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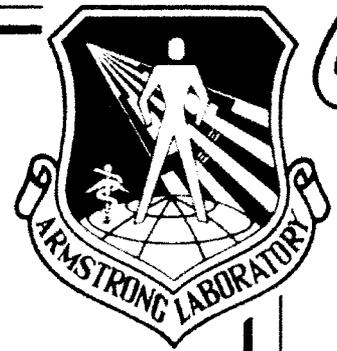
HANDEDNESS AND MOTOR PROGRAMMING EFFECTS OF MANUAL CONTROL AND MOVEMENT

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FOR THE COMMANDER

KENNETH R. BOFF, Chief
Human Engineering Division
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Four studies with a unidimensional, cursor-positioning task, employing both response-priming and response-precuing techniques, were performed to evaluate differences in motor control between the preferred and nonpreferred hands. None of the major hypotheses proposed previously to explain these differences (e.g., ones based on practice, force variability, feedback-processing speed, hemispheric specialization, and sequential movement control) was supported. Instead, hand differences may stem from greater automaticity during the execution of motor programs for moving by the preferred hand. Furthermore, the present studies do not support the distinctive-features model of motor programming proposed by Rosenbaum and other investigators. Such programs appear to be hierarchically organized and serially executed, with information about movement direction required before movement-extent information is used. This conclusion is consistent with results obtained during both the initial programming of aimed movements and their reprogramming when the original information for them turns out to be incorrect.

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Since the content of my research should be of interest to a wide range of people involved with the design, test, and evaluation of aircraft cockpits, it is being published as an Armstrong Laboratory technical report. The document does not follow standard technical report format since it was originally published as a dissertation.

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CHAPTER I

INT ODUCTION

Most people have a right and left hand, one of which is usually preferred to the other for making different kinds of complex movements. For example, about 90% of the population exhibit a preference for the right hand (Barsley, 1970). It therefore seems intuitively obvious that the degree of manual dexterity would vary with handedness for a majority of the human population.

What remains considerably less obvious is the source of the differences between the two hands and the conditions under which these differences manifest themselves. Since many types of equipment are designed for one-handed operation, designers often attempt to determine if a particular hand is optimally suited to the task, and then attempt to work around this constraint. However, it would be much more useful to determine the precise **nature** of the difference between the two hands. After this is accomplished, it should be possible to predict when and how asymmetries between the hands would affect performance on a variety of tasks.

Aircraft controls provide an excellent example of an arena that would benefit from such research. Since most people are right-handed, the primary flight control in light aircraft (the stick) is optimized for use by this hand, while the left hand controls the throttle(s). In larger aircraft both a pilot and copilot are present and a somewhat different control method is employed. Either of them can control the aircraft using a yoke, a device vaguely resembling a steering wheel with attitude control, one of which is located directly in front of each operator. The throttles are located between the two pilots and are shared by them. This layout has been standard for well over fifty years.

Some newer military aircraft (notably the General Dynamics F-16 Falcon) have shifted the stick from its traditional position between the pilot's knees to the right-side console, providing greater support for the pilot's arm during high-G maneuvers, reducing fatigue, and increasing instrument panel visibility. This arrangement has worked well in single-seat aircraft and has been readily accepted by their pilots. Recently, this design change has been implemented in larger aircraft crewstation designs (NASA and Lockheed-Georgia's concept flight station, and the Airbus A320 transport) [Wiener and Nagel, 1988].

One possible problem with the introduction of sidestick controllers into these aircraft is that the concept of a shared, centrally-located throttle control has been maintained. This means that to avoid the necessity of operating both the stick and throttle simultaneously with the same hand, the command pilot's stick has been shifted completely to left-handed operation.

Given that the average pilot has learned to fly right-handed (regardless of his personal preference) and has spent several years flying as a copilot with this hand before upgrading into the command seat, the introduction of a left-hand stick seems to be a prescription for disaster.

Conversations with pilots who have had several thousand flight hours in traditionally designed heavy aircraft (with yokes) reveal that even in conventional cockpits, the transition between seats entails a great deal of trepidation. Such trepidation may stem from the fact that although one can usually still fly primarily with the right hand, many tasks require throttle adjustments while making precise control movements (e.g., landings and aerial refuelings). The transition from flying predominantly right-handed to predominantly left-handed is usually accomplished easily in practice; most pilots believe that they fly equally well with either hand after the initial adjustment is made. This belief is difficult to substantiate, however, and may well stem from the fact that with yoke, pilots can use **both** hands on the controls during any condition in which power-setting modifications are not required.

The fact that the most experienced fliers (almost invariably the command pilots) take control of aircraft in emergency conditions raises several interesting and practically important questions. Are right-handed pilots really able to fly equally well with both hands? How is this performance affected by emergencies? Most research on performance during emergencies shows that people revert to their earliest training in these cases. The pilots of side-stick aircraft all have their earliest training in flying with the opposite hand. Are control reversals probable? What is the nature of the performance decrement that can be expected using the nonpreferred hand?

To date, these questions have not been adequately addressed. A major goal of the present investigation is therefore to help obtain some of the needed answers. In Chapter II, the various current hypotheses regarding the cause or causes of performance differences between hands are discussed. Chapter III provides some necessary background on the topic of motor programming, while Chapter IV does the same for the control of aimed movements. Chapter V gives a general overview of the experiments to be performed during the course of this study, the equipment to be used, and the present data-analysis procedure. Chapter VI presents the first of four experiments, a test of hypotheses that the source of hand differences involves the execution phase of movement. In Chapter VII, a second experiment investigated the possibility that the differences between hands involves a motor-programming process. Chapters VIII and IX detail experiments that further investigated the nature of the programming process. In Chapter X, a general discussion of all data gleaned during this study is presented.

The goal of the experiments performed here was to determine which of the various hypotheses regarding hand differences is correct. The obtained data show that none of these hypotheses provides a good explanation. A new theory based upon the preferred hand's greater consistency in making similar movements is presented and discussed.

A second goal of the present experiments was to investigate the motor-programming process per se. There are many highly disparate theories regarding the nature and organization of this process. The data obtained here

are consistent with <u>some</u> elements of several past theories, but do not precisely duplicate those of any single study. However, the obtained data are highly consistent with a hierarchically-organized, serially-executed programming process.

CHAPTER II

HANDEDNESS

To compare the relative performance of each hand, it is first necessary
to understand why one hand is preferred to the other. The source of hand
preference in humans is difficult to explain satisfactorily. Why do
individuals exhibit a marked bias toward one hand over the other? What is the
nature of the performance difference between the two hands?

Answers to these questions are not obvious from an evolutionary
perspective. Right-handedness is almost universal in *homo sapiens;* it is a
characteristic of all cultures, suggesting a biological rather than social
basis. However, bilateral symmetry is by far the norm in the rest of the
animal kingdom. While some lower species may have a minor tendency to favor
one appendage over another, only in man is there marked propensity to favor
effectors on one side of the body. Other species may also show some cerebral
asymmetries of function, but in no case do these approach those found in
humans (Corballis, 1983).

Cultural Accounts of Handedness

Given these considerations, some researchers have postulated that the
development of a dominant hand is a relatively recent cultural phenomenon
associated with the introduction of edged weapons and armor in battle
(Fincher, 1977). Since the left hand was needed to hold a shield (thus
protecting the left side of the body in general, and the heart in particular),
the right was free to perform the more complicated task of wielding a sword or
spear. Warriors who fought in such a fashion may have been more likely to
survive combat than those who adopted the opposite strategy, thus passing on a
tendency toward greater use of the right hand to their offspring in a
Darwinian "survival of the fittest" process (Fincher, 1977). This trait could
have been further strengthened through social pressure on the non-conformist,
left-handed minority to behave in the more accepted pattern. Evidence of
social pressure still exists today in the English language, which retains the
pejorative connotations of the French and Latin words for left (gauche and
sinister, respectively) [Glass, Holyoak, and Santa, 1979].

Archaeological evidence, however, suggests that the preceding account is
probably not a valid explanation of the original source of hand preference.
Well before sword and buckler became the weapons of choice, ancient Egyptian
tomb paintings dating back six thousand years show most people engaged in
right-handed tasks (Hicks & Kinsbourne, 1978). Coren and Porac (1977)
examined 1,180 pieces of artwork dating back to 15,000 B.C. from all over the
world and reported that some 93% of them depicted the use of the right hand.
Analysis of tools dating back to the Upper Paleolithic (about 35,000 B.C. to

8,000 B.C.) also show patterns of wear consistent with right-handed use (Semenov, 1964). Similarly, tools from an even earlier period (Lower Paleolithic---50,000 to 100,000 year ago) exhibited wear patterns corresponding to use by the right hand. Even going back some 2 million years, there is evidence that humanity's ancestor, *Australopithecus*, was right-handed. Remains of both this species and baboons suggest that some of them died in combat as a result of crushed skulls (Dart, 1949). In these cases, the skull of the loser was usually damaged on the front left side or the right rear, suggesting that the opposing rock wielder had used his or her right hand. This supports the position that handedness is not a recent phenomena tied to the march of technology, but rather stems from some other source.

While it is conceivable that right-handedness evolved with the early use of tools by humanity's primitive forebears, it is also puzzling why there was no accompanying structural development of the preferred arm into a more useful form (such as the specialized claws of the lobster) [Lang, Govind, & Costello, 1978]. In humans, the hands are almost perfectly symmetrical; the asymmetry is functional, not structural. This suggests that the source of hand preference may be at the cerebral level.

Some researchers have argued that there is a link between the development of the speech center in the left hemisphere and right-hand dominance in manual tasks. Hewes (1973) believed that language was initially based upon various gestures, with the more dexterous right hand normally used for this task. Supposedly, this led to the development of specialized structures and processing modes within the left hemisphere for controlling communication and, eventually, speech. However, Hewes gave no explanation for the underlying cause of greater right-hand dexterity. Calvin (1982) suggested that Hewes might have the order of development backward; right-handedness probably first manifested itself in throwing accuracy, and this practice in temporal sequencing lent itself well to the modulation of speech patterns.

Regardless of the initial cause of lateral asymmetry in human beings, it is universally acknowledged that such a condition now exists. The nature of this asymmetry is, however, less accepted. Little agreement has been reached about what originally led to the performance difference between the hands, what the difference is caused by, and how it expresses itself. The underlying cause of handedness is beyond the scope of the present research and will not be discussed further here. Such information is much less useful than an understanding of the nature of the difference between hands; most of us are manually lateralized and there is probably no way to alter this fact.

What we now need is knowledge about the nature of the difference between the preferred and nonpreferred hands that will be useful in areas such as equipment design. In what types of movements or situations do hand differences arise? Can tools be designed to reduce the disparity between hands? Answers to these questions could greatly aid in the design of future manually-controlled systems. Thus, the following sections focus on hypotheses concerning how performance with the preferred hand differs from that with the non-preferred hand.

Hypotheses About Hand Differences in Manual Performance

Examination of the literature shows that most of the hypotheses about performance asymmetries between the hands fit into one of five related categories.

1. The ability of each hand to make fine manual movements is a function of the primary processing mode employed by the cerebral hemisphere controlling that hand.

2. The mechanism controlling the preferred hand is significantly faster at processing visual feedback obtained during the course of fine movements.

3. The left cerebral hemisphere of right-handed individuals is uniquely specialized to deal with sequences of actions.

4. The mechanism for controlling the preferred hand is superior in the regulation of force variability within a movement.

5. The only difference between the hands is that the preferred hand has had more practice on most tasks.

Hypotheses #2 through #4 could each actually be special cases of Hypothesis #1. Only Hypothesis #5 is qualitatively different from the preceding four. Each of these hypotheses will be discussed below in a separate section.

Processing Modes

The cerebral hemispheres seem to be specialized in terms of function, with the left (in right-handed individuals) optimized for serial information processing and analytical reasoning, while the right excels at spatial tasks and uses parallel processing (Glass et al., 1979). Since the contralateral cerebral hemisphere exerts primary control over each side of the body, the right hand should be (and is) superior at tasks involving sequential motor operations and those necessitating feedback control (Lomas & Kimura, 1976; McFarland & Ashton, 1975; Nachson & Carmon, 1975; Peters, 1976; Wolff, Hurwitz, & Moss, 1977). In contrast, left-hand performance should be superior in tasks involving spatial discrimination and position reproduction (Nachson & Carmon, 1975; Roy & Hodgson, 1977; Smith, Chu, & Edmonston, 1977).

It is possible to evaluate the contributions of cerebral processing mode to differences between preferred and nonpreferred hands by comparing the performance of various subject populations. Different relationships between preferred hand and processing mode should lead to different performance levels between subjects. These differences have, however, not been fully tested yet. Todor and Doane (1978) noted that most studies of hemispheric specialization in motor performance have used only right-handed individuals, so the cerebral organization of subjects corresponded to the left (sequential processing) versus right (parallel processing) dichotomy. Left-handed subjects, however, may exhibit either the same organization as right-handed subjects or have their hemispheric dominance reversed. If this cerebral dominance is not assessed, the relationship between motor control and hemispheric

specialization in left-handers may be obscured. The existence of ambilaterals (those who exhibit no marked hand preference) further compounds this problem. In many motor tasks, such subjects perform as though they have two **nonpreferred** hands, doing worse than subjects who are lateralized to either side (true left- or right-handers).

