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A Hand Advantage in Preparation of Simple Keypress Responses: Reply to Reeve and Proctor (1984)

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Miller (1982) introduced an experimental paradigm to discriminate between discrete (e.g., Sternberg, 1969) and continuous (e.g., McClelland, 1979) information processing models. The paradigm required the assumption that preparation of two response fingers on the same hand leads to faster responses than does preparation of two fingers on different hands, at least with the response set used. Data supporting this assumption were obtained using a movement precuing experiment. However, Reeve and Proctor (1984) challenged the assumption, noting a potential artifact in the design of the experiment supporting it. They repeated that experiment, including an additional response set to correct the artifact, and obtained results contrary to the assumption in question. It is argued that the new response set used to correct for the artifact was very different from the original response set and that results obtained with this response set cannot be used to draw conclusions about preparation of the original responses. A new experiment is reported that corrects the artifact using a response set similar to the one used by Miller (1982), and the results support the assumption in question.

Miller (1982) developed an experimental paradigm to compare discrete stage (e.g., Sternberg, 1969) and continuous output (e.g., McClelland, 1979) models of human information processing. Specifically, the paradigm was designed to determine whether response preparation can begin before stimulus recognition finishes, as assumed by continuous models but prohibited by discrete models. The results supported a class of models intermediate between the discrete and continuous extremes, referred to by Miller (1982, 1983) as *asynchronous discrete coding* models. In these models, response preparation can begin as soon as the recognition process has completely identified a distinct stimulus attribute or code (Garner, 1974; Posner, 1978), even if other stimulus attributes have not yet been fully recognized. Response preparation cannot begin if an attribute has been only partly recognized.

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Reeve and Proctor (1984) disputed an assumption critical to the paradigm used by Miller (1982): that a small amount of preparation of two response fingers on the same hand leads to faster responses than does a small amount of preparation of two fingers on different hands, at least with the responses actually used in the experiments. Miller (1982) obtained data supporting this assumption in an experiment using the movement precuing technique (Rosenbaum, 1980). However, Reeve and Proctor (1984) pointed out a potential artifact in the design of the precuing experiment and repeated the experiment using an additional response set to correct the artifact. With the new response set, preparation of two response fingers on the same hand did *not* produce faster responses than did preparation of two fingers on different hands, and they concluded that the artifact was probably responsible for the preparation effect in the original cuing study. These results led them to reject the assumption in question and to express serious doubt about Miller's paradigm and conclusions.

In this article, the paradigm introduced by Miller (1982) is defended against Reeve and Proctor's criticisms. It is argued that the new response set they used to eliminate the artifact involved responses quite different from those used in Miller's (1982) original experiments. Preparation effects with these responses might well be different from preparation effects with the original responses, and it is not surprising that preparation favored different pairs of fingers. Because the original paradigm did not require the assumption that fingers on the same hand would benefit most from preparation for any response set, the results of Reeve and Proctor are not damaging to it. A new experiment is reported that corrects the suspected artifact by using responses similar to the ones used originally (Miller, 1982), and the results provide further evidence for the assumption required by Miller's (1982) paradigm.

In defense of Miller's (1982) paradigm, it is also argued that the artifact noted by Reeve and Proctor (1984) could account for at most a small number of the results reported by Miller (1982) and is therefore not very plausible as an alternative hypothesis.

The Hand-Preparation Advantage

To study the interface between perceptual and response processes, Miller (1982) used choice reaction-time (RT) tasks with four alternative keypress responses made by the index and middle fingers of the two hands. Subjects responded using four keys on the bottom row of a computer keyboard, and they placed their fingers on keys in the most natural fashion (left middle finger on the leftmost key, then left index finger, etc.). Miller's (1982) paradigm was based on the assumption that *for this response set* responses would be faster if there were advance preparation of two response fingers on the same hand than if there were advance preparation of two response fingers on different hands, at least for small amounts of advance preparation (less than 1 s). A movement precuing experiment (Rosenbaum, 1980, 1983) was used to establish this hand-preparation advantage. In this experiment a target stimulus was a plus sign appearing in one of four positions in a horizontal row, and targets were assigned to response keys in the most compatible left-to-right order (i.e., leftmost position to leftmost key, etc.). On each trial, three rows of visual stimuli were presented. First, a warning signal was presented in the top row. It had four plus signs showing the four possible stimulus positions, and it remained on throughout the trial. Next, the middle row appeared directly below the warning signal, and it was a cuing stimulus that gave partial advance information (Kantowitz & Sanders, 1972) about the upcoming response. This row had plus signs in two of the four positions, and subjects could selectively prepare the two responses indicated by the middle row. The cuing stimulus also remained on for the remainder of the trial. Finally, the target stimulus was presented in the bottom row, located directly below the other two rows. This stimulus was a single plus sign in one of the four positions. Subjects were to respond by pressing the response key associated with this position as quickly as possible.

