relationship, he found that the observed correlation for one subject (KM) was not significantly different from the correlation due to a simple part–whole artifact. The correlation for Subject AP was, however, significantly higher than the correlation due to a part–whole artifact (\( .92 \) vs .78).

Of course, a high correlation just indicates that the component and overall durations are linearly related, not that they are proportional. Munhall kindly supplied me with the original data from his study, which I was able to analyze with both the constant proportion test and the interaction test. Munhall divided the *ka kak* sequence into three intervals (see Munhall, 1985, Figure 1, p. 1549): L1 is first vowel onset to middle consonant onset, L2 is middle consonant onset to second vowel onset, and L3 is second vowel onset to final consonant onset. When the sequence composed of all three intervals was analyzed with the constant proportion test, the data from both subjects differed significantly from the proportional duration model. The relative durations for Subject AP changed from 27% to 35%, \( t(85) = 3.88, p = <.001 \), from 30% to 32%, \( t(85) = 1.22, ns \), and from 43% to 33%, \( t(85) = -3.19, p = <.002 \), for L1, L2, and L3, respectively, as the total duration increased from 347 to 487 ms. The relative durations for Subject KM changed from 31% to 39%, \( r(41) = 2.77, p = <.01 \), from 31% to 29%, \( r(41) = -0.71, ns \), and from 38% to 32%, \( r(41) = -1.38, ns \), for L1, L2, and L3, respectively, as the total duration increased from 394 to 519 ms. Tuller et al. (1982) had proposed that the vowel–vowel onset period had a special status for relative timing, so the constant proportion test was repeated, using L1 + L2 as the total duration. In that analysis, the proportional duration of L1 for subject AP increased from 48% to 52%, \( t(85) = 2.38, p = <.02 \), as the total duration increased from 189 to 332 ms. Subject KM showed a similar change, but because of greater
scatter, the change was not significant. The proportional duration of L1 for Subject KM increased from 52% to 56%, t(41) = 1.18, ns, as the total duration increased from 232 to 376 ms.

Because Munhall (1985) used two experimental conditions (stress on first or second syllable) to manipulate the rate of speaking, it was possible to analyze these data with the interaction test. When all three intervals were analyzed together, the data did not fit the proportional duration model. The interaction between the interval (L1, L2, or L3) and the stress condition was highly significant for both Subject AP, F(2, 82) = 182, p < .001, and Subject KM, F(2, 38) = 60.6, p < .001. When only the first two intervals were analyzed, corresponding to a vowel–vowel onset period, only one subject’s data violated the proportional duration model. The interaction between the interval and the stress condition was significant for Subject AP, F(1, 41) = 5.27, p = < .05, but not for Subject KM, F(1, 19) = .118, ns.

In summary, the constant proportion test and the interaction test provide similar results with Munhall’s speech data. When the overall duration is composed of all three intervals, the data does not fit the proportional duration model. This is reasonable, because it would be surprising if the relative timing for the whole word stayed constant when stress is shifted from the first to second syllable. When the overall duration is restricted to the vowel–vowel onset period, data from one subject violated the proportional duration model, whereas the more variable data from the other subject was not significantly different from the proportional duration model.

Sternberg, Monsell, Knoll, and Wright (1978) have found that when subjects perform a rapid action sequence, the rate of performance is dependent on the number of units in the sequence. For example, the time to speak a digit is about 8 ms longer in a sequence of five digits than in a sequence of four digits. Sternberg, Knoll, Monsell, and Wright (1983) inquired whether this change in speaking rate was equally distributed through the word or was localized to a particular portion of the word. They had subjects rapidly speak sequences of two-syllable words, such as copper and token. The data were combined over instances, words, and subjects. When the acoustic waveform for each word was decomposed into six components, the increase in duration was almost entirely a result of an increase in duration of the second vowel, which increased from 17 ms (8% of the word) to 42 ms (17% of the word), as the number of words in the sequence increased from two to five and the total word duration increased from 216 to 249 ms. When the speech data (Figure 25 in Sternberg et al., 1983, p. 16d) were tested with the constant proportion test, the relative duration changed significantly for four of the six word components.

Handwriting. Hollerbach (1981) reports vertical acceleration profiles for the pen of a subject writing the word hell at three different rates (Figure 28 in Hollerbach, 1981, p. 154). If the letter boundary is taken to be the moment of zero acceleration at the bottom of the stroke, then the relative durations for three of the four letters changed significantly as the word duration changed from about 800 ms to about 2,000 ms [all values of t(2) > 6.6, p < .05].

