

## Human Movement Initiation: Specification of Arm, Direction, and Extent

David A. Rosenbaum  
Bell Laboratories, Murray Hill, New Jersey

### SUMMARY

This article presents a method for discovering how the defining values of forthcoming body movements are specified. In experiments using this movement precuing technique, information is given about some, none, or all of the defining values of a movement that will be required when a reaction signal is presented. It is assumed that the reaction time (RT) reflects the time to specify those values that were not precued. With RTs for the same movements in different precue conditions, it is possible to make detailed inferences about the value specification process for each of the movements under study.

The present experiments were concerned with the specification of the arm, direction, and extent (or distance) of aimed hand movements. In Experiment 1 it appeared that (a) specification times during RTs were longest for arm, shorter for direction, and shortest for extent, and (b) these values were specified serially but not in an invariant order. Experiment 2 suggested that the precuing effects obtained in Experiment 1 were not attributable to stimulus identification. Experiment 3 suggested that subjects in Experiment 1 did not use precues to prepare sets of possible movements from which the required movement was later selected.

The model of value specification supported by the data is consistent with a distinctive-feature view, rather than a hierarchical view, of motor programming.

This article is concerned with the events in the human nervous system that immediately precede and allow for the execution of voluntary movements. The aim of the research is to investigate how plans for voluntary movements, or motor programs, are constructed prior to the time of their motor execution. The focus of the research is less on the *structure* of already prepared motor programs than on the *process* by which motor programs are constructed.

The article is organized as follows: First, I discuss what information is likely to be contained in motor programs. By delineating the possible contents of motor programs, one can pose questions about how motor programs are constructed, and at least some of those questions will be presented here. Next, I consider methods that exist for studying motor programming (i.e., the

process of constructing motor programs). I argue that one of the most promising methods—obtaining reaction times (RTs) for movements of varying complexity—cannot answer most of the questions about programming that are raised here. The next section presents a new RT method that may be better suited to answering these questions; I have called the method the *movement precuing* technique. After outlining how the movement precuing technique can be used, I report on an experiment that used the technique to explore the construction of programs for a restricted set of aimed hand movements. Two control experiments are reported in the next two sections. In the final section I discuss the importance of the present results for theories of motor programming, and I suggest possible future uses of the movement precuing technique.

### Assumptions and Questions About Motor Programs

In an influential article published in 1968, Keele argued for the functional significance of the motor program, which he defined as "a set of muscle commands that are structured before a movement sequence begins, and that allows the entire sequence to be carried out uninfluenced by peripheral feedback" (p. 387). Keele had two main reasons for asserting that motor programs play a major role in movement control. One was that coordinated movements can often be performed when feedback is physiologically interrupted. The other was that movement sequences can usually be performed skillfully even when there is insufficient time for feedback from any one of the movements in the sequence to trigger the movement immediately following it.<sup>1</sup>

Contrary to widespread belief, Keele's definition of the motor program does not require that programmed sequences of movement be ballistic. By Keele's definition, although a programmed sequence *can* be unaffected by feedback from the periphery, it need not be. In fact, a motor program, as defined by Keele, can be used to govern how a movement sequence should unfold depending on the feedback that arises during its execution. A motor program, seen in this way, can be regarded broadly as a plan for movement (Keele & Summers, 1976; Kerr, 1978).

### *Motor Programs and Computer Programs*

Why use the term *program* rather than *plan*? The main reason is to draw attention

to the possibility that a motor program, like a computer program, may go through a number of stages of development. Consider how a computer program is developed. Initially, before the program begins to be written, the programmer has some general idea about what he or she wants to accomplish; the goal might be, for example, to identify the first hundred prime numbers. Then the programmer develops a general strategy for achieving the goal. Next, either without further effects on the goal or strategy, or sometimes with such effects, the set of instructions for carrying out the strategy (i.e., the program) is written. Once the program has been written, it is compiled into executable form, and finally it is "run" or executed.

In the case of the motor program, we can begin again with the programmer's, or actor's, goal. Once the actor has developed a general strategy for achieving a goal, details for carrying out the strategy are specified in the set of instructions comprising the motor program. After the motor program has been written and possibly also compiled into muscle-usable form, it is executed via delivery of efferent commands to the muscles, with resultant muscular contractions and relaxations.

The analogy between computer programming and motor programming provides a potentially useful framework for conceptualizing the process of movement initiation. It indicates, for example, that the present research is aimed at elucidating the set of events occurring after the establishment of general goals and before the execution of programs meant to achieve those goals.

### *Information in Motor Programs*

To address the issue of how motor programs are constructed, it is useful to consider what information is likely to be contained in motor programs. If a motor pro-

---

Aspects of the data reported here were presented at the Second Symposium on the Psychophysics of Musical Performance, Upper Montclair, New Jersey, May 5, 1978, and at a number of university colloquia. The data were collected at Stanford University with the help of a National Science Foundation Graduate Fellowship and National Institute of Mental Health Grant MH 13950-08 to Gordon H. Bower.

The research benefited greatly from the help of Gordon H. Bower, Judith F. Kroll, James R. Lackner, Richard W. Pew, Mary C. Potter, and Roger N. Shepard. I am especially indebted to Beth Kerr, J. A. Scott Kelso, L. Henry Shaffer, and Saul Sternberg for their valuable criticism.

Requests for reprints should be sent to David. A. Rosenbaum, Bell Laboratories, 2D-448, 600 Mountain Avenue, Murray Hill, New Jersey 07974.

---

<sup>1</sup> An opponent of programming theory could offer a simple rejoinder to this argument which, to my knowledge, has not been presented before. It is simply that feedback arising from one movement may not be used to trigger the next movement in the sequence but instead may be used to trigger one (or more) movements occurring later on.

gram governs the execution of a movement, the information contained in a motor program can be assumed to define what movement should be performed. That is, the information in a motor program can be assumed to consist of prescriptions for the *values* that a forthcoming movement should have on *dimensions* that are under the program's control. For example, the information in a motor program for an aimed hand movement might prescribe a time value on a duration dimension, a distance value on an extent dimension, and so on.

If one adopts the view that a motor program prescribes values on movement dimensions, one can assume that the process of constructing a motor program consists, at least in part, of specifying the values that the program should prescribe. With this perspective, a number of questions about program construction come to mind:

1. On what dimensions are values actually specified? Since some dimensions are defined with respect to others (e.g., force = mass  $\times$  acceleration), values on some dimensions may not have to be explicitly specified (e.g., only force or acceleration, but not both, may have to be specified).

2. How much time is required to specify each of the necessary values?

3. What are the average specification times for each of the dimensions that the program controls?

4. Are different values specified independently of one another? That is, are the identities and/or specification times for individual values unaffected by identities of other values that have been or are being specified?

5. Are different values specified serially or in parallel?

6. Are specifications of values on different dimensions ordered or unordered? That is, can the specification of a value on one dimension not begin before the specification of a value on some other dimension (an *ordered* process), or can the specification for either value begin before the other (an *unordered* process)?

The foregoing questions are functional in nature. They point toward an information-processing model of motor programming.

## Current Methods for Studying Motor Programming

How can one arrive at a viable information-processing model of motor programming? One method is to obtain simple RTs for movements of varying complexity. Here the approach has been to record latencies to produce one movement that is followed by varying numbers or types of other movements in different experimental conditions (e.g., Henry & Rogers, 1960; Sternberg, Monsell, Knoll, & Wright, 1978). Because subjects usually become highly prepared to respond in simple RT experiments—as is clear from the rapidity of their responses, changes in reflex excitability during the preparation period (e.g., Hayes & Clarke, 1978), and subjects' subjective reports—it has generally been assumed that subjects preprogram the required responses. Consequently, with the reaction signal held constant across experimental conditions, and with the mechanical properties of the first movement assumed to be invariant across conditions (Sternberg et al., 1978), differences in RTs for the first movement have been attributed to differences in the time to (a) load an already constructed motor program into a response-output buffer (Henry & Rogers, 1960), (b) make "last minute" adjustments in the motor program (Rosenbaum & Patashnik, 1980a, 1980b), or (c) search the response-output buffer for the section of the loaded program, already constructed for the entire movement sequence, that contains instructions for the first element of the sequence (Sternberg et al., 1978). It should be noted that these alternative interpretations of simple RT effects have been offered to account for different sets of experimental results, and no one, as far as I know, has attempted to account for all response-complexity effects on simple RTs with any one interpretation. As is clear from the nature of the interpretations, however, there is agreement that simple RT studies may primarily aid our understanding of how fully constructed programs (or nearly fully constructed programs) are executed. It seems less likely that simple RT studies will provide rich information about how motor programs are initially constructed.

An alternative to the simple RT procedure is the choice RT procedure, in which there is uncertainty about which of two or more possible responses will be required on a trial. With this method, the amount of preparation that can be achieved for any given response is usually less than in simple RT experiments. Consequently, choice RTs may include the time to complete construction of programs for required responses, which implies that choice RTs may reveal more about motor programming than simple RTs do (Klapp, 1978). Nonetheless, the kinds of inferences about motor programming that one may be able to draw from choice RT studies are limited because

subjects in choice RT tasks may be able to do at least some preprogramming of more than one of the alternative possible responses. Evidence for such multiple-response preparation comes from studies in which it is found that choice RTs for one response can be affected by identities of other response alternatives (Berlyne, 1957; Blyth, 1963; Gottsdanker, 1966, 1969; Kantowitz, 1973; Kornblum, 1965; Megaw, 1972; Megaw & Armstrong, 1973; Sanders, 1967).

There are at least two motor-programming interpretations of such "response competition" effects, as is seen in Figure 1. One is that motor programs for each of the

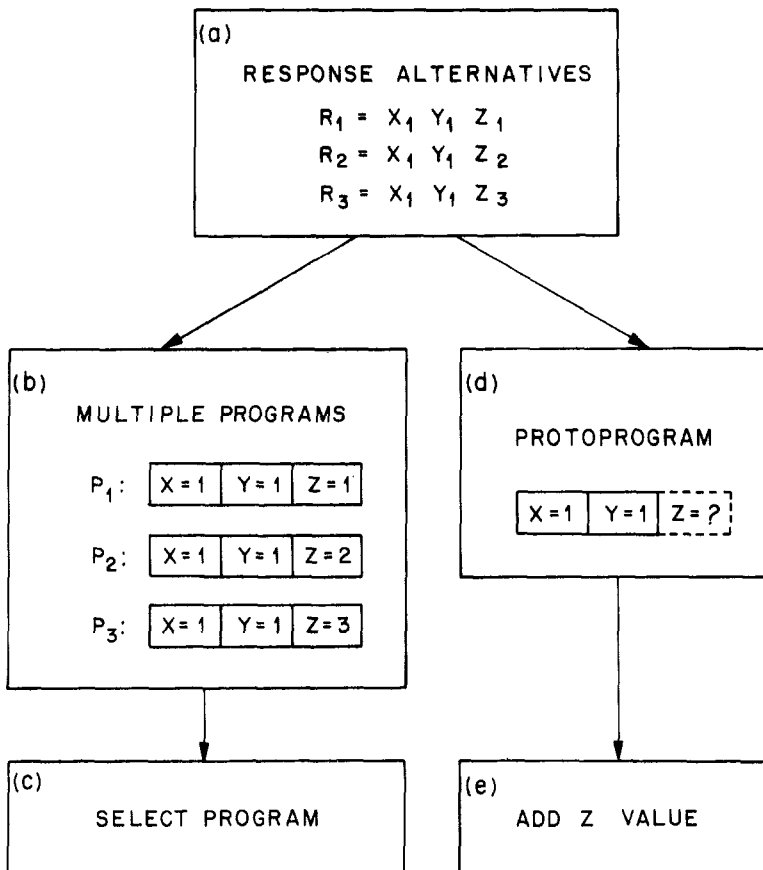


Figure 1. Two views of the processes involved in producing a correct response in a choice reaction time task (a) where the three possible responses,  $R_1$ ,  $R_2$ , and  $R_3$ , differ with respect to their defining values on dimension  $Z$ . (According to one view, the subject [b] constructs distinct motor programs  $P_1$ ,  $P_2$ , and  $P_3$ , for the three responses and [c] selects the appropriate program when the reaction signal is presented. According to another view, the subject [d] constructs a protoprogram containing information common to the possible responses and [e] after the reaction signal adds the information to the protoprogram that distinguishes the required response from the other two.)

alternative responses are fully constructed in advance, and the time to select the motor program for the one required response is affected by the discriminability of the constructed programs. An obvious problem with this interpretation is that it may only apply to choice RT tasks in which there are a relatively small number of response alternatives, for it seems implausible that in the choice RT experiments conducted by Seibel (1963), for example, subjects could have constructed in advance motor programs for all of the 1,023 responses that were possible.