In this paradigm, Miller (1982) used cuing stimuli corresponding to four different response preparation conditions. In the *prepared: hand* condition, the cue indicated the two leftmost or rightmost positions, thereby enabling preparation of two fingers on the same hand, either left or right. In the *prepared: finger* condition, the cue indicated the two inside or two outside positions, thereby enabling preparation of two homologous fingers on different hands, either index or middle. The other two pairs of positions were cued in the *prepared: neither* condition, indicating preparation of the index finger of one hand and the middle finger of the other. Finally, there was an *unprepared* condition in which cues appeared in all four positions, so no selective preparation of responses was possible.

Overall, responses were approximately 50 ms faster in the *prepared: hand* condition than in any of the others, which were all approximately the same. Miller (1982) attributed this advantage to more efficient response preparation with cuing of two fingers on the same hand than with cuing of fingers on different hands. It is also relevant that the size of the hand advantage initially increased with the time between cue and test stimulus (preparation interval), leveling off at an interval of about 400 ms. As preparation interval increased from 125 to 375 ms, the hand advantage more than doubled. Though the small hand advantage at the shortest preparation intervals might result from other factors, the increase in the effect with increasing interval strongly suggests a preparatory effect of the cuing information.

The hand-preparation advantage is important for two reasons. First, it can help determine whether certain stimulus attributes enable response preparation to begin before the stimulus as a whole has been identified, using the paradigm developed by Miller (1982). For example, Miller (1982, Experiment 2) used four consonant–vowel pairs as stimuli (*BE, BO, ME, MO*) and varied the assignments of stimuli to responses. When the consonant was presented before the vowel, responses were faster if the two responses consistent with the consonant were on the same hand than if they were not, and this advantage increased with the time between the consonant and the vowel. This finding suggests that the consonant can be used to prepare responses on the indicated hand before the vowel has been recognized. In another experiment (Miller, 1982, Experiment 3), the stimuli were four letters varying in name and size—*s, S, t, T,* with the name discrimination much easier than the size discrimination. With these stimuli, responses were faster if the two responses consistent with each letter name were on the same hand than if they were not, suggesting that letter name could be used to start preparing responses before size had been determined. Thus, the paradigm indicates whether or not an attribute allows response preparation by comparing conditions that differ only in the benefit that would be received from preparation. Such conditions will differ only if preparation does take place.

Second, the hand-preparation advantage has implications about the structure of the motor system components responsible for control of finger movements, components that are particularly interesting because of the sophistication of finger control, the practical implications for tasks like typing and piano playing (Shaffer, 1975, 1981), and the methodological implications for studies using manual RT. It is generally assumed that properties of the motor system are revealed in studies of how various pairs of movements are selected and prepared together (e.g., Rosenbaum, 1980, 1983; Rosenbaum & Kornblum, 1982). Specifically, if a pair of responses is especially easy to prepare together, they are thought to share common attributes at a relatively high level within the motor system. Given this assumption, the hand-preparation advantage suggests that the attribute of hand often takes precedence within the system for manual control. Data in support of this conclusion have also been obtained in studies of serial finger movements, both typing and piano playing (Shaffer, 1975, 1981). One obvious possibility, consistent with much neurological evidence (e.g., Brinkman & Kuypers, 1973; Gazzaniga, 1970; Wiley, 1975), is that the system is structured hierarchically with hand at the highest level, but other possibilities have also been suggested (e.g., Goodman & Kelso, 1980). Though the mechanisms of motor preparation are interesting and important in their own right, it should be noted these mechanisms need not be specified before one can use the hand advantage to determine which stimulus attributes allow response preparation to occur.

Reeve and Proctor's (1984) Objections to the Hand-Preparation Advantage

Reeve and Proctor (1984) questioned the hand-preparation advantage because the *prepared: finger* and *prepared: neither* conditions were no faster than the *unprepared* condition. The lack of preparation in these two conditions suggests that response hand must be specified before any other attribute of the movement can be prepared. Most studies with other cued movements have found that any type of preparation is better than no preparation at all (Rosenbaum, 1983; but see Zelaznik, 1981), suggesting that movement attributes can be prepared in any order. Therefore, Reeve and Proctor conducted three additional experiments to see if the hand-preparation advantage observed by Miller was actually caused by response preparation or if it was caused instead by some nonmotoric factor(s) in the experimental setup. Their first two experiments were not directly incompatible with the hand-preparation advantage assumed by Miller (1982) and so will be discussed only briefly in this article. The third presented a major challenge to the critical assumption, however, so it will be considered in detail.