Viviani and Terzuolo (1980) asked people to write letters of the alphabet at different speeds and recorded the pen positions with a digitizing table. They report velocity profiles for nine instances of a letter written by one person (Figure 4 in Viviani & Terzuolo, 1980, p. 529). Analysis of their data with the constant proportion test indicated that none of the intervals between velocity maxima and minima showed a relative change as the letter duration changed from 245 to 680 ms (first maxima to last maxima), thus supporting the proportional duration model.

In a final study of handwriting, Wing (1978) examined timing within single handwritten letters (v, n, w, and m). On the basis of correlations of individual instances, he concluded that “these data do not show overall time scaling of successive segments” (p. 164).

Overall then, the studies of handwriting have yielded mixed results. The data of Hollerbach (1981) and Wing (1978) do not fit the proportional duration model, whereas the data of Viviani and Terzuolo (1980) support the proportional duration model. Perhaps these different results arise from the different component boundaries used, but certainly any definitive study would have to be based on much larger data samples.

Typing. In addition to the study of rapid speech mentioned earlier, Sternberg et al. (1983) also examined the rapid typing of short letter sequences. Like their finding with short speech sequences, the interstroke intervals of short typewriting sequences increased as the length of the sequence became longer. In order to determine whether these increases in the interstroke interval were evenly distributed over the interval, Sternberg et al. (1983) examined the index finger trajectories in alternating-hand sequences. They divided the trajectory into five components and found that the increase in the interstroke interval (actually the period covered two interstroke intervals because they examined alternating hand sequences) was entirely localized in one component of the trajectory. They found that the “late lift” component increased from 80 ms (36% of the trajectory) to 240 ms (62% of the trajectory) as the number of letters in the sequence increased from three to five and the total trajectory duration increased from 220 to 390 ms. When tested with the constant proportion test, the relative duration changed significantly for three of the five components. The results are very similar to their results from short speech sequences: The changes were localized to one component of the sequence and therefore do not fit the proportional duration model.

Probably the most commonly cited evidence for the rate parameter model is the work of Terzuolo and Viviani (1979, 1980; Viviani & Terzuolo, 1980) on typing. Terzuolo and Viviani examined the performance of expert typists during continuous typing to determine how the keystroke times within a word change as the overall duration of the word changes. They analyzed repeated instances of words, spontaneously varying in total duration. In addition, for the word enclosed, the longest instances were obtained by having the typist wear heavy rings. They found that when the keystroke times for repeated instances of a word are plotted in the proper manner, the times for each letter appeared to radiate from a common origin, thus showing that relative timing was maintained as the overall duration of the word changed. Terzuolo and Viviani (1980) have presented these radial plots for two words: 42 instances of the word enclosed (Figure 6A in Terzuolo & Viviani, 1980, p. 1092; and Figure 2A in Viviani & Terzuolo, 1980, p. 527) and 27 instances of the word trouble (Figure 1A in Terzuolo & Viviani, 1979, p. 115). Although these radial plots are intuitively clear and appealing, there is no quantitative measure to determine how well the data fit the radial lines or to summarize results over a large
number of words and typists. In fact, as shown in Table 4, when analyzed with the constant proportion test, these data did not support the proportional duration model. For both words, the majority of interstroke intervals did not maintain the same relative duration as the overall word duration changed. Similar results were obtained when the data for the two words were analyzed in terms of time after the first letter rather than in terms of interstroke intervals (see Table 4). Thus, the typing data presented by Terzuolo and Viviani (1979, 1980) do not support the proportional duration model.

In an earlier paper (Gentner, 1982), I examined data from prose transcription by a group of expert typists for evidence of the proportional duration model. Two predictions of the proportional duration model were tested on data from repeated instances of the word. The first prediction was that two interstroke intervals within a word should tend to maintain a constant ratio over repeated instances of the word. (The constant ratio prediction is closely related to the constant proportion test used in the present article, but the constant proportion test seems a more direct test of the proportional duration model than the test for a constant ratio of intervals that I used in my 1982 article.) The constant proportion analysis was restricted to the pairs of intervals with significant positive correlations, but even then, 60% of the pairs deviated significantly from a constant ratio. The results from both tests were taken as evidence against the proportional duration model.

**Summary.** Data from highly practiced skills do not generally support the proportional duration model. Clark and von Euler (1972) found that the breathing phases were proportional in humans but not in cats. Changes in speech duration do not affect the components proportionally; at least below the syllable level; vowel durations account for most of the change, whereas consonant durations are relatively stable. Handwriting durations generally change in a nonproportional manner. Finally, the data from typewriting do not support the proportional duration model.

As with the studies of laboratory tasks and locomotion, the proportional duration model can generally be rejected, whether the changes in overall duration were the result of spontaneous variation or experimental conditions. There is some suggestion from the speech data that the proportional duration model may be a better description for larger units of action (a second or longer) than it is for smaller units of action.