A second motor-programming interpretation of response competition effects is shown in the right half of Figure 1, where it is assumed that a fragment of a single motor program, or "protoprogram," is constructed before presentation of the reaction signal. The protoprogram contains information common to the various response alternatives. According to this model, the choice RT includes the time to add to the protoprogram whatever information is needed to produce the one response that must be performed. Response competition effects can then be explained by saying that it takes different amounts of time to add different types of information to protoprograms, or that it takes different amounts of time to add information of a particular kind to different kinds of protoprograms.<sup>2</sup>

Because one does not know whether choice RTs reflect program discrimination, program completion, or some other kind of response selection process, one may not be able to make detailed inferences about motor-program construction using traditional choice RT experiments. Furthermore, even if one did know that some multiple-response preparation had occurred (as in the first model described above), the question would remain as to how the one or more programs that were constructed in advance actually came to be constructed. It would be unsatisfactory to assume, for example, that the various prepared programs were simply selected from a vast warehouse of "prepackaged" programs, for as Mac-Neillage (1970) has argued, the fact that a person with normal motor control can perform an indefinitely large number of move-

ments makes it extremely unlikely that distinct motor programs exist for all of the movements that the person can perform.

### The Movement Precuing Technique

The foregoing remarks lead me to suggest that a new method is needed to study the construction of motor programs. The main purpose of this article is to introduce one such method.

The method works as follows: In a block of trials, there are several possible test responses. The responses differ in  $v$  ( $v \geq 2$ ) values on each of  $d$  ( $d \geq 2$ ) dimensions. For example, in the present study the possible responses differ on  $d = 3$  dimensions, namely, arm, direction, and extent, with  $v = 2$  values on each dimension, namely, right or left (on the arm dimension), toward or away from the frontal plane (on the direction dimension), and 32 mm or 76 mm (on the extent dimension); hence there are  $v^d = 2^3 = 8$  possible responses. In the present study, the number  $v$  is the same for all dimensions. However, in general, the movement precuing technique does not require that equal numbers of values be represented on all dimensions.

As in traditional choice experiments, each of the possible responses is assigned a unique stimulus, and on each trial when the stimulus is presented, the subject is required to perform the one designated response as quickly as possible. What distinguishes the new method from traditional choice RT methods is that before the reaction stimulus is presented a precue is presented. The precue gives information about some, none, or all of the values defining the response that will be required on that

<sup>2</sup> An interesting property of this model is that it can explain why choice RTs increase with the logarithm of the number of response alternatives (Hick, 1952; Hyman, 1953). As the number of response alternatives doubles, the number of unspecified movement dimensions increases by one (at least). For example, if the left and right *middle* fingers are added to the left and right *index* fingers as possible responding members (thereby increasing the number of response alternatives from two to four) choice of *finger* is added to choice of *hand*. By assuming that additions of single choices add constant times to RTs, the logarithmic relationship is obtained.

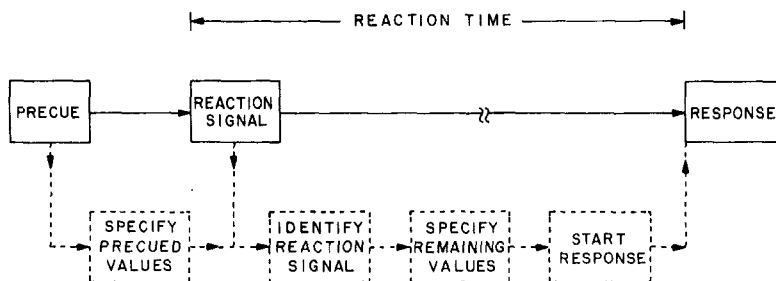


Figure 2. The main observable events (solid boxes and lines) and the main unobservable events (dashed boxes and lines) that are assumed to allow the subject to benefit from precues in one trial of a movement precuing experiment.

trial. For example, in the present study, the precue can indicate that the right arm will be used (1 value), or that the right arm will have to be moved away from the frontal plane (2 values), or that the right arm will have to be moved away from the frontal plane and over the shorter of the two possible extents (3 values); or the precue can give no information at all (0 values). Regardless of the informativeness of the precue, the subject is not allowed to produce the required response until the reaction signal is presented. In the present application of the movement precuing technique, precues always give reliable information about the movements that will be required, although in general this need not be the case. Furthermore, in this study every possible combination of 0, 1, 2, and 3 appropriate values for each response is precued in different trials, although again this is not a general requirement of the movement precuing technique.

### Working Assumptions

Figure 2 illustrates the major working assumptions of the method. The first assumption is that the subject carries out whatever operations are needed to specify all and only the motor values given in the precue. The second assumption is that the subject uses precues to adjust perceptual readiness for the reaction signal. The third assumption is that the RT to produce a required response after the appearance of the reaction signal is the sum of three components

$$RT = \alpha + \beta + \gamma, \quad (1)$$

where  $\alpha$  is the time to identify the reaction signal,  $\beta$  is the time to specify values on all dimensions that were *not* precued, and  $\gamma$  is the time to evoke the response. The value  $\alpha$  is assumed to depend on stimulus identity and uncertainty (a consequence of the second assumption), and  $\gamma$  is assumed to depend on response identity and uncertainty (a consequence of the first assumption). The main reason for assuming that  $\alpha$  and  $\gamma$  are affected by stimulus and response uncertainty, respectively, is to make it as difficult as possible to attribute differential precuing effects to motor value specification ( $\beta$  in Equation 1).

### Possible Inferences About Value Specifications

With the preceding working assumptions, one can make a number of inferences about how movement values that were not precued are specified during RTs. These inferences are illustrated below in connection with a hypothetical experiment in which there are  $d = 2$  dimensions, A and B, with  $v = 2$  values, 1 and 2, on each dimension. Suppose that precues are given about all possible combinations of values for each of the four possible responses. Hypothetical mean RTs for each response in each precue condition are shown in Figure 3.

*Differences in specification times for individual values.* Consider the RTs in the condition in which A values alone have to be specified (second panel from left); here B values alone are precued. Note that RTs are longer for  $A_1$  responses than for  $A_2$  responses. This result could mean that

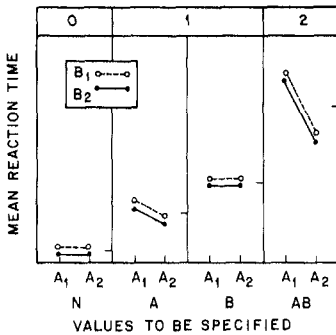


Figure 3. Hypothetical data from a prototypical movement precuing experiment involving four responses differing orthogonally in terms of their defining values on dimensions A and B. (N = no value).

stimulus identification takes longer for A<sub>1</sub> reaction signals than for A<sub>2</sub> reaction signals, that response evocation takes longer for A<sub>1</sub> movements than for A<sub>2</sub> movements, that specification of value A<sub>1</sub> takes longer than specification of value A<sub>2</sub>, or a combination of these. However, in the condition in which no A or B values have to be specified (leftmost panel), there is a much smaller difference between RTs for A<sub>1</sub> responses and A<sub>2</sub> responses. Given the working assumptions of the movement precuing technique, this result permits one to conclude that the time to specify value A<sub>1</sub> is longer than the time to specify value A<sub>2</sub>. (To go about testing such a difference, one can use Sternberg's, 1969, additive-factor method. One can test whether there is an interaction between the precuing of a dimension and the effects of the values of that dimension on RTs.)

*Differences in specification times for different dimensions.* Next, consider the condition in which values of B alone have to be specified during the RT (second panel from right); here A values alone are precued. The mean RT in this condition is longer than the mean RT when A values alone have to be specified. Since the number of precued dimensions is the same in these two conditions, the difference in mean RTs cannot be attributed to stimulus identification or response evocation (at least within the bounds of the working assumptions). Therefore, it can be concluded that it takes longer to specify B values than A values.

*Independence of specifications for different dimensions.* Next, consider the mean RTs when values on dimensions A and B have to be specified during the RT (rightmost panel); here no values are precued. For both levels of A, the difference between RTs for B<sub>1</sub> and B<sub>2</sub> responses is the same as when B values alone have to be specified. This result implies that the times to specify values B<sub>1</sub> and B<sub>2</sub> are not affected by the additional requirement of specifying A values. By contrast, the difference between RTs for A<sub>1</sub> and A<sub>2</sub> responses is affected by the additional requirement of specifying B values. Here, the difference between A<sub>1</sub> and A<sub>2</sub> responses is exaggerated when B as well as A values have to be specified. This result implies that A specification times depend on B specifications. (To test for independence between dimensions, one can again use Sternberg's additive-factor method.)

*Serial or parallel specifications.* Two characteristics of the hypothetical data in Figure 3 suggest that A and B values are specified serially. First, RTs are longer when A and B values both have to be specified than when only A or B values have to be specified. If this were not the case, one would be able immediately to reject the idea of serial specification. Of course, the increase in RTs could have resulted from increases in stimulus-identification times, response-evocation times, or both; or the increase could have resulted from the slowing of B specifications during their cooccurrence with A specifications. A second property of the data that adds weight to the serial specification hypothesis is that when values on dimensions A and B both have to be specified, RT differences within each dimension are at least as large as when values on each of the dimensions alone must be specified. For example, the difference between RTs for A<sub>1</sub> and A<sub>2</sub> responses is at least as large when an A value and B value have to be specified as when an A value alone has to be specified. This outcome supports a prediction of the serial specification hypothesis, namely, that the time to specify an A value and either B value should equal or exceed the sum of times to specify the A value alone and just that B value.

(Note that the above criterion for serial specification does not require independence of specification times for different dimensions.)

In addition to the above criteria for serial specification, a number of other criteria are possible when more than  $d = 2$  dimensions can be precued. Consider the case of  $d = 3$  dimensions, called A, B, and C, with  $v = 2$  possible values on each dimension. Let  $T(A)$  denote the mean RT when a value on dimension A alone must be specified during the RT, let  $T(AB)$  denote the mean RT when a value on dimension A and a value on dimension B must be specified, and so on. Suppose it is found that  $T(A) < T(B) < T(C)$ . In the three experimental conditions in which the estimates of  $T(A)$ ,  $T(B)$ , and  $T(C)$  are obtained, the same reaction stimuli are presented, the same responses are made, and the same amounts of stimulus and response uncertainty exist. Therefore, it can be inferred that

$$T(C) - T(A) = \beta(C) - \beta(A) \quad (2)$$

and

$$T(B) - T(A) = \beta(B) - \beta(A). \quad (3)$$

Since it is assumed that  $\beta(A) > 0$ , it can also be inferred that

$$T(C) - T(A) < \beta(C) \quad (4)$$

and

$$T(B) - T(A) < \beta(B). \quad (5)$$

These inferences allow for a prediction about how RTs should behave if values on two dimensions, say B and C, are specified serially, that is, if

$$\beta(BC) \geq \beta(B) + \beta(C). \quad (6)$$

The prediction is that adding the requirement to specify C to the requirement to specify B should cause an increase in mean RT that is greater than or equal to  $\beta(C)$ , that is,

$$T(BC) - T(B) \geq T(C) - T(A). \quad (7)$$

Similar predictions can be generated to test the hypotheses that A and C values are specified serially and that A and B values are specified serially. In addition, this method can be used to evaluate

whether three or more values are specified serially.

In addition to asking whether values are specified serially, one can ask whether specification times are additive. To test for additivity one must posit that specification times are additive for at least two pairs of dimensions, with one dimension in common to both pairs. For example, it may be hypothesized that

$$\beta(AB) = \beta(A) + \beta(B)$$

and that

$$\beta(AC) = \beta(A) + \beta(C). \quad (8)$$

Assuming  $T(B) \neq T(C)$ , a prediction of the additivity hypothesis is

$$T(AC) - T(AB) = T(C) - T(B). \quad (9)$$

(Without stipulating that  $T(B) \neq T(C)$ , one could confirm the prediction in Equation 9, even though A and C values or A and B values are specified in parallel).

*Order of specifications.* The movement precuing technique allows one to decide whether specifications of values on different dimensions must be ordered in time, that is, whether the specification of a value on one dimension cannot begin before the specification of a value on another dimension. The technique also allows one to identify what the order is. The kinds of results that allow for order inferences are illustrated below.

Suppose that when precue information is given about dimension B, RTs are shorter than when no precue information is given; however, this facilitation of RTs occurs only when precue information is also given about dimension A. This result implies that values on B cannot be specified before values on A.

Suppose next that precue information about dimension A facilitates RTs regardless of whether precue information about dimension B is also given. This result implies that values on A can be specified before values on B.

Now consider another outcome. Suppose that precue information about B facilitates RTs only if precue information about A is also given (as before), and that precue information about A facilitates RTs only if



B is also precued. This result implies that B cannot be specified before A and that A cannot be specified before B, that is, that A and B must be specified in parallel.