In Experiment 1, Reeve and Proctor (1984) replicated the hand-preparation advantage for preparation intervals of less than 1 s but found that the advantage disappears when the preparation interval is extended to 3 s. This finding is consistent with other evidence suggesting that hand preparation would lead to the *slowest* responses if even more preparation time were provided (Kornblum, 1965; Rosenbaum & Kornblum, 1982). As they acknowledged, one explanation of these results is that hand preparation is the best for brief preparation intervals, even it if is not the best for longer preparation intervals. Because all the experiments of Miller (1982) involved brief preparation intervals, this explanation is completely consistent with the assumption required for his paradigm.

Reeve and Proctor (1984) also emphasized the fact that they had obtained a hand advantage with simultaneous presentation of precue and target (Experiment 1). They argued that this effect "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" (p. 546). It is possible, however, that subjects adopt a strategy of using cues for some preparation even with simultaneous presentation. That is, subjects may partially process the cue before attending to the target even when both come on at the same time. Furthermore, even if response preparation is not the cause of the hand advantage with simultaneous presentation, the *increase* in this advantage with increasing preparation interval still suggests a preparation advantage for responses on the same hand.

In Experiment 2, Reeve and Proctor (1984) varied the percentage of trials with simultaneous presentation within a block (either 20% or 80%), using a 3-s preparation interval for the remaining trials. In previous experiments (Miller, 1982; Reeve & Proctor, 1984, Experiment 1) the hand advantage with simultaneous presentation was primarily an interference effect: The *prepared: finger* and *prepared: neither* conditions were slower than the *unprepared* condition, and the *prepared: hand* condition was only slightly faster than *unprepared*. In Experiment 2, this interference was again found in blocks with simultaneous presentation on only 20% of trials, but it was not observed in blocks where 80% of the trials had simultaneous presentation. This finding suggests that the interference results from active strategies of cue processing (Reeve & Proctor, 1984). This conclusion is not incompatible with the idea that the hand advantage is due to response preparation, however, because response preparation is known to be influenced by strategies (Requin, 1980; Sanders, 1983). In any case, the preparation intervals used in this experiment (0 s and 3 s) preclude any unambiguous conclusions about the hand advantage observed in the first few hundred milliseconds of preparation, and it is the latter advantage that is required for the paradigm of Miller (1982).

The third and most critical experiment of Reeve and Proctor (1984) addressed a potential cuing artifact in the experiment used to establish the hand-preparation advantage. Specifically, Miller (1982) used different pairs of stimulus locations as cues in the *prepared: hand, prepared: finger,* and *prepared: neither* cuing conditions. Reeve and Proctor (1984) pointed out that responses might have been fastest in the *prepared: hand* condition because the cues were easiest to process in that condition. Response preparation might have been identical for the three *prepared* conditions but simply initiated sooner in the *prepared: hand* condition because of faster cue processing. Thus, the hand-preparation advantage observed by Miller (1982) may not have arisen in the process of response preparation. If not, Miller (1982) erred in using the advantage to infer that response preparation was caused by preliminary information about a stimulus attribute. The effects attributed to preparation of responses using preliminary information might actually have arisen from some other mechanism.

To test this alternative explanation, Reeve and Proctor's (1984) third experiment was designed to show that the hand-preparation advantage disappears when the confounding between cue positions and type of response preparation is removed. They used the same stimuli, cues, and responses as Miller (1982) but varied the assignment of fingers to response keys. For half of the subjects, fingers were assigned to response keys in the compatible left-to-right order (*adjacent hands* condition) used by Miller (1982). For the other half, the hands were overlapped, so that the four response keys, from left to right, were pressed by the right index, left middle, right middle, and left index fingers (*overlapped hands* condition). Positional and response preparation effects of the cues could be separated by including both adjacent and overlapped hand positions, because the cues that indicated the *prepared: hand* condition for one group indicated the *prepared: neither* condition for the other group, and vice versa.

As predicted by their hypothesis of cuing stimulus effects, Reeve and Proctor (1984) found faster responses following cuing of the two leftmost or two rightmost response keys (a *side advantage*), even with overlapped hands. Averaging across hand positions to remove effects of cues, there was no overall advantage for cuing two fingers on the same hand versus cuing two fingers on different hands. Unfortunately, it is difficult to interpret this average, because the overall RTs were much larger with overlapped than adjacent hands (751 ms vs. 529 ms). With two unequally difficult response sets, it may be inappropriate to measure a "true" effect of hand preparation with an average across them. The effects with overlapped hands may have been exaggerated by whatever factor(s) increased overall RT (cf. Biederman & Tsao, 1979), and a true average hand advantage may have been concealed by an exaggerated counteracting effect in the overlapped condition.

A Reinterpretation of Reeve and Proctor's Results

Despite Reeve and Proctor's (1984) discussion, the results of their third experiment do not directly contradict the assumption on which the paradigm of Miller (1982) is based. The crux of Reeve and Proctor's (1984) argument is that the preparation effects resulted from differential processing of cuing stimuli (e.g., recognition, S–R translation) rather than from differential response preparation. However, the fact that the same cuing stimuli produced the fastest responses for both hand positions does not prove that the cuing stimuli were responsible for the speed of those responses,[1] nor does it rule out the possibility that those responses benefited from differential response preparation, consistent with the assumption of Miller (1982).