**New Typewriting Data**

Practically all the data on the effects of duration change in the literature suffer from one of two problems. Either the data have been averaged over different instances and subjects or the data are from a very few selected instances. Because the proportional duration model describes how timing is controlled for individual instances of an action sequence, it is obviously preferable to examine individual instances directly. Averaging the data before analysis can only remove information from the data and may obscure the underlying mechanisms. The constant proportion test and the interaction test permit analysis of individual instances and then yield a convenient statistical summary of these tests over many different actions and subjects. Therefore, in addition to analyzing data from the literature, I have applied the constant proportion test, the interaction test, and other analyses to extensive body of data that I have collected over the past 5 years from expert typists.

**General Method**

All subjects were professional typists recruited from the university and local businesses. They typically typed 14 hr per week at work (range = 2–25), and their median typing speed was 71 wpm (range = 53–112) measured over approximately 40 min of typing and uncorrected for errors. Subjects were paid for participation. The five subjects in Experiment 1 were also subjects...
in Experiment 2. Otherwise, subjects participated in only one experiment.

In Experiment 1, subjects typed at a Hazeltine 1500 computer terminal connected to a minicomputer that recorded keypresses and the corresponding times with an accuracy of 1 ms. Typed characters were displayed on the terminal screen. The typists were all familiar with this terminal, having used it in conjunction with the campus word-processing system. In Experiments 2 through 4, subjects typed on a high-quality, electronic keyboard (Microswitch 51SD12-4) with a layout identical to the IBM Selectric typewriter and a similar feel. The keyboard was connected to a microcomputer that recorded keypresses and the corresponding times with an accuracy of 1 ms. Typed characters were displayed on a CRT screen in front of the typist. In all experiments, the text to be transcribed was presented as printed or typewritten copy in a convenient place next to the keyboard. After a warm-up period, typists were asked to transcribe the text at their normal, rapid rate and to ignore any errors they might make.

Analyses

The data used for these analyses were the interstroke intervals (the interval between successive keystrokes) for words that occurred several times in the text. In each study, the set of words analyzed consisted of all words occurring at least 10 times in the original text, at least three letters in length, and containing only lowercase letters. The data for a given word were the interstroke intervals within the word; for example, the four interstroke intervals within a five-letter word. All analyses were based on data from individual typists. Because the analyses can be strongly affected by outlying data, two procedures were used to eliminate atypical instances of words. First, instances containing an interstroke interval greater than 400 ms (typically about 9% of the instances) were eliminated. Second, instances containing an interstroke interval more than 3 standard deviations (SD) away from the mean of that interval for that particular word and typist (another 5% of the instances) were eliminated. Finally, if less than five instances of the word remained, the word was not used for that typist.

Correlation analysis. Most of the typing studies in this section, as well as in the literature, examine the spontaneous fluctuations in rate that occur in normal typing. When a word is typed repeatedly in the course of transcribing a text, the interstroke intervals for a given diagraph vary from one instance of the word to another. To take a typical example, in 30 repetitions of the word interest by one typist, the interstroke interval for the re digraph varied from 79 to 169 ms ($M = 117, SD = 24$). It would be helpful to have a method to estimate how much of the observed variability is due to variations that affect the whole word, such as changes in typing rate, and how much is due to short-term variations that affect only a single keystroke. The correlational analysis provides this estimate.

The basic approach is based on the observation that if a change affects the whole word, the durations of any two intervals within the word should be positively correlated over instances of the word. That is, if one interval is longer than average in a particular instance, the other intervals in that instance should tend to be longer than average also, and therefore the intervals within a word should be positively correlated. If we assume that the variability of an interstroke interval is composed of the sum of two terms—a common term, common to all interstroke intervals in the word, and an independent term, different for all the interstroke intervals—then we can estimate the relative contributions of the common term and the independent term from the correlation between intervals within a word. It is clear that if most of the variability comes from the common term, the correlation between interstroke intervals will be high. Conversely, if most of the variability comes from the independent term, the correlation between interstroke intervals will be close to 0. The exact relation between source of variability and correlation depends on the details of the model assumptions.

The additive rate parameter model presented earlier (Equation 2) fits the assumptions in the last paragraph exactly. The variability of interstroke intervals is the sum of two components: variability in $r_c$, that is common for all intervals in the instance and variability in $e_i$, that is independent for all intervals. For this model, the proportion of variance due to the common term is equal to the correlation of two interstroke intervals over instances of the word. If the multiplicative rate parameter model of Equation 5 would also fit these assumptions exactly if the correlations were calculated between the logarithms of the intervals, but an empirical study showed that it was not really necessary to go to all that trouble. The correlation analysis estimated the contribution of the multiplicative rate parameter within 4% of the true value even when the intervals were correlated directly, without taking their logarithm. Even if this simple model of intervals—where the variability is the sum of normally distributed common and independent terms—is not completely valid, a correlational analysis can still provide an approximate measure of the relative contribution of common-variability terms, such as changes in typing rate.