Recent evidence has indicated that, based on their relative proficiency with each hand, ambilaterals can be divided into two subgroups: a) **ambisinistrals**, who show poor performance in motor control tasks with both hands, and b) **ambidextrals**, who have performance levels equivalent to the dominant hand of lateralized subjects when using either hand (Doane & Todor, 1978). Ambisinistrals are believed to exhibit less hemispheric specialization than ambidextrals do.

Todor and Doane (1978) hypothesized that if performance differences between the two hands stem from the processing modes of the controlling hemispheres, then motor performance in ambidextrals (but not ambisinistrals) should exhibit the pattern typically associated with hemispheric specialization. Regardless of which group a subject belongs to, his/her preferred hand should show a marked superiority for movements requiring extensive feedback control (a process involving both serial and analytical reasoning), while his/her nonpreferred hand should excel when the movement can be performed using a completely preprogrammed motor plan (taking advantage of the contralateral hemisphere's superiority in spatial tasks).

To test this hypothesis, Todor and Doane (1978) performed a study with a Fitts' (1954) reciprocal-tapping task involving three groups: strictly lateralized subjects, ambidextrals, and ambisinistrals. For strongly lateralized subjects, the nonpreferred hand did better in conditions requiring little feedback, while there was no difference between hands in conditions requiring feedback control, possibly due to a practice effect. The ambisinistral group exhibited no significant difference between hands, while the ambidextrous group's results approximated those of the lateralized subjects (the left hands of right-handed and ambidextral subjects had superior performance in conditions involving the greatest amount of preprogramming).

Unfortunately, the work of Todor and Doane (1978) raises almost as many questions as it answers. If hemispheric specialization is a key factor in preferred-hand performance, why do ambidextrous subjects perform equally well with both hands? Why was no advantage demonstrated by lateralized subjects in the condition involving greater feedback control? Explanations in terms of different cerebral processing modes do not answer these questions well and do not adequately account for performance asymmetries between preferred and non-preferred hands of lateralized subjects. We must therefore look elsewhere for an explanation.

Visual Feedback Processing

Another possible hypothesis to explain differences in performance between the preferred and nonpreferred hands concerns visual feedback processing. Flowers (1975) argued that the performance advantage for the preferred hand on precision pointing tasks may stem from higher processing speed during the continuous control phase of a movement. For example, consider the task of

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bowing while playing a violin (Flowers, 1975). This action requires continuous feedback monitoring in which the output of the motor system is essential for making precise responses. The movements may be relatively simple, but are limited in accuracy by the maximum speed of the serial corrections (Craik, 1948; Poulton, 1969).

To test his ideas, Flowers (1975) conducted a series of experiments with left- and right-handed subjects as well as ambilaterals. These subjects performed a Fitts' reciprocal-tapping task and a rhythmic tapping task. For lateralized subjects, significant performance differences occurred between the preferred and nonpreferred hands in visually-controlled aiming tasks (reciprocal tapping), but none were present during strictly ballistic movements (rhythmic tapping). This is consistent with Flowers' ideas. Apparently, a critical difference in the movement-control process involves the sensorimotor feedback loop, where some processing transmits feedback information to the motor system. Ambilaterals did not exhibit the same pattern as lateralized subjects, having a lower level of skill with each hand regardless of their normal preference. This suggests that neither hand in ambilaterals has developed the faster sensorimotor monitoring achieved by the preferred hand of the lateralized subjects.

Following Flowers' study, Roy (1983) examined the visual-feedback processing hypothesis by having right-handed subjects perform a serial pointing task with both their preferred and nonpreferred hands. Subjects pointed to a series of target symbols with a pencil under two conditions. In the first condition, they moved as quickly as possible to the target while attempting to be accurate; in the second, they tried to be as accurate as possible regardless of speed. The results further supported the visual-feedback hypothesis; the nonpreferred hand displayed an approximate 80% loss in accuracy during the high speed condition, while the accuracy of the preferred hand decreased only 45%. Roy inferred that the higher movement velocity reduced the time available to make corrections, yielding a commensurately greater effect on the hand connected to the hemisphere less adept at processing visual feedback.

To investigate this phenomenon more fully, Roy and Elliot (1986) used a single-aiming task and a wider range of movement times. One condition in the study involved removing visual feedback during the positioning task. A steeper slope in the speed-accuracy trade-off function was found for the nonpreferred hand (performance fell off faster), suggesting that the superior performance of the preferred hand stemmed from more rapid feedback processing. However, removing the visual feedback did not eliminate the preferred-hand advantage. This strongly suggests that the nature of the performance difference between the hands does not stem merely from differences in processing such feedback and must involve another aspect of the movement-control process.

Movement Sequencing

Another possibility is that the advantage of the preferred hand may lie in more rapid transitions between sequential elements of a movement. Many (if not most) studies of performance with the preferred versus nonpreferred hands have used repetitive finger- or stylus-tapping tasks. The usual result has

been an advantage in tapping speed (the rate of back and forth movement) for the preferred hand. For example, Kimura and Davidson (1975) studied right-handed subjects who made tapping movements with the eight joints in each arm (the five fingers, wrist, elbow, and shoulder). Their results showed that each joint differed in overall tapping speed, but not in degree of asymmetry. The preferred effector always exhibited higher tapping speeds.

The observations of Kimura and Davidson become even more interesting when they are compared to experiments performed on split-brain monkeys. In the monkeys, distal movements are mediated by the contralateral side of the brain (the left hemisphere controls the right hand), but movements with more proximal musculature are primarily controlled ipsalaterally (Brinkman & Kuyper, 1972). Since there was no change in the degree of asymmetry between proximal and distal joints in the Kimura and Davidson study, the difference cannot lie within the motor cortex.

Yet the situation is not as clear as one might like. Other studies of rapid finger tapping have led observers to different conclusions. Todor and Smiley-Owen (1987) had subjects perform a finger-tapping task with both preferred and nonpreferred hands. Here, significant differences occurred in the inter-tap interval, the duration of key closure, interval between force peaks, and the variance of the force-peak intervals. The preferred hand tapped faster, and the difference in tapping speed occurred at least partially because the subjects were able to change direction faster at the end of each keypress. Previous studies by Peters (1980), Todor and Kyprie (1980), and Kimura (1977, 1979) have also indicated that preferred-hand tapping advantages arise during the movement phase in which direction reversals are made. Since the differences seem to be in the phase of the tap cycle requiring postural transitions, Todor and Smiley-Owen (1987) concluded that the preferred hand and its associated cerebral hemisphere are more att ned to performing sequences of actions.

Another test of the movement-sequencing hypothesis has been conducted by Provins (1956), who investigated performance on a series of three tasks that varied in level of motor complexity. At the lowest level, the task was to make graded contractions of the finger-flexor muscles. The second level required alternate contractions of the finger flexors and extensors with the interval between the contractions of antagonistic muscle groups being as short as possible. The highest complexity level involved not only a particular order for the contraction/extensions, but also a critical time interval between them. For the simplest movements, there was no difference between the preferred and nonpreferred hands, while for any task that required the timing of component parts of the movement, a highly significant hand effect appeared. Provins (1956) suggested that this effect did not stem from some inborn characteristic of the brain or the muscle system, but was determined largely by training and environmental factors. Supporting this contention, he observed that when no previous practice on similar tasks was likely to have occurred, there was no difference between the preferred and nonpreferred hands.

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Force Variability

Hand differences may also be explained in terms of a force variability hypothesis. According to it, there is greater variation in the nonpreferred hand's ability to moderate and control the intensity of the impulses sent to the effector muscles. This possibility is supported by the work of Todor and Cisneros (1985). They noted that requiring either speed or accuracy alone in simple movements does not always produce significant hand differences. Such differences often appear only when accuracy demands for rapid movements are increased, with an increase in the overall level of task difficulty (Flowers, 1975; Sheridan, 1973; Steingruber, 1975; Todor & Doane, 1977). For example, Annett, Annett, Hudson and Turner (1979) reported that most of the performance differences between the preferred and nonpreferred hands depended on the required degree of accuracy rather than on movement amplitude (target width rather than movement distance.) Detailed analysis of movements has shown that the nonpreferred hand moves relatively slowly during the positioning phase of aimed movements (when small corrective submovements are required), while the preferred hand moves much more quickly (Annett et al., 1979). Analysis of the type and number of errors suggests that this result is not a function of movement duration; it seems to stem from greater frequency of corrective movements with the nonpreferred hand. Perhaps the higher accuracy exhibited by the preferred hand during aimed movements is a function of lower output variability.

This hypothesis also fits well with the motor-output variability model proposed by Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979). According to it, the output of the muscular system contains noise that causes trial-to-trial deviations in the terminal accuracy of a movement. The variability of the movement is directly related to the amount of force involved. Since faster movements require more force, they should therefore exhibit greater variability and larger errors. To achieve greater accuracy in final positioning movements, lower force levels must be used, resulting in longer positioning times for the more variable hand.

Todor and Cisneros (1985) performed several studies that strongly supported these contentions. They found slower nonpreferred-hand movements during rapid aimed movements. This resulted primarily from an increase in the time spent in the terminal, homing-in phase of the movement, especially as the size of the target decreased. When error rate was tightly controlled, major hand differences occurred during the later phases of movement, presumably as error corrections were being performed.

Another complementary experiment by Roy and Elliot (1989) using a serial tapping task investigated the effects of varying movement time, movement distance, and visual feedback. Their results indicated that the nonpreferred hand was generally more variable than the preferred hand under all conditions, with the difference becoming more pronounced under the no-visual feedback condition. Again, this supports the variability hypothesis at least indirectly, in that the condition allowing the fewest corrections (no feedback) yielded the greatest performance decrement. Unfortunately, these results also support the feedback-processing hypothesis as well, so no clear-cut conclusions can be drawn from them.

Practice Effects

A final hypothesis to explain the superior performance of the preferred hand is simply that people use this hand more often and are therefore more highly trained to perform specialized tasks with it. Some support for the practice hypothesis has been provided by Peters (1976). After prolonged practice (1300 10-second trials), the tapping speed of the nonpreferred hand reached the same rate as that exhibited by the preferred hand. The variability of the intertap interval, however, remained significantly higher for the nonpreferred hand and seemed immune to practice effects. Also, a later study by the same investigator indicated that when both hands were given similar amounts of practice, both improved, with the relative performance difference between them remaining fairly constant. Consequently, the practice hypothesis, like all the previous ones, has some serious limitations.

Conjecture for Research

While several higher cerebral functions are strongly lateralized in humans, the case for handedness is much less clear-cut. Most investigators agree that preferred/nonpreferred hand differences do exist, but it is difficult to determine exactly when they occur and what their source is. Of the several competing hypotheses that attempt to account for hand differences, none can muster overwhelming experimental support. When it is available, such support often seems consistent with several opposing hypotheses.

I believe that none of the existing hypotheses regarding preferred/nonpreferred hand performance is adequate to explain known phenomenon. Instead, a new one is required. For example, some work by Meyer, Smith, and Wright (1982) may be helpful here. They proposed that the level of neuromuscular "noise" within a given movement is a function of the duration and amplitude of the movement, and therefore no difference should exist between hands unless these parameters differ across them. This proposal may be correct, but not go far enough. There may be a background level of neuromuscular noise within the system that is slightly higher for the nonpreferred hand than for the preferred. Such noise could be separate and distinct from the noise produced as a function of the force parameter. Differences between the hands would then occur only when the level of background noise is high relative to the strength of the force pulse, just as one only notices background hiss on an audio tape player when the signal strength is relatively low.

If this analogy is correct, significant differences between hands should emerge only when very small movements are made or when movements are made at very low velocities. Under these conditions, the "signal strength" of the force pulse would be at a very low level compared to the baseline noise levels within the system, and differences between the hands should then be significant. As a result, more submovements should occur for slow continuous movements, since the interference from the high noise level would cause more frequent interruptions of the movement signal, and thus more inadvertent halts. Greater endpoint variability also should result under these circumstances, since the noise would adversely influence the standard deviation of the force pulse. The latter situation should become increasingly

apparent as the width of the target decreases and the amplitudes of the final series of required corrective submovements diminish.

My conjecture is similar to the force-variability model in some respects. If I am correct, however, the larger number of corrective submovements exhibited by the nonpreferred hand is not a function of greater overall variability within the entire movement, but only within the corrective phase. As target widths decrease, the size of the final corrective submovements become smaller, as do their force pulses, and the effect becomes more pronounced. Large ballistic movements would be only minutely affected under my conjecture, while they are affected by the same relative amount as small movements in the force-variability model. This goes far to explain why the ballistic portion of the movement does not seem to be strongly affected by the presumed variability between the hands.