It is easy to explain *all* of the obtained cuing effects (Miller, 1982; Reeve & Proctor, 1984) in terms of response preparation, because response preparation could favor different pairs of fingers in different conditions. This would allow response preparation to produce a hand advantage with adjacent hands and a side advantage with overlapped hands. One plausible explanation[2] is that responses are coded with respect to spatial position (e.g., left or right of body midline) as well as hand (Nicoletti, Anzola, Luppino, Rizzolatti, & Umiltà, 1982; Wallace, 1971) and that preparatory cues are especially useful if they completely specify a response code. In the condition with overlapped hands, the unnatural arrangement of the fingers may have caused subjects to code responses in terms of spatial position rather than hand, in which case a stimulus indicating response side would produce a larger preparation effect than would a stimulus indicating response hand. With adjacent hands, of course, hand and spatial codes are completely confounded, so side cuing would produce a big response preparation effect no matter which response coding scheme the subjects used. Indeed, the hand-preparation advantage observed with adjacent hands may have resulted as much from cuing of spatial response codes as from cuing of hands.

Another factor may also have contributed to the tendency for response preparation to favor different pairs of fingers in different conditions: Preparation effects may depend on the movements being prepared (cf. Sternberg, Monsell, Knoll, & Wright, 1978). It should be emphasized that overlapping the hands not only reassigns movements to re-

[1] Note that it could easily have been just chance that the same cues signaled optimal preparation in both conditions. Because only three different classes of cuing stimuli were compared, this would occur randomly 33% of the time—hardly a remote possibility. Certainly, the co-occurrence cannot be taken as conclusive evidence that cue processing speed is an important source of variation among preparation conditions, let alone the only important source.

[2] I am indebted to David Rosenbaum for major contributions to this explanation.

sponse keys, but also *alters the set of response movements.* With hands overlapped, the fingers impede each others' movements, so the act of pressing a single key requires a more complicated motion than is needed with adjacent hands. Indeed, the data reported by Reeve and Proctor show quite clearly that overlapping the hands increases response difficulty. Though stimulus conditions were identical, RTs averaged 529 ms with adjacent hands versus 751 ms with overlapped hands, a highly significant difference, $F(1, 30) = 31.37$. $p < .001$). Introspection also suggests that different movements are required in the two conditions, as the reader can easily verify by typing the four letters *VBNM* with the hands in the adjacent and overlapped positions. If overlapping the hands introduced new movements, albeit with the same fingers, it could certainly have introduced new types of preparation as well, and these new types of preparation may have favored different pairs of fingers.

Because response preparation effects can easily account for the results with both adjacent and overlapped hands, the results of Reeve and Proctor's (1984) third experiment may simply indicate that preparation of two fingers on the same hand does not always lead to faster responses than does preparation of two fingers on different hands: specifically, not in the condition with overlapped hands. In Miller's experiments, the hands were always adjacent, however, and the paradigm requires only that there be a hand-preparation advantage with hands *in this position.* The paradigm uses the hand advantage with this response set to determine whether or not various stimulus attributes cause preparation, and it does not require specific assumptions about the mechanisms of preparation responsible for the advantage. Because the paradigm does not depend on the mechanism of preparation, it does not require a hand advantage for all possible sets of finger responses (i.e., all possible positions and movements), but only with the particular responses actually used. Admittedly, the label *hand-preparation advantage* is poor terminology to the extent that it suggests the advantage should be obtained for all hand positions.

The side advantage with overlapped hands may have important implications concerning the motor system even if it does not invalidate the paradigm of Miller (1982). It strongly suggests that the hand advantage with adjacent hands is not a consequence of a motor system requirement to specify hand first (Reeve & Proctor, 1984; Rosenbaum, 1980, 1983). This means that the hand-preparation advantage depends on the particular movements rather than being universal—a conclusion that also has other support. For example, Heuer (1982) showed that preparation of similar movements is more efficient than preparation of dissimilar movements, other things being equal. Thus, a normal hand advantage might disappear with overlapped hands if movements by fingers on the same hands became highly dissimilar in this condition. It is important to emphasize, however, that a dependence of the hand advantage on the response set does not contradict the assumption necessary for the paradigm introduced by Miller (1982), because that paradigm requires only that there be a hand-preparation advantage with adjacent hands.

