

Are Movements Prepared in Parts? Not Under Compatible (Naturalized) Conditions

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SUMMARY

This set of experiments is concerned with the specification of movement parameters hypothesized to be involved in the initiation of movement. Experiment 1 incorporated the precuing method developed by Rosenbaum in which a precue provided partial information of the upcoming movement before the stimulus to move. Under conditions in which precues were provided by letter symbols and stimuli were color-coded dots mapped to response keys, Rosenbaum found reaction times to be slower for the specification of arm than for direction, and both to be slower than the specification of extent. In Experiment 1, using precue and stimulus conditions that paralleled those employed by Rosenbaum, we obtained very similar findings. The three follow-up experiments extended these findings to more naturalized stimulus-response compatible conditions. We used a method in which precues and stimuli were directly specified through vision and mapped in a one-to-one manner with responses. In Experiment 2, although reaction times decreased as a function of the number of parameters precued, there were no systematic effects of precuing *particular* parameters. In Experiments 3 and 4, we incorporated an ambiguous precue that, while serving to reduce task uncertainty, failed to provide any specific information as to the arm, direction, or extent of the upcoming movement. Initiation times did not systematically vary as a function of the type of parameter precued nor were there significant differences between specific and ambiguous precue conditions. In sum, only in Experiment 1 in which precues and stimuli involved complex cognitive transformations was there support for Rosenbaum's parameter specification model. When we employed highly compatible conditions, designed to reflect a real-world environment, we failed to obtain any tendency for movement parameters to be serially specified. We discuss grounds for suspecting the generality of parameter specification models and propose an alternative approach that is consonant with the dynamic characteristics of the motor control system.

One of the dominant facts to emerge in the area of movement control in the last decade is that complex sequences of behavior may be produced even when all information from the periphery is removed. Physiological evidence for the presence of endogenous neural networks in a variety of invertebrate phyla is near unassailable (e.g., Davis, 1976; Miles & Evarts, 1979; Stein, 1978). Moreover, it is well established that the isolated spinal cord of vertebrates possesses intrinsic functions capable of generating the basic flexion-

extension pattern of locomotion (cf. Grillner, 1975; Shik & Orlovskii, 1976).

Direct efforts to extend these findings—often interpreted as evidence for “central programming”—to the coordination of human skilled movements have met with limited success. Reversible deafferentation methods have been employed in conjunction with various motor tasks (e.g., Laszlo, 1966), but interpretation of the resultant data is clouded by the co-occurrence of sensory and motor impairment (Kelso,

Stelmach, & Wanamaker, 1974) and the presence of residual sensation in nearby anatomical structures (Glencross & Oldfield, 1975).

An alternative approach, germane to the present article, is to use reaction time (or more properly, initiation time; Kerr, 1978) as an index of central motor preparation. The idea, first introduced by Henry and Rogers (1960), is simple. If a motor program is prepared in advance, the time to prepare it should be a reflection of the upcoming movement's complexity. In contrast, if no prior programming takes place, reaction time for simple and complex movements should not differ. There is considerable body of data favoring the former proposition in both choice (cf. Klapp, 1978, for review) and simple reaction time paradigms (cf. Keele, 1980, for review).

Much of the recent work has been directed toward identifying the content of the basic programming unit; for example, the stress group (Sternberg, Wright, Knoll, & Monsell, 1980) or syllable (Klapp, Anderson, & Berian, 1973) in speech, or the type stroke in nonsense typing (Sternberg, Monsell, Knoll, & Wright, 1978). In addition, some investigators have related reaction time to various components of the upcoming movement such as extent and duration (cf. Kerr, 1978, for review). Little, however, is known about the actual construction of motor programs, an issue that Rosenbaum (1980) has addressed recently in some detail. Rosenbaum adopts an "information-processing" view of motor programs in which

the program is assumed to undergo progressive differentiation from some abstract, "nonmotoric" level to a "muscle-usable code." After cognitive decisions have been made, the role of the program, according to Rosenbaum, is to prescribe values on certain kinematic parameters (which he terms *dimensions*) that are under program control. A major question at this level of programming concerns how movement dimensions such as arm, direction, and extent are specified, and whether they follow any particular ordering rules. To investigate this issue, Rosenbaum introduced a movement precuing technique that took the following form: On a given trial a subject received prior information (via alphabetic letters) about all, some, or none of the values defining the upcoming response (e.g., RFX meant prepare a right-hand [R] forward [F] movement, the X providing no information about actual movement extent). Then, at the onset of the signal (a colored dot), the subject initiated the motor response. Assuming the subject used the precues effectively, initiation time should reflect the amount of time to program the value on the remaining, undefined parameter (in this example a short or long extent).

Using these procedures, Rosenbaum (1980) found that reaction time was shortest when extent was left to be selected, longer when a directional decision was required, and still longer when arm remained to be selected. Further, when two of three parameters had to be specified, reaction times were elevated overall and followed a pattern consonant with singly precued conditions. Although not ascribing a particular fixed order to the various parameters, Rosenbaum noted that arm, direction, and extent tended to be specified serially. The implications of these findings are potentially far reaching, and the technique itself (when combined with electrophysiological procedures) could afford new insights into the nature of movement initiation processes (cf. Requin, 1980, for a review of neurophysiological work on movement preparation).

Our first goal in this set of experiments, given the putative significance of Rosenbaum's (1980) results, was to replicate his major experiment (Experiment 1) in its entirety. This is not to imply that Rosen-

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baum did not perform a careful experiment and a thorough analysis, merely that we feel this often-ignored step constitutes sound practice. Overall, the pattern of results that emerges in our first experiment supports Rosenbaum's data quite well.

But if there is a flaw in the movement precuing technique as developed by Rosenbaum (1980), it is that the procedure itself is rather artificial. As indicated earlier, Rosenbaum used letters to precue the subject and previously learned color-coded labels as signals to respond. In our remaining experiments, we attempt to naturalize the precuing technique so that much less cognitive transformation (cf. Teichner & Krebs, 1974) is required. Our procedure was to precue the subject directly via vision and to map precues and stimuli with response buttons in a compatible manner. Thus, unlike Rosenbaum's procedure, which requires a color-to-position translation, our technique is referred to as direct because (a) it involves minimal stimulus coding activity and (b) the precue, stimulus, and response sets are in direct one-to-one correspondence. With these highly compatible procedures, which we feel are more representative of real-life motor skills, we demonstrate three basic findings: First, reaction times across precue conditions are considerably reduced over comparable conditions that require more stimulus-response translation time (e.g., our Experiment 1 and Rosenbaum's 1980, Experiment 1). Second, like Rosenbaum, reaction times are reduced as the amount of precue information increases. Third, but most important, within any particular precue condition the pattern of reaction times appears the same for all precued parameters. This last result, which shows no tendency for movement parameters to be serially ordered, persuades us of the need to reexamine the viability of "feature" specification models (Rosenbaum, 1980) especially when the geometric configuration of stimulus to response is naturalized and not artificially contrived.

Experiment 1

Experiment 1 was essentially a direct replication of Rosenbaum's (1980) first experiment with two additional modifications.

Like Rosenbaum, we precued subjects by providing partial information about the upcoming movement and then required them to respond as quickly as possible to a stimulus by moving to the appropriate response key. Thus, some (or all) of the parameters of movement (e.g., arm and direction) could be prepared in advance, leaving only the remaining unknown parameter(s) (e.g., extent) to be specified. In addition, we incorporated two further experimental manipulations. First, two types of stimuli, a number or a color word, were used. Since a number to spatial location mapping requires fewer transformations than does a color word to spatial location (Teichner & Krebs, 1974), one might expect faster initiation times in the former case. Second, two precue durations, 3 and 5 sec, were employed to evaluate whether differential effects on parameter specification were due, in part, to incomplete precue processing.

Method

Subjects

Twenty-four right-handed persons between the ages of 18 and 30 yr. served as subjects. They were paid \$5 for their services.