In the following experiments, correlations were calculated between pairs of interstroke intervals across all instances of each word examined. All possible combinations of interstroke intervals were used, but to avoid undue bias toward long words, a mean correlation was calculated for each word, and these correlations were then averaged to produce a grand mean correlation for each typist. Parallel models of timing production can produce negative correlations between adjacent intervals (see Gentner, 1982; Wing, 1980) and could affect the interpretation of correlations that included adjacent intervals. Therefore, the mean correlation between all nonadjacent intervals was also calculated. As it turned out, neither within-word averaging nor exclusion of adjacent intervals made any appreciable difference in the results of the correlational analysis.

The constant proportion test. The constant proportion test has already been described. Whereas the correlational analysis estimates the variability resulting from typing rate changes, the constant proportion test determines whether these rate changes

1 In an earlier article (Gentner, 1982), I stated in error that a mean correlation between intervals of .2 indicated that rate changes accounted for 4% (that is, $r^2$) of the variance. Although the square of the correlation coefficient between an independent variable and a dependent variable gives a measure of the proportion of variance accounted for by the independent variable, in this case the correlation is between two independent variables. The proportion of variance common to two independent variables is given by $r$, so a correlation of .2 suggests that 20% of the variance is due to rate changes.
follow the proportional duration model. Each interstroke interval was tested to determine if the relative duration of the interstroke interval remained constant as a function of the overall word duration. The measure reported is the percentage of tests that reject a constant proportion with $p < .05$. Interstroke intervals rather than times were used with the constant proportion test, because typing data fit a serial model of timing better than a parallel model of timing (Gentner, 1982). When the constant proportion tests were repeated using times after the first letter of the word, the rejection rates were slightly higher.

Experiments 1 and 2: Prose

Method

In Experiment 1, five typists transcribed a collection of magazine articles adapted from Reader's Digest, totalling 9,371 words, at their normal typing rates. In a similar study about a year later, the five typists from Experiment 1 and six additional typists participated in Experiment 2, in which they transcribed one of the magazine articles from Experiment 1 with a total of 2,067 words.

Results

The results from Experiment 1 are shown in the first section of Table 5. They are based on an analysis of 542 words over five typists (1,841 interstroke intervals), with an average of 22 instances per word. On average, the range of durations for a word was 38% of the mean duration for that word. The within-word correlation of .17 for separated interstroke intervals suggests that about 17% of the observed variance of the interstroke intervals was due to changes in typing rate.

When tested with the constant proportion test, the hypothesis of a constant relative duration was significantly rejected for 34% of the interstroke intervals. The lowest rejection rate for any typist was 28%. This rejection rate is, of course, much higher than the 5–10% rate expected with the proportional duration model. It is interesting to note that the rejection rate is also much higher than the 17% rejection rate found in the simulation studies when 20% of the variance was contributed by an additive rate parameter (see Table 1), indicating a serious deviation from the behavior expected with a simple multiplicative or additive rate parameter.

Experiment 2 included more typists but fewer words than Experiment 1. The results from Experiment 2 are similar to the results from Experiment 1 and are shown in the second section of Table 5. They are based on a total of 207 words (584 interstroke intervals), with an average of 18 instances per word. On average, the range of durations for a word was 49% of the mean duration for that word. In this experiment, the mean within-word correlation for all interstroke intervals was much lower than the correlation for only separated intervals. This was because 9 of the 19 words examined were three-letter words that did not have separated interstroke intervals, and the interstroke intervals of alternating-hand, three-letter words had a strong negative correlation for many typists. For example, the correlation between the th and he interstroke intervals in the word the ranged from −.67 to .54 across the typists, with an average correlation of −.29. The average within-word correlation of .20 for the separated intervals suggests that about 20% of the observed variance of the interstroke intervals was due to changes in typing rate.

In accord with Experiment 1, there was a 31% overall rejection rate in the constant proportion test. The rejection rate for individual typists ranged from 15% to 50%, once again failing to support the proportional duration model.

Experiment 3: Random Words

Method

The text for Experiment 3 was a set of 69 words, from 5 to 11 letters in length. The words were presented in 20 blocks, each block consisting of a different random arrangement of the words. Presenting the text as random words rather than prose appears to have no effect on the performance of skilled typists (Fendrick, 1937; Shaffer, 1973; West & Sabban, 1982).

