Does Motor Programming Necessitate Response Execution?

Allen Osman
University of California, San Diego

Sylvan Kornblum and David E. Meyer
University of Michigan

The complexity of a movement is known to affect the time it takes to initiate the movement. This effect is thought to reflect changes in the duration of processes that operate on a motor program. This question addressed here is whether programming a movement compels the start of its overt execution. If it does, then the programming processes may be said to occur after the "point of no return." We report results from an empirical procedure and a theoretical analysis designed to study processes before and after this point separately. According to our results, changes in the complexity of a movement affect only the prior set of processes. From this we argue that motor programming does not necessitate response execution and that the point of no return occurs very late in the information-processing system.

In his book *Thinking*, Bartlett (1958) observed that a "character which belongs to all bodily skills is perhaps most vividly described in the airman's phrase 'the point of no return'" (p. 17). By this he meant that many actions, once launched, cannot be successfully modified. "In cricket, for instance, in the battle of wits between the bowler and the batsman, the former is always trying to deliver a ball which does something out of the ordinary after the latter is well launched upon his intended stroke" (p. 18).

There is little doubt that speeded voluntary movements, such as the batsman's stroke, are difficult to stop or modify just prior to their overt initiation. What remains uncertain, however, is whether some voluntary movements are really preceded by a "point of no return." In order to be effective, signals indicating the need to stop or to change a movement must precede the movement by a certain amount of time (Logan & Cowan, 1984). Such countermanding signals (whether externally or internally generated) may in some cases take considerable time to process, as they may require central computation (Poulton, 1981) or be subject to refractory effects (Smith, 1967; but see Logan & Burkell, 1986). Nevertheless, it is conceivable that, given enough time to respond to a countermanding signal, any movement can be modified at any point during its preparation, right up to its overt execution.

The existence of a point of no return implies a failure of voluntary control over and above that caused by the reaction time necessary to exert such control. It implies that a move-

ment is immediately preceded by a set of processes that, once begun, necessitate the start of overt movement regardless of the speed with which any attempt to stop or to modify the movement can be executed. We call these *ballistic* processes. Ballistic processes are preceded by, and may be distinguished from, *controlled* processes. Although controlled processes may be automatic in other senses (cf. Jonides, 1981), they are under central control with respect to whether they ultimately lead to overt movement (cf. Logan, 1981). A point of no return would be the temporal boundary between controlled and ballistic processes (i.e., the point at which the response becomes ballistic).

In this article we are concerned with the existence and location of the point of no return. By location we do not mean the length of time by which it follows a stimulus or precedes a response. Rather, we are concerned with the functional nature of the processes before and after the point of no return. Determining the location of the point of no return thus involves specifying which motor processes (e.g., response selection or motor programming) are controlled and which are ballistic. The discovery that a particular process is ballistic is especially important, because ballistic processes imply the existence of a point of no return.

We report here an investigation in which we sought to determine whether the point of no return occurs before, during, or after "motor programming." A motor program is a set of commands that control, and are set up in advance of, a sequence of movements (Keele, 1968). The discovery that longer or more complex movements often take more time to initiate than do shorter or simpler ones (Henry & Rogers, 1960) was an important impetus to the study of motor programming. This "response-complexity" effect is thought to occur because more complex movements require more elaborate motor programs, which in turn take longer to prepare or utilize (Henry & Rogers, 1960; Keele, 1981; Klapp, 1978; Sternberg, Monsell, Knoll, & Wright, 1978). The specific question we address here is whether the motor programming processes affected by response complexity are controlled or ballistic.

The answer to this question may help us to discriminate between alternative models of motor programming. For example, one model attributes response-complexity effects to differences in the time required to read the motor program from long-term memory into a short-term motor-program buffer (Klapp, 1976, 1978). Because this model hypothesizes a single mechanism that ought not to require response execution, it implies that response complexity should affect only controlled processes. A second model explains response-complexity effects in terms of the time needed to edit the program while it resides in the buffer and to traverse its hierarchical structure from the highest to the lowest node that controls the first element of the movement (Rosenbaum, Hindorff, & Munro, 1987; Rosenbaum, Inhoff, & Gordon, 1984). The traversal process could conceivably be either controlled or ballistic, but editing ought not to cause response execution. This model therefore implies that at least some of the processes affected by response complexity are controlled. Finally, according to a third model (Sternberg et al., 1978), the processes affected by response complexity involve searching the motor-program buffer for the "subroutine" that controls the first element of the movement and then performing a second set of "unpacking" operations on the subroutine. Since both searching and unpacking could be either controlled or ballistic, this model cannot be rejected on the basis of the particular class of processes that are affected by response complexity.

The question of whether motor-programming processes are controlled or ballistic is also relevant to the issue of whether simple or choice reaction time should be used to study response-complexity effects (Klapp, 1978; Sternberg et al., 1978). In the simple reaction time procedure, subjects know precisely what movement they will have to make before the occurrence of the response signal. If programming involves only controlled processes, and if the results of these processes can be stored, subjects could preprogram their responses before the signal. Because reaction time is measured from the onset of the signal, the effects of response complexity on motor programming would not be reflected in the reaction time. Yet, response-complexity effects are consistently found in simple reaction time experiments (e.g., Henry, 1980; Henry & Rogers, 1960; Sternberg et al., 1978). One reason for this might be that at least part of motor programming is a ballistic process. Subjects would then be forced to wait for the response signal to complete programming in order to avoid responding on catch trials or making anticipations.

General Approach

Our aim is to determine whether response complexity affects controlled or ballistic processes. To accomplish this goal we employed an approach developed in a previous article (Osman, Kornblum, & Meyer, 1986). The approach utilizes a countermanding procedure and race model to measure separately the effects of experimental manipulations on controlled and ballistic processes. This particular application of the race model to the results of the countermanding procedure builds upon previous work by Ollman (1973) and Logan (1981) and is similar to that of Logan and Cowan (1984). We

briefly describe this approach below. (For a fuller discussion refer to Logan and Cowan (1984) or Osman et al. (1986)).

The Countermanding Procedure

The name *countermanding* comes from the fact that subjects are sometimes required to cancel a response to a previously issued command. The procedure involves randomly interleaving two types of trials: *go* trials and *stop* trials. Go trials are like those used in standard simple and choice reaction time experiments, in which subjects must make a designated response to a go signal as quickly as possible while maintaining a high degree of accuracy. Stop trials are similar to go trials, except for the occurrence of a stop signal following the go signal. Subjects must respond quickly to the go signal but should attempt to avoid responding if they subsequently detect the stop signal. Of course, subjects never know whether the current trial is a go or a stop trial until the actual occurrence of a stop signal.

We will be especially concerned with three dependent variables that are associated with the countermanding procedure: the reaction time on go trials; the reaction time on stop trials in which subjects fail to withhold their responses; and *response functions*. Response functions, denoted $P_R(SOA)$, give the probability of responding on stop trials (i.e., failing to inhibit) as a function of the time interval (stimulus onset asynchrony, or SOA) between the go and stop signals. We call this interval the *signal lag*. As the signal lag increases, the probability of response inhibition $[1 - P_R(SOA)]$ typically decreases.

The Race Model

The model that we use to interpret these variables involves three independent sets of processes and a point of no return. The three sets consist of the controlled and ballistic processes introduced earlier, and an inhibition process. According to the model, stop trials involve a race between the controlled and inhibition processes with the point of no return as the finish line: If the controlled process wins, then the response will occur in spite of the stop signal; if the inhibition process wins, then the response will be aborted.

Equations 1–3 show how the race model defines the dependent measures of the countermanding procedure. T_C, T_I, and T_B correspond to the completion times of the controlled, inhibition, and ballistic processes and are assumed to be independent random variables. Equation 1 shows the reaction time on go trials:

$$RT_{Go} = T_C + T_B. \tag{1}$$

Here there is no race, so reaction time is simply the sum of the completion times for the controlled and ballistic processes. Equation 2 expresses the reaction time on stop trials in which a response occurs:

$$RT_{Stop} = [T_C | (T_C < (T_I + SOA))] + T_B. \tag{2}$$

Here there *is* a race, and it was won by the controlled process. Reaction time is therefore the time taken by the controlled

process, given that it beat the inhibition process, plus the time taken by the ballistic process. The response function, or probability of responding on a stop trial, is shown in Equation 3:

$$P_R(SOA) = P[T_C - T_I) < SOA]. \tag{3}$$

The right side of the equation represents the probability that the signal lag plus the time taken by the inhibition process is greater than the time taken by the controlled process to reach the point of no return. Plotting this probability as a function of signal lag gives us the entire response function, which may be viewed as a type of psychometric function or cumulative distribution function that has its own mean and variance over the temporal domain.

Measuring Controlled and Ballistic Effects

We now have the machinery in place to measure separately the effects of various factors on controlled and ballistic processes. These effects cannot be observed directly. However, they can be inferred, by means of the race model, from changes in reaction time on go trials and in the response functions. According to the race model, any change in mean go-trial reaction time is the sum of the change in mean controlled-process time and the change in mean ballistic-process time, as shown in Equation 4:

$$\Delta M_{Go} = \Delta M_C + \Delta M_B, \tag{4}$$

where ΔM_{Go}, ΔM_C, and ΔM_B denote respectively the changes in the means of go-trial reaction time, controlled-process completion time, and ballistic-process completion time. Similarly, any change in the mean of the response function equals the change in the mean controlled-process time minus the change in the mean inhibition-process time, as shown in Equation 5:

$$\Delta M_R = \Delta M_C - \Delta M_I, \tag{5}$$

where ΔM_R and ΔM_I denote changes in the means of the response function and inhibition processes. If we assume further that the inhibition process remains unchanged by the factor manipulation under study, Equation 5 reduces to Equation 6:

$$\Delta M_R = \Delta M_C, \tag{6}$$

where the change in the response function simply equals the change in the controlled processes alone. The change in the mean ballistic-process time would then equal the change in the mean go-trial reaction time minus the change in the mean of the response function, as shown in Equation 7:

$$\Delta M_B = \Delta M_{Go} - \Delta M_R \tag{7}$$

Thus, by observing changes in the response function and comparing these changes to those in go-trial reaction time, we can study the separate effects of factors on controlled and on ballistic processes. Note, however, the importance of the assumption that the inhibition processes remain unchanged by these factors.