Apparatus

The experiment took place in a sound-insulated experimental chamber. The subject sat in an adjustable chair in front of a standard laboratory table 155 cm long, 66 cm wide, and 96 cm high. The reaction keys were mounted in a 46 cm × 31 cm Plexiglas base that was tilted at an angle of 20° to the horizontal. Two keys placed 21 cm apart and centered on the Plexiglas base served as the home keys for the left and right index fingers. Like Rosenbaum's (1980) configuration, eight target keys were situated so that two were directly above and two below each home key. The distance from the home keys to the near target was 3.5 cm and to the far target 7.0 cm. Home keys and reaction keys were standard keyboard switches (Cherry momentary contact switches) and required a 40-g operating force. The width of the response keys was equated for index of difficulty (Fitts, 1954; 1.3 cm diameter for near keys; 2.6 cm diameter for distant keys). A black piece of felt mounted above the response board prevented the subject from viewing the response keys but did not interfere with the response movements. A video computer terminal situated above and slightly behind the response board was used to display precues and stimuli. The precue consisted of capital letters displayed in the center of the video screen. Letters conveying arm information were R (right) and L

(left). Letters conveying direction information were F (forward) and B (backward). Letters conveying extent information were C (close) and D (distant). Each precue consisted of three letters, and the letter X was used as a filler when the precue consisted of less than three informative letters. The reaction signal consisted of either a number (1-8) or a color word (e.g., RED). Each number or color word was mapped one-to-one to a response key. A Digital Equipment Corporation PDP 8/A computer was programmed to present the precues and the stimuli, as well as to time the initiation and movement times, and record them on a floppy disk for later off-line analysis.

Procedure

Each subject participated in a single experimental session lasting approximately 1 hr. and 20 min. Before testing began subjects were given as much time as needed to familiarize themselves with the position of each response key and its unique mapping to a given stimulus. An initial block of 64 practice trials was performed for familiarization purposes. This was followed by two blocks of 128 trials, separated by a 3-min. rest period. The eight precue conditions (no precue; a single-parameter precue for arm, direction, and extent; a two-parameter precue for arm and direction, arm and extent, and direction and extent; and a completely precued condition) were presented such that 16 trials of each precue condition occurred within each block. Each possible stimulus within each type of precue was presented equally often. This resulted in two stimulus-response pairs to each of the eight response keys for each precue condition in each block.

The order of trials was randomized for each subject. The subjects were told the meaning of precues and were instructed to make use of them. Their task was to try to respond as quickly as possible without making errors. A trial sequence consisted of a precue display for 3 or 5 sec (depending on the condition), a fixed foreperiod of .5 sec, followed by the stimulus to move (either a number or color word, again dependent on experimental condition). The stimulus remained on the screen until the subject responded. Following the subject's response there was a 4-sec intertrial interval before the onset of the next precue.

Design

The first block of 64 practice trials was not included in any of the following analyses. There were, therefore, four responses to each of the eight response keys in each of the eight precue conditions, making a total of 256 trials. Trials in which the subject responded with the wrong hand, missed the response key, or hit the wrong response key were noted but excluded from the main data analysis. Furthermore, trials with reaction times greater than 2,000 msec (considered to be due to lack of attention) or less than 70 msec (considered to be due to anticipation of stimulus) and movement times greater than 600 msec were excluded.

Mean reaction time and mean movement time were computed for each combination of precue and response

movement. Three types of analysis for each dependent measure were performed. The first analysis was conducted to determine the effect of the number of precued parameters. That is, the conditions of no precue, one precue (arm, direction, or extent), two precues (arm and direction, arm and extent, direction and extent), and the totally precued condition were treated as eight levels of precue condition in a six-way analysis of variance. Time of precue (3 or 5 sec) and type of stimulus presentation (number or color word) were between-groups variables; precue condition (eight levels) and response movement (consisting of two levels of arm, direction, and extent) were repeated variables. The second analysis, to determine the effects of the different parameter(s) precued, was performed only on the three conditions in which one parameter was precued. Similarly, a third analysis, to determine the effect of the various combinations of two precued parameters, was performed only on the three conditions in which two parameters were precued. Error rates were examined in the same manner.

Results and Discussion

The analysis that follows will be discussed with respect to the three types of analysis performed. First we report reaction time, then movement time, and then errors.

Reaction Time Analysis

Full design. The mean reaction times for both the 3- and 5-sec precue display and for type of stimulus presentation (numbers and color words) are shown as a function of precue condition in Figure 1.¹ This figure also displays the breakdown of response movement (arm—left/right, direction—forward/backward, extent—short/long) across all precue conditions. For reaction time there was a significant main effect of precue, $F(7, 140) = 190.1, p < .001$. Post hoc analysis of the main effect of precue using a Newman-Keuls test revealed that the completely precued condition was responded to fastest. The next fastest were those conditions in which only a single parameter remained to be specified (two parameters precued), followed by the singly precued condition, with the condition of no precue having the longest reaction time.

¹ Note that on the ordinate of all figures we equate "value(s) to be specified" with "precue condition" for ease of interpretation and comparison with Rosenbaum's (1980) data.

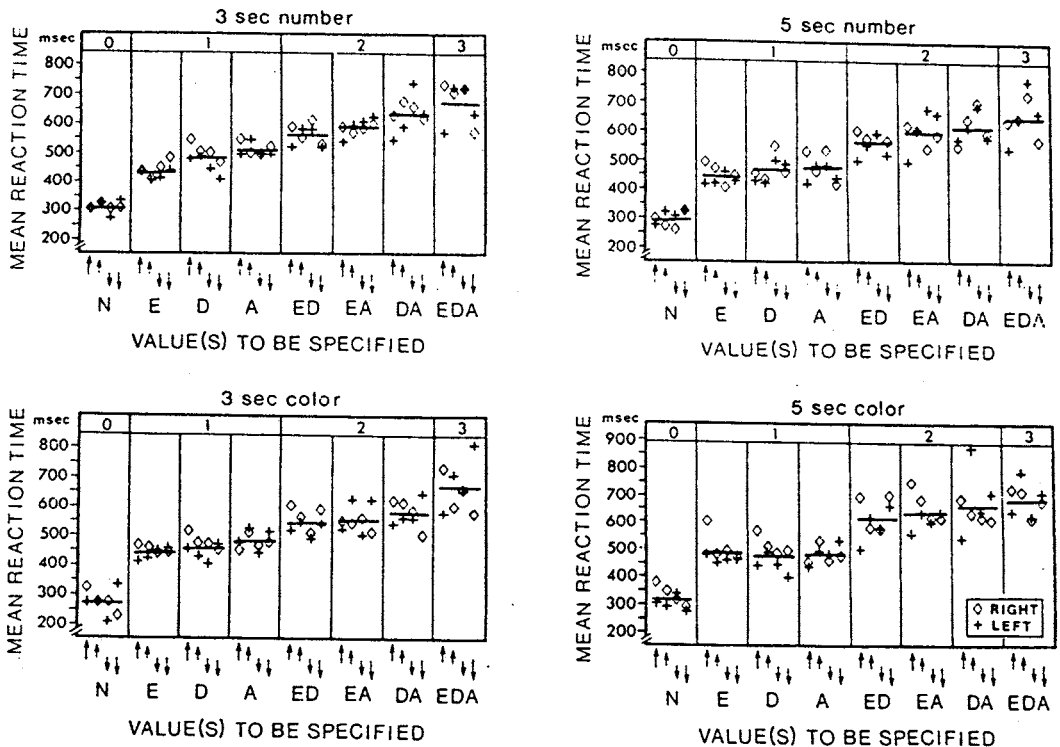


Figure 1. Mean reaction time for 3- and 5-sec precue displays and number and color-word stimulus presentations across the eight precue conditions. (In each condition, the overall mean is represented by a horizontal line. N = none; E = extent; D = direction; A = arm.)

These results appear to be accountable, at least in part, on the basis of uncertainty (Hick, 1952; Hyman, 1953). As the number of stimulus-response alternatives was reduced (i.e., as more parameters were precued), there was a commensurate reduction in reaction time. Thus reaction time increased with the number of possible choices, whether these involved direction (Ells, 1973; Glencross, 1973; Kerr, 1976), extent (Glencross, 1973; Kerr, 1976), limb (Glencross, 1973), or any combination of the three parameters. This finding is consistent with Rosenbaum's (1980) finding that mean reaction times increased with the number of values to be specified after the reaction signal. Neither time of precue display (3 or 5 sec) nor type of precue (number or color word) was statistically significant ($F_s < 1$). However, there were some complex interactions involving both between- and within-subjects variables, the results of which are clarified in the following analyses.