There is a potential problem with the above criteria for making judgments about specification orders. Precues about a movement dimension might facilitate RTs even though subjects cannot select values on that dimension before the appearance of the reaction signal. Instead, the precue information might simply allow for a reduction in stimulus identification time ( $\alpha$  in Equation 1). In view of this possibility, one could argue generally that for any set of precue conditions that supply equal amounts of information, in the precue condition in which RTs are the longest, subjects cannot specify precued motor values before the reaction signal. The problem for the researcher is to determine whether such precues are relatively ineffective because they do not allow for advance motor value specification or because the motor value specifications that they make unnecessary during RTs take less time than any others. A solution to this problem is offered in the next section.

#### *Other Potentially Useful Data*

In addition to RTs, other data from movement precuing experiments may provide clues about the construction of motor programs. In the present study I make use of two kinds of data other than RTs: movement times and errors. The potential uses of these two kinds of data are discussed next.

*Movement times.* In connection with aimed hand movements, the term *movement time* refers to the time to move the hand from a starting position to the target of the movement. (Reaction time, in contrast, is the time to *begin* the aimed hand movement after the presentation of a reaction signal.) It may be useful to study how movement times (MTs) are affected by precues, primarily because specification of defining values of aimed hand movements may not be completed before RTs are over (see Kerr, 1978).

An MT result that would support the conclusion that decisions about a movement dimension are made during MTs is that

MTs are lengthened when precue information about that dimension is not given. Another result that would support the same conclusion is that MT differences within a dimension are affected by whether that dimension is precued. For example, suppose that when values on some dimension D must be specified during RTs, MTs for movements with value  $D_1$  are longer than MTs for movements with value  $D_2$ . However, when values on dimension D do not have to be specified during RTs, MTs are equal for  $D_1$  and  $D_2$  movements. One could then conclude that at least part of the specification process for D occurs during MTs and also that more time is needed during MTs to specify value  $D_1$  than  $D_2$ .

It is easy to see that many of the questions raised earlier about value specifications during RTs can be extended to value specifications during MTs and can be addressed accordingly with MT data. One issue for which the analysis of MT data seems particularly well suited is order of value specification. If it can be shown that specifications for one dimension occur during MTs and that specifications for another dimension do not occur during MTs, it can be inferred that at least part of the specification process for the latter dimension precedes at least part of the specification process for the former dimension. This inference, like other inferences based on MTs, can be compared with inferences based on RTs in order to test, and hopefully strengthen, one's model of programming.

*Errors.* In addition to analyzing RT and MT data, it is useful to consider the types of errors that subjects make in different precue conditions. Such data may be useful for reaching conclusions about independence of different dimensions. Suppose that subjects have a high error rate for some dimension E (i.e., they tend to produce movements with the wrong values on that dimension) when values of that dimension and another dimension F must be specified after the reaction signal. If the E error rate in this condition is higher than when E must be specified and F need not be specified, one can conclude that E specifications depend on F specifications.

Error data may be most useful for addressing the issue of whether values are specified in an ordered or unordered fashion. The reason is that they can help to clarify the problem raised earlier of whether precues about some dimension, which facilitate RTs the least within an uncertainty level, allow for movement-value specification as well as stimulus preparation. If such precues do in fact allow for movement-value specification, one would expect about as few errors on the dimension in question when precue information is given about all dimensions as when precue information is given about that dimension but not given about one or more other dimensions. The reasoning here is that when complete precue information is given, subjects presumably can specify all necessary motor values in advance. Thus, if one finds that error rates within a precued dimension are approximately equal when all other dimensions are precued and when some other dimensions are not precued, it seems reasonable to conclude that it is possible to specify motor values on that dimension before motor values on other dimensions (which are not precued) are specified.

### *The Issue of "Basic" Dimensions*

The reader may have noticed that it has not yet been explained how the movement precuing technique can be used to answer the first question about motor programming that was raised earlier: On what dimensions are values actually specified? One way to address this issue is to draw on Turvey's (1977) application of the mathematical concept of the *basis* to motor control. According to Turvey,

A "basis" is a mathematical structure found in the theory of vector spaces. It is defined as a linearly independent (nonredundant) set of vectors that under the operations of addition and scalar multiplication spans the vector space. Essentially, a "basis" contains the minimum number of elements that are required to generate all members of the set. (p. 219)

Although Turvey argues that *reflexes* serve as the basis for the "infinitely large set of all acts" (p. 219), here we may regard the basis for a set of movements as the minimal set of independent dimensions whose values

determine the identities of all the movements in the set. With this perspective, the discovery of independence among dimensions in a movement precuing experiment enables one to conclude that the dimensions being studied either are, or correspond in a one-to-one fashion to, the dimensions that form at least part of the basis for the set of experimental movements.

### Experiment 1

The empirical research described in this article concerns the programming of aimed hand movements. The movement precuing technique is used here to investigate the specification of the arm (left or right), direction (toward or away from the frontal plane of the body), and extent (32 or 76 mm) of such movements. With  $v = 2$  values on each of  $d = 3$  movement dimensions, there are eight possible movements.

One reason for studying the specification of direction and extent is that a considerable amount of work has already been done on this topic, although not with movement precuing procedures. With the conclusions of this previous research, it should be possible to judge the plausibility of the model of direction and extent specification reached here. I will briefly review some of the previous research before turning to the method of Experiment 1.

### *Previous Research on Aimed Hand Movements*

The major impetus for modern work on aimed hand movements came from Fitts (1954), who sought a formula for the relative effects of movement extent and required endpoint accuracy on MTs. On the basis of experiments in which subjects used one hand to alternately tap two target areas which varied in width ( $W$ ) and the amplitude ( $A$ ) of their center-to-center distances, Fitts proposed that MT is a linear function of the "index of difficulty" (ID) for such movements, where

$$ID = \log_2 (2A/W). \quad (10)$$

The relation

$$MT = a + b \log_2 (2A/W) \quad (11)$$

is known as Fitts' law, the term *law* having been bestowed on the relation because of the large amount of data that it can account for (see Langolf, Chaffin, & Foulke, 1976; Schmidt, Zelaznik, & Frank, 1978). Fitts' law is a purely descriptive account of the determinants of MTs in manual positioning tasks, although explanations of the law have been given in terms of feedback-based movement corrections (Keele, 1968) and efference variability (Schmidt et al., 1978).

Fitts and Peterson (1964) intensified the investigation of the mechanisms underlying the control of manual positioning movements. Instead of having subjects repeatedly move between two targets, they had subjects make one movement per trial, with the dependent measures being RTs as well as MTs and errors. With this "discrete movement" approach, several patterns of results concerning extent control have been obtained. First, the extent to be covered has little or no effect on RTs (Brown & Slater-Hammel, 1949; Fiori, Semjen, & Requin, 1974; Fitts & Peterson, 1964; Glencross, 1972; Gottsdanker, 1969; Henry, 1952, 1961; Lagasse & Hayes, 1973; Megaw, 1972; Megaw & Armstrong, 1973; Searle & Taylor, 1948). Second, extent uncertainty in choice RT situations has no significant effect on RTs (Gottsdanker, 1966, 1969; Megaw, 1972; Megaw & Armstrong, 1973). Third, if a signal presented during the RT indicates that the subject must cover a different extent than was originally signaled, there is little or no effect on RT (Gottsdanker, 1966, 1969; Semjen, 1971).

One way to interpret these findings is to say that premotor extent decisions take a constant and/or negligible amount of time, and also that such extent decisions can be updated once movements are under way. Support for the claim that there are premotor extent decisions comes from Megaw's (1972) observation that aimed hand movements covering different extents have different accelerations within 25 msec of the initial hand displacement; 25 msec is almost certainly too short for post-RT decisions to affect acceleration levels.<sup>3,4</sup> Support for the claim that extent decisions can be updated once movements are under way

comes from the observation that the hand may go through more than one acceleration-deceleration cycle before reaching a target (Annett, Golby, & Kay, 1958).

Reaction time studies pertaining to directional control of aimed hand movements indicate that premotor decisions about direction are more time consuming than premotor decisions about extent. Two major results lead to this conclusion. First, uncertainty about direction in choice RT situations causes increases in RTs (Ells, 1973; Fitts & Peterson, 1964; Gibbs, 1965; Griew, 1958; Kerr, 1976; Megaw, 1972; Megaw & Armstrong, 1973), whereas there is usually no such effect for extent uncertainty. Second, if a signal presented during the RT indicates that the subject must move in a different direction than was originally signaled, RTs are much longer than if no movement change or an extent change is indicated (Gottsdanker, 1966, 1969; Semjen, 1971).

Semjen (1971, Note 1) concluded from the above result that direction decisions precede extent decisions. Megaw (1972) concluded from the differential effects of direction and extent uncertainty on choice RTs that direction and extent decisions are made at different programming levels. He wrote:

Choice of direction mainly involved establishing the correct sequence of firing of muscles [while] . . . choice of extent involved establishing the precise nature of each pulse of activity. (p. 184)

<sup>3</sup> This statement is made in spite of the fact that recent physiological studies indicate that cortical potentials related to tactile and proprioceptive stimulation are observable within 10 msec in some cases (see Adams, 1976). However, recent behavioral studies (e.g., Allum, 1975; Crago, Houk, & Hasan, 1976; Melvill Jones & Watt, 1971) indicate that delays between (load-change) stimuli and effective motor responses to those stimuli are considerably longer, usually on the order of 200 msec.

<sup>4</sup> Additional data related to the question of whether extent decisions can be made premotorically comes from a study by Klapp (1975). He found that choice RTs varied with extent for very short movements (11 mm or less). Unfortunately, it is difficult to tell from his finding whether the RTs reflected differences in preparation time for different extents or whether RTs and movement executions were affected similarly by some other factor (e.g., greater concern for accuracy at smaller distances).

(See Kerr, 1976, for criticisms of Megaw's study and conclusions.)

In all of the studies of aimed hand movements cited above, subjects could see the various possible targets before the reaction signal was presented, and they also could use visual feedback once their hand movements were under way. The fact that the possible targets were in view creates a potential problem for the interpretation of the RT data. The problem derives from the fact that arrangements of possible targets differed depending on whether the possible targets differed in direction or extent. For example, in Megaw's (1972) study, the visual angle subtended by pairs of targets differing in extent was smaller on the average than the visual angle subtended by pairs of targets differing in direction. Therefore, subjects may have been able to visually localize required targets more quickly in extent uncertainty conditions than in direction uncertainty conditions. Apparently, there is no way conclusively to reject such a perceptual interpretation of any of the results presented above.<sup>5</sup> In addition, it is difficult to tell whether Fitts' law should properly be viewed as a description of motor control or visuomotor coordination. To avoid such problems of interpretation in the present study, reaction signals and precues are presented tachistoscopically, and subjects are not permitted to see the response panel on which their aimed hand movements are performed.

### Method

#### Apparatus

While seated at a table, the subject looked into a three-field Iconix tachistoscope. Directly beneath the tachistoscope, lying flat on the table, was a response panel whose top surface is illustrated schematically in Figure 4. The round (target) buttons had distinct colors that were chosen to be as nonconfusable as possible. The colors of the targets also served as tachistoscopically presented reaction signals. Using Fitts' (1954) index of difficulty (ID), the ID for target buttons close to the square (home) buttons was 1.29 bits, and the ID for target buttons far from the home buttons was 2.24 bits.

Precues were presented in the top half of a vertically split field in the tachistoscope. The precues consisted of typed capital letters that conveyed information as follows: Letters conveying arm information were R (right) and L (left). Letters conveying direction information were F (forward) and B (backward).

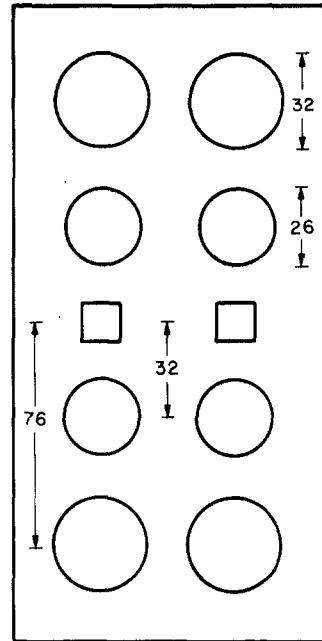


Figure 4. Schematic diagram of the button panel as viewed from the top. (The round and square buttons were 5 mm above the panel surface, which measured 103 × 208 mm. The buttons were about 45 mm above the tabletop on which the panel was secured. The numbers [in mm] and arrows appearing in the figure did not appear on the button panel.)

Letters conveying extent information were N (near the square buttons) and D (distant with respect to the square buttons). The letter X served as a filler that provided no information. Three horizontally spaced letters appeared in each precue, regardless of the informativeness of the precue, in order roughly to equate the reading requirements in all precue conditions. When only one informative letter appeared, it was surrounded by two Xs; when two informative letters appeared, they were followed by a single X; three Xs appeared when no information was given. The reaction signal consisted of a single colored dot (Dennison Pres-a-ply) centered in the lower half of the visual field. One mapping of colors to targets was used for all subjects.

Reaction times and movement times were recorded to the nearest millisecond with standard digital timers. A light panel displayed which buttons were pressed and whether the panel surface was pressed.