Results

The results from Experiment 3 are shown in the third section of Table 5. They are based on a total of 688 words (4,505 interstroke intervals), with an average of 16 instances per word. The range of durations for a word averaged 33% of the mean duration for that word. The within-word correlation of .12 for the separated intervals suggests that about 12% of the observed variance of the interstroke intervals was due to changes in typing rate.

In close accord with the results from Experiments 1 and 2, there was a 36% overall rejection rate in the constant proportion test. The rejection rate for individual typists ranged from 24% to 48%, all well above the rate expected with the proportional duration model.

Experiment 4: Slow, Normal, and Fast Typing

One possible objection to the preceding experiments is that the range of typing speeds was not wide enough, and any effects of a multiplicative rate parameter could be swamped by other effects. Note that these other effects cannot be just random error, because even a large random error with a small multiplicative rate parameter would still produce a rejection rate of only 5–10% (see Table 1). These other effects would thus have to systematically change the interstroke intervals in a nonproportional manner. In any event, Experiment 4 was an attempt to increase the relative effect of a rate parameter by explicitly asking the typists to type at slow, normal, or fast rates.

Method

The text was based on a set of eight sentences (99 words), all in lowercase and without punctuation. Each page to be transcribed was a different random arrangement of these sentences. Ten typists were asked to transcribe six pages as slow as they could comfortably type, six pages at their normal rate, and six pages as fast as possible. The typing rate alternated for successive pages of text.

Results

The typists were able to vary their rate on demand. Their typing rates for the three experimental conditions are shown in Table 6. Not surprisingly, typists were more effective at slowing
Table 5
Correlational Analysis and Constant Proportion Test Applied to Data from Expert Typists

<table>
<thead>
<tr>
<th>Experiment and typist</th>
<th>Wpm</th>
<th>Number of words</th>
<th>Mean correlation</th>
<th>% rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>All intervals</td>
<td>Separated intervals</td>
</tr>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t01</td>
<td>77</td>
<td>108</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>t02</td>
<td>60</td>
<td>109</td>
<td>0.31</td>
<td>0.23</td>
</tr>
<tr>
<td>t03</td>
<td>71</td>
<td>108</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>t04</td>
<td>62</td>
<td>109</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>t05</td>
<td>61</td>
<td>108</td>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>M</td>
<td>66</td>
<td></td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t01</td>
<td>90</td>
<td>19</td>
<td>-0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>t02</td>
<td>66</td>
<td>19</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>t03</td>
<td>76</td>
<td>19</td>
<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>t04</td>
<td>75</td>
<td>19</td>
<td>0.01</td>
<td>0.28</td>
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<tr>
<td>t05</td>
<td>61</td>
<td>19</td>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>t06</td>
<td>82</td>
<td>19</td>
<td>0.16</td>
<td>0.21</td>
</tr>
<tr>
<td>t07</td>
<td>110</td>
<td>19</td>
<td>0.26</td>
<td>0.18</td>
</tr>
<tr>
<td>t08</td>
<td>112</td>
<td>19</td>
<td>0.06</td>
<td>0.24</td>
</tr>
<tr>
<td>t09</td>
<td>86</td>
<td>18</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>t10</td>
<td>85</td>
<td>19</td>
<td>0.03</td>
<td>0.20</td>
</tr>
<tr>
<td>t40</td>
<td>92</td>
<td>18</td>
<td>-0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>M</td>
<td>85</td>
<td></td>
<td>0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>Experiment 3</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
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<td>64</td>
<td>68</td>
<td>0.28</td>
<td>0.25</td>
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<td>t61</td>
<td>101</td>
<td>69</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>t62</td>
<td>69</td>
<td>69</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>t63</td>
<td>84</td>
<td>69</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>t64</td>
<td>92</td>
<td>69</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>t65</td>
<td>68</td>
<td>69</td>
<td>0.14</td>
<td>0.11</td>
</tr>
<tr>
<td>t66</td>
<td>72</td>
<td>69</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>t67</td>
<td>69</td>
<td>69</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>t68</td>
<td>66</td>
<td>69</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>t69</td>
<td>66</td>
<td>68</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>M</td>
<td>75</td>
<td></td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Experiment 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t70</td>
<td>71</td>
<td>67</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td>t71</td>
<td>69</td>
<td>67</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>t72</td>
<td>71</td>
<td>68</td>
<td>0.64</td>
<td>0.61</td>
</tr>
<tr>
<td>t73</td>
<td>81</td>
<td>68</td>
<td>0.47</td>
<td>0.49</td>
</tr>
<tr>
<td>t74</td>
<td>64</td>
<td>68</td>
<td>0.84</td>
<td>0.83</td>
</tr>
<tr>
<td>t75</td>
<td>101</td>
<td>69</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>t76</td>
<td>74</td>
<td>69</td>
<td>0.41</td>
<td>0.44</td>
</tr>
<tr>
<td>t77</td>
<td>69</td>
<td>69</td>
<td>0.92</td>
<td>0.93</td>
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<tr>
<td>t78</td>
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<td>69</td>
<td>0.79</td>
<td>0.79</td>
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<td>t79</td>
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<td>69</td>
<td>0.53</td>
<td>0.51</td>
</tr>
<tr>
<td>M</td>
<td>72</td>
<td></td>
<td>0.69</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Note. wpm = words per minute.