Summary

The six hypotheses presented here can be subdivided into two basic groups: 1) those that attribute the handedness difference to the programming phase of movement; and 2) those that attribute it to the execution of the movement. To understand the manifestations of these differences, it is necessary to have a firm understanding of how controlled movements are both prepared and executed. These topics are covered in Chapters III and IV, followed by reports of some experiments designed to test the alternative hypotheses further.

CHAPTER III

MOTOR PROGRAMMING

Motor programs form a basic building block of many movement theories. They were originally postulated by Lashley (1917) to account for the movements of a patient who had complete anesthesia of the lower back. The patient could control the extent of his leg movements with almost normal accuracy, and make rhythmic flexions and extensions, though all afferent pathways had been severed by a gunshot wound.

Following this discovery, the most widely accepted definition of a motor program was provided by Keele (1968). He described motor programs as sets of muscle commands that are structured before a movement sequence begins, and that allow the entire sequence to be carried out uninfluenced by peripheral feedback. This is a strict interpretation of the program concept; a somewhat more flexible position is that though a movement can be made without feedback, it need not be. The motor program thus can be regarded as a general plan for movement (Sheridan, 1984).

Motor theorists have proposed that the preparation of a motor program involves a process in which the spatial and temporal parameters for a movement are selected depending on the initial state of the motor system and the purpose of the movement (Rosenbaum, 1980). The initial parameters are supposedly translated into commands for the particular effectors to be used in the movement. These commands control the biomechanical and kinematic properties of the movement. This is the basis of the parametric model of motor programming (Lepine, Glencross, & Requin, 1989).

The parametric model has been challenged on three major points. First, the control of every possible movement by an appropriate program implies that the instruction register for such a program is of unlimited size. This objection may be eliminated by postulating that a hierarchical structure exists, with an upper level consisting of a limited number of basic movement prototypes and a lower level at which these fundamental structures are modified to fit existing conditions. These prototypes have been variously termed "generalized entities" (Schmidt, 1980), "abstract (nonmotoric) representations" (Keele, 1981), "action plans" (Paillard, 1982; Requin, 1980), and "movement prototypes" (Rosenbaum, 1983).

A second criticism of the parametric model involves the translation of the program into specific muscle commands. The existence of such a stage is a necessary component of the model, but it cannot be directly observed. The nature of such a translation and how it occurs are totally unknown.

The third criticism of the model concerns its assumption that the program relies on the same physical and geometric variables used by observers to describe the movement. This constraint seems somewhat arbitrary at best (Lepine, Glencross, & Requin, 1989).

Most experimental evidence compiled to support the parametric model of motor programming has been derived from two types of techniques: 1) movement precuing, and 2) movement priming. Both these techniques are based on the assumption that the programming process can be subdivided into distinct components, each of which is of measurable duration. When partial information regarding a forthcoming movement is provided to the individual, analysis of reaction time then permits conclusions to be drawn about the nature of the programming process.

The Movement-Precuing Technique

The movement-precuing technique was originally developed by Rosenbaum (1980). In studies using this technique, the experimenter first selects a set of responses that differ orthogonally with respect to v values on each of d dimensions, providing v^d possible responses. As in traditional choice-reaction experiments, a unique stimulus is associated with each response. When the stimulus is presented, the subject has to react as rapidly as possible by producing the appropriate response.

The difference between this technique and more traditional ones is that, shortly before the presentation of the stimulus, advance precue information is given to the subject about all, some, or none of the defining values of the response to be produced. For example, regarding a given movement, information might be provided about the arm to be used, the direction to be moved, the extent of the movement, or some combination of these. The reaction time for the subsequent stimulus is then assumed to be a function of three elements:

$$RT = a + b + c.$$

Here a is the time to identify the stimulus, b is the time required to specify the values on all dimensions of the movement not given by the precue, and c is the time to evoke the response.

Using the movement-precuing technique, one may determine whether the information required to construct a motor program must be specified in a set order and, if so, what that order is. For example, suppose reaction times were significantly shorter when information regarding a particular dimension "Y" of the required movement was contained within the precue, but this reduction only occurred when information about dimension "X" was present as well. Then this would imply that values on "X" must be specified before those on "Y" in planning the movement. If information about either "X" or "Y" decreased reaction time, regardless of whether other information was present, then this would suggest instead that these two dimensions do not have a set order of precedence within the motor program. Finally, if each dimension facilitated reactions only when the other is present, this would mean that they must be specified in parallel, not serial, order.

To test these alternative possibilities, Rosenbaum (1980) presented
subjects with precue and stimulus information for a button-pressing task. The
task involved three movement dimensions: arm, direction, and extent. The
precue symbol contained three letters, representing various dimensions of the
movement to be performed: for the arm dimension, L (left) and R (right); for
direction, F(forward) and B(backward); and for distance, N (near) and D
(distant). If information about only one dimension was presented in the
precue, the appropriate letter came in the center of the screen, preceded and
flanked by an "X". When two dimensions were precued, two informative letters
appeared along with an "X"; three informative letters appeared when all
dimensions were precued. The subsequent movement stimulus was a colored dot
centered in the .PAlower half of the visual field. The dot's color
corresponded to the color of a button to be pressed.

The manual apparatus used in this study is depicted in Figure 3.1. Here
the circles represent the buttons that the subjects had to press for the
response stimulus, and the squares represent "home" positions on which the
hands rested before the start of each trial. The farther buttons are slightly
larger than the nearer ones to maintain a constant index of movement
difficulty (cf. Fitts, 1954).

With his procedure, Rosenbaum (1980) showed that precuing any single
dimension or combination of dimensions significantly reduced reaction time.
He concluded that arm, direction, and extent were specified in serial order,
but that this order was **not** invariant. If the order had been invariant, only
the higher-level precues would have facilitated reaction time; a parallel
structure would have required the same amount of processing time in all cases.
A model with a hierarchy in which arm, direction, and extent are specified in
a top-down serial order thus was rejected.

Instead, Rosenbaum proposed a distinctive-feature programming model in
which movement dimensions are specified independently of one another. Here
any dimension may be prespecified, without affecting the others, decreasing
overall reaction time by a certain decrement. For example, when performing
the same movement with each hand, the arm dimension would simply be
reprogrammed from left to right. Using a hierarchical model, the same change
might require complete reprogramming of the movement.

Subsequently, however, a series of very similar studies conducted by
Larish and Frekany (1985) provided little support for Rosenbaum's position.
These investigators found that the programming of direction required more time
than did the programming of either arm or extent (which were equivalent).
Also, information regarding direction was required before information
concerning movement extent or arm had any value. This latter result suggests
a hierarchical representation within the motor program.

The pattern of results in the Larish and Frekany study also suggested
that program elements were processed in parallel, rather than serially, since
there was no difference in reaction time between conditions in which one, two,
or all three parameters had to be specified. This again conflicts with
Rosenbaum's original study, which suggested serial processing. Larish and
Frekany suggested that subjects may completely preplan several movements when
the number of alternatives is small (a dimension-reduction hypothesis in which
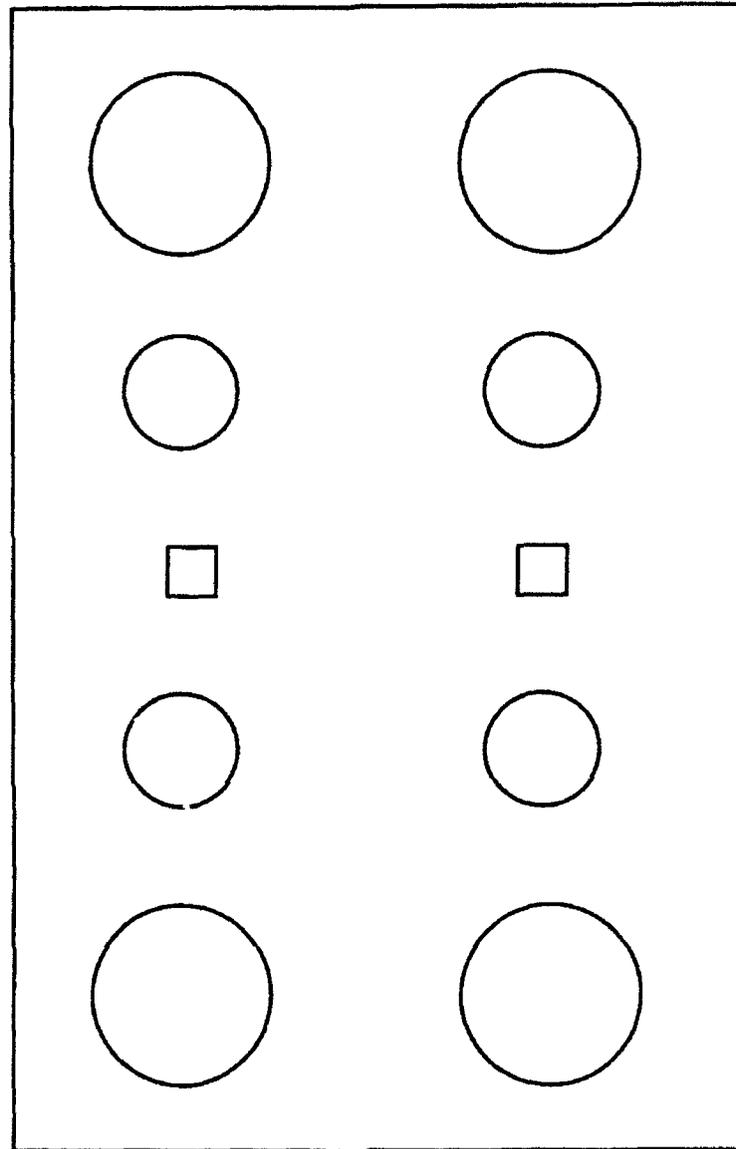
FIGURE 3.1: Apparatus for Rosenbaum's Movement
Precuing Studies---circles represent buttons
to be depressed in response to the stimulus
and squares are the home positions for each
hand. Buttons were sized such that all
possessed an equal index of difficulty value.

all possible alternatives are prepared when one or two dimensions are held constant.)

Rosenbaum's (1980) conclusions (as well as those of Larish and Frekany) have also been challenged by Goodman and Kelso (1980), who performed several experiments with the movement-precuing technique. They argued that the stimuli used by Rosenbaum were so artificial (involving a memory-search task and then a color/position translation) that his results stemmed from the format of the precue rather than the information in it. To check their idea, Goodman and Kelso employed stimuli formed from patterns of eight light-emitting diodes that corresponded to the positions of the eight response buttons. Using the same parameters as those in the Rosenbaum study, they found no systematic effects on reaction time for any particular precue condition. Instead, the data conformed to Hick's Law (1952). Precuing more parameters simply reduced the number of possible motor actions, thus reducing choice reaction time. This led Goodman and Kelso to conclude that Rosenbaum's (1980) results obtained only under conditions of low stimulus-response compatibility.

Nevertheless, Goodman and Kelso's (1980) work is substantially contradicted in a series of investigations by Lepine, Glencross, and Requin (1989). They used highly compatible stimulus-response pairings. The reaction time needed to specify extent was still significantly shorter than that needed to specify either direction or hand, while there was no difference between the latter. The results supported the dimension-reduction hypothesis of Larish and Frekany (1985) for conditions where only two alternative movements were possible.

It would seem that the results of both Larish and Frekany (1985) and those of Lepine et al. (1989) are most reasonable in this case, since they provide mutual support for each other. However, examination of the precues used in each of these studies reveals that both sets still may be somewhat confusing to the subjects, leading to potentially biased results. Since Goodman and Kelso (1980) used virtually the same stimuli as Rosenbaum, the possibility in this case is even greater. Additional studies with more comprehensible precues is necessary before any definitive decision can be made about the exact nature of the programming process.

The Response-Priming Technique

Another complementary method for investigating the nature of the programming process is the response-priming technique (Meyer, Sternberg, Knoll, & Wright, 1978; Rosenbaum & Kornblum, 1982). It involves creating a bias toward one response and then, on occasion, requiring some different response instead. The assumption is that if subjects believe a particular response will be required, it benefits them to prepare the primed response; since preparing multiple responses would slow the execution of the primed response, only a single response is assumed to be readied. Reaction times for unprimed responses can then be used to make inferences about whether the subject's state of readiness for a primed response systematically affects the production of unprimed ones (Rosenbaum and Kornblum, 1982).

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One study with this technique involved responses by the middle or index fingers of the left or right hand (Rosenbaum & Kornblum, 1982). Primed responses were initiated significantly faster than nonprimed responses, supporting the assumptions underlying the technique. Results also showed that more time was required to switch between responses made with fingers of the same hand than to switch between responses made with different hands, but the same (homologous) fingers (e.g., left and right index). These results suggest that subjects prepared multiple motor programs when response uncertainty was low, but only the primed response was readied when response uncertainty was high. This is consistent with a serial, nonhierarchical programming model.