One-precued parameter. To assess the main effects of interest, namely type of precue within the single precue condition (arm, direction, or extent), four separate analyses of variance were carried out on the 3- and 5-sec number and color conditions. This procedure, basically a simple effects analysis, was carried out due to the complex interactions of the between-subjects variables (time of precue display and type of stimulus presentation) and some of the within-subjects variables. Precue type was crossed with response movement (two levels of arm, two levels of direction, and two levels of extent). In the 3-sec number condition, the main effect of precue type (arm, direction, or extent) failed to reach significance, $F(2, 10) = 2.08$, $p > .05$, nor were any interactions with precue type significant. With respect to response movements, the only significant result was in the extent condition, $F(1, 5) = 91.55$, $p < .01$, where shorter movements were initiated

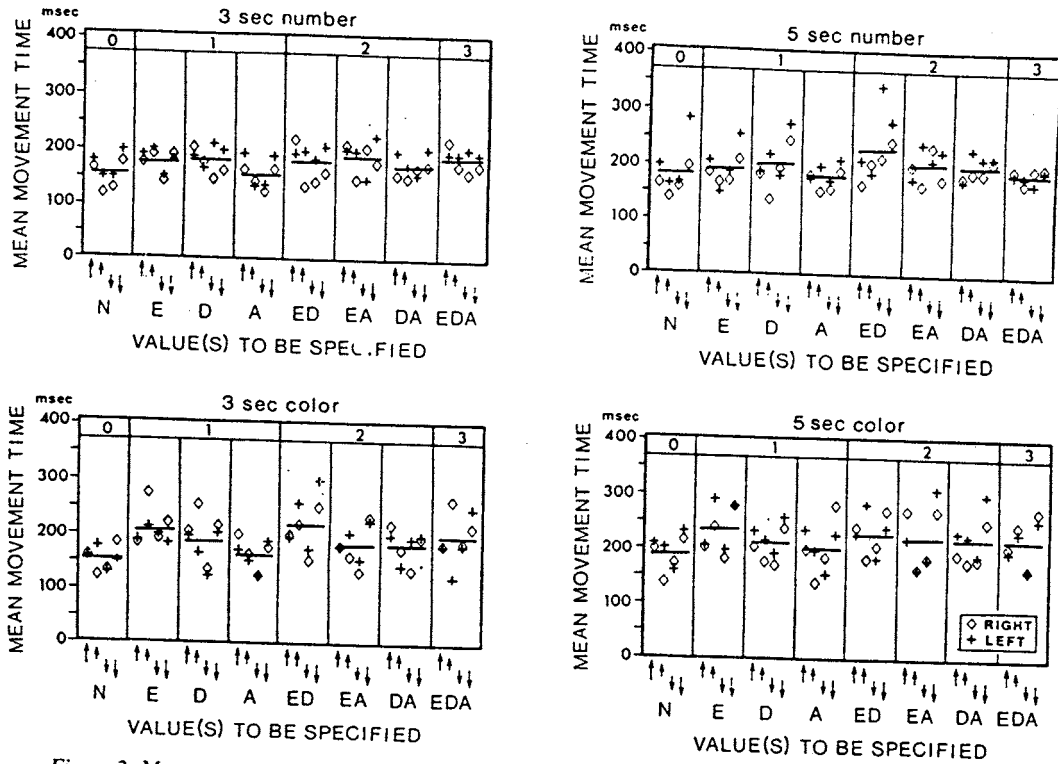


Figure 2. Mean movement time for 3- and 5-sec precue displays and number and color-word stimulus presentations across the eight precue conditions. (In each condition, the overall mean is represented by a horizontal line. N = none; E = extent; D = direction; A = arm.)

34.1 msec slower than longer ones in spite of attempts to equate the movements in terms of index of difficulty. In the 5-sec number condition, there was no significant effect of precue type, $F(2, 10) = 3.68, p > .05$. None of the other main effects or interactions were significant.

The 3-sec color-word condition showed the same pattern of results as above with respect to precue type, $F(2, 10) = 3.36, p > .05$, but there was a three-way interaction involving response movements (Arm \times Direction \times Extent), $F(1, 5) = 21.7, p < .01$. For the left arm, short backward movements were initiated faster than short forward movements, whereas long forward movements were initiated faster than long backward movements. This effect was not present in right arm movements, a finding for which there is no ready explanation. Only in the 5-sec color-word condition was there an effect of precue, $F(2, 10) = 8.62, p < .01$. Post hoc analysis revealed

that precuing arm resulted in faster initiation times than precuing movement extent but that neither precue type was reliably different from direction. A response movement interaction between direction and extent was also significant, $F(1, 5) = 8.02, p < .05$. Forward movements were initiated faster for longer extents, whereas backward movements were initiated faster for shorter extents.

Two-precued parameters. An identical analysis to the one-precued parameter condition was carried out in the two-precue condition. In the 3-sec number condition, there was a main effect of precue type, $F(2, 10) = 5.92, p < .05$. Post hoc analysis revealed that precuing arm and direction (extent remaining to be specified) was faster than precuing direction and extent (arm remaining to be specified). In the 5-sec number condition, the main effect of precue was not significant, $F(2, 10) = 2.08, p > .05$, but precue did interact with direction,

$F(2, 10) = 8.17, p < .01$. For backward movements, initiation time was faster when arm and direction were precued than when arm and extent were precued. But for forward movements, precuing arm and extent were significantly faster than precuing direction and extent. A response movement interaction between arm and direction was also evident, $F(1, 5) = 8.24, p < .05$: For the left arm, forward movement was initiated faster than backward movement, whereas for the right arm there were no directional differences.

In the 3-sec color-word condition, there was a significant precue effect, $F(2, 10) = 5.16, p < .05$. Further analysis revealed that movements were initiated faster when extent, rather than arm, remained to be specified (i.e., arm and direction versus direction and extent precued). No other effects were statistically significant. In the 5-sec color-word condition, there was no effect of precue type ($F < 1$). As in the 5-sec number condition, arm and direction interacted, $F(1, 5) = 7.12, p < .05$. But in this case, backward movements were initiated faster than forward movements only for the right arm.

Movement Time Analysis

A parallel breakdown of the experiment in terms of movement time to that provided in Figure 1 for reaction time is shown in Figure 2.

Full design. The initial analysis of the movement time data revealed that neither time of precue display (3 or 5 sec) nor type of stimulus presentation (number or color word) were statistically significant (both $F_s < 1$). Nor were there any interactions involving these variables. There was a main effect of precue, $F(7, 140) = 7.19, p < .01$, which we explore in more detail in the following analysis.

One-precued parameter. In the single-precue condition, there were no effects of time of precue display or type of stimulus ($F_s < 1$). There was a main effect of precue, $F(2, 40) = 7.59, p < .01$. Precuing extent resulted in faster movements (21 msec) than precuing arm. Since this effect is in the opposite direction to the trend evident in

reaction time, there may be some type of trade-off between the two dependent variables. Movements of the right arm were made approximately 17 msec faster than those of the left, $F(1, 20) = 7.93, p < .05$. Movements to near targets were 27 msec faster on the average than movements to far targets, $F(1, 20) = 16.86, p < .01$, in spite of efforts to control for index of difficulty (Fitts, 1954). A three-way response movement interaction (Arm \times Direction \times Extent), $F(1, 20) = 4.60, p < .05$, indicated that the general finding of faster movement times for short movements was not present in left arm forward movements, which were actually slower for short than for long movements.

Two-precued parameters. The null findings of precue display time and stimulus display type were also apparent in the two-precue condition. Again, an effect of precue was present, $F(2, 40) = 8.94, p < .01$. Precuing extent and direction (arm to be specified) resulted in somewhat faster movement times (27 msec) than precuing arm and direction (extent to be specified). This finding poses a potential problem with the interpretation of the reaction time data because the two dependent variables go in opposite directions. That is, reaction time was longer in the 3-sec color and number conditions when arm rather than extent remained to be specified, but movement time was shorter in these conditions. This trade-off is not particularly surprising, since final extent can be determined after the movement has been initiated, whereas determination of arm must occur before movement initiation or an error occurs. As in single-precue conditions, short movements were carried out faster than long movements (29 msec on the average), $F(1, 20) = 19.81, p < .01$. The two-way response movement interaction between extent and direction, $F(1, 20) = 15.29, p < .01$, revealed this difference to be greater in backward than in forward movements.