Overview of Experiments

Here we report two experiments designed with three goals in mind.

First, we wanted to use our approach to discover whether response complexity affects controlled or ballistic processes (Equations 6 and 7). If response complexity affects controlled processes only, then it should produce equal effects on mean go-trial reaction time and the mean of the response function. If response complexity affects ballistic processes only, then it should affect go-trial reaction time, but not the response function. Finally, if response complexity affects both controlled and ballistic processes (in the same direction), it should affect both measures, but mean go-trial reaction time to a greater degree.

In these experiments, we manipulated response complexity by requiring subjects to press a response key a different number of times in quick succession. Based on previous research on typing (Sternberg et al., 1978) and key presses (e.g., Rosenbaum et al., 1987, 1984), such a manipulation seemed likely to produce the desired effect. Moreover, such response-complexity effects may be quite general. Qualitatively similar effects have been found for both typing and speech production (Sternberg et al., 1978). We manipulated response complexity in slightly different ways in each experiment. In Experiment 1, we varied the number of taps that were all made by the same finger. In Experiment 2, we varied the number of taps made by one finger that followed a single tap by the homologous finger on the other hand. We refer to these manipulations as "within hand" and "between hands," respectively.

Our second goal was to reinforce our inferences concerning response complexity by verifying whether the assumptions underlying our approach were satisfied in these particular experiments. One check involved manipulating an additional control factor—lexical status. This factor distinguishes words from nonwords and affects the time taken to make a lexical decision. When subjects have to decide whether a letter string is an English word, they are faster to respond "yes" to words than "no" to nonwords (Meyer & Schvaneveldt, 1971). This difference presumably stems from an effect of familiarity on perceptual and memorial processes. Our previous research (Osman et al., 1986) has shown that the effect of lexical status is entirely before the point of no return and that it does not affect the time necessary to process a stop signal. If all the assumptions underlying our approach are satisfied (Equations 1 and 3), this factor should again produce equal effects on mean go-trial reaction time and the mean of the response function (Equations 4 and 5).

Another check involved comparing the reaction time distributions for go trials and stop trials with different stop signal delays (Equations 1 and 2). If the internal response to the stop signal merely prevents some of the slower controlled processes from contributing to overt reaction time (RT) without affecting their distribution of finishing times, the cumulative distribution functions [P(RT < t) for any given time t] for the different trial types should fan out from a common minimum. All the distributions should contain the same fastest reaction

times, but the duration and proportion of the slower times should increase with signal lag and be greatest on go trials.[1] Consequently, mean reaction time should also increase with signal lag on stop trials, and be slowest on go trials (Osman et al., 1986).

Our third goal was to specify further the location of the point of no return by acquiring additional information about the location of response-complexity effects in the information-processing system. By comparing within- and between-hands response-complexity effects, we hoped to determine whether processes peripheral enough to be unique to the control of a single hand were involved. By observing whether response complexity and lexical status had additive or interacting effects on reaction time, we hoped to determine whether they affected any processes in common (Sternberg, 1969).

Finally, in addition to achieving these goals, the extended sequences of taps used here also provided us with an opportunity to study how a response is stopped *after* it has begun. We were particularly interested in comparing this with how a response is stopped before it has begun. We hoped that such a comparison would provide evidence concerning the generality of the stopping mechanism and would reveal any effects of serial position on the ballistic processes that immediately preceded each tap. However, in these experiments, we did not generate complete response functions for taps other than the first. Consequently, it was not possible to calculate and model the effect of a tap's serial position in a sequence on the mean of its response function. Instead, we relied on an approach developed by Logan (e.g., Logan, 1981; Logan & Cowan, 1984; Logan, Cowan, & Davis, 1984). According to this approach, if two responses differ only with respect to the speed of their associated controlled processes, they should be equally stoppable. By "equally stoppable," we mean that stop signals preceding the expected occurrence of each response by the same interval should be equally effective. Thus, in these experiments, we compared the stoppability of the first tap in a sequence with the stoppability of the second tap, when the first tap was not inhibited.

Experiment 1

In Experiment 1, we varied response complexity by having subjects press a response key either once or three times in quick succession with the same finger while performing a lexical-decision task. In the low-complexity conditions they indicated whether the go signal was an English word or a nonword by a single press on one of two response keys. In the high-complexity conditions, subjects had to press the correct response key three times.

Method

Subjects. Twelve undergraduate students at the University of Michigan served as paid subjects. Each subject was tested individually in a single 1-hour session.

Apparatus. Subjects sat in a moderately illuminated, sound-attenuating booth throughout each session. Visual and auditory stimuli were presented with a Hewlett Packard 2126A video terminal viewed at a distance of about 35 cm. Manual responses with the right and left index fingers were made by depressing the Z and / keys on the

terminal keyboard. The keyboard was located in front of the terminal and placed so that subjects' arms rested comfortably on the table. Stimulus presentation and response collection were controlled by a digital computer (DEC-PDP 11/34).

Stimuli. The stimuli included a warning signal, four-letter strings for go signals, and a stop signal. The warning signal was a dashed line that appeared on the terminal immediately below the location of the go signal. The go signals each contained four capital letters, which together subtended about 1.4° of visual angle in width and about 0.5° in height at the viewing distance of 35 cm.

There were 120 different English words (e.g., *food*) and 120 different nonwords (e.g., *mafe*) used as go signals. The words consisted of familiar nouns and verbs whose frequency of occurrence in ordinary text equaled or exceeded 32 per million (Kucera & Francis, 1967). The nonwords were pronounceable strings obtained from other English words by altering individual vowels or consonants without violating the orthographic rules of English (Venezky, 1970).

The stop signal was a brief tone presented at a comfortable listening level. Signal lags were adjusted for each subject by a staircase tracking algorithm that independently adjusted the lag values for each of four experimental conditions to yield average response probabilities of 50% in each (Levitt, 1971). The algorithm decreased the signal lag by 50 ms whenever subjects responded on a stop trial and increased the lag by 50 ms whenever they successfully inhibited their response.

Design. The experimental design is shown in Table 1. Two independent variables, lexical status and response complexity, were manipulated orthogonally to produce four experimental conditions. Stop signals were presented on one fourth of all trials, occurring equally often in each experimental condition. Words and nonwords occurred equally often in each block, and low- and high-complexity response sets were alternated between blocks. Both the stimulus-response mapping and the order of block presentation were balanced across subjects.

Procedure. Subjects were tested with the countermanding procedure described earlier. Their fingers rested on the relevant response keys at all times. At the start of each trial, a warning signal appeared in the center of the terminal screen and was replaced 500 ms later by a four-letter string that served as the go signal. The go signal was either a word or a nonword, and subjects had to make a lexical decision that determined whether to press the right or left key. In the low-complexity conditions, the correct response key had to be pressed just once. In the high-complexity conditions, the correct key had to be pressed three times in quick succession. The first keypress caused the go signal to vanish from the screen. Stop trials were identical to go trials except that the stop signal followed the go signal, which disappeared immediately if it was still on the screen. The warning signals on successive trials were separated by an interval of 2.25 s plus feedback presentation time.

Feedback was presented on all stop trials, after errors on go trials, and after each trial block. The word ERROR appeared on go trials if the subjects pressed the wrong key, pressed the incorrect number of times, or did not respond within 1.5 s after the go signal. On stop trials, GOOD was presented if the subjects inhibited their response successfully, and OOPS was presented if they failed to withhold the

---

[1] One way to understand this predicted pattern is to consider the implicit response to stop signals as a filter for controlled processes induced by the go signal. On stop trials, only the controlled processes that beat the inhibition process activate ballistic processes and thus contribute to reaction time. When the stop signal occurs early, only the fastest controlled processes escape inhibition. When the stop signal occurs later, slower controlled processes also contribute to stop-trial reaction times. On go trials, all controlled processes, both fast and slow, contribute to reaction time.

Table 1
Design of Experiment 1

| | | Relative frequency of trial types | | | |
| | | Words (e.g., *food*) | | Nonwords (e.g., *mafe*) | |
Complexity	Response	Go	Stop	Go	Stop
Low	1 Li or 1 Ri	3/16	1/16	3/16	1/16
High	3 Li or 3 Ri	3/16	1/16	3/16	1/16

Note. Li and Ri denote the left and right index fingers.

entire response. The trial feedback remained visible for 250 ms immediately below where the warning signals were presented. After each block, the subjects' mean reaction time on go trials, number of errors on go trials, and number of inhibited responses on stop trials for that block were displayed.

The instructions to subjects stressed speed on go trials over successful inhibition on stop trials. Subjects were told to complete the entire response sequence as quickly as possible without making more than 5% errors on go trials. They were also told that they should try hard to stop themselves from responding if they detected the stop signal but that this would not always be possible.

Subjects were tested in a single session with 16 blocks of 48 trials each. The first two trial blocks included only go trials, to familiarize subjects with the lexical-decision task. The next six blocks were used to familiarize subjects with the countermanding procedure (stop plus go trials) and to let the tracking algorithm locate the right vicinity for the stop-signal lags. Only the last 8 blocks were included in the data analysis.