Though response preparation provides a reasonable account of the results of Reeve and Proctor (1984) as well as those of Miller (1982), it is also instructive to consider Reeve and Proctor's alternative idea that the cuing stimuli cause the advantages attributed to response preparation. One shortcoming of this alternative explanation is that it does not address the hand advantage observed with other stimulus sets (e.g., *BE, BO, ME, MO; s, S, T,* and *T*), in which cuing stimuli and preparation conditions could be counterbalanced to eliminate cuing stimulus artifacts. Such effects would be expected if the hand advantage results from response preparation, and they are strong evidence that the hand advantage in the cuing paradigm was not an artifact of the cuing stimuli (Rosenbaum, 1983). Indeed, no explicit cues were even presented in Miller's (1982) later studies. Second, the explanation does not account for the lack of preparation effects in *prepared: finger* and *prepared: neither* conditions, neither of which was faster than the *unprepared* condition. If preparation in these conditions simply began later due to difficulty in processing the cues, there should still have been some preparation with a full second between cue and stimulus. Third, the cuing explanation also seems incompatible with the time course of the hand advantage. If the advantage results from faster recognition of certain cues, it should develop across preparation intervals long enough to allow recognition of those cues but too short to allow recognition of the other cues (assuming preparation effects are negatively accelerated, as they seem to be in most cuing studies). However, the hand advantage continues to increase over several hundred milliseconds, and it seems unlikely that recognition could be that much faster for the side cues than for the other cues. In fact, given the stimulus conditions, it seems unlikely that recognition was much faster for the side cues than for the others. The warning signal, which remained on throughout the trial, provided reference points that should have made identification of all pairs of cued positions relatively easy.

Experiment

For the paradigm of Miller (1982), the most important point in dispute is that, with the adjacent-hands response set, preparation of two fingers on the same hand leads to faster responses than does preparation of two fingers on different hands. This experiment was designed to replicate the hand advantage obtained by Miller (1982) in a situation satisfying three constraints. First, the experiment had to allow counterbalancing of cues and response preparation conditions, so that differences among preparation conditions could not be attributed to a cuing stimulus artifact. Second, the mapping of stimuli to responses had to be at least reasonably compatible, because cuing effects may change with incompatible mappings (Goodman & Kelso, 1980). Third, the response set had to be as similar as possible to that used by Miller (1982), because small differences in the response set are unlikely to alter the relative effects of preparing different pairs of responses.

In this experiment, stimuli were asterisks that appeared in one of four positions directly above, below, to the left of, or to the right of a fixation point, as shown in the top panel of Figure 1. As in the earlier experiments, partial advance information was presented by displaying plus signs in two of the four possible stimulus positions. In this experiment the two cued positions were always along one of the diagonal sides of the diamond, as shown in the lower panels of Figure 1.

Responses were keypresses with one of the index or middle fingers. Four response keys on a computer keyboard were chosen to match the diamond configuration of the stimuli and to allow finger positions comparable to those of the conditions with adjacent hands. The top stimulus in the diamond was assigned to a response key in the top row of letters on the keyboard, such as (Y), the bottom stimulus to a key in the bottom row, such as (B), and the left and right stimuli to left and right keys in the middle row, such as (G) and (H). Fingers were assigned to response keys in one of two orientations that were identical except for reversed rotations of the arms and wrists. In the positive hand-diagonal group, the left middle and index fingers were assigned to the top and left response keys, respectively, and the right middle and index fingers were assigned to the right and bottom response keys. In the negative-hand diagonal group, the left middle and index fingers were assigned to the left and bottom response keys, and the right middle and index fingers were assigned to the top and right response keys. Thus, two fingers of the same hand were on either the two positive or the two negative diagonals of the four response keys arranged in a diamond.

Though these hand positions are not identical to the adjacent position used by Miller (1982), it is unlikely that they are different enough to alter substantially the relative effects of preparing different pairs of fingers. The positions differ only in the angles of the arms and wrists, and these are unlikely to have much influence on the particular finger movements necessary to press response keys. Relative to the adjacent-hands condition, these positions maintain the relations of the fingers to each other, to the palms of the hands, and to the keys. Thus, it is likely that the finger movements used to produce responses in these positions are very similar to those with adjacent hands. Note that movements in the condition with overlapped hands would be much different from both of these, because in that condition the fingers (and hands) act as obstacles to each others' movements.