#### Procedure

Prior to testing, subjects took as long as needed to memorize the locations of the colored buttons. Then,

<sup>5</sup> For a further discussion of possible confoundings between perceptual and motor factors in choice RT experiments, see Christina and Cornell (1979).

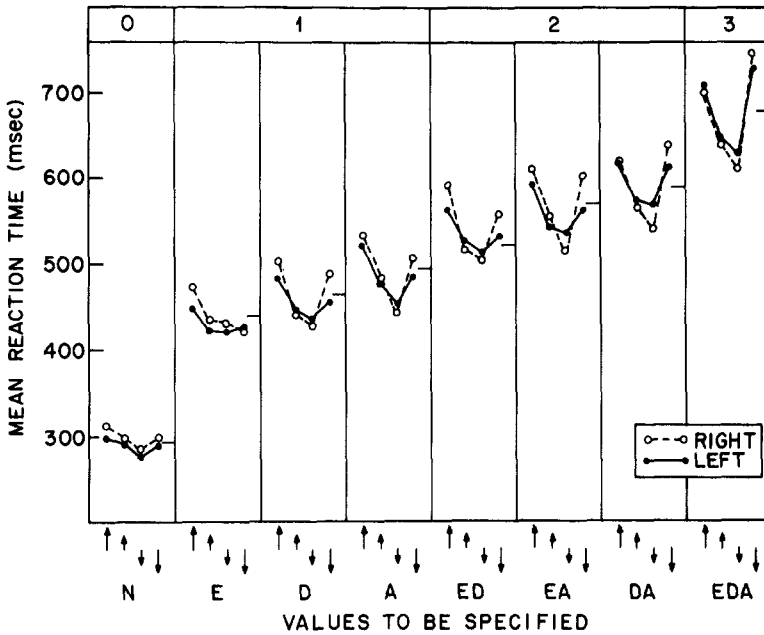


Figure 5. Mean reaction times (RTs) in Experiment 1 for forward movements (upward arrows) and backward movements (downward arrows) over long extents (long arrows) and short extents (short arrows) for the right and left hands when no values (N) had to be specified after the reaction signal and when the values to be specified were extent (E); direction (D); arm (A); extent and direction (ED); extent and arm (EA); direction and arm (DA); and extent, direction, and arm (EDA). (The horizontal marker in each panel indicates the mean RT for the corresponding precue condition. The numbers on the top of the graph indicate the number of values to be specified in the precue conditions represented beneath them.)

during a half-hour training session, subjects practiced making rapid, blind movements to each of the colored buttons and learned to read the precues. In the experiment, subjects looked into the tachistoscope and began each trial by pressing the left square button with the left index finger and the right square button with the right index finger. When both square buttons were pressed, a blank illuminated field appeared in the tachistoscope for .5 sec. Immediately thereafter, the precue was presented for 3 sec. The precue could specify any possible combination of 0, 1, 2, or 3 values that defined any of the eight possible movements. A half second after the precue was extinguished, a colored dot appeared in the lower tachistoscopic field. The subject's task was to move as quickly as possible to the target having the color designated by the dot, using the right index finger for buttons on the right side and the left index finger for buttons on the left side.

Subjects were instructed that the precues would always give reliable information about the movement that would be required when the reaction signal appeared. Subjects were told to use the precues to help them reach the designated target as quickly and accurately as possible after the appearance of the reaction signal. Subjects were not told about the distinction between RTs and MTs.

On each trial three measurements were taken: (a) RT, defined as the time between appearance of the colored dot and release of either square button; (b) MT, defined as the time between release of either square button and the first depression of any round button or of the panel surface; (c) accuracy, where an error was defined as the release of an incorrect square button, depression of an incorrect round button, or depression of the panel surface.

Within each block of trials, each of the eight colored dots was preceded twice by each of the eight types of precues, and the order of trials was randomized for each subject. The horizontal arrangement of informative letters in the precues was counterbalanced across six experimental blocks. The assignment of horizontal arrangements to blocks was random, as was the assignment of block orders to subjects. Each subject underwent a total of 768 trials. Testing occurred on 2 consecutive days for a total of 3 hr.

### Subjects

Five right-handed male and five right-handed female students between the ages of 22 and 30 years participated in exchange for pay.

### Results

The analyses to be reported here are concerned with RTs, MTs, and errors. They will be presented in that order in the next three sections.

#### Reaction Times

Figure 5 shows mean RTs for each of the eight responses in each of the eight precue conditions. The data contributing to each point, and to the analyses reported below, are each subject's mean RT for errorless trials.

*Differences in mean specification times for different dimensions.* As can be seen by the positions of the horizontal markers in each panel of the figure, mean RTs increased with the number of values to be specified after the reaction signal. This effect was obtained for every subject, so it is clear that all subjects made use of the precues.

To assess the statistical significance of differences in mean RTs among the three conditions in which one movement value had to be specified and among the three conditions in which two movement values had to be specified, separate analyses of variance (ANOVAS) were carried out for these two sets of conditions. When one value had to be specified, there was a main effect on RTs of the dimension requiring value specification,  $F(2, 18) = 13.27$ ,  $p < .001$ . As tested with the Newman-Keuls procedure, RTs when extent had to be specified were significantly shorter than RTs when direction had to be specified ( $p < .05$ ), which in turn were significantly shorter than when arm had to be specified ( $p < .05$ ). These results suggest that during the RTs, specification of direction took more time than specification of extent and less time than specification of arm.

When two values had to be specified, there was again a main effect of dimensions requiring value specification,  $F(2, 18) = 24.16$ ,  $p < .001$ . All pairwise differences between the three main conditions in which two values had to be specified were statistically significant ( $p < .01$ ), as tested with

the Newman-Keuls procedure. This result suggests that during the RTs, specification of extent and arm took more time than specification of extent and direction and less time than specification of direction and arm.

*Differences in mean specification times for individual values.* The above conclusions pertain to differences in mean specification times for different dimensions. Next, we consider whether individual values within dimensions had different specification times (e.g., whether it took longer to specify forward than backward on the direction dimension). Recall that to test for such a difference, one must determine whether RT differences within a dimension are affected by the requirement that a value on that dimension be specified during the RT. To address this issue, a set of 12 ANOVAS was conducted to test the effects of Types of Values to be Specified  $\times$  Arm  $\times$  Direction  $\times$  Extent  $\times$  Subjects. In each ANOVA, two precue conditions were included that differed by the addition of one type of value to be specified. Thus, in the pairs of conditions that were tested, the types of values to be specified were N and E, N and D, N and A, E and ED, E and EA, D and ED, D and DA, A and EA, A and DA, ED and EDA, EA and EDA, and DA and EDA. The results of these 12 ANOVAS were consistent: Interactions between types of values to be specified and the movement dimension for which value specifications were added were statistically nonsignificant ( $p > .20$ ) in all cases. This outcome allows for tentative acceptance of the hypothesis that specification times did not differ within dimensions. (Other results from these ANOVAS, to be presented later, indicate that the ANOVAS were powerful enough to justify acceptance of this null hypothesis.)

*Independence of specifications for different dimensions.* The ANOVAS reported above can be used to determine whether values on different dimensions were specified independently. The question is whether the addition of one type of value to be specified affected RT differences within another dimension for which values also had to be specified. Statistically, this kind of dependence would be expressed as an inter-

action between types of values to be specified (where the two levels of this factor are types of values differing by the addition of one value) and dimension(s) for which values must always be specified.

In the 12 ANOVAS described above, only two such interactions turned out to reach or approach statistical significance. In comparing the condition in which extent had to be specified and the condition in which extent and arm had to be specified, there was a significant interaction between types of values to be specified and extent,  $F(1, 9) = 6.15, p < .05$ . The difference between RTs for near and far movements was larger when arm and extent had to be specified than when extent alone had to be specified. This result suggests that the time to specify extent was affected by whether arm also had to be specified (but see the next paragraph).

The other statistically salient interaction was obtained in the comparison of the condition in which no values had to be specified and the condition in which arm had to be specified. Here the difference between RTs for short and long movements was affected by precue condition,  $F(1, 9) = 4.00, p < .10$ . The difference between RTs for movements to near and far targets was larger when arm had to be specified than when arm did not have to be specified. This interaction implies that the need to specify arm affected stimulus-identification time, response-evocation time, or both, because extent did not have to be specified in either of the conditions entering into this ANOVA. Thus, it is unnecessary to conclude that the time to specify extent was affected by whether arm also had to be specified (as suggested in the last paragraph).

Aside from the two interactions reported above, no other interactions between types of values to be specified and movement dimensions had probabilities less than .20. In each of the 10 ANOVAS in which there were no such interactions, the proportion of variance accounted for by each of the interactions was no greater than .01. However, the total proportion of variance accounted for by main effects and interactions among movement dimensions ranged from .87 to .97.

*RT differences for different types of movements.* The ANOVAS reported in the preceding sections contained information about RT differences for different types of movements. The qualitative aspects of the RT differences were fairly consistent in the 12 ANOVAS and were also consistent with an omnibus ANOVA that tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Types of Values to be Specified (with all eight levels included)  $\times$  Subjects. The major results of the omnibus ANOVA are reported below.

Mean RTs for the two arms differed by a nonsignificant 8 msec,  $F(1, 9) = 1.06$ . There was an effect of direction,  $F(1, 9) = 4.29, p < .10$ , with backward movements beginning 15 msec faster than forward movements. Of special interest was a main effect of extent,  $F(1, 9) = 87.28, p < .001$ , in which movements to near targets were begun 48 msec faster than movements to distant targets. (This large a difference has not been observed before in traditional manual-positioning experiments.) Only one interaction among movement dimensions was statistically significant, namely, Arm  $\times$  Extent,  $F(1, 9) = 5.24, p < .05$ ; the difference between RTs for long and short movements was 32 msec larger for the right arm than for the left. No other interaction among movement dimensions accounted for more than 1% of the overall variance.

*Serial or parallel specifications.* Several aspects of the RT data support the hypothesis that specifications of arm, direction, and extent during RTs were serial. First, RTs increased as more values remained to be specified. Second, increases in RTs produced by the addition of values to be specified always exceeded estimates of the minimal specification times for the added values (see Equations 2–7). Third, the difference between the mean RT when three values had to be specified and the mean RT when a pair of values, contained in the set of three, had to be specified was always greater than the largest estimate of the specification time for the added type of value. Fourth, specification times appeared to be additive, as is shown by the tests of Equation 9 described below.

The additivity hypothesis presented in Equation 9 can be extended to the specifica-

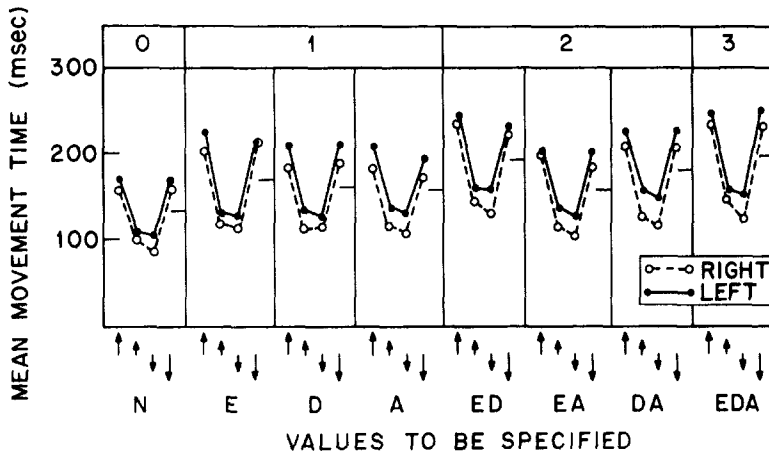


Figure 6. Mean movement times for the eight responses in the eight precue conditions of Experiment 1. (N = no value.)

tion of arm (A), direction (D), and extent (E) as follows:

$$T(DA) - T(EA) = T(D) - T(E) \quad (12)$$

$$T(DA) - T(ED) = T(A) - T(E) \quad (13)$$

$$T(EA) - T(ED) = T(A) - T(D). \quad (14)$$

Each of these hypotheses was tested by estimating the differences in the left and right sides of each equation for each subject. Then three paired-difference *t* tests were used to determine whether the two sets of differences in each of the three equations were significantly different. In all three cases they were not. The three *t* values (*df* = 9 in all cases) were .53, .78, and 1.00 for Equations 12, 13, and 14, respectively. These results provide strong support for the hypothesis that arm, direction, and extent were specified serially during the RTs.

*Order of specifications.* Because precues for all types of values facilitated RTs, it appears that value specifications were not ordered because any kind of value could be specified before another. Nevertheless, it is possible that precues about extent did not facilitate motor preparation (when there was incomplete precue information) because extent precues facilitated RTs less than arm or direction precues and therefore may have merely facilitated stimulus-identification times. (As it turns out, an analysis of errors, to be presented later, does not support this conjecture.)