Some subsequent priming studies have not replicated these results, however. In a priming study by Lepine et al. (1989), response time depended on the number of dimensions that had to be reprogrammed, with the reprogramming of movement extent requiring less time than any other dimension. In cases in which only a single dimension was primed, however, reaction times were the same as those in which no priming occurred. When only one dimension was primed, the fastest reaction times were obtained with extent information, but when two dimensions were primed, reprogramming of movement extent was fastest.

Lepine et al. (1989) used these data to support a dimension-reduction hypothesis. It assumes that when either two of three or all dimensions were primed, a correlation among unprimed dimension values made a compound programming process possible (Lepine et al., 1989). In other words, when multiple dimensions were primed, all the possible movements that corresponded to the unprimed dimension were prepared. When movements that varied on several dimensions were possible, such preparation did not occur. This amounts to preprogramming multiple movements if and only if they differ on a single dimension.

Other studies have suggested different conclusions as well. In a priming experiment by Larish and Frekany (1985), results indicated that when the movement arm or extent differed from the primed response, these dimensions could be (and were) changed individually and selectively within the motor program prior to response execution. When direction information was incorrectly primed, however, reprogramming time was not a function of the number and type of parameters being changed, indicating that the movement was totally reprogrammed. This suggests a hierarchical structure within the programming process such that changes from the primed response dictate the type of reprogramming required.

To explain their results, Larish and Frekany (1985) hypothesized that information regarding direction of movement was necessary to establish the required pattern of muscular enervation between agonist and antagonist muscles, while extent changes required only a change in gain between the same pairs of muscles. According to this hypothesis, the shorter reaction time for changes in movement arm and extent is a function of the same agonist/antagonist pairing being appropriate in both cases. One simply shifts the existing program to the opposite effector. When the **pattern** of enervation remains constant, modifications are made within the existing motor program. When the muscles involved are different (as in direction changes), the entire program must be scrapped, and a new one constructed from scratch.

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Data from other types of movements suggests hierarchical control as well, with speech being the most frequently investigated. Current theories propose that information is coded at progressively higher levels of abstraction in a hierarchical structure ranging from conceptual-dependency networks (Schank, 1972), or surface-structure sequences of words (Chomsky, 1965) at the top, down to motor commands (Fromkin, 1966) or acoustic templates (Ladefoged, DeClerk, Lindau, & Papcun, 1972) at the bottom.

Investigating these latter possibilities, Meyer and Gordon (1985) used the response-priming technique to examine speech latency. They had subjects prepare to utter a primary and secondary series of nonsense syllables in response to experimental stimuli. Their results indicated that the greater the number of shared features between the responses, the greater the difference between response latencies.

Meyer and Gordon (1985) attributed this delay to a hierarchical structure in which there are phoneme nodes (differing sounds) at the top, a middle layer of feature nodes (e.g. voiceless, labial, voiced) by which the phonemes are modified, and a lowest level of articulatory mechanisms (e.g. diaphragm, lips/tongue, glottis) that further affect the speech segments. Under this arrangement, as each link is activated (due to response priming), it in turn inhibits adjacent nodes to prevent their accidental activation. When the secondary responses require these adjacent nodes to be activated, the inhibition must first be overcome. When activating a non-adjacent node, no inhibition is encountered, and the reaction time is shorter. A similar structure could explain the results obtained by Rosenbaum and Kornblum (1982), in which changes between fingers on the same hand yielded longer latencies than those between homologous fingers on opposite hands.

The lack of any consistent pattern of results across the previously reviewed studies suggests that a common thread among them all may have been obscured by differences between the techniques used in the investigations. It is not clear that speech and aimed movements are controlled by similar motor programming mechanisms, and it is difficult to determine how the programming process proceeds in either case. Is it accomplished in series or in parallel? Are the elements ordered hierarchically or are all equally important? At this point, neither of these questions can be answered conclusively.

CHAPTER IV

MOVEMENT EXECUTION

To examine the differences between the hands in performing aimed movements, some familiarity with not only motor programming, but also the area of movement execution is necessary. The execution of rapid voluntary movements may be divided into two distinct components: an initial (ballistic) impulse phase, followed by a current-control phase (Woodworth, 1899). The initial-impulse phase involves a very rapid, programmed movement that moves the effector quickly away from some starting location and into the general area of the target without feedback. The current-control phase occurs later in the movement, and proceeds more slowly, relying on feedback to correct prior errors, ultimately closing in on the target. The various hypotheses about handedness mentioned earlier differ with respect to which movement phases yield performance differences across the preferred and nonpreferred hands (impulse variability and practice focus on the initial-impulse phase and the others on the control phase).

Fitts' Law.

One way of better understanding movement is in terms of speed-accuracy trade-offs. Generally, the spatial accuracy (precision) of an aimed movement varies inversely with its speed (velocity). Performance may, however, depend quantitatively and qualitatively on details of the movement task, yielding different trade-off functions. By examining these trade-offs carefully, it is possible to derive many basic principles of motor psychophysics (for a thorough review, see Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

Fitts (1954) described the motor-control system in terms of its information-processing capacity during movement execution. He reasoned that the degree of precision required in any movement should depend on the number of other possible movements that could have been made. In his investigations, subjects alternately tapped two rectangular plates as rapidly as possible with a stylus. Both the distance between the plates and their widths were systematically varied over a series of trials. The results revealed a logarithmic relationship between the average movement time and the ratio of the tolerance (W, target width) and amplitude (A, distance to the target) of the movement. The general form of this relationship is given by the equation:

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

where a and b are empirically determined positive constants, and $\log_2(2A/W)$ represents the index of difficulty (ID) of the movement. This relationship,

known as "Fitts' Law," holds for a variety of tasks and effectors (Langolf, Chaffin, & Foulke, 1976).

However, Fitts' Law has generated considerable controversy, with some researchers proposing alternative logarithmic trade-off functions (e.g., Crossman & Goodeve, 1963; Sheridan, 1979; Welford, 1968) and others suggesting that power or linear functions might be more appropriate (e.g., Meyer, Smith, & Wright, 1982; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Kvalseth, 1980). The nature of the trade-off function may depend on the type of task employed. Wright and Meyer (1983) drew a distinction between spatially and temporally constrained movement tasks. In spatially-constrained movement tasks, the subject is instructed to move as rapidly as possible and stop within a specified target region. Temporally-constrained movement tasks are those where the goal is to come as close as possible to some predetermined movement time while attempting to make the movements end close to some discrete target point. The logarithmic trade-off function appears to fit better for spatially-constrained movements, while a linear function is more appropriate for temporally-constrained movements (Schmidt, et al., 1979; Wright and Meyer, 1983).

The nature of this trade-off may play a key role in differences between movements by the preferred and nonpreferred hands. For example, movements of one hand may be better described by a linear function, while movements of the other hand are better fit by a logarithmic function. Such a possibility would dovetail nicely with the hemispheric specialization theory of handedness. However, the nature of differences between the preferred and nonpreferred hands has not been addressed empirically in conjunction with theories of movement execution.

Movement Models

Fitts' contention that the speed-accuracy trade-off is a function of the information-processing capacities of the motor system is no longer widely accepted (Sheridan, 1984). A major problem with his original formulation was that it implied nothing about how movements are controlled; movements could have the same ID value, but be controlled and executed in far different fashions. Consequently, a variety of movement models have been proposed to account for Fitts' Law while describing the nature of the movement process.

These models tend to fall in one or the other of two main categories: 1) mass-spring models, and 2) impulse-timing models. Mass-spring models specify the endpoint of a movement as a function of the equilibrium point between forces generated by the agonist and antagonist muscles. These models do not specify the distance moved. When a movement is programmed, the system selects a new equilibrium point based on length-tension relationships between opposing muscle groups at the selected position. Since the only important factor here is the final relative tension of the two muscle groups involved, movements can be made without requiring any knowledge about the initial starting point of the effector.

Work using deafferented monkeys (Bizzi, Polit, & Morasso, 1976) has supported the mass-spring model. It showed that, in spite of unexpected changes in initial starting position, movements can be accurately made to

known target locations. Similarly, Kelso (1977) showed that under conditions in which visual feedback cannot be used, human subjects are better at reproducing location information than distance information. However, a drawback of the mass-spring model is that it cannot explain Fitts' Law. If the relationship between agonist-antagonist muscle pairs is the only determining factor regarding movement endpoint, target distance and width should not affect movement speed-accuracy trade-offs.

On the other hand, impulse-timing models may provide a better account of such trade-offs. They assume that some derivatives of the distance and direction of movement are embedded within the motor program. A movement in these models consists of an initial acceleration, followed by a deceleration as the target is approached. The force pulses that accelerate and decelerate the limb are supposedly produced by the motor program and are the determinants of the movement trajectory. Within this framework, several hypotheses have been proposed in an attempt to relate Fitts' Law to various aspects of the impulse-timing models (Sheridan, 1984).

The iterative-corrections model. One such hypothesis involves an iterative-corrections model, which was originally proposed by Crossman and Goodeve (1963) and later elaborated by Keele (1968). It attributes Fitts' Law to the current-control phase of the movement, rather than the ballistic impulse. Here, any positioning movement supposedly consists of a finite series of submovements, with each one occupying a constant fraction of the total movement time and covering a constant proportion of the remaining distance between the current position and the center of the target. All except the first submovement are assumed to be guided by visual feedback, and movement ceases as soon as the effector enters the target region. Given that a subject receives adequate visual feedback, the number of required submovements should increase with target distance and decrease with width. Since each submovement requires a constant increment of time, the overall movement time also increases logarithmically with distance, yielding Fitts' Law (Keele, 1968).

Evidence regarding the iterative-corrections model has been mixed. Crossman and Goodeve (1963) reported periodic fluctuations in the velocity profiles of rapid wrist rotations, indicating that multiple muscle enervations were occurring, consistent with the existence of submovements. Discrete submovements have also been noted by Langolf, Chaffin, and Foulke (1976), and by Jagacinski, Repperger, Moran, Ward, and Glass (1980). However, Langolf et al. (1976) and Carlton (1979) also reported movements for which no periodic velocity fluctuations occurred and no submovements could be detected, yet they still found a logarithmic trade-off between movement speed and accuracy.

The studies of Langolf et al. (1976) and Jagacinski et al. (1980) also indicated increases in initial-impulse velocity as a function of target width. This observation violates a prime assumption of the iterative-corrections model, i.e., that the first submovement covers a fixed distance in a given time. Similarly, Meyer et al (1988) have shown that movement time varies logarithmically with A/W even when visual feedback is not provided to the subject, disproving another important element of this model. These results cannot be explained in terms of kinesthetic rather than visual feedback, since target errors (misses) increase greatly in the absence of visual feedback, though total movement time is unaffected by eliminating visual feedback.

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The impulse-variability model. Another alternative is the impulse-variability model, which was introduced originally by Schmidt et al. (1979) and elaborated subsequently by Meyer et al. (1982). It is based on five main assumptions: 1) the impulse for acceleration (i) has a magnitude proportional to the product of a force parameter (f) and a time parameter (t), such that

$$i = K_i ft,$$

where K is a non-negative constant; 2) following the accelerative impulse, there is an opposing decelerative force that slows the limb as it approaches the target region; 3) the force parameter f is a random variable whose standard deviation (S_f) increases proportionally with its mean ($S_f = K_f F$); 4) the movement time (t) is an independent random variable whose standard deviation (S_t) increases proportionally with its mean ($S_t = K_t T$, where K_t is a positive constant); and 5) in a given experimental condition, people set the force and time parameters to generate movements whose mean distances and durations equal those specified for a given target condition.

This model predicts a linear, rather than logarithmic, speed-accuracy trade-off involving temporally-constrained movements (Wright and Meyer, 1983). Some experimental support has been obtained for its assumptions (Abrams, Meyer, & Kornblum, 1989; Schmidt et al., 1979; Wright and Meyer, 1983; Zelaznik et al., 1988).

The stochastic optimized-submovement model. To explain Fitts' Law more fully, Meyer, Abrams, Kornblum, Wright, and Smith (1988) developed the stochastic optimized-submovement model, an extension of the impulse-variability model. They assumed that all aimed movements consist of just one or two discrete submovements. According to this assumption, there is an initial impulse (first submovement) programmed to hit the center of the target region. If the primary submovement ends within the target, then no corrective submovement follows. The primary submovement may, however, miss the target because of neuromotor noise (a function of the duration and amplitude of the movement), whereupon a secondary corrective submovement would be executed to eliminate the error.

Under the stochastic optimized-submovement model, the endpoints of primary submovements have a normal distribution whose standard deviation increases proportionally with the average velocity of the initial impulse, as expressed by the following equation:

$$S_i = K(D/T_i).$$

Here D is the mean distance covered by the initial impulses, T_i is their mean duration, and K is a positive constant. The initial ballistic submovements are assumed to exhibit the same type of linear speed-accuracy trade-off as temporally-constrained movements.

