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On the Advance Preparation of Discrete Finger Responses

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Most studies that examined the precuing of motor responses have been interpreted as indicating that response specification is a variable-order process. An apparent exception to this conclusion was obtained by Miller (1982) for the preparation of discrete finger responses. Precuing was beneficial only when the precued responses were on the same hand, suggesting that response specification occurs in a fixed order, with hand specified before other aspects of the response. Three experiments examined this discrepant finding for discrete finger responses. Experiment 1 demonstrated that with sufficient time (3 s), all combinations of responses can be equally well prepared. Experiments 2 and 3 showed that the precuing advantage for same-hand responses at shorter precuing intervals is due to strategic and decision factors, not to an ability to prepare these responses more efficiently. Preparation of finger responses, thus, also appears to be variable. This conclusion poses problems for Miller's extension of the precuing procedure to the evaluation of discrete versus continuous models of information processing.

The manner in which motor responses are prepared for execution is an important issue in the study of human movement (Schmidt, 1976). One focus of the research on this issue has been to determine the influence that response requirements, such as movement length and movement time, have on the time to initiate responses. In general, the latency of response initiation has been found to be a function of the response's temporal and organizational complexity, rather than of its physical characteristics (see Kerr, 1978, for a discussion).

More recently, several studies have employed a precuing (or priming) procedure in which the target stimulus is preceded by a cue stimulus that limits the possible response alternatives (Bonnet, Requin, & Stelmach, 1982; Goodman & Kelso, 1980; Miller, 1982; Rosenbaum, 1980; Rosenbaum & Kornblum, 1982; Stelmach & Larish, 1981; Zelaznik, Shapiro, & Carter, 1982; see also Leonard, 1958). Assuming that, whenever possible, subjects use the advanced information provided by the precue to prepare the cued aspects of the response, reaction time to the target should reflect the time required to specify the remaining unprepared response components. By distinguishing between the combinations of responses that benefit from being precued and those that do not, evidence can be obtained regarding whether the component aspects of the movement are prepared in parallel or in serial, and if serially, whether the components are specified in a fixed or variable order (Rosenbaum, 1980, 1983).

Rosenbaum (1980) used the precuing procedure to examine the preparation of arm, direction, and extent components of limb movements. Subjects were to make one of eight movements using either the right or left arm, moving either forward or backward with long or short movements. Precues allowed the subject to prepare a component or some combined components of the response prior to the stimulus to move. Analysis of the reaction times under the various precued conditions indicated that specification of these movement features occurred in a serial order, with the order of specification being variable. Rosenbaum (1983) reviewed subsequent studies that also used the precuing procedure and concluded

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that serial, variable-order specification of movement features occurs in most movement situations.

One exception to this conclusion noted by Rosenbaum (1983) is the research of Miller (1982) that examined the preparation of discrete finger responses. In the most directly relevant experiment (Experiment 1 in Miller's article), subjects made one of four responses using the middle and index fingers of both hands. The particular response to be executed was indicated by the occurrence of a plus sign in one of four positions on a horizontal row, with the positions mapped to the responses in a spatially compatible manner. On some trials, a precue of two plus signs appeared immediately above the row in which the target occurred. The precue signified that the required response would be one of the two alternatives indicated by the locations of the plus signs (i.e., the other two responses were eliminated as possibilities). Four response preparation conditions were examined: *prepared:hand* (precuing two responses from the same hand—e.g., middle and index fingers of left hand); *prepared:finger* (precuing the same finger from both hands—e.g., middle fingers on left and right hands); *prepared:neither* (precuing opposite fingers from both hands—e.g., middle finger of left hand and index finger of right hand); and *unprepared* (precue uninformative—i.e., all four responses indicated). Miller found a benefit of precuing only when the precued responses were on the same hand (the *prepared:hand* condition). When the precued responses were on different hands (the *prepared:finger* and *prepared:neither* conditions), responses were no faster than when there was no precue (the *unprepared* condition).

Miller's (1982) results are consistent with a hierarchical, or fixed order, control of response specification for discrete finger movements, in which hand must be specified prior to the other component aspects of the movements. That is, precuing should not be beneficial when the precued responses are on different hands, as Miller found, if the hand must be specified before any other aspect of the response. Because this apparent fixed-order control of discrete finger responses contrasts with the variable-order control implicated for most other situations (Rosenbaum, 1983), it is a finding of considerable interest and of potential importance. For example, Rosenbaum (1983) concluded that the fixed-order preparation of finger responses is likely due to the neurophysiological arrangement of the brain. According to him, because

> fingers on the same hand are almost entirely controlled within one hemisphere while fingers on different hands are almost entirely controlled within different hemispheres, it is easy to see how selection of a finger movement might require a previous choice of the hand on which the finger is located (Rosenbaum, 1983, p. 258).

Before concluding that the specification of hand must precede the specification of other aspects of discrete finger responses and before attributing this limitation to the lateralization of the central nervous system, however, Miller's (1982) procedure must be carefully scrutinized. That is, because his results are inconsistent with those obtained in numerous other precuing studies, there is a likely possibility that Miller's results are attributable to nonmotoric factors, rather than to limitations in the ability to prepare responses. The present experiments were designed to provide the systematic examination of Miller's procedure necessary to distinguish between motoric and nonmotoric accounts of the same-hand advantage that he obtained.