Error-Rate Analysis

The error-rate data, differentiated by error type, are presented as a function of precue condition in Table 1. Although the

Table 1
Percentage Error Rate Categorized by Error Type as a Function of Precue Conditions and Stimulus Presentation Type: Experiment I

Type of error	Parameters to be specified							
	N	E	D	A	ED	EA	DA	EDA
3-sec number								
Anticipation ^a	2.6	.0	.5	7.8	1.0	6.3	5.2	6.3
Inattentiveness ^b	2.1	1.0	1.6	2.1	3.1	1.6	4.7	3.6
Response ^c	7.3	.0	.0	.0	.0	1.0	.0	.0
Total	12.0	1.0	2.1	9.9	4.1	8.9	9.9	9.9
5-sec number								
Anticipation	1.0	1.6	.5	5.2	2.1	10.4	8.3	6.3
Inattentiveness	4.2	4.2	3.1	1.6	6.8	2.6	3.1	2.6
Response	5.2	5.2	.0	2.1	.5	1.6	1.6	1.6
Total	10.4	11.0	3.6	8.9	9.4	14.6	13.0	10.5
3-sec color								
Anticipation	2.1	1.6	.5	6.8	.5	6.8	5.7	5.2
Inattentiveness	1.6	3.7	2.6	.5	3.7	1.0	3.1	2.6
Response	7.3	5.2	.0	.5	.0	.0	5.2	.0
Total	11.0	10.5	3.1	7.8	4.2	7.8	14.0	7.8
5-sec color								
Anticipation	3.1	.5	.5	6.8	2.1	10.9	8.3	3.7
Inattentiveness	.5	3.7	2.1	1.0	4.2	1.6	4.2	2.1
Response	4.7	.5	.0	.5	.0	1.0	.5	.5
Total	8.3	4.7	2.6	8.3	6.3	13.5	13.0	6.3

Note. N = none; E = extent; D = direction; A = arm.

^a Reaction times < 70 msec. ^b Reaction times > 2 sec. ^c Initiated movement with wrong hand, struck wrong response key, or missed target altogether.

error rate, averaged across precue duration and stimulus type, ranged from 3% to 11.2%, the no-precue condition (8.6%) and the totally precued condition (10.7%) were well within these ranges, suggesting that error rate, at least in this experiment, bore no particular relationship to stimulus-response uncertainty. Analysis of variance on each Precue Display Time (3 or 5 sec) \times Stimulus Type (number or color word) combination revealed a main effect of precue only in the 3-sec color condition, $F(2, 10) = 4.76, p < .05$. Precuing extent (direction and arm to be specified) resulted in significantly more errors than precuing arm (extent and direction to be specified). This effect, however, does not change the interpretation of reaction time, as the error

rate was lowest in the condition with the fastest reaction time.

In the two-precue condition, only the 3-sec number condition provided evidence for an effect of precue type, $F(2, 10) = 16.04, p < .01$. The error rate when extent and direction were precued was greater than that of the other two precue conditions. As in the single-precue condition, the directionality of the errors as a function of precue type followed the reaction time analysis.

The findings of Experiment I are generally in support of the differential parameter specification hypothesis (Rosenbaum, 1980), although the effects observed in our experiment are not always statistically reliable. For example, in the conditions in which two parameters were precued, only

in the 3-sec number and 3-sec color condition were there statistical effects of precue type on reaction time. Similarly, in the conditions in which one parameter was precued, only the 5-sec color condition provided any statistical evidence for differential specification times. But when we compare our reaction time data and those of Rosenbaum, there is considerable similarity in the two sets of data (see Table 2). The inequality $B_A > B_D > B_E$, where these terms represent value specification times for arm, direction, and extent, respectively, seems to hold in seven of the eight Precue Display Time \times Stimulus Type conditions.

Some caution is warranted, however, in interpreting this trend completely in terms of parameter specification, at least prior to movement initiation. There was some evidence in the movement time data that extent decisions were actually made after the limb had begun to move. Rosenbaum (1980) observed a similar effect in his movement time data, and, clearly, kinematic information about movement trajectories would help clarify the issue. In addition, the magnitude of precue effects in our experiment diminished as precue display time was increased from 3 to 5 sec. Interestingly, Rosenbaum (1980, Footnote 5) mentions an informal study indicating the same result but offers no rationalization for it. Perhaps the most realistic, though speculative, possibility is that the subject can make maximum use of the time to process precues: With additional time, the need to employ a parameter specification strategy may be less crucial. On the other hand, and equally speculative, the expectancy state brought about by precuing the subject may have only a brief duration, after which the subject ceases to prepare individual response parameters. Why such a hypothetical state should extend to 3 but not 5 sec is somewhat mysterious.

Whatever the case, there is little doubt that the experiment situation created by Rosenbaum (1980) and by us in Experiment 1 is far removed from anything that would represent real-life movement control. Although there is little argument that animals and humans can effectively use prior information about upcoming movements of

Table 2

Comparison of Reaction Times (in msec) in the Four Conditions of Experiment 1 and Rosenbaum's Experiment 1

Condition	Reaction time		
	One parameter precued		
	A	D	E
3-sec number	559	588	634
5-sec number	562	598	616
3-sec color	540	551	575
5-sec color	613	634	660
Rosenbaum ^a	537	565	591
	Two parameters precued		
	A and D	A and E	D and E
3-sec number	431	477	512
5-sec number	441	465	469
3-sec color	442	457	478
5-sec color	486	478	481
Rosenbaum ^a	434	461	489

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

^a From Rosenbaum (1980).

limbs (e.g., Kelso, Pruitt, & Goodman, 1978) and eyes (e.g., Bizzi, 1974) to control them effectively, it is rare indeed for such prior information to take the form of letter precues. Even less often (except possibly in psychological experiments) does an individual have to make color transformations to produce a movement. On the other hand, the extensive experiments of Simon and colleagues (e.g., Simon, 1969; Simon & Rudell, 1967) show that initiation and movement time performance improves considerably when the stimuli exploit "natural" response tendencies of subjects. The possibility arises therefore that the experimental arrangement employed by Rosenbaum and ourselves may be too artificial to draw meaningful conclusions about the phenomenon of interest, namely, the parameterization of motor programs.

Even if one is suspicious about the need for ecological validity (which we believe is well motivated here; see Neisser, 1976, chap. 3 for discussion), Rosenbaum's results—which receive reasonable support in our Experiment 1—would be much stronger if obtained under more natural conditions. One way to examine this issue is to link

spatially precues and stimuli more directly to responses (via vision) and thus reduce the number of cognitive transformations required. Recently, Lee (1980) has presented evidence from a wide variety of activities—preserving balance in a “swinging room,” catching, hitting, driving a car—along with a detailed mathematical analysis of optical flow, demonstrating the intricate and nonarbitrary relationship between vision and the motor system. This coupling can also be well motivated at several different levels of neural processing (cf. Arbib, 1980, for review). In the experiments to follow, therefore, we mapped precues and stimuli to required responses in a highly compatible way. Thus, subjects received prior information about the parameters of upcoming movement via vision, and visual stimuli (not color-coded dots or names) specified the appropriate responses. There was then an attempt to maximize differential parameter specification by visual means and instructions to subjects about how to use this information effectively. If Rosenbaum is correct, that is, if his data speak to the “programming of movement” *after* nonmotoric decisions have been made, there is no a priori reason to expect the hypothesized differential parameterization effects obtained under these rather contrived conditions to be eliminated under more natural conditions.

Experiment 2

Method

Subjects

The subjects were 10 right-handed adults who were not paid for their services.

Apparatus

The apparatus was similar to that employed in Experiment 1, with one major modification in the way precues and stimuli were displayed to the subject. The video computer terminal was replaced by a display board (for precue and stimulus presentation), which consisted of a 21-cm × 41-cm Plexiglas board mounted vertically at eye level. Eight red light-emitting diodes were mounted in the same configuration as the response board. A ninth light-emitting diode mounted above the eight precue diodes was used to indicate that the display was a precue display rather than a stimulus

to move. The same diodes served as the stimulus lights. A Digital Equipment Corporation PDP 8/A computer was programmed to present the precues and the stimuli, as well as to time initiation and movement times, and record them on floppy disks for later off-line analysis.

Procedure

Each subject participated in a single experimental session lasting approximately 1 hr. and 40 min. Within this session there were four blocks of 128 trials, each consisting of a randomly presented precue followed by a stimulus to respond, in the same trial sequence as in the previous experiment.