Moreover, the initial submovements are assumed to be programmed such that they have an ideal average velocity that minimizes the average total movement time (T) while achieving a set probability of hitting the target. This ideal average velocity is a trade-off between the average time required for the primary submovement (T_1) and that required for the secondary corrective submovements (T_2). A trade-off is necessary because, while faster initial

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submovements contribute less to the total movement time, they also result in larger and more frequent target misses, since S_i varies inversely with T_i. Thus, to reduce the number of corrective submovements and minimize the average total movement time, the initial submovement must not be too fast.

The stochastic optimized-submovement model makes a variety of quantitative predictions. Average total movement time is predicted by the equation:

$$T_m = A + B(D/W)^{1/2},$$

in which A and B are non-negative constants, D is the distance to the target, and W the target's width. Also, according to the model, duration of the primary submovement should be governed by a square-root function of D/W. The predicted equations are negatively accelerated. Unlike Fitts' Law, however, they do not involve a logarithmic function. Interestingly, empirical observations by Kvalseth (1980) have shown that a power function with an exponent of one-half may indeed describe the speed-accuracy trade-off better than Fitts' Law does.

The stochastic optimized-submovement model was extended by Meyer, Smith, Kornblum, Abrams, and Wright (1990). Its original formulation, which assumed a maximum of two component submovements, was redesignated the "optimized dual-submovement model", and a more general "optimized multiple-submovement model" was postulated. This new formulation added the assumption that movements may include up to a maximum of *n* submovements. Accordingly, a given aimed movement sequence would continue until either the target is attained or *n* submovements have been completed. The value of *n* is assumed to be independent of target distance and width. Consistent with the extended model, analysis of existing data has shown that the average total movement time (*T*) is a quasi-power function of *D/W* with an exponent of 1/*n* (typically, *n*=3). As *n* grows larger (no restriction on the number of submovements), the trade-off relation becomes a progressively better approximation to the natural logarithm of *D/W*, approaching Fitts' Law.

Relevance to issues about handedness. The models of movement execution outlined in this section may be relevant to understanding differences in movement performance between the preferred and nonpreferred hands. A comparison of individual aimed movements may serve to shed some light on whether the same or different processes are being employed by both the preferred and nonpreferred hands. One possibility is that the nonpreferred hand moves according to the standard impulse-variability model, while the optimized multiple-submovement model applies only to the preferred hand. Another possibility is that both hands are fit by a single model, but the speed-accuracy trade-off curves differ from hand to hand. Either of these possibilities could explain a variety of the observed differences between the hands, while still fitting with the previously discussed handedness hypotheses.

CHAPTER V

OVERVIEW OF RESEARCH

Issues to be Addressed

This dissertation examines performance differences between the preferred and nonpreferred hands, as well as the nature of motor programming in general. Since ambiguous experimental support exists for a variety of different hypotheses (i.e., ones concerning practice, force variability, feedback processing speed, hemispheric specialization, and sequential movement control) that claim to explain such differences, it is extremely difficult to choose the most appropriate one. The matter is important because of its strong impact on equipment design and the selection of personnel (e.g., aircraft pilots) for occupations that require high manual dexterity.

The present series of studies attempted to test the opposing hypotheses about hand differences by id r* .rying particular aspects of controlled movements that are dissimilar between the preferred and nonpreferred hands. This was accomplished by requiring subjects to perform controlled movements with each hand and by analyzing various aspects of the movement trajectories, their endpoints, and timing parameters. Differences in performance between the hands may result from different speed-accuracy trade-off functions or from some other element of the motor-programming process. Analysis of aimed movements relative to predictions derived from theories of motor programming and movement may provide considerable insight about the source of hand differences.

Four experiments were performed here (Chapters VI-IX). They involved tasks where rapid wrist-rotation movements were made using a light-weight handle t, position a cursor at a target on a video display. Wrist rotations were selected because they entail one dimension (rotation angle) of movement; an added benefit of this movement type, given the original impetus for this dissertation, is its similarity to the control movements made by pilots of side-stick aircraft.

There were also other important aspects of the present design. The subjects were prevented from seeing the actual position of their hand, but the wrist rotations produced visible motion of the cursor on the display. By controlling the visual information presented to the subjects and the parameters of their movements, it was possible to address almost all the issues raised earlier in considering the handedness hypotheses.

Unfortunately, the obtained results did not lend much support to **any** of these hypotheses, forcing a reconsideration of this entire area. However, such reconsideration did provide some new insights about the possible sources

of hand differences. It also helped shed further light on the nature of motor-programming and movement-execution processes in general.

GENERAL EXPERIMENTAL PROCEDURES

Task Environment and Equipment

In each experiment, the subjects sat in a dimly lit room, with the forearm of the moving wrist firmly supported. The forearm was parallel to the floor, and the upper arm next to the body. Subjects grasped a light metallic handle that fit comfortably into the palm. The handle was located behind a cloth-covered fiberglass shield and rotated freely (i.e., with very low inertia and friction) around the axis of the forearm in the clockwise and counterclockwise directions. Attached to the handle was an optical encoder that converted the position of the handle to binary values (making the handle a zero-order controller). Handle position was sampled at a rate of 100 Hz with a resolution of approximately $\pm.0879°$ of handle arc.

As part of each experiment, various types of stimuli were presented. Visual display of the subjects' movements and feedback information appeared on a CRT screen located in front of the subjects. Warning tones and response tones were presented over a loudspeaker located on the subject's front-left side. A digital computer (IBM PC-AT) controlled the sequence of events and collection of data. The subject's head was held steady with a chin rest adjusted according to the subject's sitting height.

Movement Analysis

A parsing algorithm was developed to separate movements into component submovements, using techniques introduced by previous investigators to detect corrective submovements (e.g., Jagacinski et al., 1980; Langolf et al., 1976; Meyer et al., 1988). These techniques entailed a systematic evaluation of the velocity and acceleration profiles recorded for each movement. Submovements were defined in terms of criterion events chosen to take account of known differences between the dynamics of voluntary movements, the residual activity of muscles (oscillation), and physiological tremor.

Data preparation. The data were first translated into degrees of handle rotation with respect to the home position ($5°$ pronation from the vertical) defined as the zero-point (starting position). Data were then low-pass filtered with a cutoff frequency of 7 Hz (transition band from 5 to 9 Hz) by a maximally flat low-pass filter (Kaiser and Reed, 1977). Velocity and acceleration profiles were then generated by differentiating the handle-position values.

Movement parsing. Six steps were taken to parse each movement into its component submovements:

1) A search for the beginning of a primary submovement was performed. A minimum velocity threshold of $4°$/sec was used here; handle rotations with lower velocities were dismissed as inadvertent movements. If the velocity was below threshold when the search for the movement initiation point began, a

search was made for the nearest threshold crossing. After detecting a section of movement above the minimum velocity threshold, a check was performed to insure that it remained there for longer than 20 msec. If this movement was not maintained, then the search continued for the next time that the minimum velocity threshold was exceeded.

2) A search for the relative maximum velocity in this movement subsection was performed.

3) For the first section of movement, a check was made to insure that the maximum velocity exceeded a minimum threshold value (set at $35°$/second).

4) A search for the end of the current movement section was then made.

There were four different events that could define the end of a particular movement section. The movement record was searched after the first relative maximum velocity for any of these events (a-d):
  a. A zero point in velocity.

  b. A change in acceleration from negative to positive relative to the current direction of movement. This represented a relative minimum in velocity whose magnitude had to differ from the preceding maximum by a certain threshold value (set at $10°$/second).

  c. A relative minimum in the absolute value of acceleration, while the signed acceleration was negative relative to the current direction of movement (a major slowing in movement velocity, even if the movement did not totally stop). The magnitude of the minimum acceleration compared to the relative maximum acceleration for any of the submovements had to exceed a certain threshold (set at $200°/sec^2$).

  d. A movement "tail." "Tails" were defined as periods of movement (glissades) that fell below the movement threshold velocity and did not contain any events satisfying the above criteria. Tails had to last 60 msec or more, during which the velocity never exceeded $4°$/second. The end of the movement section was then marked as the point at which a crossing of the minimum velocity threshold first occurred.

5) Following any one of these preceding four events (a-d), a check was made to see if the current movement subsection qualified as a submovement according to certain other criteria. To qualify, a section of the movement had to pass four more tests (e-h):

  e. Duration. The section of movement exceeded a certain minimum duration (60 msec).

  f. Velocity. The section of movement exceeded the minimum velocity threshold ($4°$/sec).

  g. Distance. The movement section subtended at least 1 degree of arc.

  h. Glissade. If the duration of the movement section exceeded 150 msec, then its average and maximum velocities had to differ by more than $6°$/second.

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If the preceding four tests (e-h) were not passed, the current section of movement was continuously above the movement threshold, and the previous submovement had qualified, then the segment under evaluation was added to the previous submovement.

6) Finally, the data were checked to see if the movement had ceased. Movement cessation was defined to occur at the first moment at which there was 160 msec with no movement thereafter.

Endpoint adjustment. After the entire movement had been parsed, a final adjustment was made to the nominal beginnings and ends of the submovements. The submovement ends were moved to the nearest relative minima in velocity with respect to the directions of the movements on either side of them. This involved two more steps (i and j):

i) If a relative minimum was found before the beginning of the first submovement, it was used as the beginning of the first submovement.

j) For each remaining submovement, if the previous submovement ended with zero velocity or with a transition from negative to positive acceleration, and if the current and previous submovements both traveled in the same direction, then the end of the previous submovement was moved forward to the nearest relative minimum velocity (and the beginning of the current submovement was moved back to this point as well).

CHAPTER VI

EXPERIMENT 1: MOVEMENT EXECUTION

Rationale

The first experiment investigated the visual-feedback, impulse-variability, practice, movement-sequencing, and background-noise hypotheses regarding the source of differences between movements by the preferred and nonpreferred hands. This was done by employing a variety of target width and distance combinations in a cursor-positioning task.

Based on the earlier discussion of handedness (Chapter II), the preceding hypotheses that concern the execution of hand movements can be further divided into two subgroups: 1) those in which the differences between movements by the preferred and nonpreferred hands are attributed primarily to the initial ballistic impulse (the impulse-variability and practice hypotheses); and 2) those that attribute the differences to the current-control phase (visual feedback, movement sequencing, and background noise). Each of these hypotheses therefore makes specific predictions about which aspects of movement performance will differ most across the two hands.

If the impulse-variability hypothesis is correct, then a difference should emerge favoring the preferred hand on measures such as the standard deviation of movement distance and constant error in the first submovements, a lower number of corrective submovements, and a lower total movement time. This would follow from the superior force modulation capabilities of the preferred hand.

If the practice hypothesis is correct, the preferred hand might yield superior positioning performance initially, depending on the extent to which the preferred hand has had more prior experience making wrist rotations. However, with extended practice, the disparity between hands should decrease.

If the visual-feedback hypothesis is correct, positioning performance for the preferred hand should be consistently superior during the current-control phase of movement, but not during the ballistic-impulse phase. This should result in fewer corrective submovements for the preferred hand, producing shorter movement times.

If the background-noise hypothesis is correct, preferred-hand superiority should be apparent mainly for the shortest movement distances and the narrowest target widths (those movements where the level of intrinsic noise within each hand is highest in comparison to the ballistic impulse). This assumes that the initial ballistic impulse for the shortest target distance requires a sufficiently small force to be affected by the disparity in signal-

to-noise ratios between the preferred and nonpreferred hands. During the current-control phase, the narrowest target width should require correspondingly smaller corrective submovements to hit the target accurately, again demonstrating a superiority of the preferred hand.

The movement-sequencing hypothesis predicts a superiority for the preferred hand only in terms of total movement time. This would stem from the preferred-hand's assumed greater facility at making transitions between component submovements. The time required for the complete movement should be shorter because of less "dead-time" (i.e., pausing) between the end of one submovement and the beginning of the next.

The preceding predictions are summarized in Table 6.1. Here, "lower" indicates that superior performance with the preferred hand is to be expected; "none" indicates that no difference is expected between hands. No differences are anticipated in initiation time, since full information is provided before each movement.

Table 6.1: Summary of Predicted and Observed Handedness Effects for Experiment 1

| | Handedness Hypotheses | | | | | |
Dependent Measures	Impulse Variability	Practice	Background Noise	Movement Sequencing	Visual Feedback	Observed Effects
1st Submovement Time	None	Lower*	None	None	None	None
Std Dev of 1st Submovement Distance	Lower	Lower*	Lower***	None	None	None
Con. Error of 1st Submovement Distance	Lower	Lower*	Lower***	None	None	None
Total Movement Time	Lower	Lower*	Lower**	Lower	Lower	None
Std Dev of Total Movement Distance	None	Lower*	Lower**	None	None	None
Con. Error of Total Movement Distance	None	Lower*	Lower**	None	None	None
Probability of Missing Target	None	Lower*	Lower**	None	None	None
Number of Submovements	Lower	Lower*	Lower**	None	None	None

* - Decreasing difference between days

** - For narrower targets only

*** - For shortest distances only

Method

Subjects

Six right-handed males between the ages of 21 and 35 served as paid subjects. Each received $4 per hour plus a bonus based on good task performance.