In addition to their implications regarding the nature of response preparation, the present experiments also are relevant to evaluating an extension of the precuing procedure that Miller (1982, 1983) developed to distinguish between discrete and continuous models of information processing. Models of the former type (e.g., Sternberg, 1969) propose that response selection begins only after the target stimulus has been identified, whereas models of the latter type (e.g., Eriksen & Schultz, 1979) propose that responses receive activation continuously as the target stimulus is being processed. Based on the same-hand advantage for response preparation, Miller argued that if partial information were used to prepare responses, this information should produce a benefit when it indicates responses on the same hand, but not when it indicates responses on different hands. In a series of experiments, he varied the relative time at which partial information within a single stimulus should be available and, through varying assignment of stimuli to responses, controlled whether or not this partial information would indicate the two responses on the same hand. The response preparation effect occurred only when stimuli were combinations of two distinct codes, with the first available code associated to responses on the same hand. Thus, Miller proposed an asynchronous discrete coding model in which preparation of responses occurs whenever a component code becomes available.

This interpretation of Miller's (1982, 1983) discrete/continuous experiments relies on the assumption that only responses on the same hand can be prepared in advance or, in other words, that finger response components are specified in a fixed order, with hand selected first. Thus, the conclusions that Miller drew regarding the discrete versus continuous issue are valid only to the extent that preparation of discrete finger responses is in fact a fixed-order process. Therefore, careful examination of his basic precuing results takes on added significance, particularly because Miller's studies are among the few that apparently provide insight into this very fundamental issue of discrete stage versus continuous processing.

When Miller's (1982) precuing procedure is compared to those of other studies, one notable distinction is evident. In his experiment, the maximum precuing interval was 1 s, whereas in the other studies, the precuing intervals ranged from 2 s to 5 s (Bonnet, Requin, & Stelmach, 1982; Goodman & Kelso, 1980; Rosenbaum, 1980; Stelmach & Larish, 1981). Experiment 1, thus, extended the precuing intervals examined by Miller up to 3 s, an interval used in many of the other studies. The primary intent was to determine if, with sufficient time, all pairwise combinations of discrete finger responses could be equally well prepared. Results of Experiment 1 indicated that such was the case. Experiments 2 and 3 examined alternative reasons for the same-hand advantage at short preparation intervals. This advantage was shown to be attributable to processing strategies and decision factors, not to a greater relative efficiency at preparing responses on the same hand.

Experiment 1

Experiment 1 was a replication of Miller's (1982) Experiment 1 that closely followed his method, using similar precue and target stimuli and a spatially compatible mapping of the stimuli to the finger responses. The primary change was in the precuing intervals examined. Whereas Miller used a maximum interval of 1 s, the present experiment examined precuing intervals of up to 3 s. If the planning of finger responses is a fixed-order process, as suggested by Rosenbaum (1983) and Miller (1982), the advantage of precuing responses on the same hand, relative to precuing responses on different hands, should be equally apparent at both short and long precuing intervals. However, if the planning process is variable, all precuing conditions should show equivalent benefits when the preparation interval is sufficiently long.

Method

Apparatus and stimuli. Stimuli were presented on the display screen of a Radio Shack TRS-80 Model III microcomputer. Viewing distance was not controlled, but was approximately 50 cm. Responses were made by pressing one of four permissible keys on the computer's keyboard (a standard typewriter keyboard). Stimulus durations, intervals, and response latencies were controlled and recorded by the computer.

The stimulus display for each trial consisted of a warning stimulus, a cue stimulus, and a target stimulus, with the entire display centered on the viewing screen. The warning signal was a row of four plus signs from the standard character set of the computer. Each sign was approximately 3 mm square, with a black space of 6 mm separating each sign in the row. The total visual angle subtended by the row was, thus, approximately 3.43°. The precuing stimulus occurred immediately below the warning stimulus. It also consisted of plus signs located in either all four of the horizontal positions occupied by the warning stimulus or in only two of the four positions. The target was a single plus sign that occurred immediately below the cue row, with its horizontal position always being one of those indicated by the cue. The warning and precue rows and the precue and target rows were each separated by 5 mm, making the vertical extent of the display approximately 2.18°.

The subject's task was to indicate the position in which the target occurred by making one of four responses. The four permissible responses involved pressing an appropriate response key with the middle or index finger of either hand. These fingers were placed (in a left-to-right order) on the (Z), (X), (.), and (?) keys of the keyboard (the two left-most and right-most keys on the bottom row of the keyboard). The assignment of responses to target positions was also in a left-to-right order, so that, for example, the correct response to a target in the far left position of the display was the middle finger of the left hand.

The four precuing conditions from Miller's Experiment 1 (1982) were used in this study. These precuing conditions differed in terms of the responses (targets) indicated by the precue. Examples of each condition are shown in Table 1 for a left hand, middle finger response. For the *unprepared* condition, the precuing stimulus contained all four plus

Table 1
Stimulus Displays for Each Preparation Condition When the Target Indicated Left Middle-Finger Response

Response	LM	LI	RI	RM
	Finger placement			
	Unprepared			
Warning	+	+	+	+
Precue	+	+	+	+
Target	+			
	Prepared:Hand			
Warning	+	+	+	+
Precue	+	+		
Target	+			
	Prepared:Finger			
Warning	+	+	+	+
Precue	+			+
Target	+			
	Prepared:Neither			
Warning	+	+	+	+
Precue	+		+	
Target	+			

Note. L = left hand; R = right hand; M = middle finger; I = index finger.

signs, and the target occurred in any of the four positions. For the three *prepared* conditions, the precuing stimulus contained only two plus signs, and the target occurred in one of the two positions indicated by the precue. In the *prepared:hand* condition, the cue indicated the two positions assigned to either the left hand or the right hand. In the *prepared:finger* condition, the cue indicated the two positions assigned to either the index fingers or the middle fingers. In the *prepared:neither* condition, the cues indicated positions assigned to the index finger for one hand and to the middle finger for the other hand.