down from their normal rate than at speeding up. For the constant proportion test, data from all three conditions were pooled; the three conditions just served as a device to encourage a wide range of word durations. The cutoff point for eliminating outlying instances was increased from the normal 400 ms to an interstroke interval of 700 ms because of the many long interstroke intervals in the slow condition.

The results from the constant proportion test for Experiment 4 are shown in the last section of Table 5. They are based on a total of 685 words (4,505 interstroke intervals), with an average of 18 instances per word. The range of durations for a word—an average of 107% of the mean duration—was much larger than in the previous experiments. The within-word correlations were also much larger, ranging from .44 to .95 for separated interstroke intervals, reflecting the larger changes in typing rate. The average within-word correlation of .69 for the separated intervals suggests that about 69% of the observed variance of the interstroke intervals was due to changes in typing rate.
Patterns of Change With Typing Rate

First, what is the evidence for changes in typing rate? If, as has been demonstrated, the interstroke intervals of skilled typists are not described by a proportional duration model, is there any systematic pattern of rate change, or are these data merely the result of random variation? There are three strong arguments that expert typists can vary their rate. First of all, Experiment 4 clearly demonstrates that typists can vary their typing rate over a large range on demand. Second, the positive mean correlations from the correlational analyses show that even when typing at normal rate, fluctuations in rate occur that persist for at least the duration of a word. Third, an autocorrelation study indicated that while typing at their normal rate, some typists have rate changes that persist for many words. The word durations from Experiment 3 were normalized by dividing the observed duration of the word by the mean duration for that word and typist. Then autocorrelation coefficients were determined at lags of 1–50 words for the sequence of normalized words. The extent of rate changes was conservatively estimated by determining the lag before the first negative autocorrelation. Individual differences between typists were very pronounced. Rate changes persisted for only one word for two of the typists, 3–6 words for two typists, 13–31 words for three typists, and more than 50 words for the remaining three typists. So we can conclude that at least some typists normally exhibit changes in typing rate that persist for many words.

Given that typing rates can change, are there any regularities in the details of how performance changes with overall rate? In another study (Gentner, 1983), I analyzed the interstroke intervals of typists who transcribed normal prose under fast and slow conditions. In the fast condition, they were told to assume they were typing a rough draft and to type as fast as possible without concern for errors. In the slow condition, the typists were told to assume they were typing a final copy and to type carefully and minimize errors. For purposes of analysis, the letter–letter digraphs were divided into four classes based on the fingers used in touch typing: (a) doubles, such as dd; (b) one-finger digraphs, nondoubles typed by a single finger, such as de; (c) two-finger
digraphs were divided into four classes based on the fingers used in touch typing: (a) doubles, such as dd; (b) one-finger digraphs, nondoubles typed by a single finger, such as de; (c) two-finger


**Table 7**

<table>
<thead>
<tr>
<th>Typist</th>
<th>Fast</th>
<th>Slow</th>
<th>Double</th>
<th>1-finger</th>
<th>2-finger</th>
<th>2-hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>t02</td>
<td>72.5</td>
<td>59.1</td>
<td>7.6</td>
<td>6.7</td>
<td>20.0</td>
<td>28.8</td>
</tr>
<tr>
<td>t03</td>
<td>80.3</td>
<td>72.9</td>
<td>1.5</td>
<td>5.4</td>
<td>11.7</td>
<td>12.9</td>
</tr>
<tr>
<td>t04</td>
<td>84.3</td>
<td>73.1</td>
<td>4.1</td>
<td>9.7</td>
<td>9.2</td>
<td>16.8</td>
</tr>
<tr>
<td>M</td>
<td>79.0</td>
<td>68.4</td>
<td>4.4</td>
<td>7.3</td>
<td>13.6</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Note: wpm = words per minute, ISI = interstroke interval.