Procedure

The subjects' task involved moving a display cursor from one of eight possible initial starting positions to a target region located in the center of the display. On each trial, a display similar to the one shown in

Figure 6.1 was presented. In this display, the long vertical lines
represented the target region for the movement, the shorter vertical line was
a cursor, and the small box in the center was an alignment marker.

Each trial was initiated by placing the cursor within the alignment
marker for a period of 0.5 sec. This required the subject to rotate the
handle to a neutral posture, with the wrist pronated 5° from vertical. Next,
a second display was presented with information about the direction and
distance of the movement to be made (Figure 6.2). The target region appeared
again in this display, but instead of a single cursor, there were eight
possible cursors (short vertical lines). Also, a movement cue symbol appeared
over the target region. It consisted of a semicircle with eight tick marks
around an arc. The tick marks represented the possible movements that might
be required during the trial (10, 20, 30, or 40 degrees of rotation to the
left or right), corresponding to the eight cursors.

A line extended from the center of the circle to one of the tick marks,
indicating the appropriate final wrist position for the upcoming trial. In
Figure 6.2, the appropriate movement to reach this position would be a 30°
rotation to the right. This stimulus preview lasted for two seconds, after
which the screen was blanked for 1 sec. The movement cue then reappeared,
and a response-signal was sounded (1250 Hz tone), indicating that the movement
should be initiated. All eight cursors were visible until the movement
commenced, after which the seven inactive cursors disappeared. In Figure 6.2,
for example, the active cursor is the one located 30° to the **left** of the
target region, requiring a **rightward** movement (i.e., clockwise rotation) to
shift it into the target region. An "outside-in" display was used to
discourage the subject from visually searching for the target, which might
corrupt the initiation-time data. With such a display, the cursor moved from
the left or right periphery of the display to a single, centrally-located
target, rather than having a single central starting point with several
possible peripheral target regions. In principle, subjects could therefore
focus attention strictly on the central target without having to fixate on the
cursor directly until it entered the foveal visual field.

The subject had to look at the movement cue, determine the direction
(left or right) and extent of the required movement (10°, 20°, 30°, or 40° of
wrist rotation), and initiate the movement after the onset of the response
signal (auditory tone). Target width (1°, 2°, or 3°) could be determined
before the movement by examining the target region during the cuing phase.
Subjects were instructed to examine the cue and then move the cursor from the
starting location to the target region as quickly and accurately as possible
when the response signal occurred. As the handle rotated, the cursor could be
followed visually as it moved across the screen. The movement could begin at
any time up to 1 sec. after the response signal.

Each trial thus consisted of five steps:

1) Positioning the initial cursor within the alignment marker for
one-half second.

2) A two-second cue for the movement to be performed.

3) A one-second blank screen.

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Target Region | Alignment Marker | Cursor
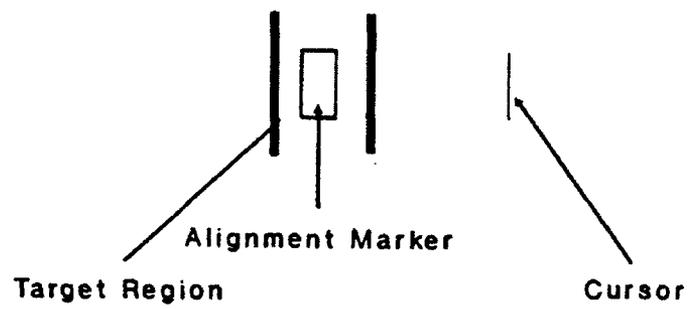
Figure 6.1: Display Prior to Trial Initiation
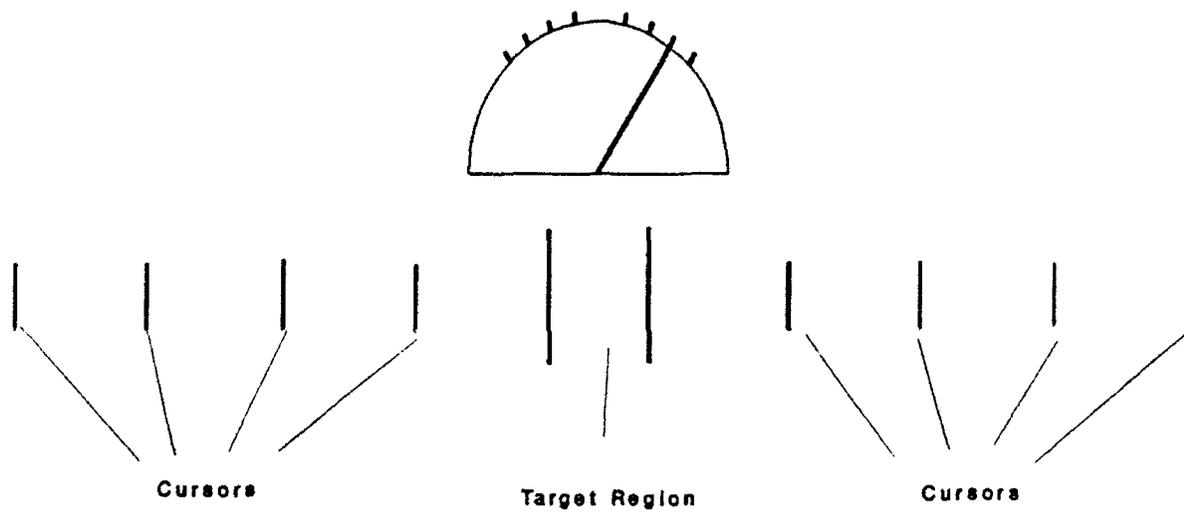
Figure 6.2: Movement-Cueing Display in Experiment #1

4) Trial initiation accompanied by an audible response signal and the activation of one of the eight cursors to be moved.

5) A positioning movement by the subject.

If movement preceded the response signal or did not begin within 1 sec. after it, a message was presented to the subject ("STARTED TOO SOON" or "STARTED TOO LATE"), and the trial was repeated at the end of the block. Subjects were paid a bonus for short movement durations that ended within the target region. Thus, it was advantageous for them to be both as fast and as accurate as possible. Movements that required over 1500 msec. to complete elicited a message saying "MOVED TOO SLOW" and were repeated at the end of the block.

Following the completion of each movement, the subjects saw a display with the target and the position of the cursor when the movement ended. Also displayed was a message that included their total movement time and the number of points earned on that trial. Points were inversely related to the movement time and the distance from the center of the target region at the end of the movement. For any movement that ended outside the target region, an error message was displayed ("MISSED; 0 POINTS"). Subjects had complete and immediate knowledge-of-results about the spatial and temporal aspects of each movement.

After each block of trials, subjects were presented with a message that included their average score, movement time, and the number of hits and misses that they accumulated during the block. This information was discussed with the subjects. They were encouraged to move as quickly as possible while still landing within the target region.

Design

Each subject served in six 75 min. sessions on separate days over a two-week period. The first two sessions served as practice, and the data from them are not reported here. In the first practice session, the procedure was introduced, and the subject performed all movements with either their left or right hand. In the second practice session, the other hand was used. The assignment of hands to practice sessions was counterbalanced across subjects.

The movements within each session were organized into blocks of trials, with target width, direction, and distance all varied within the block. Each block consisted of 48 movements that represented two instances of each possible combination of starting point and target width. Subjects performed six blocks per day. Movements within blocks were randomized to prevent systematic order effects. Only one hand per day was used to make the movements in a session. The chosen hand alternated across days. At the beginning of each data-collection day, subjects performed a short practice block of 15 trials.

Dependent variables for the study were initiation time (defined as the time between the presentation of the response signal and the onset of movement), total and first submovement time, standard deviation of distance for total and first submovements, probability of missing the target, number of

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submovements, and constant error in distance for both the total and first
submovements (defined as the absolute distance from the center of the target
region at the end of the movement).

Results

The results from Experiment 1 were somewhat surprising. No overwhelming
preferred/nonpreferred hand differences emerged. Thus none of the hypotheses
about the source of hand differences was supported. This outcome is
summarized in the right-most column of Table 6.1. Nevertheless, other
interesting effects occurred for each dependent variable. These are outlined
in what follows. A complete listing of all the significant effects in the
ANOVA's appears in Appendix A.

Preparation Phase

Initiation time. For initiation time, there were significant effects of
target distance [$F(3,6)=11.78$, $p=\leq.0063$], target width [$F(2,4)=11.62$,
$p\leq.0216$], and a day by target-width interaction [$F(2,4)=26.94$, $p\leq.0048$].
Differences between conditions on significant effects were examined using
Tukey tests (for a discussion of this procedure, see Appendix B). The target-
distance effect occurred because the shortest distance required significantly
more time to initiate the trial than did the other three distances [$d_T=24.44$
msec, $p\leq.05$), none of which yielded significant differences (364 msec for 10°
vs 331, 316, and 327 msec respectively for the 20°, 30°, and 40° targets).
The target-width effect occurred because the smallest width (1°) required more
initiation time than did the two larger widths ($d_w=8.85$ msec, $p\leq.05$), while
the other two widths did not yield significant differences (341 msec for 1°,
versus 331 msec for the other two). The interaction between target width and
day occurred because the narrowest target required significantly more time to
react than did either of the wider targets on the first day, while on the
second day, this difference declined [$d=8.52$, $p\leq.05$] (Table 6.2).

Table 6.2: Initiation Time by Target Width and Day

Target Width	Day 1	S.E.	Day 2	S.E.
1°	345 ms	7.6 ms	337 ms	6.7 ms
2°	333 ms	6.9 ms	328 ms	6.0 ms
3°	329 ms	6.5 ms	333 ms	6.1 ms

Ballistic Phase

Time for first submovement. Examination of this measure revealed no
significant main effects of the major independent variables. The interaction
between hand, target direction, and target distance came close, however
[$F(3,6)=3.80$, $p\leq.0772$]. This seems to be the result of a supination/pronation
by square root of distance effect. First submovements of pronations

(rotations toward the body that positioned the palms facing downward) were made faster than those of supinations (rotations away from the body, which ended with the palm facing upward). This difference increased in a linear fashion with the square root of target distance (Figure 5.3). Consequently, there was a marked distance effect on supination (but not pronation) first submovement time.

Standard deviation of first-submovement distance. Analysis of this measure revealed a significant main effect of target distance [$F(3,6)=57.17$, $p \leq .0001$], and an interaction between target width and day [$F(2,4)=9.45$, $p \leq .0305$]. The standard deviation of the first-submovement distance increased as a linear function ($r^2=.9997$) of target distance (Figure 6.4). The interaction between day and target width is presented in Table 6.3. Movements to the narrowest target were significantly less variable on the second day, while movements to the wider targets did not significantly differ between days ($d_T=.453$ deg, $p \leq .05$).

Table 6.3: Standard Deviation of First Submovement Distance by Day and Target Width

Target Width	Day 1	S.E.	Day 2	S.E.
1 deg	6.59 deg	.47 deg	6.09 deg	.40 deg
2 deg	6.24 deg	.43 deg	5.90 deg	.40 deg
3 deg	5.75 deg	.43 deg	6.04 deg	.38 deg

Constant error of first-submovement distance. Significant effects on this measure were found for day [$F(1,2)=37.85$, $p \leq .0254$], target distance [$F(3,6)=27.99$, $p \leq .0006$], and target width [$F(2,4)=8.96$, $p \leq .0333$]. The hand by target-direction by target-distance interaction approached significance and is also of interest [$F(3,6)=4.18$, $p \leq .0644$].

The main effect for day resulted from the constant errors on the second day being somewhat smaller than on the first day ($-8.43°$ versus $-8.68°$). This was not unexpected, and is probably the result of practice.

The target-distance effect resulted from the constant error of the first-submovement distance being a linear function ($r^2=.992$) of target distance (Figure 6.5). A negative constant error indicates that the target was undershot, while a positive error indicates an overshoot. The width effect resulted from the error for the narrowest target being significantly greater in absolute magnitude than for the two wider targets ($-9.26°$ for the $1°$ targets; and $-8.12°$ and $-8.28°$ for the $2°$ and $3°$ targets; $d_T=.947°$).