A single light-emitting diode on the display board was activated to precue a subject completely on all parameters. To precue a subject on a single parameter, four diodes were turned on. For instance, to precue the left arm, the four lights on the left appeared. Similarly, to precue a long extent, the outermost lights were activated. Thus there were two alternative ways that each of the three singly precued parameters could be signaled. Precuing two parameters simply involved turning on the diodes formed by the intersection of the two sets of individually precued parameters: To precue arm and direction, for instance, the left or right lights indicating a forward or backward direction were turned on. There were thus four different ways to present each condition in which two parameters were precued.

The order of trials was randomized for each subject. As in Experiment 1, the subjects were told the meaning of the precues and were instructed to make use of them in order to respond as quickly as possible without making errors. A trial sequence consisted of a precue in which the appropriate light diodes were activated for 3 sec, a variable foreperiod randomly selected from a uniform distribution of .5–1.5 sec, followed by the stimulus to move. The stimulus light remained on until the subject responded. After the subject's response there was a 4-sec intertrial interval before the onset of the next precue.

Design

The first block of 128 trials was considered practice and was not included in the analysis. There were therefore six responses to each of the eight response keys in each of the eight precue conditions, making a total of 384 trials. Trials in which the subject responded with the wrong hand, missed the response key, or hit the wrong response key were noted and analyzed separately as errors. In addition, trials with reaction times greater than 600 msec or less than 70 msec and movement times greater than 600 msec were excluded for the same reasons as before.

A within-subjects design was used with all 10 subjects performing the same number of responses in each precue condition to each response key. From the six trials resulting from each combination of precue and response movement, a mean reaction time and movement time was computed. As in the previous experiments, three separate analyses of variance were

performed on each of the dependent variables. The first was an overall analysis of all precue conditions. The second and third dealt with the single and two precue conditions, respectively. As in Experiment 1, precue condition was crossed with response movement, which consisted of two levels of arm, two levels of direction, and two levels of extent, resulting in a four-way repeated measures analysis of variance. In addition, within-subjects correlation coefficients were computed between reaction time and movement time (over the 384 trials per subject), and errors were analyzed and tabulated.

Results and Discussion

Reaction Time Analysis

Full design. The mean reaction times are shown for each precue condition collapsed over response movement in Figure 3. For reaction times there was a significant main effect of precue, $F(7, 63) = 52.16$, $p < .01$. Post hoc analysis using a Neuman-Keuls procedure indicated that the completely precued condition was the fastest. The next fastest were those precue conditions in which two parameters were precued, followed by single-precue and no-precue conditions. This result replicates those of the first experiment as well as Rosenbaum (1980, Experiment 1) in which reaction times increased as a function of stimulus-response uncertainty.

One-precued parameter. In the single-precue condition, precue type was not significant, $F(2, 18) = 3.04$, $p > .05$, nor were any main effects of response movement (arm, direction, or extent) significant. Precue type did, however, interact with extent of movement, $F(2, 18) = 4.09$, $p < .05$. Post hoc analysis revealed that for short movements, precuing arm (specification or direction and extent required) resulted in slower initiation time than either precuing extent ($M_{diff} = 18.1$ msec) or direction ($M_{diff} = 19.3$ msec). In contrast, for long movements, precuing extent resulted in slower initiation times than precuing direction ($M_{diff} = 17.0$ msec). This particular interaction is troublesome for a model that predicts a fixed inequality of value specification times. That one inequality ($[B_A + B_D] < [B_D + B_E]$) should hold for short movements while another ($[B_A + B_E] < [B_A + B_D]$) should hold for long movements is less than parsimonious. Direction and extent of

response movement also interacted in the singly precued condition, $F(1, 9) = 9.08$, $p < .05$. Forward movements were initiated faster to far than to near targets and backward movements were initiated faster for near than to far targets.

Two-precued parameters. In the two-precue condition (one parameter remaining to be specified), there was again no main effect of precue, $F(2, 18) = 1.79$, $p > .05$. However, as in the single-precue condition, precue and extent of movement interacted, $F(2, 18) = 5.26$, $p < .05$. Post hoc analysis revealed that only in the longer movements was there a difference in reaction time based on type of precue: precuing arm and extent resulted in longer initiation times than precuing direction and arm. No other effects were statistically significant.

Movement Time Analysis

The mean movement times are shown for each precue condition collapsed over response movement in Figure 3.

Full design. The initial movement time analysis revealed a main effect of precue, $F(7, 63) = 8.20$, $p < .01$, which followed the same trend as the reaction time analysis with respect to number of precued parameters. When no parameters were precued, movement times were slowest, next slowest were the single-precue conditions, followed by the two-parameter precued conditions. The totally precued condition exhibited fastest movement times. This finding lends support to those of Kerr (1976) and Fitts and Peterson (1964), where movement times were found to be slower as a function of either extent or directional uncertainty. More important, movement times follow the obtained reaction time pattern thus providing no evidence for a reaction time-movement time trade-off.

One-precued parameters. In the single-precue condition, there was no effect of precue, $F(1, 9) < 1$. Right-arm movements were performed approximately 20 msec faster than left, $F(1, 9) = 24.3$, $p < .01$. In addition, short movements were performed an average of 48 msec faster than long movements, $F(1, 9) = 76.8$, $p < .01$.

Two-precued parameters. The analysis

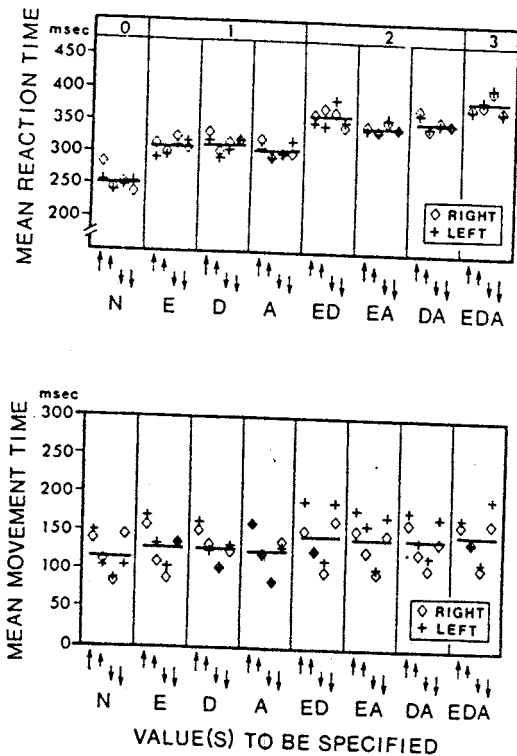


Figure 3. Reaction time and movement time for each precue condition in Experiment 2. (In each condition, the overall mean is represented by a horizontal line. N = none; E = extent; D = direction; A = arm.)

of the two-precue condition revealed similar results to those reported in the one-precued parameter condition. No effect of precue was found, $F(2, 18) < 1$. Forward movements were approximately 26 msec slower than backward movements, $F(1, 9) = 6.98$, $p < .05$. Also, short movements were performed faster than long movements ($M_{diff} = 42$ msec), $F(1, 9) = 81.32$, $p < .01$. This is

consistent with Fitts's law (Fitts, 1954), where movement time increases as a function of distance when target size is held constant.

Error-Rate Analysis

The error-rate data are presented in Table 3. The average error rate across precue conditions was 8.4%, with the highest rate in the no-precue condition (13.5%). Error rates for individual subjects ranged from a low of 1.8% to a high of 14.0%. In the single-precue condition, there was no effect of precue type on error rate, $F(2, 18) < 1$. However, more errors were made in movements to far targets (9.7%) than to near targets (5.7%), $F(1, 9) = 8.45$, $p < .05$. There were no statistically significant results in the two-precue condition, ($F_s < 1$).

The within-subjects correlation analysis revealed movement times to be largely independent of reaction times; all subjects' correlation values were less than $\pm .2$.