Results

Reaction times and error rates. Figure 1 shows mean reaction times and error rates on go trials in the left panel and on stop trials in the right panel under each experimental condition. The reaction times for go trials show an effect of lexical status [mean difference = 42 ms; $t(11) = 3.52$; p(one-tailed) < .01] and response complexity [mean difference = 30 ms; $t(11) = 3.21$; p(one-tailed) < .01], with the two effects being additive [mean interaction = 2 ms; $t(11) = 0.24$; $p >$ .85]. Stop trials were also affected by lexical status [mean difference = 24 ms; $t(11) = 1.94$; p(one-tailed) < .05] and response complexity [mean difference = 18 ms; $t(11) = 1.81$; p(one-tailed) < .05]. As predicted by the race model, mean reaction time on stop trials was faster than on go trials for each combination of the two factors: low-complexity responses to words [mean difference = 42 ms; $t(11) = 3.57$; p(one-tailed) < .01], low-complexity responses to nonwords [mean difference = 50 ms; $t(11) = 5.46$; p(one-tailed) < .001], high-complexity responses to words [mean difference = 44 ms; $t(11) = 3.55$; p(one-tailed) < .01], high-complexity responses to nonwords [mean difference = 71 ms; $t(11) = 6.74$; p(one-tailed) < .0001].

Error rates appear at the bottom of Figure 1. They were generally low and gave no indication that the effects on reaction time of lexical status, response complexity, or trial type were due to a speed–accuracy trade-off. Responses to words were no less accurate than responses to nonwords on

go trials [mean difference = −0.04%; $t(11) = -0.05$; p(one-tailed) > .50] or on stop trials [mean difference = −2.73%; $t(11) = -1.95$; p(one-tailed) > .95]. Low-complexity responses were no less accurate than high-complexity responses on go trials [mean difference = 0.31%; $t(11) = 0.35$; p(one-tailed) > .35] or on stop trials [mean difference = 1.2%; $t(11) = 0.71$; p(one-tailed) > .25]. Finally, responses were no less accurate on stop trials than on go trials [mean difference = 0.19%; $t(11) = 0.18$; p(one-tailed) > .40].

Further support for the race model is shown in Figure 2, which displays group cumulative distribution functions of reaction times on stop trials and go trials in each of the four experimental conditions. These group functions were obtained by averaging the quantiles of the functions (Vincentizing) from individual subjects (Thomas & Ross, 1980).[2] The fan pattern predicted by the model was obtained in each condition. Note that the minima are smaller for go trials. This is as anticipated because the expected value of a sample minimum decreases as sample size increases, and there were three times as many go trials as stop trials in each condition. However, after crossing at a low quantile, each pair of cumulative distribution functions increasingly diverge at longer reaction times, with stop trials to the left of go trials.

Response probability and stop signal lags. The mean signal lag and response probability for each experimental condition are shown in Table 2. We see here that the staircase tracking algorithm worked quite well in yielding response probabilities on stop trials that were close to 50% in each condition. Signal lags were shorter for responses to words than to nonwords and shorter for low-complexity than for high-complexity responses.

Group response functions appear in Figure 3. These functions were obtained by plotting the response probability on stop trials against signal lag for each subject in each condition. This was possible because the staircase tracking algorithm continuously varied the signal lags over a range wide enough to include the entire response function. The functions for individual subjects were monotonized (Barlow, Bartholomew, Bremner, & Brunk, 1972) and combined into group functions by Vincentizing (Footnote 2). The upper panel of Figure 3 allows a comparison of the response functions for word and nonword stimuli, and the lower panel allows a comparison of

---

[2] Vincintizing involves averaging the values associated with a fixed probability level (quantile) across probability functions. We applied it here to average across subjects' reaction time distributions (Figures 2 and 7), response functions (Figures 3 and 8), and stoppability functions (Figures 4 and 9). In effect, this involved averaging the abscissa values (times) associated with each ordinate (probability). This procedure yields group functions whose shapes are more representative of their individual constituents than does the more common procedure of averaging the probabilities associated with each time. In particular, if a parameter can be expressed as (or approximated by) a linear combination of quantiles, its value for the group function will be the average of its values for the individual functions (e.g., the interquartile range of the group function will be the average of the interquartile ranges of all the individual functions). Vincentizing is therefore appropriate for presenting group data in the following discussions, in which we will be concerned with the average difference between quantiles associated with the functions of individual subjects.
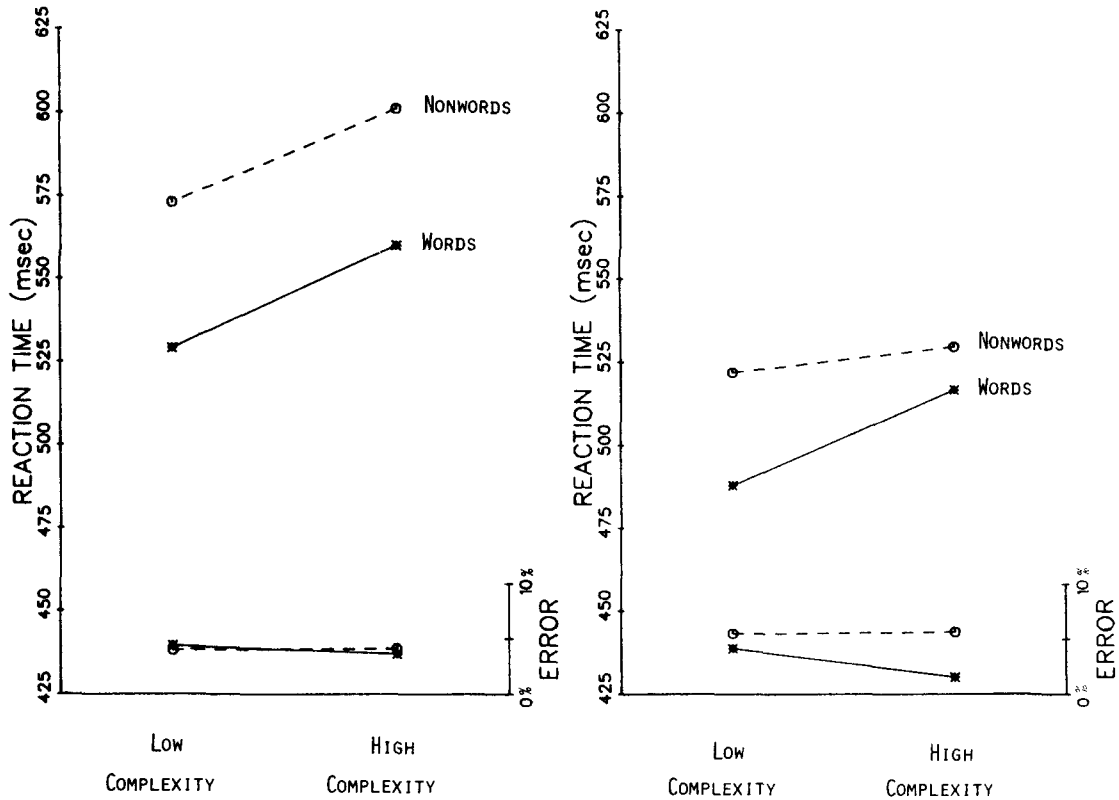
Figure 1. Mean reaction time and percentage of error as a function of response complexity and lexical status on go trials (left panel) and stop trials (right panel).

the response functions for low- and high-complexity responses. We see that for all four functions, the probability of responding increased with signal lag. Also, notice that the response functions were affected by both lexical status and response complexity. The signal lag required to produce any given level of response probability was less for words than for nonwords and was less for low-complexity than for high-complexity responses. The separations between the response functions in each pair reflect the effects of lexical status and response complexity on controlled processes before the point of no return.

Comparison of go-trial reactio 1 times and response functions. Separately assessing the effects of factors before and after the point of no return involves comparing their effects on response functions [P_R(SOA)] with their effects on go-trial reaction times (Equations 6 and 7). Response-function means were obtained by applying a discrete approximation of Equation 8 to each subject's response functions:

$$M_R = \int_{-\infty}^{\infty} t[dP_r(t)]dt , \qquad (8)$$

where M_R is the response-function mean, and $dP_R(t)$ is the differential of P_R(SOA) evaluated at time t. The individual response-function means were then averaged across subjects for each experimental condition. The same pattern of effects was evident for both factors; that is, each factor affected the

reaction time for go trials and the mean of the response functions equally. The 42-ms effect of lexical status on go-trial reaction time (544 ms for words and 586 ms for nonwords) was not significantly different [$t(11) = 0.40$; $p > .65$] from its 46-ms effect on the response function (376 ms for words and 422 ms for nonwords). Nor was the 30-ms effect of response complexity on go-trial reaction time (550 ms for low-complexity responses and 580 ms for high-complexity responses) significantly different [$t(11) = 0.03$; $p > .95$] from its 29-ms effect on the response function (385 ms for low-complexity responses and 414 ms for high-complexity responses). This implies that both factors have their effect entirely before the point of no return. The result for lexical status replicates our previous findings (Osman et al., 1986). The new result for response complexity suggests that motor programming occurs entirely before the point of no return.