In addition to the type of cue, the interval between precue onset and target onset was also varied. This precuing interval was 0, 375, 750, 1,500, or 3,000 ms. The intervals were selected to include the ranges examined by Miller (1982) and by Rosenbaum (1980) and by Goodman and Kelso (1980). Both cue type and preparation interval were within-subject variables that randomly varied within the session. Following the procedure of Miller's Experiment 1, a total of 280 test trials were conducted. These consisted of 40 *unprepared* trials and 80 trials for each of the three *prepared* conditions. Each of these sets were divided equally among the five preparation intervals, with each possible cue-target combination sampled equally often for each interval. Thirty additional trials that were regarded as practice were added to the beginning of the list. Four different orders of the trials were prepared, with each order used for one fourth of the subjects.

Subjects and procedure. Subjects were 24 students enrolled in psychology courses at Auburn University who participated for extra credit. Data from 3 additional subjects were discarded because of incorrectly performing the task in one case and because of holding a response key down across trials in the other two cases.

Subjects were given instructions regarding the nature of the task. They were told that the target would always occur in a position indicated by the precue, but they were not explicitly told to use this information to prepare responses. The sequence of trials was then started. An interval of 1 s separated the start of a trial from the response for the previous trial. The warning stimulus always preceded the cue by 500 ms, and the entire display remained in view until the subject responded. Reaction times were measured from the onset of the target.

Results and Discussion

Mean reaction times and proportions of errors were obtained for each subject as a function of precuing interval and preparation condition. Within each preparation condition, the data were averaged across target positions. The means of the reaction times are shown in Figure 1.

An analysis of variance performed on the reaction time data indicated main effects for precuing interval, $F(4, 92) = 91.2$, $p < .001$, and for preparation condition, $F(3, 69) = 24.2$, $p < .001$, as well as an interaction of precuing interval with preparation condition, $F(12, 276) = 11.39$, $p < .001$. The main effect for precuing interval reflects an overall decrease in reaction time as the interval increased (*M*s = 725, 591, 580, 535, and 527 ms for intervals of 0, 375, 750, 1,500, and 3,000 ms, respectively), whereas the main effect for preparation condition indicates faster responses for the *prepared:hand* condition (*M* = 555 ms) than for the other three cuing conditions, which did not differ reliably from each other (*M*s = 607, 593, and 612 ms for the *unprepared, prepared:finger,* and *prepared:neither* conditions, respectively).

The interaction of Precuing Interval × Preparation Condition indicates, however, that the relative advantage for the *prepared:hand* condition was not present at all precue-target delays. For delays of up to 750 ms, the results replicate closely those of Miller (1982). When the precuing interval was 0 ms, there was no benefit for the *prepared* conditions relative to the *unprepared* condition. In fact, the *prepared:finger* and *prepared:neither* conditions were reliably slower than the *unprepared* and *prepared:hand* conditions. For intervals of 375 ms and 750 ms, the *prepared:hand* condition

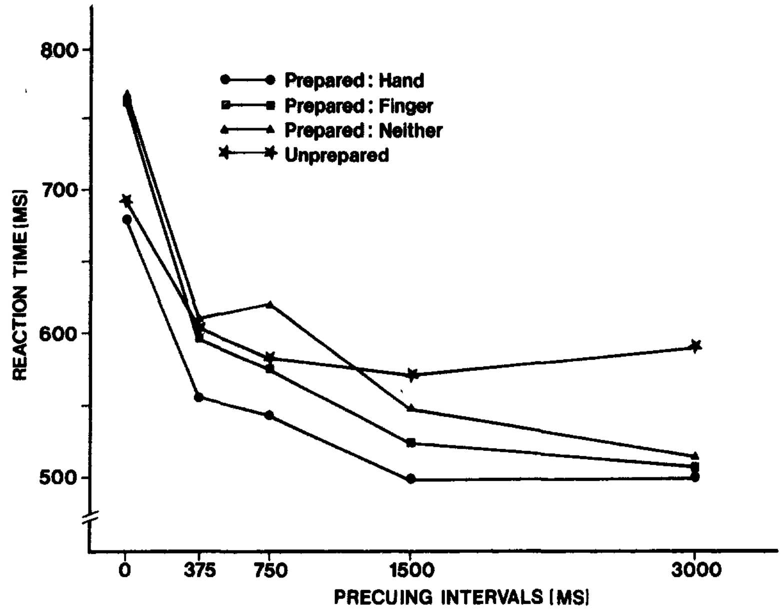

Figure 1. Mean reaction times for *prepared* and *unprepared* conditions as a function of precuing interval in Experiment 1.

showed an advantage relative to the other three conditions, which did not differ from each other.

By 3,000 ms, however, the results were consistent with those obtained by Goodman and Kelso (1980) and Stelmach and Larish (1981) for arm movements. There was no difference in response latencies among the three *prepared* conditions, with all being reliably faster than the *unprepared* condition. The 1,500-ms delay produced a transitional pattern of results intermediate to those apparent at shorter and longer delays. Thus, with sufficient time, all pairwise combinations of the four finger responses can be equally well prepared.