The present results appear, as in Experiment 1, to be accountable to a large degree on the basis of uncertainty. As the number of stimulus-response alternatives was reduced (more parameters precued), there was a commensurate reduction in reaction time. Once again, reaction time increased with the number of possible choices of direction, the number of extent alternatives, and limb uncertainty. But unlike Rosenbaum (1980) and our Experiment 1, there were no systematic effects on reaction time within a particular precue condition. Rather, it appears that directly given precues allow the subject to eliminate particular stimulus-response alternatives and pre-

Table 3
Percentage Error Rate Categorized by Error Type for Each Precue Condition: Experiment 2

Type of error	Parameter(s) to be specified							
	N	E	D	A	ED	EA	DA	EDA
Anticipation ^a	5.4	2.9	4.4	3.9	3.8	3.3	3.9	5.0
Inattentiveness ^b	2.5	2.3	1.7	2.5	1.5	3.1	1.7	5.6
Response ^c	2.5	1.5	1.0	1.5	1.9	1.3	1.5	2.9
Total	10.4	6.7	7.1	7.9	7.1	7.7	7.1	13.5

Note. N = none; E = extent; D = direction; A = arm. ^a Reaction times < 70 msec. ^b Reaction times > 600 msec. ^c Initiated movement with wrong hand, struck wrong response key, or missed target altogether.

pare those remaining in a more holistic manner. For example, in a situation in which two parameters are precued, the subject may prepare the two remaining responses (regardless of particular parameter) and simply choose between them when the stimulus light appears.

The foregoing "response selection" notion was examined by Rosenbaum (1980, Experiment 3). By identifying a response set (two or four choice) and instructing subjects to prepare multiple movements, Rosenbaum obtained similar findings to those reported here. But Rosenbaum's Experiment 3 bears little resemblance to the present experiment and is not particularly relevant to the claim we are making. First, in his Experiment 3, Rosenbaum used a color-dot display and required subjects to learn a color dot to response-key mapping. In contrast, we used a directly compatible precue stimulus-response mapping. Second, Rosenbaum actually instructed subjects to prepare multiple responses: We did not. Third, Rosenbaum used a precue display lasting 5 sec: We used a 3-sec precue display that our subjects, unlike Rosenbaum's (see Footnote 4 of Rosenbaum, 1980), had little difficulty identifying. We and Rosenbaum (1980, Footnote 5) have already shown that differential parameter specification effects are reduced or eliminated when precue display time is increased to 5 sec. The lack of evidence for such a process in Rosenbaum's Experiment 3 is therefore hardly suprising.

The results of the present experiment are more likely a reflection of the lack of robustness of the parameter specification model. Naturalizing the experimental situation appears to reduce parameter specification effects and may challenge their significance in the first place. Before rejecting the model, however, it is possible that individual parameters are specified, but that specification time is the same irrespective of the particular parameter involved (we will refer to this special case as nondifferential parameter specification). If this were the case, then two outcomes are predicted: First, reaction times should be similar when comparing conditions with the same number of parameters precued, and second, an

increase in the number of parameters remaining to be specified should be accompanied by a corresponding increase in reaction time. Unfortunately, the same predictions follow from a response selection notion, and the data from Experiment 2 cannot discriminate between the two. This led us to the third experiment, whose purpose was to further enhance the likelihood of subjects using a parameter specification process as well as an attempt to discriminate between parameter specification (differential or nondifferential) and response selection.

Experiment 3

Three major changes in procedure were incorporated into Experiment 3 to encourage parameter specification. First, trials were blocked on the type of parameter(s) precued. Thus, all trials within a single block involved precuing the same two parameters (e.g., extent and direction) such that a choice had to be made on the single remaining parameter (e.g., arm). Second, the subject was instructed to vocalize the information provided by the precue (e.g., forward, long) and to prepare those parameters. The third change was in the experimenter's role. Whereas in Experiment 1 and 2 the experimenter simply monitored the computer controlled experiment, in Experiment 3 the subject was verbally encouraged to prepare the response and respond as fast as possible. Verbal encouragement has been shown by Klapp, Wyatt, and Lingo (1974) to enhance preparation and facilitate the production of faster reaction times.

To investigate the hypothetical distinction between nondifferential parameter specification and response selection, a further condition was added in which the precue was rendered ambiguous. In this condition, the precue did not specify any particular parameter, but rather provided two stimulus-responses alternatives that differed in all three parameters. For example, consider a situation in which the visual precue specified a left forward movement to the far key and a right backward movement to the near key. Here, parameter specification as envisaged by Rosenbaum

(1980) would not be possible. On the other hand, even a nondifferential parameter specification model would predict reaction time differences between an ambiguously precued condition and a condition in which specific parameters were precued. But if the underlying process under compatible conditions involves response selection, reaction time should be the same across all situations in which there are two alternatives.

Method

Subjects

Eight right-handed adults who did not participate in either of the previous experiments served as unpaid subjects.

Apparatus

The apparatus was the same as that employed in Experiment 2. As in the first and second experiments, precue and stimulus presentation were computer controlled, with the response data collected and written out on a floppy disk.

Procedure

Each subject participated in a single experimental session lasting approximately 40 min. Within this session there were four blocks of 40 precued trials followed by a stimulus to respond. Each trial consisted of a 3-sec precue display, during which the subject was required to announce the partial information conveyed by the precue. A ½-sec delay followed and preceded the stimulus to move. The intertrial interval was 3 sec. Within a single block the same two parameters were always precued, although in different manners. For instance, arm and direction could be signaled by precuing left-arm forward or backward movement and right-arm forward or backward movement. In each case the precue allowed the subject to partially prepare the type of movement specified, thus leaving the remaining parameter to be selected (extent in this case) when the stimulus occurred. Each combination of two precued parameters accounted for three of the experimental conditions. The fourth condition was designed so as not to precue any specific parameter, although leaving the same number of alternatives as the other conditions. For example, a left-arm forward movement to the far response key was paired with a right-arm backward movement to the near key.

Each possible stimulus was presented equally often within each precue condition. This resulted in five stimulus-response pairs to each of the eight response keys in each block. The order of precue conditions was counterbalanced. The subjects were given an initial period of time in which to become accustomed to the response movements by moving to each response

key in succession, for a total of five times. As in Experiments 1 and 2, there was no visual feedback from response movements. After the period of familiarization, subjects were advised as to the meaning of the precue display. At the start of each block, explicit instructions were given stressing the requirement to prepare the movement so that only the remaining parameter would have to be selected. Furthermore, each alternative precue within the upcoming condition was explained and demonstrated to the subject. After the first eight trials within each block, there was a short pause in which the experimenter informed the subject that he/she was going too slow (regardless of the actual speed of response). Again, preparation of response parameters was encouraged. After Trials 16, 24, and 32, the subjects were once again reminded of the importance of preparing the parameters prior to the response signal. The first eight trials within each block were considered practice trials and were excluded from the analysis. Trials in which the subject responded with the wrong hand, missed the response key, or hit the wrong response key were noted but excluded from the data analysis, as were trials in which reaction times or movement times were outside the ranges used in Experiment 2.

Design

A within-subjects design was used with all eight subjects performing the same number of choice reaction times in each precue condition to each response key. From the 4 trials resulting from each different response movement in each condition, mean reaction time and movement time were computed, which then served as the dependent variables in a 4 (precue) \times 2 (arm) \times 2 (direction) \times 2 (extent) repeated measures analysis of variance. In addition, the error rate was analyzed in the same manner. A within-subjects correlation (for each block of 32 trials) between reaction time and movement time was computed.

Results and Discussion

Reaction Time Analysis

Mean reaction times are shown for each precue condition in Figure 4. The main effect of interest, type of precue condition, failed to reach significance, $F(3, 21) = 2.69$, $p > .05$. The only statistically significant result was for arm, $F(1, 7) = 6.36$, $p < .05$. Left-arm movements were initiated approximately 21 msec faster than right-arm movements. The null findings of precue condition are consistent with the null findings obtained for precue type in Experiment 2, since each precue condition had the same amount of uncertainty. Again, there was no evidence to suggest that response parameters were differentially specified. The finding that the ambiguously precued condi-

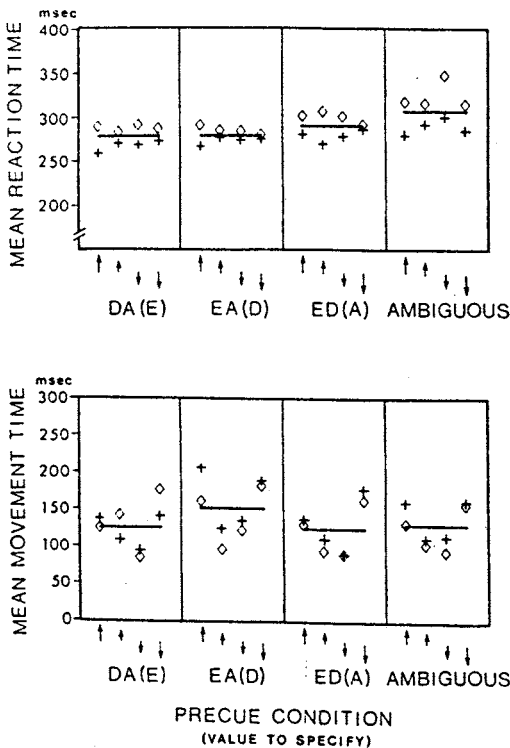


Figure 4. Reaction time and movement time for each precue condition in Experiment 3. (In each condition, the overall mean is represented by a horizontal line. (D = direction; A = arm; E = extent. Diamond = right; cross = left.)

tion was not significantly different from the other precue conditions is not consistent with a general parameter specification process. Rather, each precue condition contained the same amount of uncertainty and thus appeared to exhibit the same reaction times. Reaction times in this experiment

were somewhat faster (28 msec on the average) than comparable conditions in Experiment 2, suggesting that either verbal encouragement or the blocking of trials or both were effective means of speeding responses.