Relative stoppability of the first and second taps. Figure 4 allows a comparison of stopping performance before and during movement sequences. Recall that the stoppability of a response is defined as the interval by which a stop signal must precede the expected occurrence of the response in order to be effective a given proportion of the time. Here we have plotted response probability as a function of the time intervening between the onset of the stop signal and the time at which the response was expected to occur. The horizontal axis
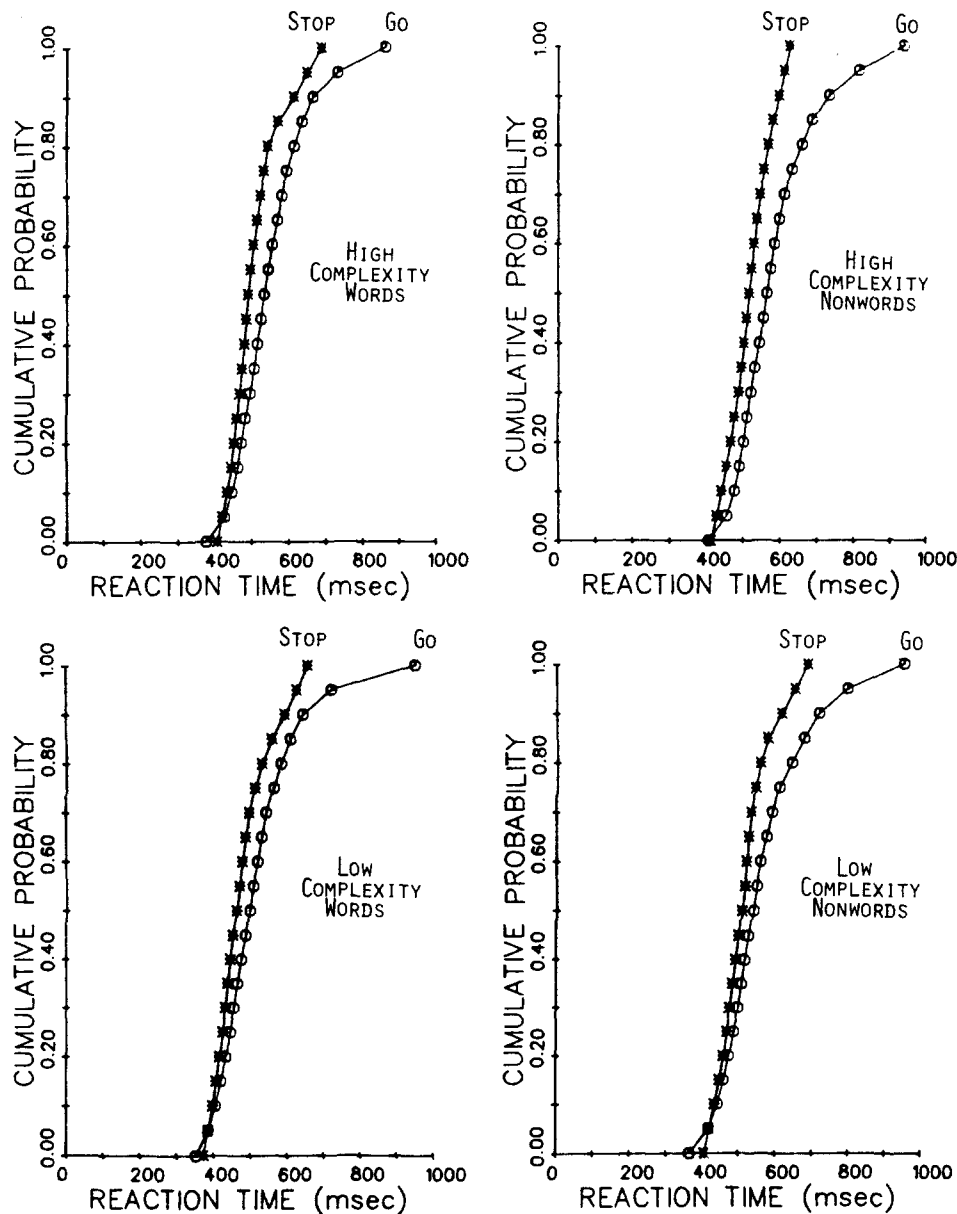
Figure 2. Group cumulative distribution functions of reaction times on stop and go trials for high-complexity responses to words (top left), high-complexity responses to nonwords (top right), low-complexity responses to words (bottom left), and low-complexity responses to nonwords (bottom right).

represents expected reaction time minus stop-signal lag and the vertical axis represents response probability.[3] The functions on the left correspond to each of the four experimental conditions for the first tap and were obtained by Vincentizing the functions for individual subjects (Footnote 2). We have seen that both lexical status and response complexity affect response functions, which express response probability as a function of the interval by which the stop signal follows the go signal. However, when we plot response probability against the interval by which the stop signal precedes the expected response, the functions from all four conditions are closely aligned. This means that in order to produce any given probability of response inhibition, the stop signal must pre-

cede the expected response by the same interval in each condition. Logan and his colleagues (e.g., Logan, 1981; Logan et al., 1984) have previously shown this to be the case for

[3] The expected time of occurrence for the first tap was estimated from mean go-trial reaction time. The expected time of occurrence for the second tap, when the first tap was not inhibited, was estimated by adding two quantities: mean reaction time for first taps that were not inhibited on stop trials and the mean of the interval between the first and second taps on go trials. Note that the accuracy of the estimated occurrence of the second tap depends on stochastic independence between the times before the first tap and the times between the first and second taps.

Table 2

*Mean Response Probabilities and Signal Lags for
Experiment 1*

	Words		Nonwords	
Response type	Probability (%)	Lag (ms)	Probability (%)	Lag (ms)
Low complexity	51	338	52	392
High complexity	48	372	49	411

factors that affect controlled processes only. The two isolated points on the right of the functions are associated with the second taps from the multiple-response conditions, *on those stop trials in which the first tap was not inhibited*; one point is for words and the other for nonwords. Each point was obtained by averaging response probability and expected reaction time minus mean signal lag across subjects.[4] In order to produce a given probability of response inhibition, the stop signal had to precede the second response by approximately 100 ms more than it had to precede the first response. In

Figure 3. Group response functions for words and nonwords (upper panel), and high- and low-complexity responses (lower panel).

other words, the stop signals were more effective at inhibiting the entire response sequence than at stopping it once it had begun.[5]

Discussion

The results of Experiment 1 suggest that motor programming does not necessitate response execution. If it did, we would have found an effect of response complexity on ballistic (i.e., unstoppable) processes. Instead, response complexity produced the same pattern of effects as lexical status did. Each factor affected mean go-trial reaction time and the mean of the response function equally. This is the pattern expected when a factor affects controlled (i.e., stoppable) processes only (cf. Equation 7).

Further evidence that response complexity and lexical status affect controlled processes only is provided by the results concerning the stoppability of the first taps in our response sequences (Figure 4). The functions relating response probability to the interval by which the stop signal preceded the expected reaction time (RT_{Go}) were closely aligned for all four conditions. This result may be better understood by considering Equations 3 and 4. From Equation 3, it can be seen that the probability of responding equals the proportion of the $T_C - T_I$ density function that is less than SOA. Changes in the mean of T_C merely translate the distribution along the time axis. Equal changes in SOA will thus preserve the proportion of the distribution less than SOA, leaving response probability unaffected. From Equation 4, it can be seen that changes in the mean of T_C are reflected by equal changes in the mean reaction time on go trials. Consequently, if an experimental manipulation affects only the mean duration of the controlled processes, holding RT_{Go} − SOA constant should leave the probability of responding on stop trials unaffected. The similar response probabilities at each value of RT_{Go} − SOA suggests that the reaction time differences
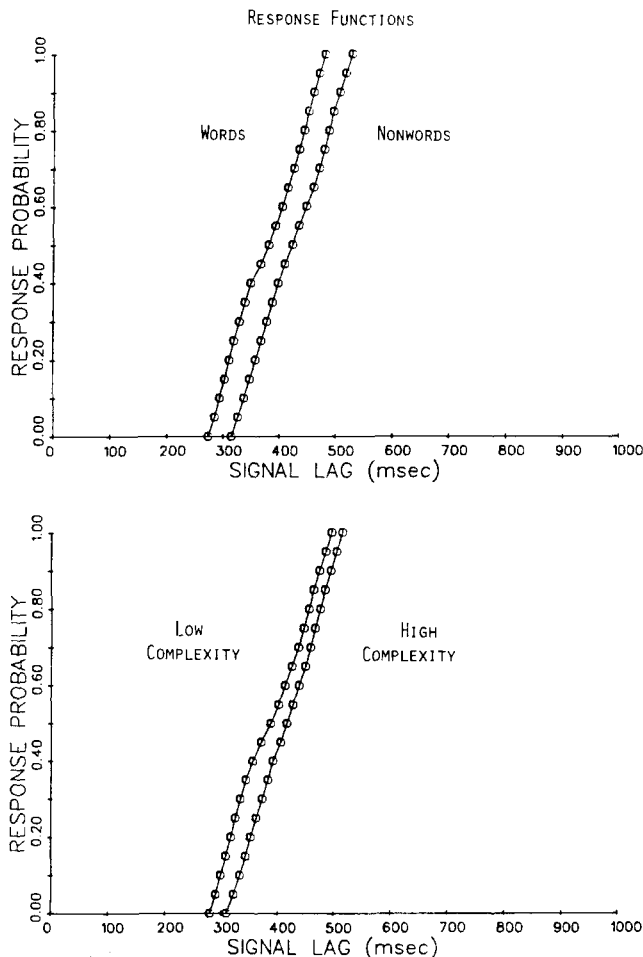
---

[4] The averaging procedures used for studying the second taps (see also Figure 9) may produce misleading results. First, the points calculated for individual subjects may not lie on their stoppability functions. Because of the staircase tracking algorithm, the stop signal occurred at several lags for each subject within each condition. Thus, each point is really based on several response probabilities at several lags. Second, averaging response probability and expected reaction time minus mean signal lag across subjects may produce points that are not representative of the points calculated for the individual subjects. Nevertheless, it seems highly unlikely that differences in the stoppability of the first and second taps as large as those observed here could be due entirely to biases caused by averaging.