The RT data do allow for the conclusion that arm and direction were not specified in a strict order. Since arm precues and direction precues facilitated RTs more than extent precues, it can be concluded (if one accepts the working assumptions of the movement precuing technique) that both types of precues allowed for advance specification of their corresponding movement values. Moreover, since arm precues and direction precues each facilitated RTs when presented alone, it was presumably possible for subjects to specify values on either dimension before specifying values on the other dimension.

#### Movement Times

Mean MTs for the eight responses in the eight precue conditions are shown in Figure 6.

*Omnibus test.* This ANOVA tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Precue Condition  $\times$  Subjects. There was a significant difference between MTs for the left and right arms,  $F(1, 9) = 21.39$ ,  $p < .01$ . On the average, MTs were 18 msec faster for the right arm than for the left. There was no effect of the two directions of movement,  $F(1, 9) = .91$ . Extent had a main effect on MTs,  $F(1, 9) = 206.81$ ,  $p < .01$ , with movements to near targets being 69 msec faster on the average than movements to far targets. No interactions among arm, direction, and extent were obtained;



Table 1  
*Percentage of Errors in Experiment 1*

Value to be specified	Type of errors								
	All	Miss	E	D	A	ED	EA	DA	EDA
N	2.39	1.26	.10	.31	.62	.00	.10	.00	.00
E	3.22	1.57	<i>1.04</i>	.20	.41	.00	.00	.00	.00
D	3.72	1.66	.41	<i>1.35</i>	.20	.00	.10	.00	.00
A	6.22	1.66	.20	.20	<i>4.06</i>	.00	.00	.00	.10
ED	4.57	2.29	.52	.93	.00	.83	.00	.00	.00
EA	5.90	1.97	.20	.10	<i>3.43</i>	.00	.20	.00	.00
DA	6.65	1.66	.52	<i>1.25</i>	<i>2.60</i>	.00	.00	.62	.00
EDA	6.95	1.87	.52	<i>1.87</i>	<i>1.97</i>	.00	.31	.41	.00

*Note.* N = no value; E = extent; D = direction; A = arm; Italics are for errors on dimensions that were not precued.

the  $p$  values for all such interactions were above the .10 level and the proportion of variance accounted for each of these interactions never exceeded .01. There was a main effect of precue conditions,  $F(7, 63) = 5.29$ ,  $p < .01$ . However, there were no statistically significant interactions between precue conditions and arm, direction, or extent, and none of these interactions accounted for more than 1% of the overall MT variance.

*Differences within uncertainty levels.* As a further breakdown of the effects of precue conditions, separate ANOVAs were performed for the two-precue and one-precue conditions. Within the two-precue conditions (i.e., when extent, direction, or arm had to be specified), the effect of type of precue was not statistically significant,  $F(2, 18) = 1.59$ ,  $p > .10$ , but within the one-precue conditions there was a main effect of type of precue,  $F(2, 18) = 5.94$ ,  $p < .05$ . As tested with the Newman-Keuls procedure, MTs obtained when extent and direction had to be specified were significantly longer than MTs when extent and arm had to be specified ( $p < .05$ ). There were no other statistically significant pairwise differences within the set of one-precue conditions.

*Further tests of value specification times and independence among dimensions during MTs.* The logic underlying these tests was similar to the logic underlying the corresponding tests used earlier with the RT data. A series of 12 ANOVAs was car-

ried out in which the conditions compared in each ANOVA differed by the presence of a single precued value. Only one statistically significant interaction was obtained. In comparing the condition in which no values had to be specified with the condition in which extent alone had to be specified, there was an interaction between precue condition and extent,  $F(1, 9) = 5.74$ ,  $p < .05$ . The difference between MTs for near and far targets was larger when extent had to be specified than when no values had to be specified. No other interactions involving precue conditions were statistically significant, and none of these interactions accounted for more than 1% of the variance in any of their respective comparisons. According to the assumptions I stated earlier, since the difference between MTs for near and far movements was affected by whether extent had to be specified, extent decisions apparently could be made during MTs. Moreover, because there was no evidence that arm or direction decisions were made during MTs, it is possible to conclude further that at least part of the specification process for extent tended to occur after at least part of the specification process for direction and arm.

### Errors

Table 1 shows mean error rates in the eight precue conditions of Experiment 1.

Error rates contributing to the leftmost column of Table 1 (All) were transformed

using the arc sine transformation for proportions near zero (Winer, 1962, p. 400) and were then subjected to an ANOVA that tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Precue Condition  $\times$  Subjects. (Here, arm, direction, and extent refer to the properties of the required movements.) There were no main effects of arm,  $F(1, 9) = 1.27$ ; direction,  $F(1, 9) = 1.86$ ; or extent,  $F(1, 9) = .94$ . The only interaction among these factors was an Arm  $\times$  Direction interaction,  $F(1, 9) = 9.45$ ,  $p < .05$ , in which more errors were made for left forward movements than for left backward movements, whereas there was no difference in error rates for right forward and right backward movements. There was a main effect of precues,  $F(7, 63) = 10.71$ ,  $p < .001$ , but there were no reliable interactions between precue conditions and movement dimensions. Within the set of conditions in which one value had to be specified, Newman-Keuls tests of pairwise differences (using the Precue  $\times$  Subjects term of an ANOVA limited to these conditions) showed that more errors were made when arm had to be specified than when direction ( $p < .05$ ) or extent ( $p < .05$ ) had to be specified. Within the set of conditions in which two values had to be specified, the results of a comparable analysis showed that there were fewer errors when extent and direction had to be specified than when extent and arm ( $p < .05$ ) or direction and arm ( $p < .05$ ) had to be specified, although the frequencies of errors in the latter two conditions were not significantly different from one another.

The eight remaining columns of Table 1 give percentages of all 960 trials in each precue condition in which there were errors of missing a target and striking the button panel (Miss), striking a button that had the wrong extent (E), striking a button that had the wrong extent and direction (ED), and so on. The italicized numbers correspond to types of errors associated with dimensions that required specification during the RT. As expected, these numbers were larger than the nonitalicized numbers, for types of errors other than misses. (Unfortunately, it was impossible to classify misses in terms of direction and extent inaccuracy because the surface of the button panel was not

divided into subregions and also because if an arm error and miss occurred, the miss was not recorded. Thus, tabulated rates for extent and direction errors are underestimates of the true rates for errors with extent and direction components.)

The data in Table 1 allow for two important inferences about the specification process for arm, direction, and extent. First, the data do not contradict the idea that the three dimensions were essentially independent. This is because, with only one exception, error rates on each dimension were no higher when values on that dimension and another dimension had to be specified than when values on just that dimension had to be specified. The one exception was for direction errors, which were slightly more common when three values had to be specified than when only direction had to be specified; however, this was a difference of only five errors in the entire experiment. In fact, error rates on dimensions requiring specification tended to be somewhat lower when other dimensions required specification than when only one dimension required specification, although with the unclassifiable miss rates it is difficult to judge the significance of this reduction.

The second major inference allowed by the data of Table 1 is that specifications of arm, direction, and extent were not strictly ordered. Recall that earlier it was unclear if subjects could specify extent when extent precues were given and there was uncertainty about direction or arm. The reason for the ambiguity was that, with extent precues facilitating RTs less than arm or direction precues, it was possible that extent precues only facilitated stimulus identification. The error data suggest, however, that subjects could specify extent in advance of arm and direction because extent error rates were only very slightly higher when extent was precued and arm or direction was not precued than when precues were given about all three dimensions.

### Discussion

The major results of Experiment 1 can be summarized as follows. As less informa-

tion was given in the precue, RTs increased. The increase was greatest when arm was omitted from the precue, less when direction was omitted from the precue, and least when extent was omitted from the precue. These increases appeared additive. If it is assumed that the RTs reflected a motor value specification process, this process may be considered serial and characterized by the inequality  $\beta_A > \beta_D > \beta_E$ . It appeared that specifications of values on different dimensions were independent, although there was some indication that the requirement to specify arm affected the difference between stimulus-identification times and/or response-evocation times associated with movements to near and far targets. The reason for this effect is as yet unclear. It also appeared that arm, direction, and extent could be specified in any order, that is, that precues about any of the dimensions allowed for advance specification of their corresponding movement values. That there was a tendency for some decisions about extent to be made after decisions about arm and direction was suggested by the fact that extent decisions apparently could be made during MTs, whereas arm and direction decisions apparently were not made during MTs.

Why did it take longer during the RTs to specify arm than direction and longer to specify direction than extent? One explanation can be given in terms of stimulus identification: The speed with which subjects could recall the location of a target, given a reaction signal, depended on the memorial arrangement of targets allowed by the precues. The next experiment was meant to test this possibility.

Several motor explanations are also possible. One is a response competition explanation. Here it is assumed that subjects prepared the various responses allowed by the precues, and the speed with which they could select the one required response from the set depended on the relationships among the responses in the set (see Figure 1, Panels b and c). The third experiment was meant to test this explanation.

Another possibility is that RTs reflected the difficulty of correcting errors during MTs. Arm errors could not be corrected

during MTs, so that arm-error rates and RTs when arm had to be specified tended to be high. Extent errors, in contrast, could be corrected during MTs, so that extent-error rates and RTs when extent had to be specified tended to be low. Direction corrections during MTs were probably harder than extent corrections (see Brebner, 1968; Henry & Harrison, 1961; Megaw, 1974; Vince & Welford, 1967) and easier than arm corrections, which may be why RTs for direction specification and direction errors had intermediate values.

A third motor explanation is that different numbers of auxiliary motor decisions had to be made during the RTs when arm, direction, or extent had to be specified after the reaction signal. Presumably, specifications of values on dimensions other than arm, direction, and extent were necessary to perform the aimed hand movements required here, and the number of such auxiliary specifications may have been larger when arm had to be specified than when direction had to be specified, and perhaps also larger when direction had to be specified than when extent had to be specified.

A fourth motor explanation is that different types of precues allowed for different levels of segmental pretuning (see Gelfand, Gurfinkel, Fomin, & Tsetlin, 1971; Turvey, 1977), so that different response evocation times ( $\gamma$  in Equation 1) could be achieved with different types of precues. The present article does not attempt to determine which, if any, of the above motor explanations is valid.

Regardless of one's specific interpretation of the RT, MT, and error data, the data do shed light on the results of previous studies of aimed hand movements. First, the present MT data bear on the functional interpretation of Fitts' law. Here, mean MTs for movements with an ID of 1.29 bits were 69 msec shorter than MTs for movements with an ID of 2.24 bits, which translates into an average information transmission rate of 13.76 bits/sec. This estimate is reasonably close to the estimate of 10 bits/sec given for aimed hand movements executed when visual feedback is available (e.g., Fitts, 1954; Langolf et al., 1976), and so it seems reasonable to conclude that

Fitts' law is not restricted to visuomotor coordination.<sup>6</sup>

The pattern of RT data obtained here also bears on the issue of whether perceptual factors accounted for previously obtained RT differences associated with the control of direction versus extent. The present data suggest that perceptual factors alone did not account for the previous RT differences, because here, RTs were found to be longer when direction was uncertain than when extent was uncertain, as was found before when subjects could see alternative target positions. There are two aspects of the present data, however, which indicate that perceptual factors may have been partly responsible for previous RT differences. First, it was found here that extent uncertainty affected RTs, whereas this was not the case in earlier studies (Gottsdanker, 1966, 1969; Megaw, 1972; Megaw & Armstrong, 1973). Second, it was found here that RTs were considerably longer for movements to far targets than for movements to near targets, whereas before, RTs for long movements were found to be either very slightly longer or nonsignificantly different from RTs for short movements (Brown & Slater-Hammel, 1949; Fiori, Semjen, & Requin, 1974; Fitts & Peterson, 1964; Glencross, 1972; Gottsdanker, 1969; Henry, 1952, 1961; Lagasse & Hayes, 1973; Megaw, 1972; Megaw & Armstrong, 1973; Searle & Taylor, 1948). One reason to suppose that perceptual factors, rather than the use of precuing, may explain this difference in results is that changes in target-preview conditions can dramatically affect RTs for manual positioning movements (Kerr, Note 2).

### Experiment 2

One of the critical assumptions in the movement precuing technique is that stimulus-identification time is facilitated to an equal degree by all precues that give equal amounts of information, regardless of the type of information they give. Although this is a convenient assumption, it may not be correct. For instance, in Experiment 1 it may have been easier for subjects to identify targets designated by reaction signals after

arm precues were presented than after direction precues were presented. If this were the case, one would not have to invoke motor value specification to explain the RT data of the first experiment.