Across the two hand-diagonal groups, cuing

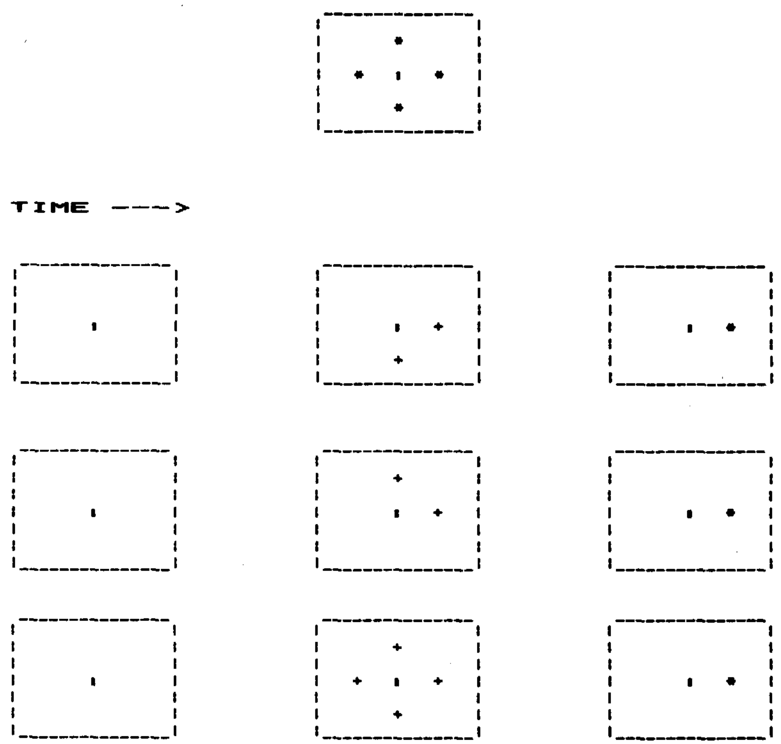

Figure 1. Top center frame shows the potential positions of the test stimulus, indicated with asterisks, in relation to the fixation point (:); next three rows show examples of the sequence of displays on trials with the lower positive diagonal cue, the upper negative diagonal cue, and the cue for the *unprepared* condition. (In all three examples, the correct response to the test stimulus is to press the rightmost response key.)

stimulus and response preparation condition were completely counterbalanced. When the hands were on the positive diagonal response keys, positive diagonal cues enabled preparation of two fingers on the same hand, and negative diagonal cues enabled preparation of homologous fingers on different hands. When hands were on the negative diagonal response keys, the roles of the cuing stimuli were reversed.

An additional factor in this experiment was the distance between the hands. In the near-keys condition, the four keys in the diamond configuration were located together at the center of the keyboard. In the far-keys condition, they were located at the left and right edges of the keyboard. In the *far* condition the configuration of keys within each same-hand diagonal was maintained even though the keys making up these two diagonals were much farther apart. It was anticipated that this manipulation would influence the response coding system used by the subjects. Coding of responses in terms of spatial position should have been much more salient in the *far* condition than in the *near* condition. Thus, same-hand preparation could benefit from advance specification of both position and hand codes in the *far* condition, but only hand codes in the *near* condition. It was not anticipated that response movements would be changed significantly by this manipulation, because it involved changes only in wrist and arm positions.

Method

Apparatus and stimuli. An Apple II+ computer controlled stimulus presentation and recorded responses and response latencies. Stimuli were plus signs, about 3 mm square, presented as light figures on the dark background of the video monitor. The four stimulus positions were about 12 mm above, below, to the left of, and to the right of a fixation point in the center of the monitor. Subjects viewed the displays from a distance of about 60 cm.

Responses were made by pressing one of four keys on the Apple keyboard. Four groups of subjects used different keys and/or assignments of fingers to keys, as shown in Table 1. The four groups made up a factorial of two hand positions (positive vs. negative diagonal) and two distances (near keys versus far keys).

Subjects and procedure. Subjects were 36 undergraduate students at the University of California, San Diego, who served in the experiment as a requirement of an introductory psychology class. Each subject served in a single session of about 45-min duration, and subjects were tested individually in small rooms with normal office illumination.

Each subject was tested in two blocks of trials, each starting with 10 warm-up trials that were not recorded. There were 36 different kinds of trials, defined by a factorial of four target stimulus positions (points of the diamond), three cue types (*unprepared, prepared: hand,* and *prepared: finger*), and three preparation intervals (400, 1,200, and 3,000 ms). Each type of trial was tested seven times in each block, and errors and trials with RTs of less than 200 ms or more than 2 s were discarded and rerun later in the block. A new random order of trials was generated for every block.

Each trial began with the appearance of a fixation point that remained on throughout the trial. Two positions were cued 500 ms after the onset of the fixation point. After the appropriate preparation interval, the cues were replaced by the target stimulus, which remained until a response was made. The next trial began about 2.5 s after the response. Subjects were instructed to respond as quickly as possible without making too many errors and to try to prepare as much as possible by using the information provided by the cues.

Results

For each subject, average correct RT and percentage of correct response (PC) were computed for each block, preparation condition, and stimulus-onset asynchrony (SOA). Figures 2 and 3 show average RT as a function of preparation condition and SOA for subjects in the near-keys and far-keys conditions, respectively. Table 2 shows the corresponding PCs. Overall, responses in the *prepared: hand* condition were 19 ms faster and 1% more accurate than those in the *prepared: finger* condition.