The three-way interaction appears to be a supination/pronation by target-distance effect. Constant errors in the first-submovement distance for both supinations and pronations increased linearly versus the square root of the target distance (Figure 6.6). Regression equations for both types of movement fit the data extremely well ($r^2_{sup}=.993$ and $r^2_{pro}=.966$). The difference between the slopes of the two lines (-3.48 for supinations, and -4.98 for pronations) was significant ($z=2.18$, $z_{crit}=1.96$), with target distance having a greater effect on pronations. In turn, this may explain (at least partially) why the

First Submovement Time by Supination/Pronation and Square Root of Target Distance
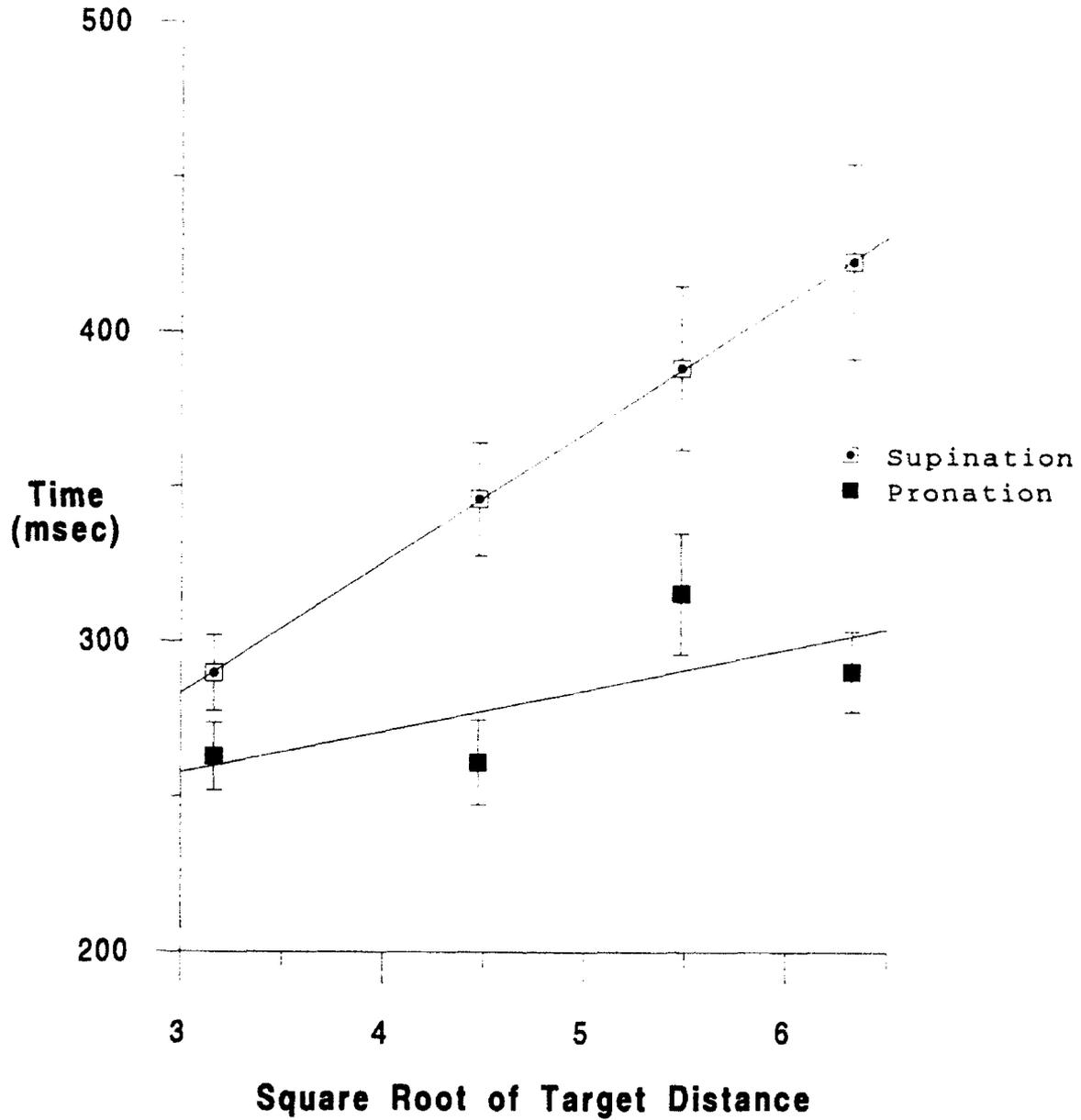
FIGURE 6.3

Standard Deviation of First Submovement Distance by Target Distance
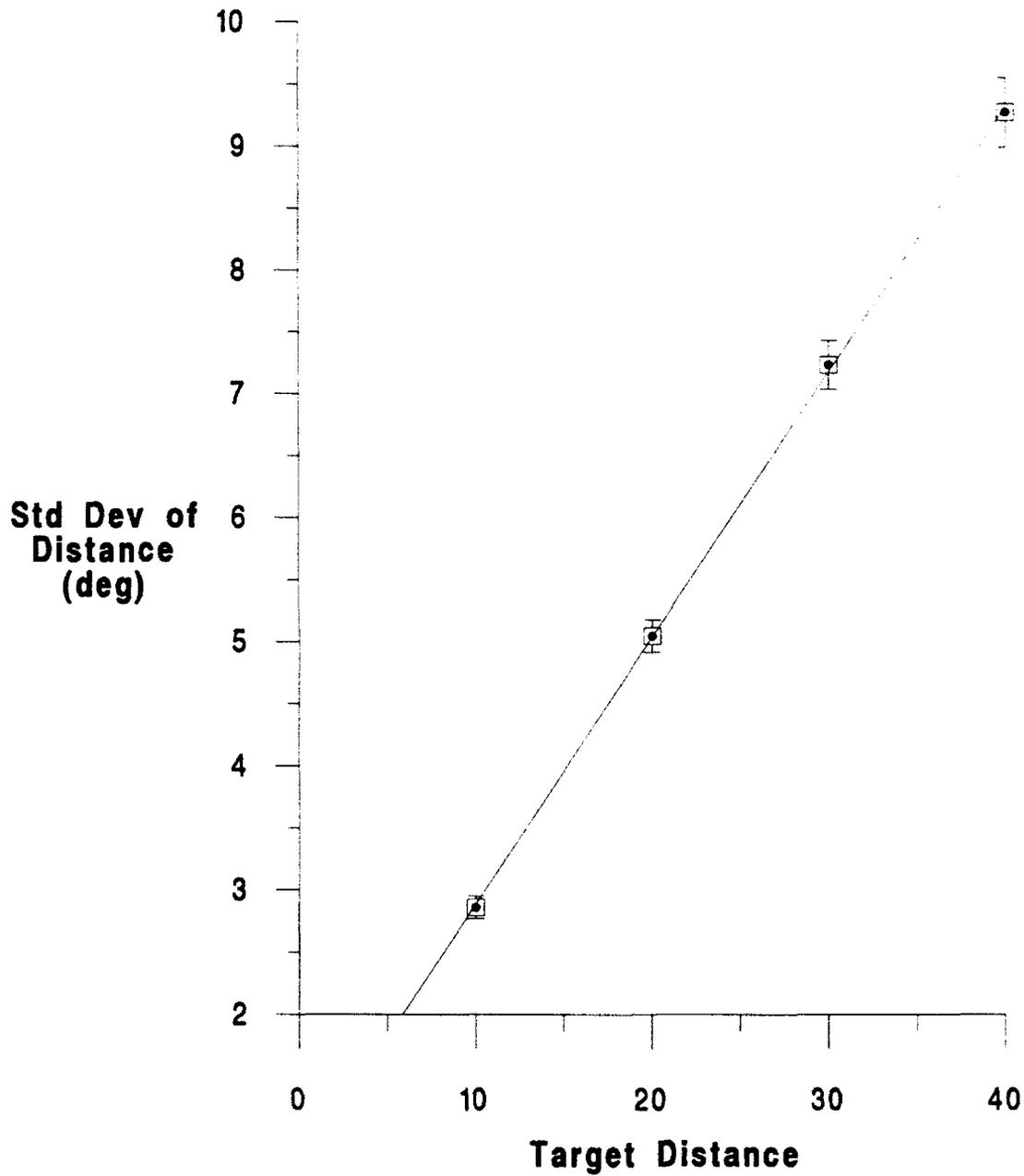

FIGURE 6.4

Constant Error of First Submovement
## Distance by Target Distance
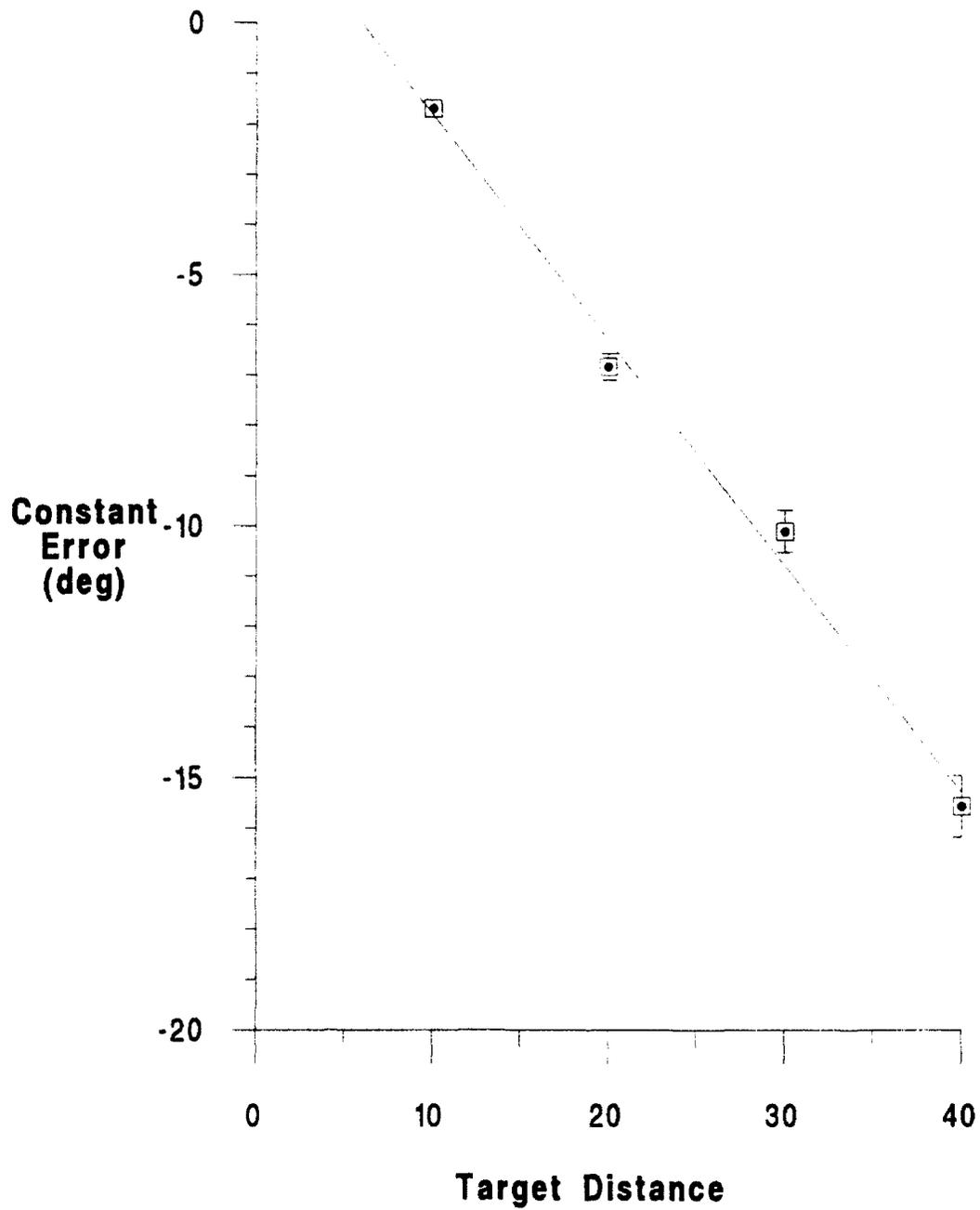
FIGURE 6.5