Experiment 2 was addressed to the question of whether the differential precuing effects in Experiment 1 could be attributed to stimulus identification. It was assumed that if the differential precuing effects were due to stimulus identification, it would be possible to obtain similar precuing effects when precues were used but movements were unnecessary. Such a situation was approximated in the second experiment. Precues and test stimuli were presented exactly as in Experiment 1, but on half the trials the precue was followed by an inappropriate test stimulus. As an example of inappropriate precuing, after a precue that specified the values *forward* and *left*, a colored dot could appear that designated a *backward* left response, a *forward right* response, or a *backward right* response. In each of these cases the subject was required to say "false" as quickly as possible. In cases in which the precue gave appropriate information, the correct response was to say "true" as quickly as possible. In replacing the eight hand movements with a pair of vocal responses, it was assumed that most of the motor requirements of the first experiment were eliminated but that most of the stimulus identification requirements were preserved. I assumed that if the differential precuing effects in Experiment 1

<sup>6</sup> In another paper (Rosenbaum & Patashnik, 1980a) it is shown that Fitts' law accounts for covert (mental) aiming as well as overt (manual) aiming. The application of Fitts' law to covert aiming comes from studies of movement timing in which subjects attempt to minimize the simple RT to begin a sequence of two responses with a specified interresponse interval (IRI). Aspects of the latency data suggest that the size of the IRI is controlled by an internal alarm clock that is "set" during the latent period by returning the clock's "pointer" through a drift distance  $A$  to within a tolerance window of size  $W$  centered on the ideal set point for the clock. This theoretical development, along with the present conclusion that Fitts' law is not restricted to visuomotor performance, implies that Fitts' law has great generality as a means of accounting for data from aiming tasks.

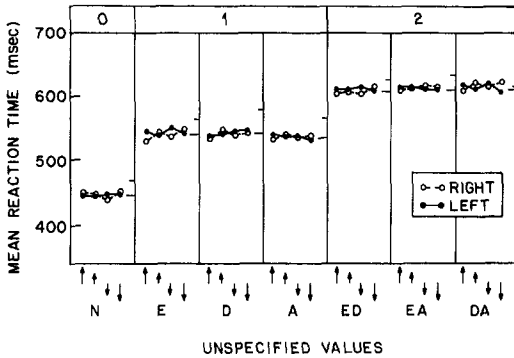


Figure 7. Mean reaction times (RTs) for true judgments associated with each of the eight targets in each of the seven precue conditions of Experiment 2. (The large horizontal marker in each panel indicates the mean RT for all correct true judgments in the corresponding condition. The small horizontal marker indicates the mean RT for all correct false judgments in the corresponding condition. N = no value.)

were due to stimulus identification, there would be similar precueing effects for true RTs in Experiment 2.

### Method

#### Procedure

Except for the addition of a Grayson-Stadler voice key, the materials were essentially the same as in Experiment 1. Subjects underwent the same training as subjects in the first experiment, except that in the last phase of the practice session, subjects made vocal true-false judgments. Stimuli were presented in the same way as in Experiment 1, and the general testing procedure and mapping of colors to targets were the same. The combinations of values that were precued were identical to those used earlier, except that there were no precues in which no information was given. Each of the eight colored dots was paired with two appropriate precues from each of the seven precue classes and with two randomly chosen inappropriate precues from each of the seven precue classes. Assignment of precues to colored dots permitted each precue to be followed equally often by appropriate and inappropriate colored dots. There were 224 trials in all, and the entire set of trials was tested twice in random order for each subject. Rests were taken intermittently during the 4-hr. session.

#### Subjects

Three right-handed male and three right-handed female students between the ages of 19 and 32 yr. participated in exchange for pay. None of the subjects had participated in Experiment 1.

### Results

#### Reaction Times

The analysis of RTs for true judgments was based on each subject's mean RT for all correct responses following the presentation of each target in each precue condition. Mean RTs for correct true judgments, averaged over subjects, for each target in each precue condition are shown in Figure 7. The large horizontal marker in each panel of Figure 7 indicates the mean RT for all correct true judgments in the corresponding precue condition. The small horizontal marker in each panel shows the mean RT for all correct false judgments, averaged over all subjects and targets, in the corresponding precue condition.

The first analysis of RTs tested the effects of Type of Judgment (true or false)  $\times$  Type of Unspecified Values (i.e., precue condition)  $\times$  Subjects. There was a main effect of type of unspecified value,  $F(6, 30) = 4.89$ ,  $p < .01$ , and a significant difference between RTs for true and false judgments,  $F(1, 5) = 20.96$ ,  $p < .001$ , but the interaction between these factors was not statistically significant,  $F(6, 30) = 1.46$ ,  $p > .20$ .

*True judgments.* As seen in Figure 7, mean RTs for true judgments had extremely similar values in the three conditions in which one value was unspecified and also in the three conditions in which two values were unspecified. It was hardly necessary to test the statistical significance of these two effects: Within an uncertainty level it was never the case that more than three of the six subjects had the same ordinal relation for mean RTs in any two conditions. This result provides a basis for rejecting the hypothesis that the main differential precueing effects for RTs in Experiment 1 were attributable to stimulus identification.

Another basis for rejecting this hypothesis comes from an ANOVA that tested the effects of Arm (i.e., side of the button panel containing the target)  $\times$  Direction  $\times$  Extent  $\times$  Dimension of Unspecified Values  $\times$  Subjects, for true RTs only. There were no statistically significant effects of side of panel,  $F(1, 5) = 1.07$ ; direction,  $F(1, 5) = .98$ ; or extent,  $F(1, 5) = 1.09$ ; and none of the interactions among these dimensions

was statistically significant ( $p > .20$ ). There was a main effect of dimension of unspecified value,  $F(6, 30) = 6.74$ ,  $p < .01$ , but there were no interactions among "movement" dimensions and type of unspecified value; for all such interactions the  $p$  values were greater than .20 and the proportion of variance accounted for was less than .01.

To provide a more stringent test of independence among dimensions, true RTs from all pairs of conditions differing by the addition of one precued value were analyzed to determine whether such additions affected differences within the dimensions. None of the interactions involving precue conditions was less likely than 10%, and none accounted for less than 1% of the variance.

*False judgments.* Reaction times for false judgments had an unexpected characteristic. In the conditions in which two values were precued, false RTs were related to the number of inappropriately precued values. As seen in Table 2, mean RTs for false judgments were shorter when both of the precued values were inappropriate to the test stimulus than when only one of the precued values was inappropriate to the test stimulus. Since the experiment had not been designed to investigate this variable, the numbers of observations in these two conditions were not identical, although it turned out that the numbers of trials with correct responses in the two conditions were approximately equal. Thus, mean RTs for each subject in each of the six cells were used in an ANOVA to test the effects of Type of Precued Value  $\times$  Number of Incorrectly Precued Values  $\times$  Subjects. Although the effect of type of precue was not statistically significant,  $F(2, 10) = 2.87$ ,  $p > .10$ , there was an effect of number of incorrectly precued values,  $F(1, 5) = 12.00$ ,  $p < .01$ . The interaction between type of precued value and number of incorrectly precued values was not statistically significant,  $F(2, 10) = 1.03$ ,  $p > .10$ .

### Errors

For the seven precue conditions depicted in Figure 7, the mean percentages of errors were (from left to right) 3.79, 5.21, 5.09,

Table 2  
*Mean Reaction Times for False Judgments in Experiment 2 When Test Stimuli Were Inappropriately Precued on One or Two Dimensions*

Unspecified value	No. of inappropriately precued dimensions	
	1	2
E	572	554
D	588	568
A	579	559

Note. E = extent; D = direction; A = arm.

5.92, 7.36, 7.60, 7.91, and 7.51. Although the error rates depended on the number of unspecified values, the effects of types of unspecified values within uncertainty levels were extremely inconsistent among subjects. Error rates for incorrectly saying "true" and incorrectly saying "false" were approximately equal for all subjects, and this was the case in all precue conditions. There was no evidence that errors of incorrectly saying "true" or "false" were especially common for particular targets or precues.

### Discussion

The underlying assumption of Experiment 2 was that if the differential precuing effects in the first experiment were due to stimulus identification, the pattern of true RTs would replicate the pattern of movement latencies in Experiment 1. Several aspects of the true RT data in Experiment 2 were markedly different from the movement RT data in Experiment 1: (a) There were no statistically significant differences among precue conditions in which equal numbers of values were precued; (b) there were no statistically significant interactions involving precue conditions; and (c) there were no main effects of "movement" dimensions. In addition to these differences for RT data, the differential precuing effects on errors that had been obtained in Experiment 1 were eliminated in the true-false experiment.

These differences allow for the tentative

conclusion that the main precuing effects observed in Experiment 1 were not entirely attributable to stimulus identification but were attributable in part to some aspect of motor preparation. Of course, this conclusion must be drawn with caution, because different subjects were used in the two experiments and because there may have been differences in the decision processes required in the movement task and verification tasks.<sup>7</sup>

How did subjects make their true-false decisions in Experiment 2? Two aspects of the RT data from Experiment 2 provide a clue: (a) RTs increased with the number of unspecified values; (b) in the conditions in which two values were precued, RTs for false judgments were shorter when two dimensions were inappropriately precued than when only one dimension was inappropriately precued. The latter result implies that subjects did not generate lists of stimuli and/or responses allowed by precues and then determine whether test stimuli (or their associated responses) were on the list. This method would not have produced RT differences related to the number of inappropriately precued features. The fact that false RTs were related to the number of inappropriately precued values implies that subjects may have (a) stored the list of values given in the precue, (b) retrieved the list of values defining the subsequently presented test stimulus, (c) checked for any mismatches between the two lists, and (d) responded as soon as a mismatch was found. With this method, rejection latencies would be expected to increase as the number of inappropriately precued values decreased, as was found here.

Now if this method was used, why might it have been used? One possibility is that subjects simply did not identify both of the stimuli (or responses) allowed by the precues in the relatively short time between precue and test stimulus. Considering that on a random third of the trials, precues were shown that had four associated stimuli and responses, it is possible that subjects may not have attempted generally to identify all of the stimuli (or responses) allowed by

the precues. If this is in fact the case, it raises the question of whether subjects would have been likely to preprogram all of the responses allowed by the precues in individual trials in Experiment 1. This is the main question the next experiment is meant to address.

### Experiment 3

If the differential precuing effects in Experiment 1 were not attributable to stimulus identification, the question remains as to what aspect of motor preparation accounted for the differential precuing effects. Experiment 3 was designed to test the response competition explanation that was given earlier. According to this explanation, subjects constructed distinct motor programs for all of the responses allowed by the precues and then activated the one program for the response designated by the reaction signal. The differential precuing effects of Experiment 1 can be explained in this model by saying that the time to activate one program from the set of already constructed programs depended on the number of such programs and on the kinds of specified values they shared.

To test the response competition hypothesis, I instructed subjects in Experiment 3 to prepare multiple responses. The responses that could be prepared in any given trial were the same as the responses that could have been prepared on the basis of precues specifying one or two values in Experiment 1. For example, in one condition of Experiment 3, subjects were instructed to prepare the four responses of the right arm, because in Experiment 1 when a precue indicated that a forth-

<sup>7</sup> To avoid this problem in future studies aimed at evaluating the effects of movement precues on stimulus identification, it may be preferable to use methods that require decision processes more akin to those used in movement tasks. One method would be for subjects to name targets as quickly as possible following different types of precues (e.g., by recalling arbitrary verbal tags for the targets). Another method would be to use several different mappings of movements to targets.

coming response would require the use of the right arm but did not indicate the direction or extent of the response, subjects theoretically could have prepared the four right-arm responses. All sets of two and four responses that were allowed by precues specifying two values and one value, respectively, in Experiment 1 were primed in Experiment 3. To ensure that subjects would be able to prepare all of the responses, pairs and quadruples of colored dots were shown in the tachistoscope for 5 sec. A half second later one of the colored dots was shown again and the subject tried to move to the target designated by that dot as quickly as possible.<sup>8</sup> I assumed that if subjects in Experiment 1 used precues to prepare multiple responses, the patterns of RTs, MTs, and errors in Experiment 3 would be similar to those obtained in the first experiment. (Of course, similar results could be obtained in the two experiments if subjects did not prepare multiple responses in either experiment. An analysis of errors was planned to evaluate this interpretation in the event that it could be seriously considered.)

### Method

#### Procedure

The pairs and quadruples of colored dots were shown in the tachistoscopic field in which the precues were shown in Experiment 1. The single colored dots that served as response signals were displayed in the same way as in Experiment 1. The pairs and quadruples of dots were arranged horizontally and were centered around the midline of the visual field. Each of the pairs of colored dots was shown 48 times, with the horizontal arrangements of the dots and the likelihoods of each one's being tested balanced so that each response was tested six times in each of the three two-response conditions. Each of the quadruples of dots was also shown 48 times. The horizontal arrangement of the dots in each of the three types of quadruples was balanced, and the test dots were chosen randomly from each of the four positions in the array. The mapping of colors to targets was the same as in Experiment 1. Each response was tested six times in each of the three four-response conditions. The order in which the 288 trials were run was haphazard for each subject. Subjects underwent the same training as subjects in Experiment 1, except that practice with the precues was replaced by practice with the multiple dots. There was only one experimental session for each subject. In all other respects

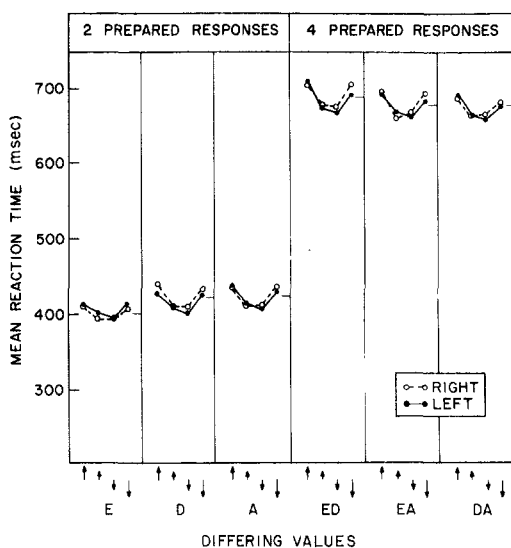


Figure 8. Mean reaction times for the eight responses in the six conditions of Experiment 3. (E = extent; D = direction; A = arm.)

the procedure was identical to the procedure of Experiment 1.