ANOVAS were computed to compare the *prepared: hand* and *prepared: finger* conditions with respect to both RT and PC. The two between-subjects factors, key distance and hand diagonal, were included in the analysis along with the within-subjects factors of block, preparation type, and preparation interval. In the analysis of RT, significant main effects were obtained for preparation type (hand vs. finger), $F(1, 32) = 14.3$, $MS_e = 2{,}760$, $p < .01$, and preparation interval, $F(1, 32) = 14.4$, $MS_e = 1{,}809$, $p < .01$. The interaction of these two factors was also significant, $F(1, 32) = 4.29$, $MS_e = 958$, $p < .02$, reflecting a decrease in the hand preparation advantage with increasing preparation interval. As shown in Figures 2 and 3, different patterns of results were obtained in the near-keys and far-keys conditions. Increases in preparation interval reduced RT more with far keys than with near keys, $F(2, 64) = 7.04$, $MS_e = 1{,}809$, $p < .01$. There was also a significant three-way interaction of preparation interval, key distance, and hand diagonal, $F(2, 64) = 3.77$, $MS_e = 1{,}809$, $p < .05$. The beneficial effect of increased preparation interval was greater for the positive-hand diagonal with far keys and for the negative-hand diagonal with near keys. If this significant interaction is not a Type I error, it is difficult to explain.

In a comparable analysis of PCs, significant effects were also obtained for preparation type, $F(1, 32) = 9.1$, $MS_e = 13.2$, $p < .01$; preparation interval, $F(2, 64) = 27.9$, $MS_e = 6.3$, $p < .01$; and their interaction, $F(2, 64) = 4.97$, $MS_e = 5.0$, $p < .02$. In addition, responses were significantly more accurate with far keys than with near keys (98.6% vs. 97.2%), $F(1, 32) = 6.45$, $MS_e = 31$, $p < .02$.

Discussion

For the paradigm of Miller (1982), the critical assumption was that preparation of two fingers on the same hand produces faster responses than does preparation of two fingers on different hands, at least with the response set used in his experiments. Miller (1982) used the hand-preparation advantage to indicate which stimulus attributes enable preliminary response preparation, and, for that purpose, it is critical that the hand advantage indicate response preparation with the response set he used.

The present experiment provides further evidence for the assumed hand-preparation

Table 1
Response Key and Response Finger as a Function of Group and Stimulus Position

	Stimulus position			
Group	Top	Bottom	Left	Right
Positive far				
Key	(W)	(.)	(A)	(;)
Finger	Left middle	Right index	Left index	Right middle
Positive near				
Key	(Y)	(B)	(G)	(H)
Finger	Left middle	Right index	Left index	Right middle
Negative far				
Key	(P)	(Z)	(A)	(;)
Finger	Right middle	Left index	Left middle	Right index
Negative near				
Key	(Y)	(B)	(G)	(H)
Finger	Right middle	Left index	Left middle	Right index

advantage with simple keypress responses similar to those used by Miller (1982), thus supporting the assumption needed for the earlier paradigm. Subjects were both faster and more accurate in the *prepared: hand* condition than in the *prepared: finger* condition, and cuing stimuli were counterbalanced across preparation conditions to eliminate the possibility of an artifact involving the cues. From the overall RTs, it appears that the response sets used in this experiment allowed unconfounding of cuing stimulus from preparation condition with movements that were similar not only to each other but also to the movements required with adjacent hands (Miller, 1982). Average RTs for the four placement groups (Key Distance × Hand Diagonal) ranged from 506 ms to 542 ms, and neither of the grouping factors nor their interaction approached significance (all Fs < 1). These times are similar to those obtained with adjacent hands (Miller, 1982; Reeve & Proctor, 1984), suggesting that movements with this response set are comparable to those with adjacent hands.

It is clear that the hand-preparation advantage is not a universal effect across all response sets, but rather depends on the exact response set used. The strongest hand-preparation advantages were obtained in the adjacent-hands condition (Miller, 1982; Reeve & Proctor, 1984) and the *far* condition of the present experiment. It is not surprising that these two conditions gave very similar preparation effects, because they are very similar response

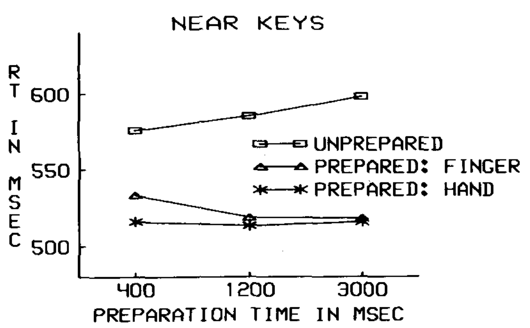

Figure 2. Reaction time (RT) for subjects in near-keys condition as a function of preparation condition and preparation interval.