[5] An anomolous result concerns the relative stoppability of the second tap for words and nonwords. Although stop signals preceded the expected occurrence of the second tap by a longer average interval for words than for nonwords, the response probability was greater for words. This result could have occurred for several reasons other than a real difference in stoppability between words and nonwords: It could have been due to a violation of the independence assumption underlying our estimation of the expected occurence of the second tap (Footnote 3), or have been an artifact of our averaging procedures (Footnote 4), or reflect sampling error due to the small number of observations.
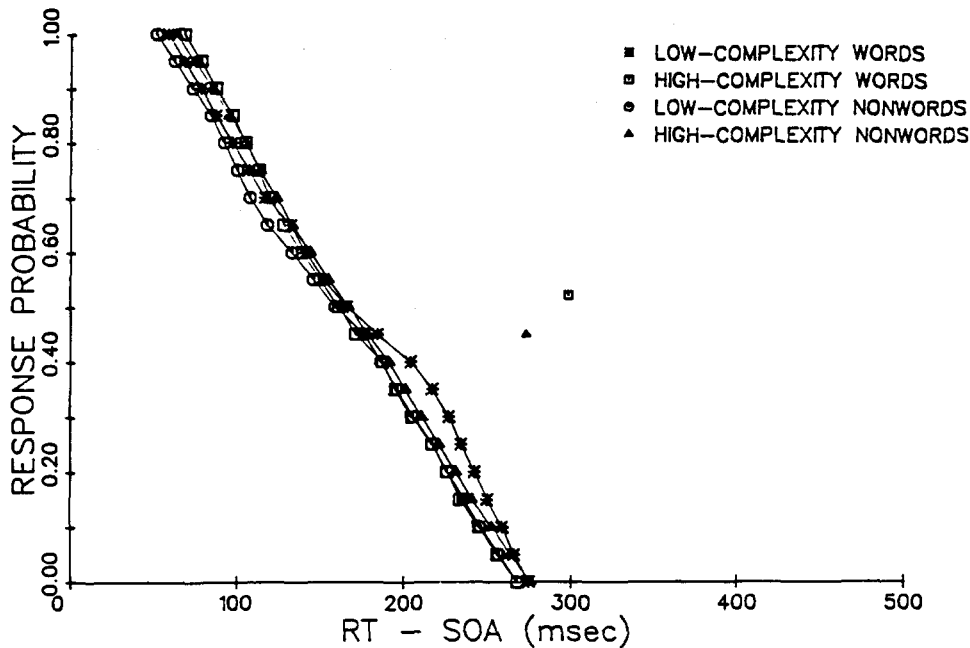
Figure 4. Response probability as a function of expected reaction time minus signal lag for first and second taps at each level of lexical status and response complexity.

between the four experimental conditions were all due to differences in the duration of controlled processes.

The results of Experiment 1 also support the validity of some of the assumptions used to infer the locus of response-complexity effects. First, finding equal effects on both go-trial reaction time and the response functions supports the assumption that the inhibition process was unaffected by manipulations of either lexical status or response complexity (Equations 4 and 5). Second, the reaction time data provide support for applying the race model to the countermanding procedure. In each experimental condition, the mean reaction time was slower on go trials than on stop trials, and the two cumulative distributions formed the expected fan pattern.

Apparently, the point of no return occurs after the processes affected by our manipulation of response complexity. But where in the information-processing sequence do these processes occur? The additivity of lexical-status and response-complexity effects is consistent with the hypothesis that the latter factor affected only motor processes. However, the motor processes affected by response complexity could be either relatively central or peripheral. Further evidence concerning the locus of response-complexity effects would help us to locate the point of no return more precisely.

Such evidence would also bear on a hypothesis that we should consider before definitely concluding that our manipulation of response complexity really affected motor programming. The response-complexity effects found in Experiment 1 could have resulted from changes in the physical parameters of the first movement, rather than from changes in motor programming (Christina, Fischman, Vercruyssen, & Anson, Klapp, 1978; 1982). Movement force, and consequently velocity, might have been greater for taps made in isolation than

for taps followed by other subsequent taps. Perhaps subjects tapped more gently in order to return quickly to a position from which to initiate the next tap. Faster movements could have resulted in shorter reaction times because the terminal keys must travel some distance before they trigger the microswitch that stops the clock. If such an artifact contributed to the response-complexity effect found in Experiment 1, the point of no return would have to occur quite late in order to follow all of the affected processes. Indeed, this could mean that subjects were able to inhibit their responses right up to the moment at which the microswitch was depressed.

Some other questions left unanswered by Experiment 1 concern the second tap in our response sequences. Are the preparatory processes preceding this tap affected by response complexity? If so, are the affected processes controlled or ballistic? We were not able to answer these questions because only the high-complexity sequences in this experiment contained a second tap. A final question concerns why stopping performance was better before the first tap of our sequences than between the first and second taps. It should be noted that previous research has found poorer stopping performance before than during a response (Ladefoged, Silverstein, & Papcun, 1973), or has found no difference (Logan, 1982). Our results complete the set of possible outcomes. Consequently, it seemed prudent to replicate the effect first before trying to explain it.

Experiment 2

Experiment 2 was designed to replicate Experiment 1, further localize response-complexity effects, and help answer

some remaining questions concerning the second tap in our response sequences. Subjects again performed a lexical-decision task, indicating whether the response signal was a word or nonword by pressing one of two response keys with either index finger. Here, however, the first keypress was always followed by another keypress made with the other finger on the opposite key. In the low-complexity conditions, subjects pressed once on the opposite key, and in the high-complexity conditions, subjects pressed three times on the opposite key. One other difference between the two experiments concerned the stop signals. Here we utilized early, middle, and late stop signals at each level of response complexity.

Method

Subjects. Eleven undergraduate students at the University of Michigan served as paid subjects. None had been in the previous experiment. Each subject was tested individually in a single 1-hour session.

Apparatus and stimuli. The apparatus and stimuli were the same as in the previous experiment, with one exception. Here the signal lags were adjusted to track average response probabilities of 29%, 50%, and 71% at each level of response complexity (Levitt, 1971). The stop signals associated with these staircases are labeled *early, middle,* and *late,* respectively. On early-signal trials, the signal lag was decreased each time a subject responded and was increased when a subject inhibited the response twice in a row. On middle-signal trials, the signal lag was decreased each time a subject responded and was increased each time a subject inhibited the response. On late-signal trials, the signal was decreased when a subject responded twice in a row and was increased each time a subject inhibited the response. The signal lag was always adjusted by an increment of 50 ms.

Design. The design is shown in Table 3. It is like that for the previous experiment, but with signal lag as an additional factor. Stop signals in each of the four experimental conditions were presented equally often at early, middle, and late lags.

Procedure. The trial-by-trial procedure, instructions, and feedback were the same as in the previous experiment. As before, go signals consisted of words and nonwords, which determined whether the response was started with the left or right index finger. Here, however, the subsequent taps in the sequence were made with the index finger on the other hand. Low-complexity sequences consisted of a single tap by one index finger followed by a single tap by the other. High-complexity sequences consisted of a single tap on one index finger followed by three taps on the other.

Subjects were tested in a single session of 18 blocks of 48 trials. The first two blocks contained only go signals. The remaining blocks contained both stop and go signals, but only the last 12 blocks were included in the analysis.

Results

Reaction times and error rates. Figure 5 shows mean reaction times and error rates on go trials for each combination of response complexity and lexical status. Again, complex responses took longer than simple ones to initiate [mean difference = 33 ms; $t(10)$ = 3.74; p(one-tailed) < .002]. Moreover, the magnitude of this effect was no less than that found in the previous experiment [mean difference = −3 ms; $t(21)$ = −.235; p(one-tailed) > .6]. Responses to words were again faster than responses to nonwords [mean difference = 51 ms; $t(10)$ = 5.40; p(one-tailed) < .0002], and the effects of lexical status and response complexity did not significantly interact [mean interaction = 7 ms; $t(10)$ = 0.63; p > .5].

Error rates appear at the bottom of Figure 5. They were generally low and gave no evidence that the effects of either lexical status or response complexity on go-trial reaction time resulted from a speed–accuracy trade-off. Low-complexity responses were no less accurate than high-complexity responses [mean difference = −3.6%; $t(10)$ = −3.02; p(one-tailed) > .95], and responses to words were no less accurate than responses to nonwords [mean difference = .33%; $t(10)$ = .339; p(one-tailed) > .25].