The pattern changes somewhat, however, when data from the slow condition of Experiment 4 are included in the analyses. The pattern of results across all three conditions is most easily seen by examining the performance of individual typists. The overall typing rate and the median interstroke intervals for each digraph class were calculated separately for each page of text (99 words) in Experiment 4. The results for two typists who had a wide range of typing rates are shown in Figure 3. The median interstroke intervals are plotted on a logarithmic axis in Figure 3, so that if they maintained a constant relative proportion the lines should be parallel. The lines are clearly not parallel, illustrating the previous finding that the data from this experiment do not fit the proportional duration model. However, two general patterns observed in this study are clear from Figure 3. The first general pattern was that the median interstroke intervals for all digraph classes were similar at the lowest typing rate, but the medians diverged as the typing rate increased. The spread in the median interstroke intervals (as measured by the standard deviation of the medians) was positively correlated with the typing rate. This was true for all 10 typists on a relative basis (mean correlation across typists = .96) and for 9 of 10 typists on an absolute basis (mean of correlation across typists = .70). The second general pattern was that at the highest typing rates, the median interstroke intervals for double and one-finger digraphs changed very little with changes in overall typing rate, relative to the medians for two-finger and two-hand digraphs. This, of course, is similar to the finding from the rough-draft/final-copy study (see Table 7), but now it is clear that the relative amount of change is dependent on the absolute rate.

**Simulation Model of Typing**

Another approach to understanding the control of timing is to construct a simulation model of performance and investigate the model's predictions of timing. Rumelhart and Norman (1982) developed a simulation model of a skilled typist that did not have any central timing control. Instead, the timing of the model's keystrokes was the result of competition and cooperation between efforts to type several letters at once. Similar to skilled typists, the model's interstroke intervals reflect the constraints of the hands and fingers and the layout of the typewriter keyboard. Although the model attempts to type several letters at once, the letters are normally produced in the correct serial order because each letter inhibits every following letter to some extent, and therefore the initial letter usually has the highest activation level. When the level of inhibition between successive letters is very high, the model essentially types just one letter at a time. As the level of inhibition is lowered, however, the model attempts to type several letters at once. In this case, movements to type successive letters can overlap in time, especially when successive letters are typed by separate fingers or hands, and the overall typing rate increases.

In an experiment with the simulation model, I had the model type an English prose text (the magazine article used in Experiment 2) at different inhibition levels. The mean interstroke intervals for the different digraph classes decreased with decreasing levels of inhibition (see Figure 4). Notice that the interstroke intervals for the digraph classes do not maintain constant relative durations, which would be indicated by parallel lines on this logarithmic plot. Doubles do not speed up at all because there is no advantage in moving the hand for the second keystroke, two-hand and two-finger digraphs speed up the most because the model can easily overlap movements on different hands and fingers, and one-finger digraphs speed up slightly because the model can move its hand into position for the second keystroke while typing the first. This pattern is similar to the results from skilled typists for changes near their normal rate (for example, see Table 7) and also matches the pattern of changes in interstroke intervals observed during the acquisition of typing (Gentner, 1983). Note, however, that the effect of changing the inhibition level in the typing simulation does not completely match the pattern of results when skilled typists change over wide ranges as in Experiment 4 (see Figure 3). Although the interstroke intervals of the simulation model for one-finger, two-finger, and two-hand digraphs appear to be converging at higher inhibition levels, the interstroke intervals for doubles are unchanged. In contrast, the interstroke intervals for all digraph classes converged at the slowest typing speeds of expert typists. This difference suggests that a model based only on peripheral mechanisms, like the Rumelhart and Norman (1982) simulation, may fail to capture some aspects of skilled motor performance, such as the ability of typists to pace their keystrokes at a very slow and even rate.
Figure 3. Median interstroke intervals for the digraph classes as a function of overall typing rate. (The vertical axis is logarithmic, so that if this data fit the proportional duration model the lines would be parallel. Instead, the interstroke intervals are similar at low typing rates and quite different at high typing rates. As typing rate increases, the interstroke intervals for some digraph classes continue to decrease, whereas the interstroke intervals for doubles appear to reach a minimum level.)

Composite Control of Timing

Some models of timing, such as the proportional duration model, seem to be based on the idea that motor performance is determined solely by central control. With the proportional duration model, a generalized motor program is stored in long-term memory and, with the specification of a multiplicative rate parameter, the output of the generalized motor program is as-

Figure 4. Results from the typing simulation model. (Mean interstroke intervals for the digraph classes as a function of the level of inhibition between letters. As the inhibition level decreases, the overall typing rate increases, but the interstroke intervals for the different digraph classes decrease at different rates.)
sired to correspond directly to the observed timing of behavior. This is similar to the way that the performance of an ideal mechanical robot is a direct reflection of its program and independent of peripheral properties, such as the mass of the robot’s arm. At the other extreme is a model, such as the typing simulation model of Rumelhart and Norman (1982), in which there is no central control of timing and the observed timing of behavior is determined primarily by peripheral constraints, such as the structure of the hands. With this model, any central control is very indirect; for example, central control might be mediated by changing the inhibition levels between successive letters.