The error data were generally consistent with those from Miller's (1982) experiment. As in his experiment, an analysis of variance indicated only a main effect for preparation condition, $F(3, 69) = 3.12, p < .05$, with neither the main effect for precuing interval, $F(4, 92) = 2.11, p > .05$, nor the Precuing Interval × Preparation Condition interaction, $F(12, 276) = 1.16, p > .05$, being significant. Subjects made the fewest errors in the *unprepared* condition (2.4%), followed by the *prepared:hand* (3.0%), *prepared:neither* (3.7%), and *prepared:finger* (4.0%) conditions. However, when the precuing interval was 3,000 ms, the percentage of errors was greater in the *unprepared* condition (3.6%) than in any of the *prepared* conditions (*M*s = 2.3%, 3.4%, and 2.1% for the *prepared:hand, prepared:finger,* and *prepared:neither* conditions, respectively). Thus, the reaction time advantage for the *prepared* conditions at that interval is not attributable to response bias, although the advantage for the *prepared:hand* condition at shorter intervals might have a bias component.

One possible basis for the *prepared:hand* advantage at the short precuing intervals lies in the arrangement of the precue stimuli. The plus signs were in closer spatial proximity for the *prepared:hand* condition than for the other *prepared* conditions. Thus, the advantage for the *prepared:hand* condition might reflect an ability to encode or prepare the particular precued locations more rapidly when the plus signs are in close proximity than when they are further apart (see, for example, Hoffman & Nelson, 1981). Miller (1982) considered this possibility but discounted it because in his study reaction times in the *prepared:finger* condition were of similar magnitudes regardless of whether the index or middle fingers were precued. If spatial proximity were the critical factor, responses should be faster when the index fingers are precued than when the middle fingers are, because the cue locations (and target locations) are in closer proximity for the former situation than for the latter. In the present experiment, responses were slower for precued index fingers (M = 635 ms) than for precued middle fingers (M = 553 ms), again providing evidence against the spatial-proximity account. Thus, the spatial proximity of the precue or target locations in the visual display is apparently not the factor that produces the benefit for the *prepared:hand* condition at short precuing intervals.

Experiment 2

Experiment 1 clearly demonstrated that, with sufficient time, any pair of the four finger responses can be equally well prepared. The question remains, however, of why responses are faster in the *prepared:hand* condition than in the other two precued conditions when the precuing interval is 1,500 ms or less. Although a simple perceptual explanation can be eliminated for this same-hand advantage that occurs at short precuing intervals, the advantage may have its basis in the decision processes that relate the stimulus to the appropriate response. Alternatively, the advantage at short intervals might indicate that responses on the same hand can be prepared more rapidly than can responses on different hands, even though all response combinations can be prepared equally well given sufficient time.

This issue is important not only because of its implications for response preparation but also because of its implications regarding Miller's (1982) extension of the procedure to the evaluation of discrete versus continuous models of information processing. That is, as indicated previously, for other stimulus situations Miller interpreted the existence of a same-hand benefit as indicating the use of partial stimulus information to prepare responses. If responses on the same hand can be prepared more rapidly than those on different hands, Miller's interpretations remain valid. However, if the advantage for the *prepared:hand* condition at short precuing intervals is attributable to decision processes, then the validity of his technique as a means for evaluating continuous and discrete models of information processing is seriously questioned. The remaining experiments were designed, therefore, to determine whether the same-hand advantage evident at short preparation intervals is attributable to motoric or to nonmotoric processes.

Experiment 2 pursued the peculiar pattern of results obtained when the precue and target occurred simultaneously. In both our Experiment 1 and Miller's (1982) Experiment 1, the *prepared:hand* condition was faster than the *prepared:finger* and *prepared:neither* conditions, even when the target occurred simultaneously with the precue. That the advantage for the *prepared:hand* condition was evident with simultaneous presentation of the precue and target suggests that response preparation is not the cause of the advantage, because the time for response preparation should be minimal, at most, when the precue does not precede the target.

What is even more strange is that when the cue and target were presented simultaneously, the advantage for the *prepared:hand* condition occurred primarily because of interference with responding in the *prepared:finger* and *prepared:neither* conditions. That is, responses in both of those conditions were slower than responses in the *unprepared* condition. This interfering effect of the precue is unusual in that valid cues should produce, at worst, response latencies that do not differ from a noncued condition. It also suggests that factors other than response preparation influence performance on the task. The purpose of Experiment 2 was to determine why the pattern of interference occurred when precues and targets were presented simultaneously and whether the precuing advantage for the *prepared:hand* condition would hold up if this interference were eliminated.

In Experiment 1, 80% of the trials had a nonzero precuing interval and, thus, provided time for the initiation of preparatory processes. This large percentage of trials on which there was a lag between precue and target onsets could be expected to cause subjects to adopt active strategies for preparation that are, in fact, inappropriate when the target occurs at the same time as the cue (see Posner & Snyder, 1975, for a related argument based on trial percentages). Such strategies would likely involve attending to the cue positions in the stimulus array and deciding which responses were indicated. In any case, the interference most likely would be attributable to processes preceding the actual response preparation.

To examine the possibility that the interference evident with simultaneous presentation reflects active processing strategies, we varied the percentage of trials on which the precue and target occurred simultaneously. All nonsimultaneous trials used a 3,000-ms delay. For one condition, there was a 0-ms delay between precue and target onsets on 20% of the trials, with a 3,000-ms delay on the remaining 80% of the trials. This condition replicates the percentage of simultaneous trials used in Experiment 1. For the other condition, the cue and target occurred simultaneously on 80% of the trials, with a 3,000-ms delay occurring on 20% of the trials. If the interference obtained in Experiment 1 when the cue and target occurred simultaneously is attributable to subjects' actively using the cue information, it should be replicated when the percentage of simultaneous trials is 20% and be absent, or at least greatly reduced, when the percentage of simultaneous trials is 80%.