The effect of response complexity on reaction time was robust across trial type, as can be seen from Figure 6. This figure shows median reaction time, averaged across subjects, for each level of response complexity on go trials and early, middle, and late stop-trials. Median reaction time, averaged across each type of stop trial, was faster for simple than for complex responses [mean difference = 25 ms; $t(10)$ = 4.13; p(one-tailed) < .001]. Figure 6 also displays some evidence supporting the race model. Median reaction time was slower on go trials than on late stop-signal trials for low-complexity responses [mean difference = 32 ms; $t(10)$ = 4.13; p(one-tailed) < .001] and high-complexity responses [mean difference = 41 ms; $t(10)$ = 17.6; p(one-tailed) < .0001]. Late stop-signal trials were slower than middle stop-signal trials for low-complexity responses [mean difference = 23 ms; $t(10)$ = 1.88; p(one-tailed) < .05] and high-complexity responses [mean

Table 3
Design of Experiment 2

Complexity	Response	Go signal	Relative frequency of trial types			
			Go	Early-stop	Middle-stop	Late-stop
Low	1 Ri + 1 Li or 1 Li + 1 Ri	Words or Nonwords	3/16 3/16	1/48 1/48	1/48 1/48	1/48 1/48
High	3 Ri + 3 Li or 3 Li + 3 Ri	Words or Nonwords	3/16 3/16	1/48 1/48	1/48 1/48	1/48 1/48

Note. Li and Ri denote the left and right index fingers.
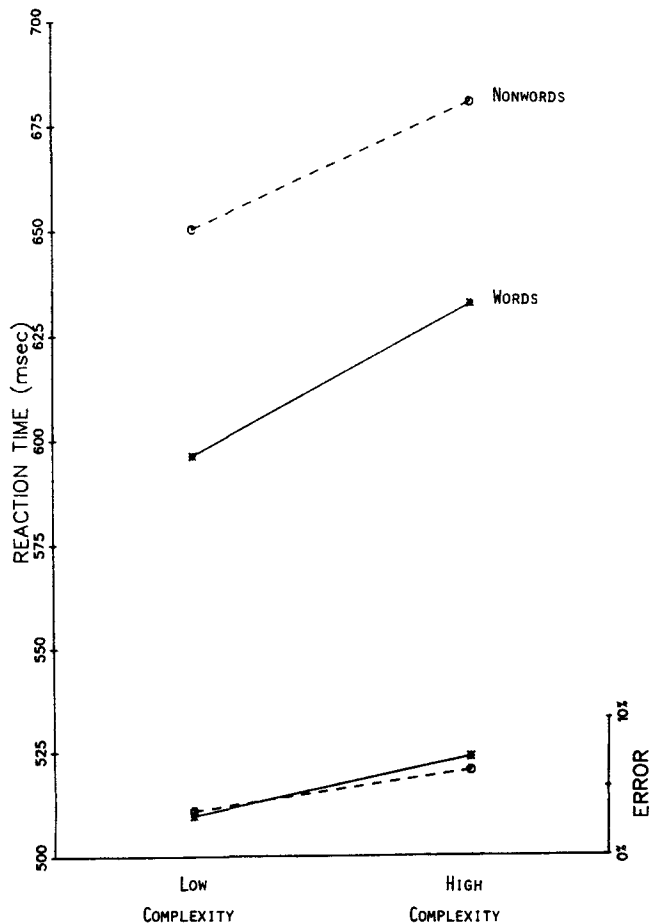
Figure 5. Mean reaction time and percentage of error as a function of lexical status and response complexity.

difference = 21 ms; $t(10)$ = 2.3; p(one-tailed) < .05]. Middle stop-signal responses were slower than early stop-signal responses for low-complexity responses [mean difference = 11 ms; $t(10)$ = 1.40; p(one-tailed) < .10] and high-complexity responses [mean difference = 24 ms; $t(10)$ = 2.06; p(one-tailed) < .05].

Further support for the race model appears in Figure 7. Group cumulative distribution functions of reaction times for each trial type are shown for high-complexity responses in the upper panel and for low-complexity responses in the lower panel. These group functions were obtained by Vincentizing the functions from individual subjects (Footnote 2). Each panel shows the fan pattern predicted by the race model. The reaction time minima on early, middle, and late stop-signal trials are virtually identical within each response condition. (Recall that go-trial responses are expected to have lower minima because of their greater number.) With one exception, the four cumulative distribution functions in each panel diverge and exhibit the predicted dominance order: early stop < middle stop < late stop < go trials. Only the early stop-trial distribution for low-complexity responses violated this pattern. However, early stop-trial distributions were estimated

less reliably than the other distributions because they contain the fewest responses, so the violation is not too troubling. Overall, these results provide good support for using the race model to interpret other facets of the data.

Response probability and stop-signal lags. The mean signal lag and response probability on early, middle, and late stop-signal trials for low- and high-complexity responses are shown in Table 4. We see here that the staircase tracking algorithm used to adjust the signal lags worked moderately well in yielding approximately 29%, 50%, and 71% response probabilities for the three signal-trial types. For both low- and high-complexity responses, late signals had greater lags than did middle signals, which in turn had greater lags than did early signals, just as we intended. Also, the average signal lags needed to produce equal levels of response probability were less for low-complexity responses than for high-complexity responses.

Group response functions appear in Figure 8. These functions were obtained by plotting response probability against signal lag, on a subject-by-subject basis, disregarding the type of stop signal (i.e., early, middle, or late) associated with each observation. The functions from individual subjects were monotonized (Barlow et al., 1972) and combined into group functions by Vincentizing (Footnote 2). As in Experiment 1, response probability increased with signal lag, and the lag necessary to produce a given response probability was always less for low-complexity responses than for high-complexity responses.

Comparison of go-trial reaction time and response functions. Experiment 2 also replicated our previous finding that the locus of response-complexity effects on the preparatory processes preceding the first response of a sequence is entirely before the point of no return. The 33-ms effect of response complexity on mean go-trial reaction time (623 ms for low-complexity responses and 656 ms for high-complexity responses) was not significantly different [$t(10)$ = 0.27; p > .75] from its 35-ms effect on the response-function mean (455 ms for low-complexity responses and 490 ms for high-complexity responses).

Relative stoppability of the first and second taps. Figure 9 shows a more complete comparison of the stoppability of the first and second responses than was possible in Experiment 1 (Figure 4). As before, the horizontal axis represents the expected reaction time minus the stop signal lag, and the vertical axis represents response probability. The functions associated with the first tap were Vincentized across subjects, and the reaction times and response probabilities associated with the second tap were averaged across subjects. We see again that the functions on the left, corresponding to the first tap, are closely aligned. Closed circles correspond to low-complexity responses and open circles correspond to high-complexity responses. On the right we see six points for the second tap when the first tap was not inhibited, each corresponding to one of the six stop signals. Experiment 2 allows us to investigate the effect of response complexity on the second tap. The interval between the first and second taps on go trials was longer for high-complexity than low-complexity responses [mean difference = 68 ms; $t(10)$ = 3.89; p < .01]. Yet, as with
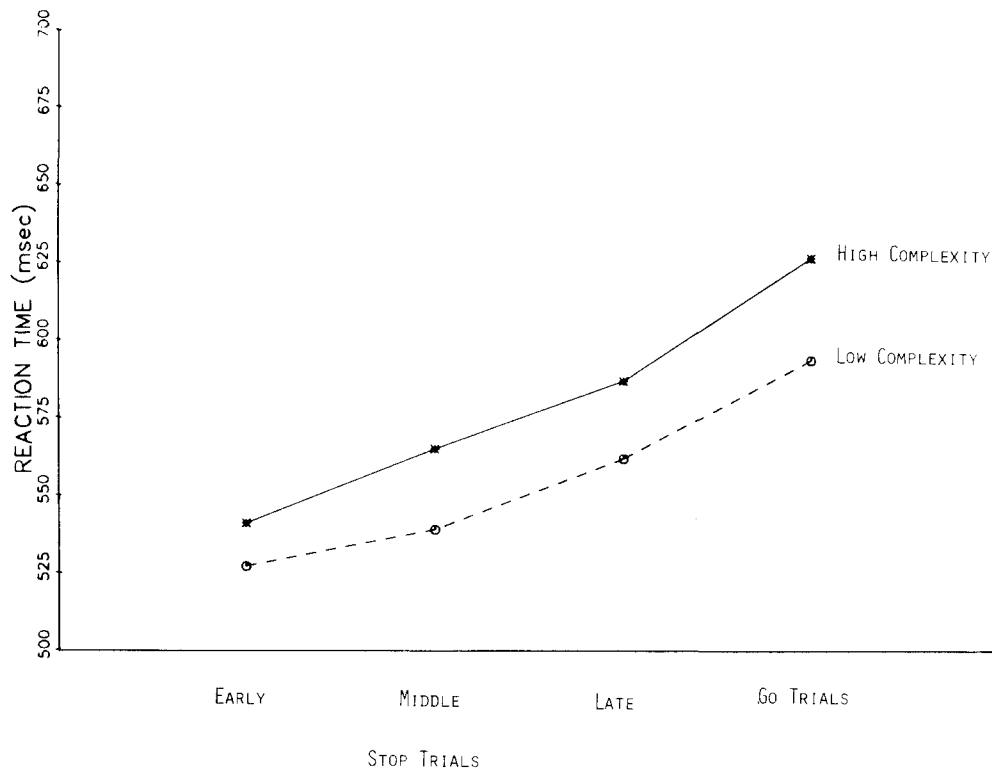
Figure 6. Average median reaction time for high- and low-complexity responses on each trial type.

the first tap, the open and closed circles seem to fall on the same function. Finally, we again found poorer stopping performance between the first and second taps than before the first tap. The function for the second tap was approximately 100 ms to the right of the functions for the first tap.

Discussion

Experiment 2 replicated all major findings of Experiment 1. Response complexity again affected only controlled processes: It produced equal effects on go-trial reaction time and on the response function; the first taps of both low- and high-complexity response sequences were equally stoppable. The race model that we use to interpret the results of the countermanding procedure was again supported: Mean reaction time increased with signal lag on stop trials and was slowest on go trials; the reaction time distributions on stop and go trials formed the expected fan pattern. Finally, we again found that response complexity and lexical status produced additive effects on go-trial reaction time and better stopping performance before the first tap than between the first and second taps.

Experiment 2 also provides further information concerning the locus of response-complexity effects. There was no need here to change the mechanical properties of the first tap in order to accommodate additional taps with the same finger. Nevertheless, we found the same response-complexity effects as in Experiment 1. Indeed, the effects were of the same magnitude in both experiments. Such a finding supports the

hypothesis that our manipulation of response complexity affected only processes central enough to be involved in the coordinated activity of both hands. Had processes peripheral enough to be unique to a single hand been affected, we might have expected a larger within-hand than between-hands effect. The equality of effects across experiments is especially remarkable since we compared one versus three taps in Experiment 1 and two versus four taps in Experiment 2. It suggests that reaction time to initiate a response may be linearly related to the number of taps in the response (Sternberg et al., 1978).