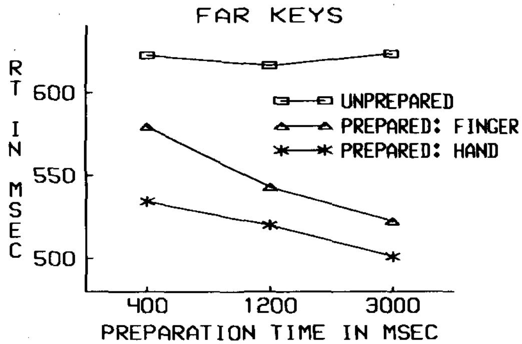

Figure 3. Reaction time (RT) for subjects in far-keys condition as a function of preparation condition and preparation interval.

Table 2
Percentage Correct as a Function of Key Distance, Preparation Condition, and Preparation Interval (in ms)

Preparation condition	Interval					
	Near keys			Far keys		
	400	1,200	3,000	400	1,200	3,000
Unprepared	98.7	98.3	97.9	96.8	97.4	96.7
Prepared: Hand	98.0	99.4	99.0	97.2	99.1	97.9
Prepared: Finger	97.0	99.2	98.9	94.3	97.4	97.4

sets, differing only in slightly different orientations of the wrists and arms. However, as Reeve and Proctor (1984) have shown, overlapping the hands reverses the advantage for hand preparation, possibly because it makes responses much more difficult or changes the way they are coded. The present results indicate that even the spatial separation of the hands can modify the hand-preparation advantage, because it was reduced in the *near* condition. This finding supports the hypothesis that spatial coding of responses has an important influence on the relative efficiency of different kinds of preparation, possibly even more important than hand coding of responses. Thus, all of the preparation effects obtained in the present study and two previous ones can be explained by assuming that response preparation depends primarily on the match between the cue and a spatial code for a subset of the responses. In the precuing studies, spatial response codes were specified by presenting two stimulus alternatives, and in the other studies (Miller, 1982, Experiments 2–8) spatial response codes were specified by an easily recognized attribute of the stimulus. The assumption that preparation effects depend on cuing a spatial response code is completely consistent with the paradigm of Miller (1982), because that paradigm did not assume any particular mechanism for producing the hand-preparation advantage.

It should be emphasized that the lack of a universal hand advantage does not contradict the assumption needed for the paradigm used by Miller (1982), because that paradigm requires only that there be a hand advantage with the response set used. The reversal of the hand advantage with overlapped hands does support an interesting claim about motor preparation, however. It appears that finger responses can sometimes be prepared even if the responding hand has not yet been specified, as noted above.

An important difference between this study and the previous ones is that there was a larger overall preparation effect (i.e., benefit for the *prepared* conditions relative to the *unprepared*.) One possible explanation is that the cues produced more perceptual facilitation in the present experiment. Alternative stimulus locations were much farther from the fixation point than in the previous studies, and cues might have allowed the perceptual system to prepare for certain of these locations (cf. Posner, 1980; Posner, Snyder, & Davidson, 1980).

The overall advantage for preparation of hand as opposed to preparation of finger was somewhat smaller in this study than in that reported by Miller (1982), but this difference may be a simple function of procedural differences. One procedural difference is that Miller (1982) used only preparation intervals of 1 s or less, the times producing the greatest hand-preparation advantage in the present experiment. It is also possible that the slight differences in arm and wrist placement caused the slight difference in preparation effects. Finally, the cuing artifact noted by Reeve and Proctor (1984) may have inflated the hand-preparation advantage in the previous study.

One of the most interesting results of this experiment was that there was more preparation in the far-keys condition than in the near-keys condition. This greater preparation was reflected in a greater hand-preparation advantage, a greater effect of preparation interval, and a greater difference between unprepared and prepared conditions. Because the most obvious correlate of the distance between hands is the extent to which the response fingers are perceived as two separate groups,[3] this result suggests that response preparation depends on a match between cuing information and a spatial response code. However, spatial separation may also increase subjects' awareness of the subgroups of responses, thereby encouraging them to adopt strategies that channel more effort into response preparation. Others have also suggested strategic components to various types of preparation. Requin (1980) and Sanders (1983) have emphasized the effortful nature of preparing to respond, arguing that it is voluntary, time consuming, briefly maintained, and difficult to combine with other processing. To the extent that response preparation is effortful, of course, it is also subject to strategic influences. Kantowitz and Sanders (1972) pointed out that in many experiments, like the present one, subjects can respond correctly without processing the partial advance information at all. Their results indicate that subjects prepare for specific stimulus attributes only when the task makes it convenient to do so. Similarly, the results of Reeve and Proctor's (1984) second experiment support the notion that preparation has an important strategic component.

In conclusion, the results of this experiment provide further evidence that the hand-preparation advantage assumed by Miller (1982) is real with the response set he used. The most direct implication of this advantage is that the inferences of Miller (1982) were valid, or, at least, not invalid because of erroneous assumptions about preparation. Thus, the results provide reassurance concerning Miller's conclusions about discrete and continuous information processing models.

[3] Distance could also influence the response movements themselves, but this seems unlikely because overall RT did not depend on distance.

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