Method

Eighteen students from the same subject pool as in Experiment 1 participated in two sessions on consecutive days. The data from an additional subject were excluded for failure to return for the second session. None of these subjects participated in Experiment 1.

The apparatus and stimuli were the same as in Experiment 1, with the exception that cue delays of only 0 ms and 3,000 ms were used. Lists of trials were shortened to 240 test trials, plus 30 practice trials. Two types of lists were constructed—one in which 20% of the trials had the 0-ms cue-target delay and 80% had the 3,000-ms delay (the 20%-simultaneous condition)—and another in which the percentages were reversed (the 80%-simultaneous condition). Within each delay, an equal number of trials occurred for all four precuing conditions (12 per condition for the less frequent precuing interval and 48 per condition for the more frequent precuing interval), with each particular cue-target combination occurring equally often. Two separate list orders were constructed for each of the percentage conditions.

Subjects received the percentage conditions in separate sessions. They were told the relative percentages of simultaneous and 3,000-ms delay trials but were not told specifically to use this information.

Results and Discussion

The primary data analyses were again based on subjects' responses collapsed across target positions within each cuing condition. Mean reaction times and proportions of errors were calculated for each subject. Figure 2 contains the group means for the reaction times.

An analysis of variance revealed significant main effects for percentage simultaneous, $F(1, 17) = 13.31$, $p < .01$, preparation condition, $F(3, 51) = 9.68$, $p < .01$, and precuing interval, $F(1, 17) = 20.08$, $p < .01$. Subjects' reaction times were faster in the 80%-simultaneous condition ($M = 567$ ms) than in the 20%-simultaneous condition ($M = 627$ ms); they also were faster in the *prepared* conditions (Ms = 575, 595, and 604 ms for the *prepared:hand, prepared:finger,* and *prepared:neither* conditions, respectively) than in the *unprepared* condition ($M = 614$ ms). In addition, responses were quicker when the precuing interval was 3,000 ms ($M = 571$ ms) than when it was 0 ms ($M = 623$ ms).

As in Experiment 1, the Preparation Condition × Precuing Interval interaction was significant, $F(3, 51) = 13.24$, $p < .01$, replicating the convergence of the response latencies for the *prepared* conditions at the 3,000-ms precuing interval. Also, the Percentage Simultaneous × Precuing Interval interaction was significant, $F(1, 17) = 8.59$, $p < .01$. This interaction is attributable to the decrease in reaction times from the 0-ms precuing interval to the 3,000-ms interval being greater in the 20%-simultaneous condition (77-ms decrease) than in the 80%-simultaneous condition (29-ms decrease).

The most important outcome, however, was a significant three-way interaction of Percentage Simultaneous × Preparation Condition × Precuing Interval, $F(3, 51) = 6.55$, $p < .01$. This interaction indicates that the relationship between the functions for the preparation conditions was different when the percentage of simultaneous trials was 80% than when it was 20%. When 20% of the trials had simultaneous onset of the cue and target, the results were similar to those obtained in Experiment 1. At 0 ms, reaction times did not differ between the *unprepared* and *prepared:hand* conditions but were faster than responses in the *prepared:finger* and *prepared:neither* conditions. At 3,000 ms, responses in all *prepared* conditions were faster than those in the *unprepared* condition.

When 80% of the trials were simultaneous,

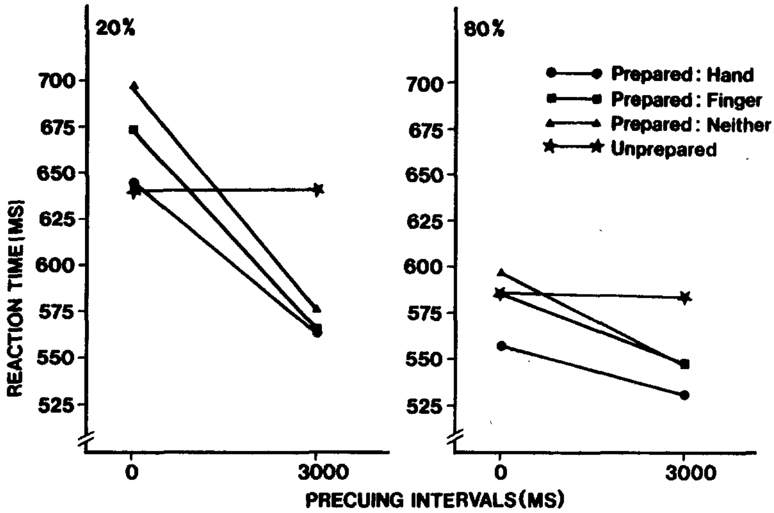

Figure 2. Mean reaction times for *prepared* and *unprepared* conditions as a function of precuing interval in the 20%- and 80%- simultaneous conditions of Experiment 2.

similar results were obtained for the cue-target delay of 3,000 ms. All *prepared* conditions showed a benefit relative to the *unprepared* condition. However, for the cue-target delay of 0 ms, the pattern differed from that obtained when 20% of the trials were simultaneous (as well as from Experiment 1). Responses were no slower in the *prepared:finger* and *prepared:neither* conditions than in the *unprepared condition,* with all three of these conditions showing slower responses than the *prepared:hand* condition. Thus, the interference obtained for the *prepared:finger* and *prepared:neither* conditions when the cue and target occur simultaneously is eliminated when the majority of trials have simultaneous onset. Despite eliminating this interference in the 80%-simultaneous condition, the advantage for the *prepared:hand* condition relative to the other *prepared* conditions was still present.