Another new result is that response complexity affected the duration of the interval between the first and second taps but did not affect subjects' stopping performance during this interval; that is, the points associated with the second tap on those stop trials when the first tap had not been inhibited all seemed to fall on the same stoppability function. This result should be regarded with caution, however, for these points are based on very little data, and the averaging procedures employed may make them unrepresentative of individual subjects' stoppability functions (Footnote 4). Nevertheless, it appears that the effect of response complexity on the interval between the first and second taps may have been limited to controlled processes. Had there been an effect on ballistic processes associated with the second tap, signals preceding the second tap by the same interval would have produced different levels of response probability at each level of response complexity. This is because the longer the duration of the ballistic processes preceding a response is, the earlier the stop signal must occur in order for the inhibition processes to reach
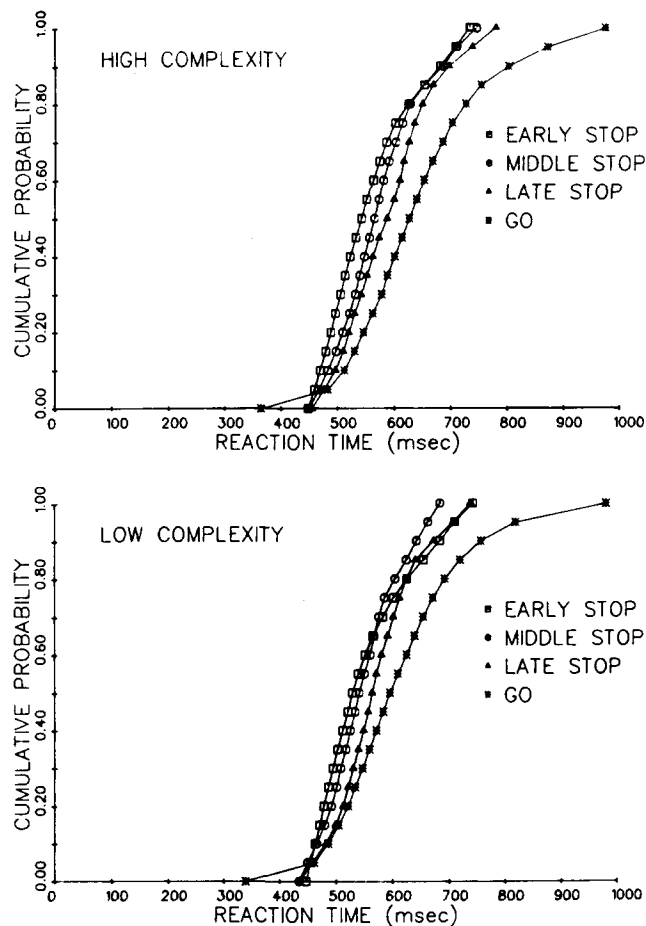
Figure 7. Group cumulative distribution functions of reaction times on each trial type for high-complexity responses (upper panel) and low-complexity responses (lower panel).

completion before the ballistic processes begin. The fact that stopping performance in both conditions appears to be characterized by the same function suggests that response complexity did not affect ballistic processes preceding the second tap.

Finally, we again found better stopping performance before the first tap than during the interval between the first and second taps. The replication of this effect for early, middle, and late signals in both complexity conditions suggests that it is reliable. Moreover, the magnitude of the effect suggests that it is unlikely to be an artifact of the procedures by which we calculated the stoppability function for the second tap (Foot-

note 4). This result could have arisen for a number of reasons. First, there might be a difference in the duration of ballistic processes preceding the two taps. If this could be verified, it would constitute a demonstration of the existence of ballistic processes. On the other hand, the inhibition process might take longer for the second tap. Making the first tap might produce a refractory effect on the processing of the stop signal, or subjects might exert less effort after having failed to stop the first tap. At present we cannot discriminate between these alternatives.

General Discussion

In this study we sought to provide evidence concerning the existence and functional location of a point of no return and to elucidate further the nature of motor programming. We hoped to achieve both of these objectives by discovering whether the motor-programming processes affected by response complexity are controlled or ballistic. This involved using a countermanding procedure and a race model to measure separately the effects of response complexity on both sets of processes. We also tried to verify the assumptions underlying these measurements by testing the applicability of the race model to the countermanding procedure and to specify further the location of the point of no return by acquiring additional information concerning the locus of response-complexity effects. Finally, the approach used here allowed us to compare how a response is stopped before and during overt movement.

An effect of response complexity on ballistic processes would have been extremely interesting. To have found that only ballistic processes were affected would have ruled out the hypothesis that any motor-programming operations can be effectively performed before the response signal (Klapp, 1976, 1978; Rosenbaum et al., 1987, 1984). To have found an effect on both controlled and ballistic processes would have suggested the existence of two qualitatively different types of motor-programming operations. Either of these findings would have provided a reason why response-complexity effects are found on simple reaction time and demonstrated the existence of ballistic processes as well.

What we found, however, was that response complexity affected controlled processes only. In our view, this result is consistent with all of the models of motor programming considered in this article. Neither reading a motor program into a memory buffer (Klapp, 1976, 1978) nor editing (Rosenbaum et al., 1987, 1984), searching (Rosenbaum et al., 1984, 1987; Sternberg et al., 1978), or unpacking (Sternberg et al., 1978) the contents of such a buffer need necessarily

Table 4
Mean Response Probabilities and Signal Lags for Experiment 2

	Response probability %			Signal lag (ms)		
Response Type	ES	MS	LS	ES	MS	LS
Low Complexity	30	42	69	372	424	481
High Complexity	39	54	68	426	474	522

Note. ES = early signal; MS = middle signal; LS = late signal.

cause overt movement. Moreover, we still lack a mechanism to account for the effects of response complexity on simple reaction time.

Nevertheless, the finding that response complexity affects controlled processes, and controlled processes only, has both theoretical and methodological implications for the study of motor programming. First, it confirms a necessary prerequisite of both Klapp's (1976, 1978) and Rosenbaum's (Rosenbaum et al., 1987, 1984) models. According to both models, motor programs can be read out of long-term memory into a short-term buffer without causing movement. Indeed, this belief is what led Klapp (1976) to suggest that motor programs may play a role in short-term verbal memory. Because Klapp's model attributes response-complexity effects entirely to the readout process, it requires that the entire effect be on controlled processes. An effect on ballistic processes would therefore have cast serious doubt on this model. Rosenbaum's model, on the other hand, attributes part of response-complexity effects to editing the program while it resides in the buffer. It therefore requires that at least part of the effect should be on controlled processes. An effect of response complexity on ballistic processes only would therefore have cast serious doubt on the editing process postulated by Rosenbaum.

Though our results do not identify the mechanism responsible for response-complexity effects on simple reaction time,
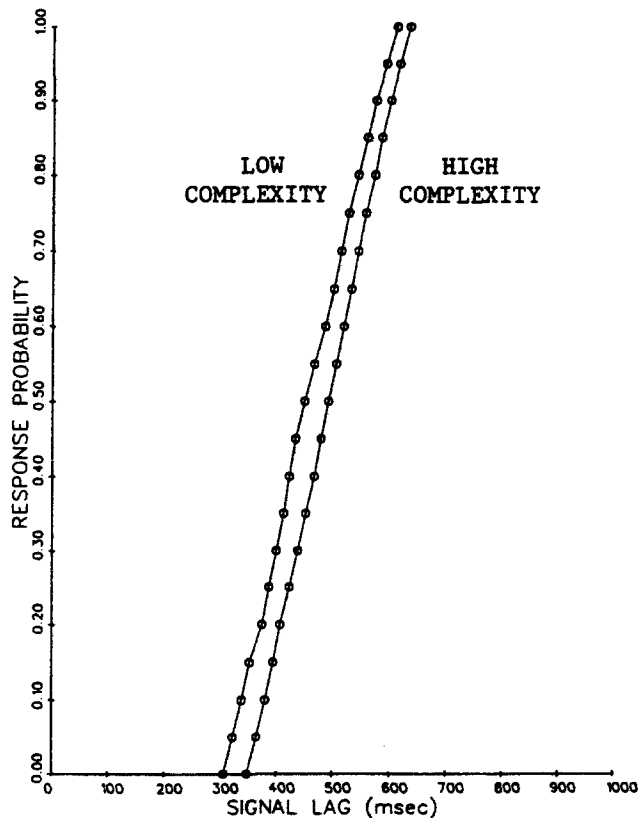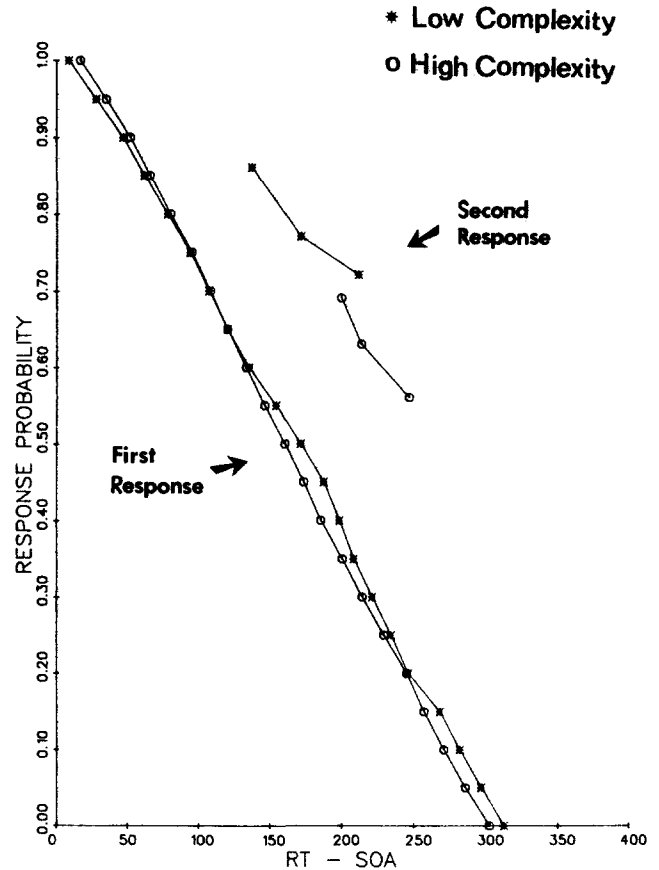

Figure 9. Response probability as a function of expected reaction time minus signal lag for first and second taps in low- and high-complexity responses.

they do rule out an important line of explanations. Both Sternberg et al. (1978) and Rosenbaum (personal communication, October 22, 1988) have suggested that initiating the search processes postulated by their respective models may engage ballistic processes and thus necessitate movement. For example, Sternberg et al. (1978) hypothesized that "Constructing or activating a motor program might be inherently tied to its execution; once the program is ready to be used, execution follows automatically and is hard to inhibit. If the preparation process took place before the signal, the subject would then respond on catch trials" (p. 134). This is clearly not the case for the processes affected by our particular manipulation of response complexity.[6]

The conclusion that response complexity affects only controlled processes is supported by our results concerning the applicability of the race model to the countermanding procedure. These results add to an already large body of evidence that supports the same conclusion: Stopping a speeded vol-

Figure 8. Group response functions for high- and low-complexity responses.