#### Subjects

Four right-handed male and four right-handed female students between the ages of 18 and 28 years participated in exchange for pay. None had participated in Experiments 1 or 2.

### Results

#### Reaction Times

Figure 8 shows mean RTs for all errorless trials, averaged over all subjects, for the eight responses in the six preparation conditions.

**Omnibus test.** The first analysis of RTs tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Number of Prepared Responses  $\times$  Preparation Condition nested in Number of Prepared Responses  $\times$  Subjects. Mean RTs did not differ for the two arms,  $F(1, 7) = 1.09$ . There was a main effect of direction,  $F(1, 7) = 5.61$ ,  $p < .05$ , with backward

<sup>8</sup> In pilot work it was found that subjects had difficulty recognizing all four colored dots when a 3-sec exposure was used. Therefore, the exposure duration was increased until subjects could identify all of the stimuli before the reaction signal appeared.



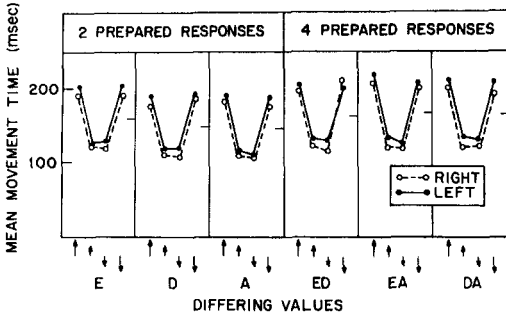


Figure 9. Mean movement times for the eight responses in the six conditions of Experiment 3. (E = extent; D = direction; A = arm.)

movements starting 12 msec faster than forward movements. As in Experiment 1, there was a main effect of extent,  $F(1, 7) = 12.73$ ,  $p < .01$ , in which RTs were 20 msec longer for long movements than for short movements. (In Experiment 1 the RTs for long movements were 48 msec longer than RTs for short movements.) There were no statistically significant interactions among arm, direction, and extent, and none of these interactions accounted for more than 1% of the variance. Increasing the number of prepared responses from two to four had a main effect on RTs,  $F(1, 7) = 30.09$ ,  $p < .001$ , but preparation condition nested in number of responses did not have an effect on RTs,  $F(2, 14) = 1.76$ ,  $p > .20$ . Neither the number of prepared responses nor preparation condition nested in number of prepared responses interacted with any of the movement dimensions, and none of these interactions accounted for more than 1% of the variance. On the other hand, the main effects accounted for a total of 91% of the overall variance.

*Differences within uncertainty levels.* To assess possible differences in RTs among the three two-response conditions and among the three four-response conditions, separate ANOVAs were carried out for each of these conditions. Among the two-response conditions the effect of type of shared values was not statistically significant,  $F(2, 14) = 2.14$ ,  $p > .10$ , and neither were any interactions between movement dimensions and type of shared values ( $p > .20$ ). The reduction of RTs when the shared values were arm and direction was

due to two subjects who showed a rather large reduction in this condition; among the six other subjects, mean RTs in the three two-response conditions differed by a maximum of 11 msec. Among the four-response conditions, the effect of type of shared value again was not statistically significant,  $F(2, 14) = 1.86$ ,  $p > .20$ , and there were no statistically significant interactions between movement dimensions and type of shared values ( $p > .20$ ).

*Further tests of independence.* The fact that there were no significant interactions in the above ANOVAs suggests that the selection and execution of one response was independent of the identities of the other possible responses. To provide a more stringent test of such independence, a series of ANOVAs compared individual two-response and four-response conditions that differed by the addition of single differing values. For example, one of the ANOVAs tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Preparation Condition  $\times$  Subjects, where in the two preparation conditions, subjects were instructed to prepare either two responses that differed in extent or four responses that differed in extent and direction. The pairs of conditions that were tested in the six ANOVAs were E and ED, E and EA, D and ED, D and DA, A and EA, and A and DA. In all of the ANOVAs there were no reliable interactions between preparation conditions and movement dimensions. The minimal obtained probability of any such interaction exceeded .20, and the highest proportion of variance accounted for by any such interaction was approximately 1%.

### Movement Times

Movement times for all errorless trials, averaged over all subjects in Experiment 3, are shown in Figure 9. The analysis of MTs tested the effects of Arm  $\times$  Direction  $\times$  Extent  $\times$  Number of Prepared Responses  $\times$  Type of Differing Values nested in Number of Prepared Responses  $\times$  Subjects. The effects of arm, direction, and extent were comparable to those found for MTs in Experiment 1. The right arm was faster than the left,  $F(1, 7) = 14.29$ ,  $p <$

Table 3  
*Percentage of Errors in Experiment 3*

Differing value	Type of error								
	All	Miss	E	D	A	ED	EA	DA	EDA
E	3.88	1.06	2.29	.36	.09	.00	.08	.00	.00
D	3.97	1.23	.12	<i>2.40</i>	.14	.00	.08	.00	.00
A	4.06	1.06	.11	.12	2.77	.00	.00	.00	.00
ED	5.32	1.58	<i>1.06</i>	<i>1.45</i>	.00	<i>1.23</i>	.00	.00	.00
EA	4.75	1.11	<i>1.09</i>	.09	<i>1.12</i>	.00	<i>1.34</i>	.00	.00
DA	5.57	1.25	.10	<i>1.39</i>	<i>1.28</i>	.10	.11	<i>1.30</i>	.04

Note. E = extent; D = direction; A = arm; Italics are for errors on dimensions containing different values for different possible responses.

.01, by 12 msec. There was no difference between forward and backward movements,  $F(1, 7) = .96$ , and movements to near targets were executed 43 msec faster than movements to distant targets,  $F(1, 7) = 29.37$ ,  $p < .01$ .

The number of prepared responses significantly affected MTs,  $F(1, 7) = 13.47$ ,  $p < .01$ , with MTs being longer when four responses were prepared than when two responses were prepared. Within the two-response conditions and within the four-response conditions, there were no effects of differing value,  $F(2, 14) = 1.02$ ,  $p > .20$ , and  $F(2, 14) = 1.72$ ,  $p > .20$ , respectively. Interestingly, the two subjects who showed the reduction in RTs when two prepared responses shared the same arm and direction were the only subjects to show a sizable increase in MTs in this same condition.

The MTs also were subjected to a series of ANOVAS in which pairs of individual conditions were compared in the manner used for RTs. There were no reliable interactions between preparation conditions and any of the movement dimensions, and none of the interactions accounted for more than 1% of the variance in each comparison.

### Errors

Mean error rates for the six preparation conditions of Experiment 3 are shown in Table 3. Mean error rates for all types of errors for all subjects were subjected to the arc sine transformation and then used in an ANOVA that tested the effect of Number of Prepared Responses  $\times$  Type of Differing

Value nested in Number of Prepared Responses  $\times$  Required Arm  $\times$  Required Direction  $\times$  Required Extent  $\times$  Subjects. Although there was a statistically significant effect of number of prepared responses,  $F(1, 7) = 9.68$ ,  $p < .05$ , the effect of type of differing values was not statistically significant,  $F(2, 14) = 1.94$ ,  $p > .10$ . There were no statistically significant effects of required arm,  $F(1, 7) = 1.06$ ; required direction,  $F(1, 7) = .87$ ; or required extent,  $F(1, 7) = .99$ ; and no interactions had  $p$  values less than .10 or accounted for more than 1% of the variance.

As is clear from the italicized values in Table 3, errors were more common for dimensions on which the possible responses had differing values than on the dimensions on which the possible responses shared values. Note that this was true when the possible responses differed in terms of two values (i.e., when there were four possible responses) as well as when the possible responses differed in terms of one value. This result suggests that subjects consistently made use of the response-priming stimuli. However, this result need not be taken to imply that subjects engaged in multiple-response preparation, or even that there was any response preparation; instead, it is possible that stimulus identification alone was affected by the priming stimuli. A result that argues that there was in fact multiple-response preparation is that errors on two dimensions were relatively frequent (e.g., ED errors in Table 3) and in some cases were actually more frequent than errors on one dimension. This is the

kind of outcome one would expect if subjects prepared a number of different responses and erroneously performed one of the responses when it was not required.

### *Discussion*

The rationale behind Experiment 3 was that if subjects in Experiment 1 had prepared multiple responses allowed by the precues, the differential precuing effects obtained in Experiment 1 would have also been obtained when subjects were explicitly told to prepare multiple responses. Overall, the differential precuing effects of Experiment 1 were not obtained in the third experiment. Of course, because different subjects were used in Experiments 1 and 3 and because the methods of stimulus presentation also differed, any conclusions about strategy differences in the two experiments must be made with caution.<sup>9</sup> Nevertheless, at least two factors support the conclusion that multiple-response preparation was used in Experiment 3 but not in Experiment 1. First, there was a relatively high incidence of errors on two dimensions in Experiment 3, but in Experiment 1 errors on two dimensions were rare. Second, in Experiment 3 the difference between RTs when two responses were primed and when four responses were primed was much larger than the difference between RTs when one value was precued and when two values were precued in Experiment 1. One way to explain this outcome is to say that it took longer to select one response from a set of four prepared responses than to specify two movement values after one movement value had been specified; at least three decisions would be required with the former method, but as few as two decisions would be required with the latter method.

Insofar as the data of Experiment 3 argue against a multiple-response interpretation of the data from Experiment 1, it also becomes possible to regard the data from Experiment 2 as arguing against a multiple-response interpretation. Recall that when two values were precued in Experiment 2, RTs for false judgments were longer when both values were incorrect than when only one value was incorrect. I argued from this

result that subjects did not use the precues to generate lists of possible target stimuli. If indeed they did not generate such lists, and if subjects in Experiment 1 also did not do so, it would have been impossible for subjects in Experiment 1 to prepare all of the responses associated with the stimuli on those lists.

### *General Discussion*

This article has been concerned with the issue of how the defining characteristics of body movements are specified prior to the time of their completion. I have argued that previous RT studies on motor programming have not explicitly addressed this question and that even if they had, their data probably would not have allowed for unambiguous answers to it. To remedy this situation, I have offered a new RT technique that in principle (and perhaps it can now be said, also in practice) allows for relatively detailed inferences about the specification of values for forthcoming movements.

The newly introduced movement precuing technique has been used here to investigate how decisions are made about which arm, direction, and extent characterize a forthcoming manual response. Subjects were given advance information about all possible combinations of values on these three dimensions prior to the presentation of reaction signals that indicated which one of the eight possible responses was required on an individual trial. I attempted to draw inferences about how the values that were not precued were specified after the reaction signals were presented by studying the patterns of RTs, MTs, and errors for all of the responses in all of the precue conditions. On the basis of these data, I was led to conclude that arm, direction, and extent tended to be specified

---

<sup>9</sup> Nevertheless, it is relevant to point out that I also obtained results like those in Experiment 3 in an informal study that used the alphabetic precues used in Experiment 1, presented for 5 sec, and in which subjects were instructed to prepare all of the responses allowed by the precues given in each trial. This result suggests that the way in which primes were presented in Experiment 3 was relatively unimportant in accounting for the main results of that experiment.

serially; that during RTs the time to specify arm was longer than the time to specify direction, which in turn was longer than the time to specify extent; and that arm, direction, and extent were not specified in an invariant order.

In Experiment 2 a different group of subjects vocally indicated whether a target, designated by a reaction signal, had the values that the immediately preceding precue indicated it would. The effect of type of precue that was obtained in the first experiment was not obtained in the second experiment; instead, there was no effect of the type of precued value, although there was an effect of the number of precued values. Although the decision requirements in Experiments 1 and 2 may have been sufficiently different to preclude any strong comparison of the results from the two experiments, the marked differences in results do seem to allow for the tentative conclusion that the motor requirements of Experiment 1 were at least partly responsible for the differential precuing effects obtained there.