The results of Experiment 2 are, thus, consistent with the hypothesis that the interference obtained in the *prepared:finger* and *prepared:neither* conditions when the cue and target occur simultaneously reflects active processing strategies employed by the subjects. That is, because this interference is eliminated when simultaneous trials are frequent, it is not an automatic consequence of the simultaneous occurrence of cue and target. Rather, it is a consequence of subjectively determined strategies.

Interestingly, the advantage for the *prepared:hand* condition relative to the other *prepared* conditions was maintained even when the interference for the latter conditions was eliminated (i.e., in the 80%-simultaneous condition). With the elimination of the interference, the *prepared:hand* condition now also showed a benefit relative to the *unprepared* condition. Thus, the interference also operates in the *prepared:hand* condition when 20% of the trials are simultaneous, offsetting the benefit that is clearly apparent when 80% of the trials are simultaneous.

Analysis of the error data revealed no significant effects. The percentage of errors was low for all conditions: *prepared:hand,* $M = 1.8\%$; *prepared:finger,* $M = 2.8\%$; *prepared:neither,* $M = 1.8\%$; *unprepared,* $M = 1.9\%$.

Experiment 3

Experiments 1 and 2 both showed that with sufficient time, precuing any combination of two finger responses results in approximately equivalent benefits. Experiment 2 also showed that the interference obtained when the precue is presented simultaneously with the target apparently reflects active strategies that are employed when simultaneous onset is unexpected. In both experiments, however, at short intervals, precuing two responses on the same hand produced a benefit that was not obtained when the responses were on different hands.

This benefit for the *prepared:hand* condition might be attributable to an ability to prepare two responses more quickly when they are on the same hand. However, with the method used in Experiments 1 and 2, the specific precuing stimuli, as well as the spatial relationships between these stimuli and the responses that they signify, are confounded with the hand distinction. In the discussion of Experiment 1, evidence was presented suggesting that the stimuli themselves are not critical (i.e., that the advantage for the *prepared:hand* condition does not have a perceptual basis in the relative proximity of the cue locations). That the benefit could be due to the spatial relationship between the stimuli and responses, though, remains a likely possibility.

Previous studies (Goodman & Kelso, 1980; Stelmach & Larish, 1981) have shown that with precuing procedures, response latencies in the alternative precuing conditions can be differentially affected by decision factors when stimulus–response relationships are incompatible. Although the stimulus–response relationships used in Experiments 1 and 2 and in Miller's (1982) Experiment 1 are spatially compatible, similar decision factors might still be involved. That is, there may be less uncertainty regarding which two responses are being cued when the two precued locations are either both to the left or both to the right (the situation for the *prepared:hand* condition) than when they are not (the situation for the *prepared:finger* and *prepared:neither* conditions).

Experiment 3 dissociated the hand and spatial-position factors by varying hand placement. To allow different hand placements, the four adjacent keys centered in the bottom row of the keyboard were used. As shown in Table 2, one group of subjects placed their hands in a manner similar to the placements used in Experiments 1 and 2, with the exception that the hands were now adjacent. The other group of subjects placed their hands on these same keys, but in an overlapped manner, so that the fingers from each hand were alternated on the keyboard. This overlapped-hands condition maintains the direct stimulus–response mapping of the adjacent-hands condition (i.e., the relationship between the targets and keys remains spatially compatible), but interchanges the spatial relationships of the responses cued for the *prepared:hand* and *prepared:neither* conditions. That is, when hands are overlapped, the precues for the *prepared:neither* condition signal either the two left-most or two right-most positions on the keyboard, which are the positions precued for the *prepared:hand* condition when hands are adjacent. The precues for the *prepared:hand* condition when hands are overlapped signal the spatial locations that correspond to those signaled in the *prepared:neither* condition when hands are adjacent. The spatial relationships for the *prepared:finger* and *unprepared* conditions do not change when hands are overlapped, although the specific assignment of fingers to keys is altered.

Table 2
Relative Finger Positions for the Adjacent and Overlapped Hand Placements in Experiment 3

Hands	Finger placement			
Adjacent	LM	LI	RI	RM
Overlapped	RI	LM	RM	LI

Note. L = left hand; R = right hand; M = middle finger; I = index finger.

The predictions from this manipulation of hand placement are straightforward. If the advantage for the *prepared:hand* condition found in the previous experiments reflects an ability to prepare two responses more rapidly when they are on the same hand, the advantage should occur not only when hands are adjacent but also when they are overlapped. Alternatively, if the spatial relationship of the precued responses is the critical factor, a benefit for the *prepared:neither* condition should be found when hands are overlapped that is of similar magnitude to that found for the *prepared:hand* condition when hands are adjacent.

Method

Thirty-two subjects, 16 in each of the two hand placement conditions, participated. All were from the same subject pool as the previous experiments, but none had participated in either. The data were excluded for 1 additional subject in the adjacent-hands condition because the subject held the keys down across trials.

As previously indicated, the placement of the hands on the keyboard was changed from that of Experiments 1 and 2. For half of the subjects, the hands were placed adjacent to each other so that the middle and index fingers of the left hand and the index and middle fingers of the right hand were to depress the *V*, *B*, *N*, and *M* keys (the four center keys on the bottom row of the keyboard), respectively. This placement is similar to that used in the previous experiments, with the exception that the hands were placed closer together. For the other half of the subjects, the fingers were overlapped and alternated, so that the placement of the fingers from left to right was right index finger, left middle finger, right middle finger, and left index finger (see Table 2). Half of these subjects performed with their left hand on top, whereas the other half performed with their right hand on top (the order of overlap does not alter the placement of fingers on keys). The four fingers depressed the same four keys used in the adjacent-hand condition. It is important to emphasize that the stimulus–response mapping was equally compatible for the two conditions and that the overlapping of the hands switched the spatial relationships of the precued responses (and the corresponding stimuli) for the *prepared:hand* and *prepared:neither* conditions but did not alter the spatial relationships for the *prepared:finger* and *unprepared* conditions. With the exception of the changes noted earlier, the method was the same as that of Experiment 1.