Consider the case of a cockroach walking at different rates. The results of Delcomyn (1971) and Pearson (1972) show that the durations of the swing and support phases do not change proportionally. In other words, a motion picture of a fast cockroach, when played back in slow motion, would not match the performance of the same cockroach walking slowly. Why should this be? Assuming that the extent of leg movement remains the same, the only way for a cockroach to walk slower is by moving the leg slower when the leg is in contact with the ground and thereby increase the duration of the support phase of the step cycle. In contrast, the leg is not in contact with the ground during the swing phase, and therefore the duration of the swing phase is not directly constrained by the speed of walking. In fact, in contrast with the support phase, the duration of the swing phase is observed to be relatively constant, perhaps in order to minimize the energy expenditure for the swing phase or to maintain stability by having more feet on the ground whenever possible. Thus, because the movement duration of the leg is directly related to speed during the support phase but approximately constant during the swing phase, the ratio of durations for the swing and support phases changes as the walking speed of the cockroach changes. It appears to be a general principle of behavior that when the details of timing are not an explicit part of the task, they will be determined by other considerations, such as minimizing energy consumption.

Motor performance is inseparable from perceptual and cognitive processes, the physical properties of the body, and the environmental context of the task (see Prinz & Sanders, 1984). The timing of any particular instance of motor performance is determined by the interaction of central and peripheral processes with the task environment. Results from typing illustrate this composite control of timing. We have seen that typists can vary their overall typing rate at will, presumably as a result of central control. Typing performance also shows other effects of central control, for example, sensitivity to the frequency of words and letter sequences (Gentner, Larochelle, & Grudin, 1986; Shaffer, 1973; West & Sabban, 1982). At the peripheral level, finger and hand constraints determine the interstroke intervals of different digraph classes when typing at high speeds. Also, constraints at both central and peripheral levels interact with the nature of the task environment, such as the particular text to be typed and the layout of the typewriter keyboard. The relative contribution of all these factors to the final performance depends on the situation. In Experiment 4, when typists were working at the slowest rates, their timing appears to have been determined by a regular central timekeeper, and all digraph classes were typed at the same rate. As the typists sped up, however, peripheral constraints began to play an important role, and double and one-finger digraphs reached their limiting rate, whereas two-finger and two-hand digraphs, where overlapped movement is easier, continued to get faster.

Novice typists show a related progression over the course of learning to type. At first their performance appears to be limited by central processes. Instead of following a central timekeeper and typing all digraph classes at the same rate (this is what experts do when typing slowly), novices appear to be limited by planning and memory processes. Novices type one-finger, two-finger, and two-hand digraphs at the same rate, but doubles (where there is no need to retrieve a new location for the second key) are typed twice as fast as the other digraphs (Gentner, 1983). As their skill level increases, novices gradually speed up their typing and move toward the pattern of expert typists whose relative interstroke intervals reflect peripheral control—such as finger and hand constraints and the keyboard layout—to a greater degree.

Finally, what is the status of the generalized motor program in a composite model of motor control? There is overwhelming evidence for the central representation of motor skills in the brain or spinal cord (Delcomyn, 1980; Grillner, 1985). In the case of locomotion, decerebrate animals whose sensory pathways have been cut still exhibit an approximately normal gait pattern, and the rate of locomotion can be altered by stimulation at specific brainstem areas, showing that there are motor programs for locomotion in the brainstem or spinal cord (Delcomyn, 1980; Grillner, 1985; Shik & Orlovsky, 1976). In other cases, of course, the motor program may be represented at higher central levels. These results confirm the basic claim of the generalized motor program: Motor skills can be represented centrally in a flexible manner, so that a single representation of an action can produce many different instances of behavior. On the other hand, the simple version of the generalized motor program, in which a multiplicative rate parameter produces proportional durations in behavior, is generally not supported by the evidence.

Although a generalized motor program might produce proportional duration changes at one level that could be modified by other control mechanisms in a composite model of motor control, there are other ways that a generalized motor program could be compatible with the finding that behavior does not fit the proportional duration model. The nervous system is inherently nonlinear, and there is no reason to expect that a generalized motor program would produce proportional durations at any level unless specifically required by the task (see Stafford & Barnwell, 1985, for an example of a neural model of locomotion that does not produce proportional duration changes). From that perspective, the proportional duration model is only one possible version of a generalized motor program. The generalized motor program should be considered one component
in a composite model of motor control with many other overlapping control mechanisms. Control of timing is determined at several levels in the perceptual–cognitive–motor system, and the nature and relative importance of these control levels can shift with skill acquisition and in response to the task environment. The examination of skilled performance over wide changes in the nature of a task appears to be one fruitful way to tease apart these different levels of motor control.

References


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