In Experiment 3 a different group of subjects was encouraged to prepare sets of two responses and sets of four responses that theoretically could have been prepared in Experiment 1 following precues about two values and one value, respectively. Differences in the patterns of results in the two experiments allowed for the tentative conclusion that in Experiment 1 subjects did not usually prepare sets of responses that shared precued values. This conclusion added weight to the contention that RTs in Experiment 1 reflected times to complete a value-specification process for required responses.

Of course, to be more confident about the conclusions reached here, additional experiments, to be described below, will be needed. Nonetheless, it is possible at the present time to ask about the general theoretical implications of the present conclusions. In particular, what are the implications of the conclusions for the view that motor programs are hierarchically organized? This view has been advocated by Keele (1968), Lashley (1951), Megaw (1972, 1974), Miller, Galanter, and Pribram (1960),

Pew (1974), Rosenbaum (1977), and Shaffer (1976), among others.

Of the conclusions reached here, the one that seems to bear most critically on the hierarchical issue is that arm, direction, and extent could be specified in any order. A natural way of conceiving of a programming hierarchy is that values on different levels are specified in a fixed order corresponding to the hierarchy's top-down arrangement. Thus, if arm were above direction, it would be natural to assume that arm must be specified before direction. With the data obtained here, it is possible to reject the hypothesis that arm, direction, and extent correspond to levels of a hierarchy for which lower levels cannot be specified before higher levels.

In an alternative kind of hierarchy, which cannot be rejected, lower levels *can* be specified before higher levels. Suppose, for example, that extent corresponded to a lower level than arm or direction in such a hierarchy. After a precue indicating only that a short extent would be required, that extent would have to be specified for each arm and direction (i.e., four times) if extent decisions were to be avoided later. Although there seems to be no way to reject this type of hierarchy with the data at hand, it does seem prudent to be skeptical of it because of its apparent lack of parsimony.

A preferable type of model makes use of the idea of *distinctive features* (Chomsky, 1965; Jakobson & Halle, 1956). In a distinctive-feature system, as it is usually discussed, there are independent dimensions with two possible values, or features, on each dimension. I do not wish to restrict myself to only two values per dimension here, since for the direction and extent dimensions (or their analogues) two possible values clearly are not enough. For present purposes, what is attractive about the distinctive-feature system is that values on different dimensions can be specified independently of one another. Thus, if a precue were given about one dimension, the appropriate value on that dimension alone could be specified, regardless of which dimension it occupied. This shows that a distinctive-feature model parsimoniously accommodates the finding that arm, direc-

tion, and extent were not specified in a fixed order.

Another advantage of a distinctive-feature system is that it allows for the efficient modification of motor programs. For example, suppose a tympanist intended to make a left-hand stroke followed by a right-hand stroke with the same direction and extent. With a distinctive-feature system, all that would be needed would be to change the *arm* value from left to right after the first stroke was initiated. With a hierarchical system (with arm above direction and extent), either the programming of the second movement would have to start "from scratch" (if programming could only progress in a top-down fashion) or the direction and extent of the left and right movements would have to be prespecified redundantly. These considerations lead me to believe that the system used for motor programming, and thus the system that was tapped in the present experiments, makes use of distinctive features rather than a hierarchy.

I would like to conclude this article by commenting on the general approach to motor programming that has been presented here. In all likelihood, the importance of this article rests more in the introduction of a new way to approach the problem of human movement initiation than in the data that have been collected or in the model that has been proposed. The movement precuing technique appears to be primarily important because it allows for considerably more detailed inferences about movement initiation than have been possible before. Perhaps most importantly, the technique can be extended to virtually any movements and movement dimensions, and for that reason may prove to have wide utility for motor-control research.

Of course, the movement precuing technique can be used in a wider variety of ways than it has been used here. One obvious extension is to vary the delay between the precue and reaction signal and to observe the effect on RTs for different types of precued values. Another extension is to present precue information about different values sequentially and in different orders rather than simultaneously, as was done

here. With this precuing method it may be possible to learn about preferred specification orders rather easily. Another extension is to give unreliable as well as reliable precues. A variable of interest with this method would be the nature of precue unreliability (e.g., what happens when one dimension tends to be precued unreliably more often than another). Finally, the kinds of data used in movement precuing experiments can be extended (e.g., to include data from electromyograms, electroencephalograms, and continuous records of movement trajectories) so that the peripheral as well as central concomitants of movement initiation can be understood more clearly.

### Reference Notes

1. Semjen, A. Personal communication, October 2, 1977.
2. Kerr, B. A. *Initiating short movements without target preview*. Paper presented at the meeting of the Psychonomic Society, San Antonio, Texas, November 1978.

### References

- Adams, J. A. Issues for a closed-loop theory of motor learning. In G. E. Stelmach (Ed.), *Motor control: Issues and trends*. New York: Academic Press, 1976.
- Allum, J. H. Responses to load disturbances in human shoulder muscles: The hypothesis that one component is a pulse test information signal. *Experimental Brain Research*, 1975, 22, 307-326.
- Annett, J., Golby, C. W., & Kay, H. The measurement of elements in an assembly task—The information output of the human operator. *Quarterly Journal of Experimental Psychology*, 1958, 10, 1-11.
- Berlyne, D. E. Conflict and choice time. *British Journal of Psychology*, 1957, 48, 106-118.
- Blyth, K. W. Ipsilateral confusion in 2-choice and 4-choice responses with the hands and feet. *Nature*, 1963, 199, 1312.
- Brebner, J. Continuing and reversing the direction of responding movements: Some exceptions to the so-called "psychological refractory period." *Journal of Experimental Psychology*, 1968, 78, 120-127.
- Brown, J. S., & Slater-Hammel, A. T. Discrete movements in the horizontal plane as a function of their length and direction. *Journal of Experimental Psychology*, 1949, 38, 84-95.
- Chomsky, N. *Aspects of the theory of syntax*. Cambridge, Mass.: M.I.T. Press, 1965.
- Christina, R. W., & Cornell, P. T. The effect of movement amplitude and target diameter on reaction time: Comments on Siegel (1977). *Journal of Motor Behavior*, 1979, 11, 87-90.

- Crago, P. E., Houk, J. C., & Hasan, Z. Regulatory actions of human stretch reflex. *Journal of Neurophysiology*, 1976, 39, 925-935.
- Ells, J. G. Analysis of temporal and attentional aspects of movement control. *Journal of Experimental Psychology*, 1973, 99, 10-21.
- Fiori, N., Semjen, A., & Requin, J. Analyse chronométrique du pattern préparatoire à un mouvement spatialement orienté, résultats préliminaires. *Le Travail Humain*, 1974, 37, 229-248.
- Fitts, P. M. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 1954, 47, 381-391.
- Fitts, P. M., & Peterson, J. R. Information capacity of discrete motor responses. *Journal of Experimental Psychology*, 1964, 67, 103-112.
- Gelfand, I. M., Gurfinkel, V. S., Fomin, S. V., & Tsetlin, M. L. [*The structural-functional organization of certain biological systems.*] (C. R. Beard, trans.). Cambridge, Mass.: MIT press, 1971.
- Gibbs, C. B. Probability learning in step-input tracking. *British Journal of Psychology*, 1965, 56, 233-242.
- Glencross, D. J. Latency and response complexity. *Journal of Motor Behavior*, 1972, 4, 251-256.
- Gottsdanker, R. The effect of superseding signals. *Quarterly Journal of Experimental Psychology*, 1966, 18, 236-249.
- Gottsdanker, R. Choice reaction time and the nature of the choice response. *Psychonomic Science*, 1969, 14, 257-258.
- Griew, S. Information gain in tasks involving different stimulus-response relationships. *Nature*, 1958, 182, 1819.
- Hayes, K. C., & Clarke, A. M. Facilitation of late reflexes in humans during the preparatory period of voluntary movement. *Brain Research*, 1978, 153, 176-182.
- Henry, F. M. Independence of reaction and movement times and equivalence of sensory motivators of faster response. *Research Quarterly*, 1952, 23, 43-53.
- Henry, F. M. Reaction time-movement time correlations. *Perceptual and Motor Skills*, 1961, 12, 63-66.
- Henry, F. M., & Harrison, J. S. Refractoriness of a fast movement. *Perceptual and Motor Skills*, 1961, 13, 351-354.
- Henry, F. M., & Rogers, D. Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly*, 1960, 31, 448-458.
- Hick, W. E. On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, 1952, 4, 11-26.
- Hyman, R. Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, 1953, 45, 188-196.
- Jakobson, R., & Halle, M. *Fundamentals of language*. The Hague, Netherlands: Mouton, 1956.
- Kantowitz, B. H. Response force as an indicant of conflict in double stimulation. *Journal of Experimental Psychology*, 1973, 100, 302-309.
- Keele, S. W. Movement control in skilled motor performance. *Psychological Bulletin*, 1968, 70, 387-403.
- Keele, S. W., & Summers, J. J. The structure of motor programs. In G. E. Stelmach (Ed.), *Motor control: Issues and trends*. New York: Academic Press, 1976.
- Kerr, B. Decisions about movement direction and extent. *Journal of Human Movement Studies*, 1976, 3, 199-213.
- Kerr, B. Task factors that influence selection and preparation for voluntary movements. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press, 1978.
- Klapp, S. T. Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance*, 1975, 104, 147-153.
- Klapp, S. T. Reaction time analysis of programmed control. In R. Hutton (Ed.), *Exercise and sports sciences reviews* (Vol. 5). Santa Barbara, Calif.: Journal Publishing Affiliates, 1978.
- Kornblum, S. Response competition and/or inhibition in two-choice reaction time. *Psychonomic Science*, 1965, 2, 55-56.
- Lagasse, P. P., & Hayes, C. C. Premotor and motor reaction time as a function of movement extent. *Journal of Motor Behavior*, 1973, 5, 25-32.
- Langolf, G. D., Chaffin, D. B., & Foulke, J. A. An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 1976, 8, 113-128.
- Lashley, K. S. The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior*. New York: Wiley, 1951.
- MacNeilage, P. F. Motor control of serial ordering of speech. *Psychological Review*, 1970, 77, 182-196.
- Megaw, E. D. Direction and extent uncertainty in step-input tracking. *Journal of Motor Behavior*, 1972, 4, 171-186.
- Megaw, E. D. Possible modification to a rapid ongoing programmed manual response. *Brain Research*, 1974, 71, 425-441.
- Megaw, E. D., & Armstrong, W. Individual and simultaneous tracking of a step input by the horizontal saccadic eye movement and manual control systems. *Journal of Experimental Psychology*, 1973, 100, 18-28.
- Melville Jones, G., & Watt, D. G. Observations on the control of stepping and hopping movement in man. *Journal of Physiology*, 1971, 219, 709-727.
- Miller, G. A., Galanter, E., & Pribram, K. H. *Plans and the structure of behavior*. New York: Holt, Rinehart & Winston, 1960.
- Pew, R. W. Human perceptual-motor performance. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition*. Potomac, Md.: Erlbaum, 1974.
- Rosenbaum, D. A. Selective adaptation of "command neurons" in the human motor system. *Neuropsychologia*, 1977, 15, 81-91.
- Rosenbaum, D. A., & Patashnik, O. A mental clock setting process revealed by reaction times. In G. E.

- Stelmach & J. Requin (Eds.), *Tutorials in motor behavior*. Amsterdam: North-Holland, 1980. (a)
- Rosenbaum, D. A., & Patashnik, O. Time to time in the human motor system. In R. S. Nickerson (Ed.), *Attention and performance VIII*. Hillsdale, N.J.: Erlbaum, 1980. (b)
- Sanders, A. F. Some aspects of reaction processes. In A. F. Sanders (Ed.), *Attention and performance*. Amsterdam: North Holland, 1967. (Reprinted from *Acta Psychologica*, 1967, 27.)
- Schmidt, R. A., Zelaznik, H. N., & Frank, J. S. Sources of inaccuracy in rapid movement. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press, 1978.
- Searle, L. V., & Taylor, F. V. Studies in tracking behavior: I. Rate and time characteristics of simple corrective movements. *Journal of Experimental Psychology*, 1948, 38, 615-631.
- Seibel, R. Discrimination reaction time for a 1,023 alternative task. *Journal of Experimental Psychology*, 1963, 66, 215-226.
- Semjen, A. Phase organization of amplitude-regulated movement: The "action threshold" of movement; the programming of its direction and amplitude. *Psychological Abstracts*, 1971, 46, 682.
- Shaffer, L. H. Intention and performance. *Psychological Review*, 1976, 83, 375-393.
- Sternberg, S. The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II*. *Acta Psychologica*, 1969, 30, 276-315.
- Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. The latency and duration of rapid movement sequences: Comparisons of speech and type-writing. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press, 1978.
- Turvey, M. T. Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and comprehending: Towards an ecological psychology*. Hillsdale, N.J.: Erlbaum, 1977.
- Vince, M. A., & Welford, A. T. Time taken to change the speed of a response. *Nature*, 1967, 213, 532-533.
- Winer, B. J. *Statistical principles in experimental design*. New York: McGraw-Hill, 1962.

Received February 5, 1979 ■