Table 3
Mean Reaction Times (in ms) for Adjacent and Overlapped Hand Placements as a Function of Precuing Intervals in Experiment 3

Preparation condition	Precuing interval (ms) 0	375	750	1,500	3,000
Adjacent hands					
Unprepared	620	548	527	535	524
Prepared:Hand	610	496	485	460	458
Prepared:Finger	643	504	500	469	466
Prepared:Neither	663	535	543	506	487
Overlapped hands					
Unprepared	814	761	770	738	770
Prepared:Hand	864	786	764	718	692
Prepared:Finger	873	762	741	699	655
Prepared:Neither	849	735	727	657	639

Results and Discussion

The mean reaction times as a function of hand placement, cue, and precuing interval are shown in Table 3. An analysis of variance performed on the reaction time data showed significant main effects for hand placement, $F(1, 30) = 31.37$, $p < .01$, preparation condition, $F(3, 90) = 9.35$, $p < .01$, and precuing interval, $F(4, 120) = 58.77$, $p < .01$. Subjects with the overlapped hand placement had slower reaction times ($M = 751$ ms) than did subjects with the adjacent hand placement ($M = 529$ ms). The main effect for preparation condition was attributable to responses for the *prepared* conditions (*M*s = 634, 631, and 634 ms for the *prepared:hand, prepared:finger,* and *prepared:neither* conditions, respectively) being faster than those for the *unprepared* condition ($M = 660$ ms), but not differing reliably between each other. The effect of precuing interval was, again, attributable to reaction times decreasing as the interval increased.

Two interaction effects were significant. The Preparation Condition × Precuing Interval interaction, $F(12, 360) = 5.72$, $p < .01$, reflects the decreasing and converging reaction times of the *prepared* conditions relative to the *unprepared* conditions. This finding replicates the convergence of the *prepared* conditions found in Experiments 1 and 2.

The other significant effect was the Hand Placement × Preparation Condition interaction, $F(3, 90) = 16.09$, $p < .01$. The means for this interaction are presented in Table 4. For both hand placements, the *unprepared* and *prepared:finger* conditions had the same relative positions, with reaction times being slowest in the *unprepared* condition and next to the fastest in the *prepared:finger* condition. The consistency of these conditions across hand placements was expected because the spatial relationships of the stimuli and the responses are the same for both placements. A reversal between the hand-placement conditions occurred for the *prepared:hand* and *prepared:neither* conditions. When the hands were adjacent, the *prepared:hand* condition produced the fastest reaction time, as in Experiments 1 and 2. However, when the hands were overlapped, the fastest responses were obtained for the *prepared:neither* condition. Thus, the facilitating effect for precuing responses on the same hand, when the hands were adjacent, was obtained for the precuing of two different fingers on different hands when the hands were overlapped.

The results of the present experiment show that the same-hand advantage found at short intervals in the previous experiments, as well as in the adjacent-hands condition of this experiment, is not attributable to an ability to more rapidly prepare responses that are on the same hand. Rather, the advantage is associated with the spatial relationships of the

Table 4
Mean Reaction Times (in ms) for the Hand Placement × Preparation Condition Interaction

Preparation condition	Hand placement: Adjacent hands	Hand placement: Overlapped hands
Unprepared	551	771
Prepared:Hand	502	765
Prepared:Finger	516	746
Prepared:Neither	547	721

stimulus and response locations involved in the respective *preparation* conditions. This association between the precuing advantage and the spatial relationships is most clearly illustrated by calculating the facilitating effects for the various *preparation* conditions. When hands were adjacent, the *prepared:hand* condition showed a benefit of 49 ms (i.e., the mean for the *unprepared* condition minus the mean for the *prepared:hand* condition, 551 − 502 = 49 ms), whereas the *prepared:neither* condition showed a benefit of only 4 ms. However, when hands were overlapped, reversing the assignment of spatial locations for the *prepared:hand* and *prepared:neither* conditions, the relative facilitation for these conditions also was reversed. The *prepared:neither* condition showed a benefit of 50 ms, whereas the *prepared:hand* condition showed a benefit of only 6 ms.

Analysis of the error data indicated a significant main effect for hand placement, $F(1, 30) = 6.30$, $p < .05$. Subjects in the adjacent-hand condition ($M = 1.9\%$) made fewer errors than subjects in the overlapped hand condition ($M = 3.9\%$). The Hand Placement × Cue × Precuing Interval interaction was also significant, $F(12, 360) = 2.01$, $p < .05$, but no consistent pattern of errors across the experimental conditions was apparent.

General Discussion

The precuing of discrete finger responses has been found previously to be of benefit only when the cued responses were on the same hand (Miller, 1982). The present study thoroughly examined this same-hand advantage and found that it is not a response preparation effect, as Miller concluded. Experiment 1 demonstrated that with sufficient time (3 s), subjects can prepare responses on different hands as efficiently as they can responses on the same hand.

The same-hand advantage was apparent at short precuing intervals in our Experiment 1 as it also was in Miller's (1982) experiment. When the precue and target occurred simultaneously, this advantage appeared as interference for precued responses on different hands, rather than as facilitation for precued responses on the same hand. Experiment 2 showed that this interference is attributable to subjective strategies being employed when simultaneous presentation of the precue and target is relatively unlikely. The interference was eliminated when simultaneous occurrence was likely, but the same-hand advantage was still evident. The advantage now appeared as a facilitation effect similar to that found at the other short precuing intervals.