---

[6] Pilot studies have found an effect of our between-hands manipulation of response complexity on simple reaction time. Moreover, the effect has the same magnitude as that found on choice reaction time and is on controlled processes only.

untary movement before it has begun may be well approximated by a race between independent excitatory and inhibitory processes (e.g., De Jong, Coles, Logan, & Gratton, 1990; Logan & Cowan, 1984; Osman et al., 1986). Besides supporting the assumptions underlying our approach, this very general finding may tell us something fundamental about the inhibition of response preparation. For example, strict independence implies that inhibition occurs in the same way, regardless of how far the controlled processes have progressed, and that the controlled processes proceed in the same way until they are terminated, regardless of whether or when an attempt at inhibition is made.

An effect of any factor manipulation on controlled processes only constrains the possible location of a point of no return. It indicates that such a point could not occur before the latest process affected by the factor. Our particular manipulations of response complexity appear to have affected relatively central motor processes. The between-hands effect found in Experiment 2 indicates that at least some of the affected processes are central enough to be involved in preparing movements of both hands. The equality of the between-hands and within-hand effects suggests that no process peripheral enough to be unique to a single hand was affected. Finally, the additive effects of response complexity and lexical status limit how early in the information-processing system response complexity had its effect, thus suggesting that the effect was limited to motor processes.

Our results therefore indicate that if a point of no return exists, it must occur after much of the response preparation leading to overt movement has been completed. These results are in agreement with recent work by De Jong et al. (1990), which show that successful attempts at inhibition do not affect the early development of a lateral asymmetry over motor cortex in event-related potentials associated with movement (see also Osman, Bashore, Coles, Donchin, & Meyer, 1989). They also extend previous work by Logan (1981), who found no evidence for a point of no return before or during the response-selection processes affected by stimulus-response compatibility. The motor-programming processes affected by response complexity occur at an even later stage in the information-processing system but still precede the point of no return. So far, the only factor found to have an effect after the point of no return is stimulus-response repetition (Osman et al., 1986). The inferred effect of this factor on ballistic processes provides some evidence for their existence. Unfortunately, it provides little information concerning the nature of ballistic processes or the location of the point of no return, because the effects of repetition are widely distributed throughout the information-processing system (Kornblum, 1973).

The presence of ballistic processes is hinted at by the better stopping performance before than during our response sequences. Better stopping performance before the first tap than during the interval between the first and second taps could have arisen from differences in the durations of the ballistic processes preceding the two taps. However, as we indicated, alternative explanations involving the duration of the inhibition process are also possible. This result is also intriguing because it might be expected if the first and second taps were

represented together as part of the same unit at some level of description in the motor program. Since a defining property of units is the common fate of their parts, parts of the same programming unit might tend to be executed together. It would be interesting to see whether differences in stoppability correspond to units defined by various criteria (e.g., linguistic or rhythmic), and how such differences are affected by the conditions under which a movement is performed (e.g., different levels of speed stress or automaticity).

In conclusion, motor programming does not necessitate response execution—at least those motor-programming processes affected by our particular manipulation of response complexity. This means that a point of no return could not occur prior to a very late stage in the information-processing system. Together with our previous demonstration of ballistic processes (Osman et al., 1986), the present results suggest that such a point may be reached between the completion of motor programming and the onset of overt movement. Future research could provide further evidence concerning the existence and functional location of the point of no return by investigating the effects on controlled and ballistic processes of factors with well-focused effects on more peripheral motor processes than response complexity.

References

Barlow, R., Bartholomew, D., Bremner, & Brunk, H. (1972). *Statistical inference under order restrictions.* New York: Wiley.

Bartlett, F. C. (1958). *Thinking: An experimental and social study.* New York: Basic Books.

Christina, R. W., Fischman, M. G., Vercruyssen, M. J. P., & Anson, J. G. (1982). Simple reaction time as a function of response complexity: Memory drum theory revisited. *Journal of Motor Behavior, 14,* 301–321.

De Jong, R., Coles, M. G. H., Logan, G. D., & Gratton, G. (1990). In search of the point of no return: The control of response processes. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 164–182.

Henry, F. M. (1980). Use of simple reaction time in motor programming studies: A reply to Klapp, Wyatt, & Lingo. *Journal of Motor Behavior, 12,* 163–168.

Henry, F. M., & Rogers, E. E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly, 31,* 448–458.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. Long & A. D. Baddeley (Eds.), *Attention and performance* IX (pp. 187–203). Hillsdale, NJ: Erlbaum.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin, 70,* 387–403.

Keele, S. W. (1981). Behavioral analysis of movement. In V. B. Brooks (Ed.), *Handbook of physiology* (Section 1, Vol. 2, pp. 1391–1414). Washington, DC: American Physiological Society.

Klapp, S. T. (1976). Short-term memory as a response-preparation state. *Memory & Cognition, 4,* 721–729.

Klapp, S. (1978). Reaction time analysis of programmed control. *Exercise and Sport Science Review, 5,* 231–253.

Kornblum, S. (1973). Sequential effects in choice reaction time: A tutorial review. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 259–288). New York: Academic Press.

Kucera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English.* Providence, RI: Brown University Press.

Ladefoged, P., Silverstein, R., & Papcun, G. (1973). Interruptibility of speech. *Journal of the Acoustical Society of America, 54,* 1105–1108.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467–477.

Logan, G. D. (1981). Attention, automaticity, and the ability to stop a speeded choice response. In J. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 205–222). Hillsdale, NJ: Erlbaum.

Logan, G. D. (1982). On the ability to inhibit complex movements: A stop-signal study of typewriting. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 778–792.

Logan, G. D., & Burkell, J. (1986). Dependence and independence in responding to double stimulation: A comparison of stop, change, and dual-task paradigms. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 549–563.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review, 91,* 295–327.

Logan, G. D., Cowan, W. B., & Davis, K. A. (1984). On the ability to inhibit simple and choice reaction time responses: A model and a method. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 276–291.

Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90,* 227–234.

Ollman, R. (1973). Simple reactions with random countermanding of the "go" signal. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 571–581). New York: Academic Press.

Osman, A., Bashore, T. R., Coles, M. G. H., Donchin, E., & Meyer, D. E. (1989, November). *Response preparation based on partial information: Evidence from event-related motor potentials.* Paper presented at the meeting of the Psychonomic Society, Atlanta, GA.

Osman, A., Kornblum, S., & Meyer, D. E. (1986). The point of no return in choice reaction time: Controlled and ballistic stages of response preparation. *Journal of Experimental Psychology: Human Perception and Performance, 12,* 243–258.

Poulton, E. C. (1981). Human manual control. In V. Brooks (Ed.), *Handbook of physiology* (Section 1, Vol. 2, pp. 1337–1389). Washington, DC: American Physiological Society.

Rosenbaum, D. A., Hindorff, V., & Munro, E. M. (1987). Scheduling and programming of rapid finger sequences: Tests and elaborations of the hierarchical editor model. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 193–203.

Rosenbaum, D. A., Inhoff, A. W., & Gordon, A. M. (1984). Choosing between movement sequences: A hierarchical editor model. *Journal of Experimental Psychology: General, 113,* 372–393.

Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin, 67,* 202–213.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II* (pp. 276–315). Amsterdam: North-Holland.

Sternberg, S., Monsell, S., Knoll, R., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. Stelmach (Ed.), *Information processing in motor control and learning* (pp. 117–152). New York: Academic Press.

Thomas, E. A. C., & Ross, B. H. (1980). On appropriate procedures for combining probability distributions within the same family. *Journal of Mathematical Psychology, 21,* 136–152.

Venezky, R. L. (1970). *The structure of English orthography.* The Hague, The Netherlands: Mouton.

Call for Nominations for *Psychological Bulletin*

The Publications and Communications Board has opened nominations for a new editor of *Psychological Bulletin.* John C. Masters is the immediate past editor. Candidates must be members of APA and should be prepared to begin receiving manuscripts by September 1990. Please note that the P&C Board encourages participation by members of underrepresented groups in the publications process and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate. Submit nominations to

Walter Mischel, PhD
Psychological Bulletin Editor Search Committee
American Psychological Association
1200 Seventeenth Street, N.W.
Suite VA-710
Washington, DC 20036

First review of nominations will begin March 1, 1990, although the nomination deadline is March 31, 1990.