Movement Time Analysis

Mean movement times are shown for each precue condition in Figure 4. Analysis revealed that short movements were performed an average of 50 msec faster than long movements, $F(1, 7) = 15.14, p < .01$. The only other statistically significant finding was the Precue \times Arm interaction, $F(3, 21) = 3.19, p < .05$. When arm and direction were precued, movement time was shorter for the left arm, whereas in the other precue conditions, movement times were shorter for the right arm.

Error-Rate Analysis

The percentage error rate for each precue condition is shown in Table 4. The analysis of the error rates indicated no differences across precue conditions, $F(3, 21) \sim 1$, nor were any other effects significant. The average error rate was 12.2%, ranging from a low of 9.8% when direction and arm were precued to a high of 15.6% when arm and extent were precued. The range for individual subjects spanned from 5.4% to 22.6%. The within-subjects correlation analysis indicated that movement times and reaction times were virtually independent (all r s less than $\pm .28$) as in Experiment 2.

The present data are not particularly

Table 4

Percentage Error Rate Categorized by Error Type for Each Precue Condition: Experiment 3

Type of error	Precue condition			
	AD (E) ^d	AE (D)	DE (A)	Ambiguous (EDA)
Anticipation ^a	3.5	6.6	4.3	5.5
Inattentiveness ^b	2.0	3.1	2.7	2.0
Response ^c	4.3	5.9	5.5	3.4
Total	9.8	15.6	12.5	10.9

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

^a Reaction times < 70 msec. ^b Reaction times > 600 msec. ^c Initiated movement with wrong hand, struck wrong response key, or missed target altogether. ^d Parameter(s) to be specified are in parentheses.

conductive to a parameter selection model, even one of the nondifferential kind. However, null effects must always be interpreted with caution, due to the possibility of Type II error. To counteract erroneous interpretation, we increased the number of subjects ($n = 24$) in a fourth experiment to increase the sensitivity of the experiment. In addition, six of the eight subjects in Experiment 3 indicated that verbalizing the upcoming movement seemed to interfere rather than aid planning of movement, so we excluded overt verbalization of the upcoming movements as well as experimenter encouragement to respond faster. Apart from these changes, the methods and procedures were identical to Experiment 3.

Experiment 4

Results and Discussion

Reaction Time Analysis

Mean reaction times are shown for each precue condition in Figure 5. As in Experiment 3, the main effect of type of precue failed to reach significance, $F(3, 69) = 2.43$, $p > .05$. However, there was a significant Precue \times Extent interaction, $F(3, 69) = 4.74$, $p < .01$. For short movements the ambiguously precued condition resulted in the slowest initiation times overall, whereas for long movements, the condition in which direction remained to be specified (arm and extent precued) resulted in the slowest initiation times. With this exception, type of precue had no significant effect on reaction time. Indeed, the slowest initiation time (when direction remained to be specified) was only 14.4 msec slower than the condition with the fastest initiation time (when arm remained to be specified). Initiation times, on the average, were elevated approximately 20 msec beyond those obtained in Experiment 3—a result that may be due to removal of experimenter encouragement. Left-arm movements were initiated approximately 11 msec faster than right-arm movements, $F(1, 7) = 12.61$, $p < .01$, which replicates the left-arm advantage found in Experiment 3. Short movements were initiated faster in forward movements, whereas responses to far targets were initiated faster

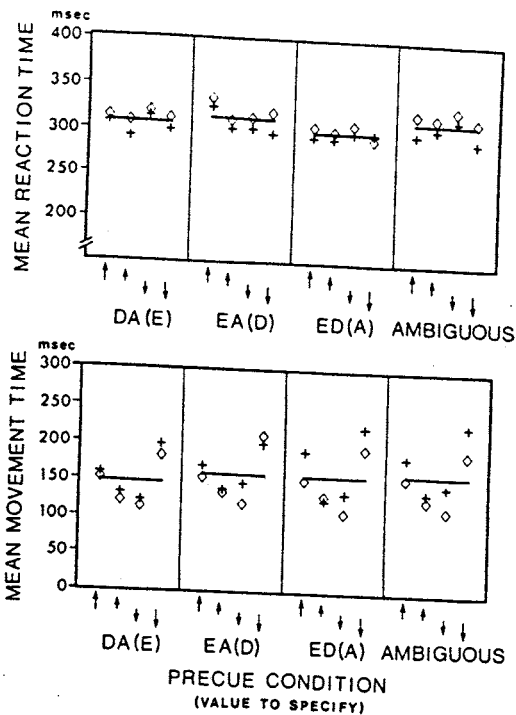


Figure 5. Reaction time and movement time for each precue condition in Experiment 4. (In each condition, the overall mean is represented by a horizontal line. D = direction; A = arm; E = extent. Diamond = right; cross = left.)

in backward movements, as indicated by the direction \times extent interaction, $F(1, 23) = 28.90$, $p < .01$. As in the previous experiment, the reaction time data appear to provide little support for a general parameter selection process.

Movement Time Analysis

Mean movement times are shown for each precue condition in Figure 5. The movement time analysis revealed no effect of precue condition, $F(3, 69) \sim 1$, nor were any interactions with precue statistically significant. As in previous analyses, short movements were performed faster than long ones ($M_{diff} = 56$ msec), $F(1, 23) = 58.12$, $p < .01$. Like Experiment 3, forward movements were faster than backward movements ($M_{diff} = 17$ msec), $F(1, 23) = 12.31$, $p < .01$, and right-arm movements were made approximately 17 msec faster than left-arm movements, $F(1, 23) = 19.29$, $p < .01$.

Table 5

Percentage Error Rate Categorized by Error Type for Each Precue Condition: Experiment 4

Type of error	AD (E) ^d	AE (D)	DE (A)	Ambiguous (EDA)
Anticipation ^a	2.2	2.7	1.6	3.4
Inattentiveness ^b	1.7	1.4	.7	2.1
Response ^c	2.9	1.7	3.6	3.5
Total	6.8	5.8	5.9	9.0

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

^a Reaction time < 70 msec. ^b Reaction time > 600 msec. ^c Initiated movement with wrong hand, struck wrong response key, or missed target altogether. ^d Parameter(s) to be specified are in parentheses.

Error-Rate Analysis

The percentage error rate for each precue condition is shown in Table 5. The analysis of errors revealed a null effect of precue condition; the ambiguously precued condition resulted in a slightly higher error rate (9%) than the other conditions, $F(3, 69) = 2.40, p > .05$, whose average error rate was 6.2%. Forward movements had a higher error rate than backward movements, $F(1, 23) = 4.81, p < .05$, and long movements were more prone to error than short movements, $F(1, 23) = 27.87, p < .01$. An ordinal interaction between extent and direction, $F(1, 23) = 5.96, p < .05$, revealed the difference in error rates between forward and backward movements to be greater for longer movements. The within-subjects correlational analysis indicated that movement times and reaction times were again relatively independent (all r s with one exception were less than $\pm .26$) as in the previous experiments.