Experiment 3 revealed, however, that this same-hand advantage at short precuing intervals is not due to an ability to more rapidly prepare responses that are on the same hand. In one condition, hands were overlapped, so that the specific stimulus–response locations were exchanged between two preparation conditions (the *prepared:hand* and *prepared:neither* conditions). The advantage was found to be a function of the stimulus–response locations and not of whether the precued responses were on the same or different hands. Together, the three experiments show that task factors, such as precuing intervals, stimulus-onset probabilities, and stimulus–response relationships, affect response preparation; however, there is no differential ability to prepare responses on the same hand as opposed to ones on different hands.

The fixed-order hypothesis for the specification of discrete finger responses states that the hand must be selected prior to the specification of the particular finger on the hand (Rosenbaum, 1983). According to this hypothesis, precuing should produce a benefit only when the cued responses are on the same hand (i.e., there should be a same-hand advantage). However, the present experiments found that there is no differential ability to prepare responses as a function of whether they are on the same or different hands. Thus, the fixed-order hypothesis is not a viable description of the response preparation process for discrete finger responses.

The preparation of finger responses is variable, rather than fixed order, because responses can be effectively prepared in advance when they are on different hands. For limb movements, the term *variable* has been used to refer to the order in which components of the movements are specified (e.g., arm, direction, and extent components; Rosenbaum, 1980, 1983). However, discrete finger responses do not seem to be specified in terms of finger (index, middle) and hand (left, right) components. If such were the case, no benefit should occur for precuing different fingers on different hands (the *prepared:neither* condition), because neither component is specified by the precue. In the present experiments, though, the *prepared:neither* condition showed a precuing benefit similar to that shown by the other *prepared* conditions. Thus, for discrete finger responses, *variable* refers to the ability to select any subset of responses indicated by the precue and not to the specification of movement components.

At short intervals, a precuing benefit was apparent for some preparation conditions, but not for others. When hands were adjacent, this benefit occurred when the precued responses were on the same hand (the *prepared:hand* condition). However, when hands were overlapped, the benefit occurred for responses on different hands (the *prepared:neither* condition). Thus, this benefit is not a response preparation effect (i.e., an ability to prepare only responses that are on the same hand; Miller, 1982).

Rather than being associated with the hand distinction, the precuing benefit at short intervals is associated with the left–right distinction of the stimulus–response arrangement. That is, the benefit occurs for preparation conditions in which the precue specifies the two left-most or two right-most responses. In these conditions, the precued locations are also in the closest spatial proximity. However, spatial proximity is not the critical factor because, as indicated previously, no similar benefit is found at short intervals for precued index fingers, even though the precued locations are also in close proximity for this situation. Thus, clearly the left–right relationship is the critical factor.

Because this left–right distinction is important only at short precuing intervals, it apparently reflects the relative ease with which the precued responses can be identified. That is, subjects can more rapidly determine the responses that are precued when the cued locations are both to the left or both to the right. These response-selection decisions are nonmotoric processes that occur prior to response preparation (Kerr, 1978).

Several authors (Goodman & Kelso, 1980; Stelmach & Larish, 1981; Zelaznik, 1978; Zelaznik, Shapiro, & Carter, 1982) have argued that for some precuing situations, nonmotoric factors are confounded with motoric factors in the reaction time measure. When incompatible stimulus–response mappings are used, a nonmotoric transformation, or response selection, process is required that can differentially affect reaction times for the various preparation conditions (Goodman & Kelso, 1980; Stelmach & Larish, 1981). Response selection has not been considered to be a factor, however, when stimulus–response mappings are compatible (Goodman & Kelso, 1980; Stelmach & Larish, 1981). Such appears to be the case in the present experiments when the precuing interval allows sufficient time to process the precue information.

The present experiments demonstrate, however, that a related, but different, type of confounding occurs in highly compatible situations when the precuing interval is short. The reaction time measure is confounded with the time to identify and select the responses indicated by the precue. That is, an implicit assumption of the precuing procedure is that reaction time to the target is affected only indirectly by the information provided by the precue and not directly by the processing of the precue itself. This assumption requires that adequate time be provided to process the precued information before the target occurs, as is the case in most precuing studies. When the precuing interval is short, as in Miller's (1982) experiment and at the intervals of 1,500 ms or less in the present experiments, the assumption is invalid because the requirement of adequate time to process the precue is not met. Thus, differences in reaction time between preparation conditions occur that are attributable to the time to select the precued responses, rather than to the preparation that is possible once response selection is completed.

Miller (1982; Experiment 1) found a precuing advantage for responses on the same hand and concluded that this advantage was a fixed-order, motoric, response preparation effect. He then developed methods that were based on this assumed response preparation effect to evaluate discrete and continuous models of information processing. These methods did not use a separate precue stimulus but varied the time at which partial information from the target stimulus would be available to indicate hand (left, right) or finger (index, middle). Because the partial information is available only shortly before the additional information, the situation is analogous to that in which the precuing interval is short. Miller's extension of the precuing procedure, thus, suffers from the same problem of confounding selection and preparation processes that occurs when precuing intervals are short. At best, the same-hand advantage obtained by Miller in these other situations cannot be attributed entirely to response preparation. Given that the present experiments show no evidence of a response preparation effect for discrete finger responses, response preparation likely plays no role in Miller's (1982, 1983) experiments that were intended to distinguish between discrete and continuous models of information processing.

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