General Discussion

The present experiments were concerned with "programming" processes hypothesized to be involved in the initiation of simple movements. Our specific interest was whether the specification of movement parameters tended to proceed in a particular serial order as suggested by Rosenbaum (1980). The first experiment used the precuing method developed by Rosenbaum and was largely supportive of his main results. That is, there was indeed a definite tendency—admittedly not always statistically significant—for reaction times to be slower for the specification of arm than

direction, and both to be slower than the specification of extent. In fact, there was some evidence in the movement time data to suggest that decisions about extent were actually made after the movement had been initiated, an effect also noted by Rosenbaum. Although this replication is heartening, the main thrust of the present article is directed toward extending these findings, if possible, to an experimental situation that bears a closer resemblance to the real-world task of controlling movement. More pointedly, the issue is one of evaluating whether the paradigm developed by Rosenbaum and employed in our Experiment 1 is really directed to the intended problem of interest, namely, the specification of motor program parameters *after* non-motoric decisions have been made (Rosenbaum, 1980). Thus, subjects in Rosenbaum's main experiment and our Experiment 1 had to determine not only the meaning of letter precues but also to translate a color-coded dot (name or number) into an appropriate response pattern. All this seems far removed from the skilled movement situation in which limb movements must be consonant with visually specified environmental changes.

In our follow-up experiments we employed a modification of Rosenbaum's (1980) method in which precues and stimuli were directly specified through vision. In the language of information processing and mental chronometry, we provided the subject with highly compatible stimulus-response conditions. Thus, much less cognitive work is involved (or in Teichner & Krebs's, 1974, analysis, fewer translational processes), a claim that receives strong sup-

port in the much faster reaction times observed in our Experiments 2-4 (see also Larish, 1980).²

In Experiment 2, although reaction times decreased as a function of the number of parameters precued, there were no systematic effects of precuing particular parameters.³ In Experiment 3, we incorporated a precue that, although serving to reduce task uncertainty, failed to provide any specific information as to the arm, direction, or extent of the upcoming movement. The parameter specification model predicts initiation time to be slower in this condition (termed *ambiguous*) than one in which some of the parameters of movements are known in advance. Such was not the case, however, as we again failed to detect movement initiation differences as a function of the type of precued parameter. Our reluctance to impute significance to null findings led us to replicate Experiment 3 with a larger sample. However, in a fourth experiment we again obtained null findings; there were no significant differences between specific or ambiguous precue conditions. In sum, of the four experiments we have performed, only in the one that used precues and stimuli of a quite complex kind (letters, color words, and numbers) did we find support for Rosenbaum's parameter specification model. When we employed highly compatible conditions, we failed to obtain any tendency for movement parameters to be serially ordered.

To the extent that compatible conditions are more natural for the subject (performance is certainly improved), we feel that some caution is warranted in adopting Rosenbaum's paradigm and generalizing his conclusions beyond the somewhat contrived situation in which the data were obtained. Note that we are not questioning the usefulness of precuing per se: This is an interesting innovation and may be very useful indeed as a tool to investigate the general nature of preparation (Kelso, in press). Our reservations speak to the specific precuing method and stimulus presentation employed by Rosenbaum (1980) and in our Experiment 1. Our suspicion, supported by the present data, is that this method has little to do with the parameterization of motor

programs—at least at the motoric level that we and Rosenbaum are interested in. If the parameter specification model envisaged by Rosenbaum were a robust one, we would not have expected the ordering effects to wash out under more natural compatible conditions.

On hindsight there are grounds for questioning the viability of models of movement initiation positing (even tendencies in) serial ordering and partial preparation of motor programming parameters. For example, serial order notions run into a class of problems that mathematicians refer to as non-deterministic polynomial-time complete (Lewis & Papadimitrios, 1978). In short, the only known algorithmic solution for such problems is one in which the execution time increases exponentially as a function of the number of variables to be regulated. Although only three parameters were investigated here, if one adopts the logical extension of this approach, more and more parameters must necessarily come into play as the task becomes increasingly more complex. This would necessarily result in an inordinate increase in programming time.

A further consideration with respect to parameter selection models is one raised by Kerr (1978). Task-defined parameters (such as arm, direction, and extent) may be quite different from the internal values that truly affect the motor control system. Thus, the parameters that experimenters define may not be considered singly or may not have one-to-one mappings in the motor control system. For instance, distance or extent of movement is not, as Keele (1980) points out, in the language of muscles, but instead is a consequence of the muscular forces that accelerate and decelerate the limb. From our perspective, the evaluation of programming effects on kinematic variables may be inappropriate: Kinematic measures

² Larish (1980), in an independent study, also showed that transformation and translation processes (manipulated with various stimulus-response configurations) were an important determinant of differential precuing effects.

³ Frekany, Kelso, and Goodman (Note 1) in a study designed to evaluate the attentional demands of precues had a built-in replication of Experiment 2. Results were virtually identical.

are merely resultants of the system's dynamics.

Let us pursue briefly the dynamics perspective. Recent work in motor control strongly suggests that the natural physical properties inherent in neuromuscular systems (e.g., damping, stiffness) are exploited during movement. They are not merely the substrate on which central commands are laid down (cf. Bahill & Stark, 1979; Bizzi, Dev, Morasso, & Polit, 1978). For example, Polit and Bizzi (1978) have shown that the final position of the limb following reaching movements in monkeys is determined via the specification of stiffness and damping parameters that establish an equilibrium point between opposing pairs of muscles. Analogous experiments have been carried out in humans (Fel'dman, 1966; Kelso & Holt, 1980) and have led to models of single trajectory movements (such as those employed in these experiments) that possess the properties of homeomorphic oscillatory systems, the most specific being the mass spring (Kelso, 1977; Kelso, Holt, Kugler, & Turvey, 1980; Polit & Bizzi, 1978). Hollerbach (1978) extended these findings by showing that cursive handwriting may be produced via coupled oscillations in the horizontal and vertical joints of the wrist-hand linkage. In Hollerbach's analysis, letters emerge from a constrained modulation of an underlying (dynamic) oscillatory process rather than a stringing together of individual motor programs. The consequence of the dynamics perspective, then, in contrast to one that views parameters as programmed for each individual movement, is that so-called complex movement behavior falls out as the *modus operandi* of a simple oscillatory pattern.

This view of coordination and control of movement as an emergent property of oscillator interactions contrasts sharply with a view of motor programs that "prescribes values on movement dimensions" (Rosenbaum, 1980, p. 446). The latter assigns to the program a *a priori* status in rationalizing motor behavior and in so doing ignores the fundamental problem for a motor control system, namely, how to regulate its internal degrees of freedom (Bernstein, 1967; Greene, 1972; Iberall & McCulloch, 1969; Turvey,

1977). In short, programming approaches, consonant with the computer metaphor, assign priority to the *order* grain of analysis and neglect entirely the *relation* grain (see Shaw & Turvey, in press, for a formal analysis of this issue). Programming languages (of computers and motor systems) are thus unidirectional and "imperative" (Steele & Sussman, 1978): in computers, command algorithms are separate from that which performs the computation just as the central program, in control theory and information-processing approaches, is held conceptually distinct from the skeletomuscular apparatus that performs the movement.

We suspect that an adequate account of systemic movement behavior must, in the long run, include, as minimal requirements, a dynamic vocabulary for control (see above) and, relatedly, extend the explanation to the relational grain of analysis (cf. Boylls, 1975; Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; Greene, 1978; Kelso et al., 1980; Kugler, Kelso, & Turvey, 1980; Shaw & Turvey, in press; Turvey, Shaw, & Mace, 1978). The latter promotes a search for the constraints that allow neuromuscular variables to be regulated in a given motor activity. In fact, some progress has already been made in this regard. Nashner (1976), for example, has shown that over wide variations in upright posture brought about by ankle rotation, the ratios and sequencing of electromyographic activity in the muscles of the ankle, knee, and hip remain fixed. In handwriting, the timing of strokes remains fixed over changes in letter size and increases in friction between pen and surface (cf. Wing, 1978). Similarly, the timing relations of the upper limbs during the performance of a task involving different spatial demands remain invariant over changes in the magnitude of force produced by each limb (Kelso, Southard, & Goodman, 1979). In sum, the fixed proportioning of activity throughout a collection of muscles and the maintenance of timing relationships is a consequence of the constraints on the system. It is not, we should emphasize, that movements are caused by constraints, rather it is that some movements are excluded by them. This analysis leads us to suspect that an act is not the

outcome of a collection of parameterizations dispersed in time but rather may be centrally or peripherally manipulated as a holistic structure.

Reference Note

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