Constant Error After First Submovement by Supination/Pronation and Square Root of Target Distance
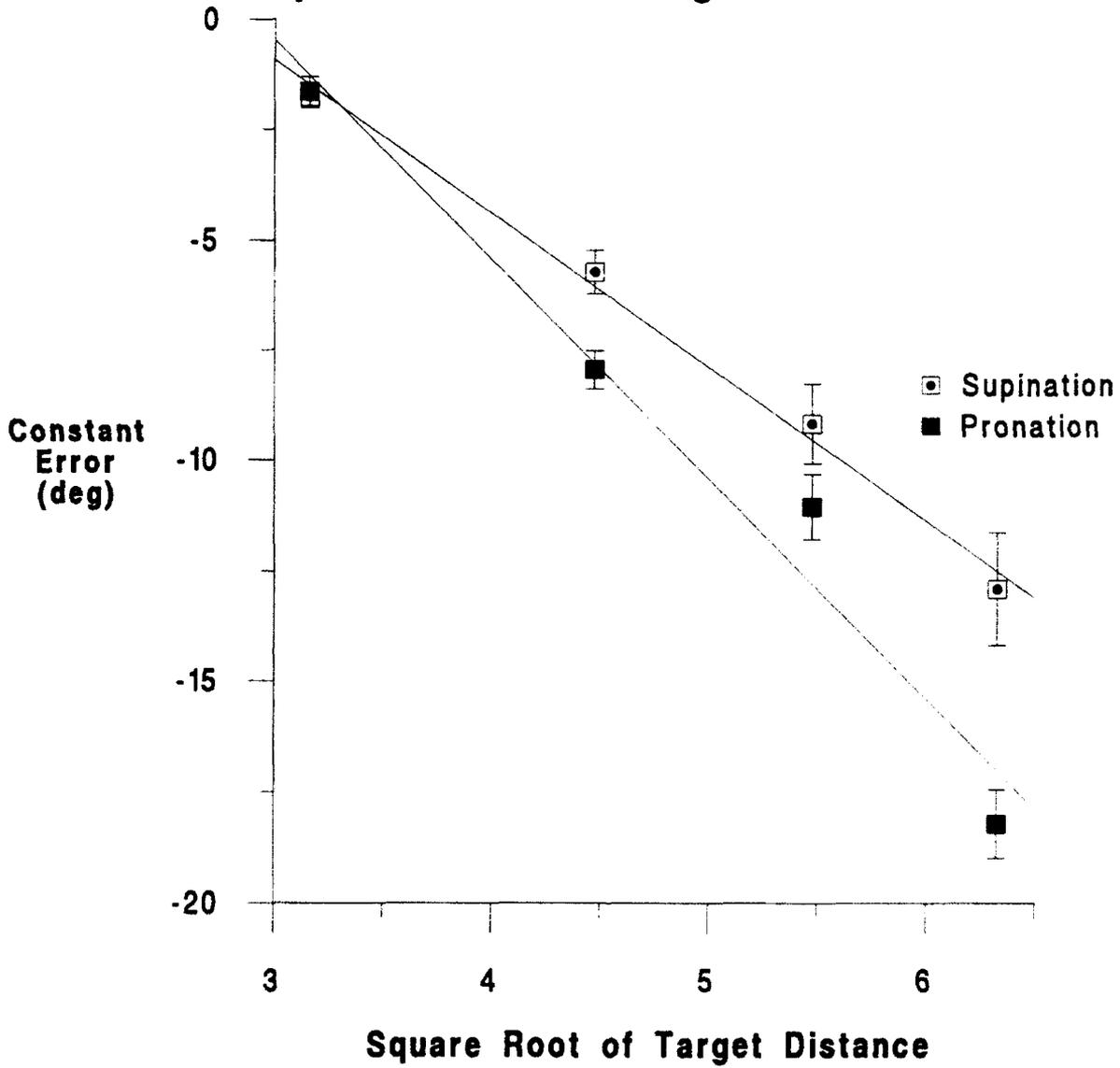
FIGURE 6.6

distance effect on first-submovement times was less for pronations than supinations; that is, a distance-time trade-off may have occurred.

Summary of ballistic-phase measures. Examination of the previous three dependent measures allows the force-variability and practice hypotheses to be eliminated for present purposes. There was no evidence of any difference between hands in the variability of the initial ballistic phase, nor was there any apparent change in the relative ability of the hands with practice.

Current-Control Phase

Total movement time. For this measure, there were significant main effects of target distance [$F(3,6)=61.87$, $p\leq.0001$], target width [$F(2,4)=10.37$, $p\leq.0262$], and a day-by-hand interaction [$F(1,2)=45.63$, $p\leq.0212$]. Also, the hand by target-direction by target-distance interaction was marginally significant and of some interest [$F(3,6)=3.69$, $p\leq.0816$].

The target-distance and target-width effects corresponded fairly well with those predicted by the optimized multiple-submovement model (Meyer et al., 1990). Movement time increased linearly with the square root of target distance ($r^2=.996$), and decreased linearly with the square root of target width ($r^2=.996$) [Figures 6.7 and 6.8]. When the total movement time was plotted as a function of the index of difficulty [$(D/W)^{1/2}$ for this model], however, the goodness-of-fit of the regression line was not impressive ($r^2=.68$). This occurred because observations from the narrowest target width (Figure 6.9, open squares) did not fit well with the rest of the data (Figure 6.9, filled squares). When the observations from both groups were plotted independently, the correlations improved markedly ($r^2=.920$ for the wider targets, and $r^2=.996$ for the $1°$ targets).

The present outcome may provide some insight concerning the limits of the optimized multiple-submovement model. It is possible that as the target becomes sufficiently small, it is not possible to position a cursor within it without using a different aiming process. This could be due to an inability of the motor system to make small enough corrective movements with a particular appendage, forcing a shift to another effector (in this case, going from controlling the handle with wrist rotations to controlling it with the fingers). This would indicate that there is a bottom line on the standard deviation of a given type of movement, regardless of the distance involved. If this minimum value is larger than the width of the target, it would prove virtually impossible to hit the target following a close miss.

The interaction between hand and day for total movement time stemmed from a superiority of the preferred hand during the first day (Table 6.4). This advantage disappeared on the second day. This would normally support the practice hypothesis, except that on the second day, an _increase_ in movement time occurred with the preferred hand, rather than there being a decrease for the nonpreferred hand. There was no identifiable reason for the drop in performance, either theoretically or through direct observation of the subjects' behavior.

Total Movement Time by
Square Root of Target Distance
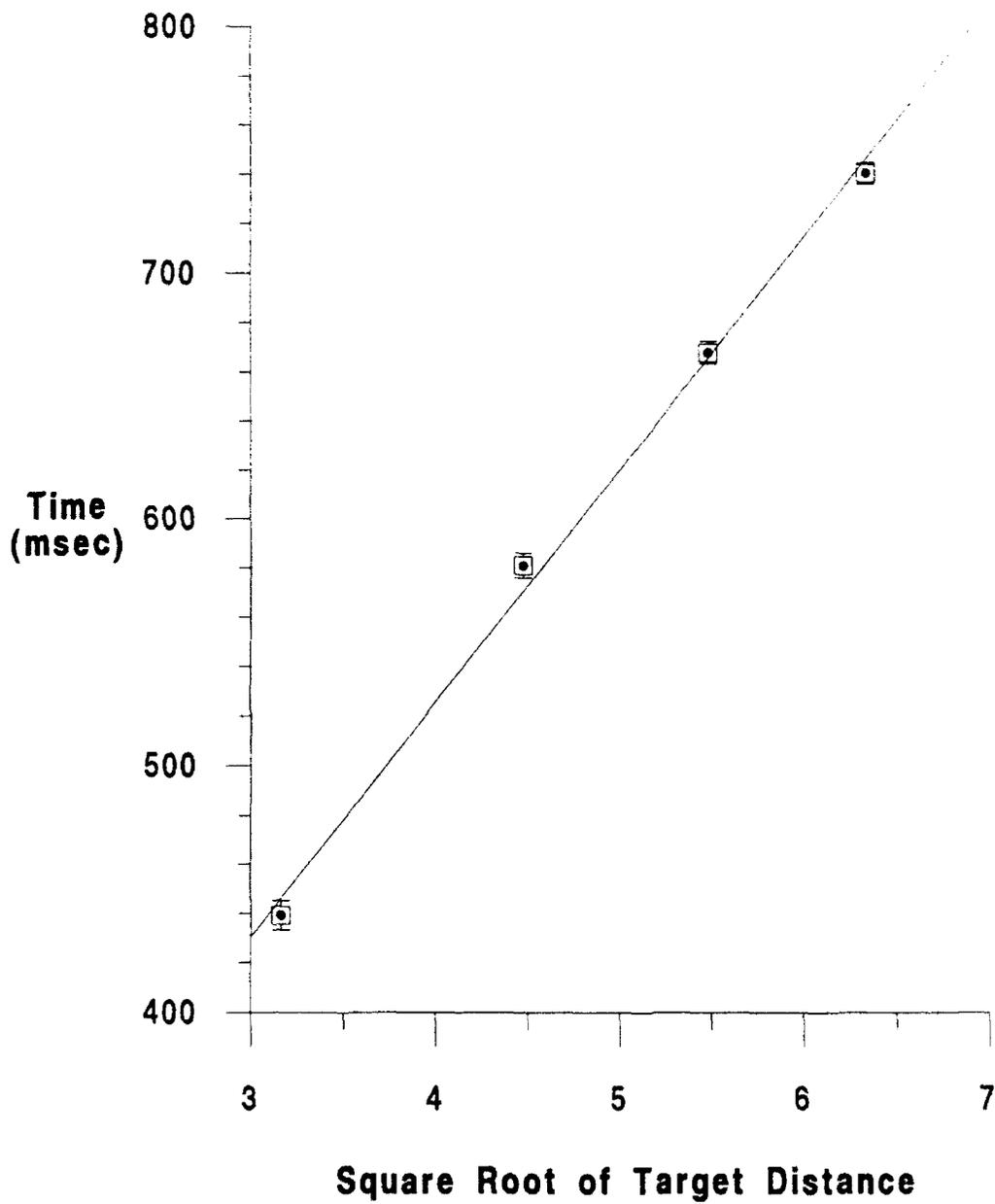
FIGURE 6.7

Total Movement Time by
Square Root of Target Width

FIGURE 6.8

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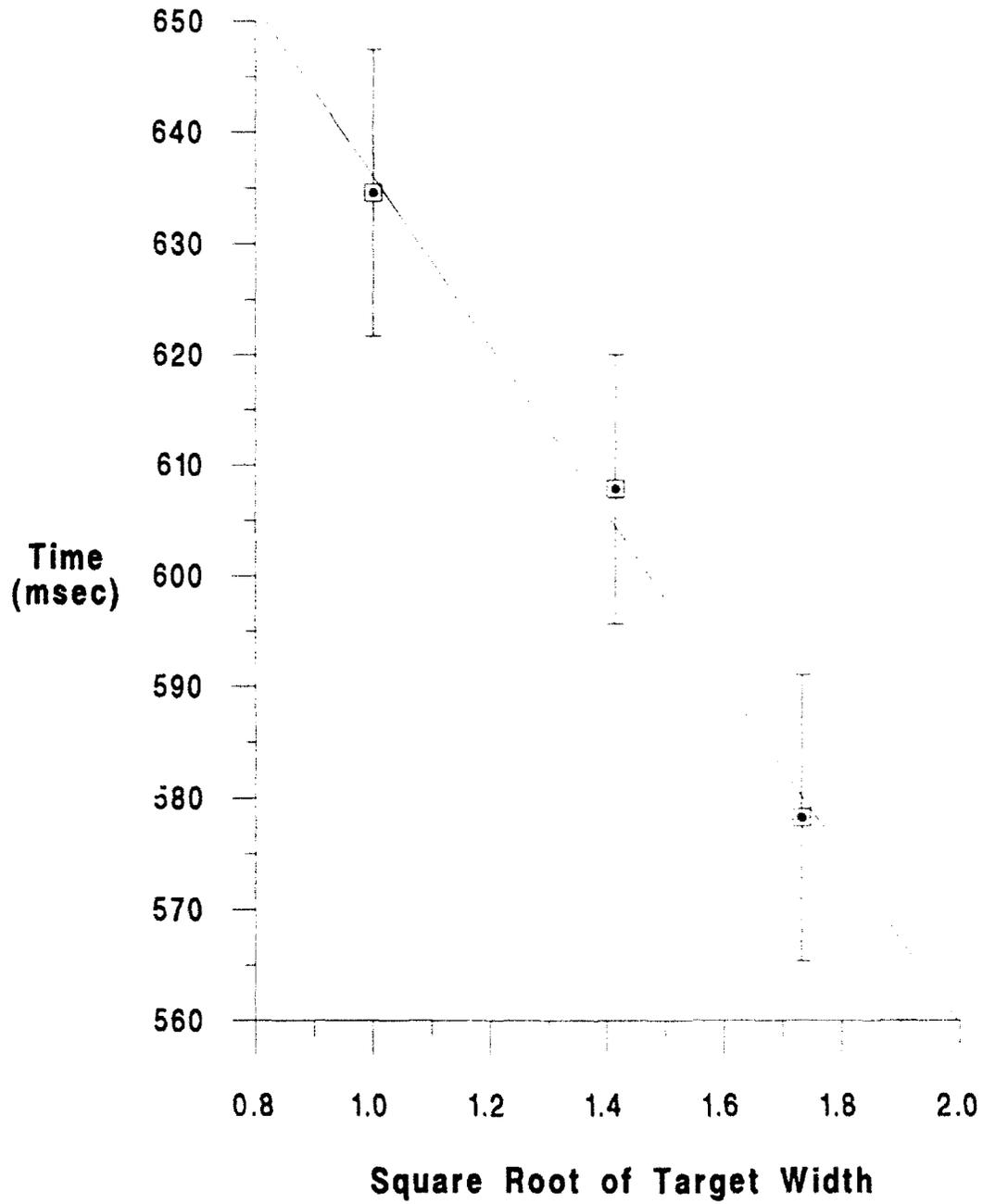
Total Movement Time by Index of Difficulty

FIGURE 6.9

44
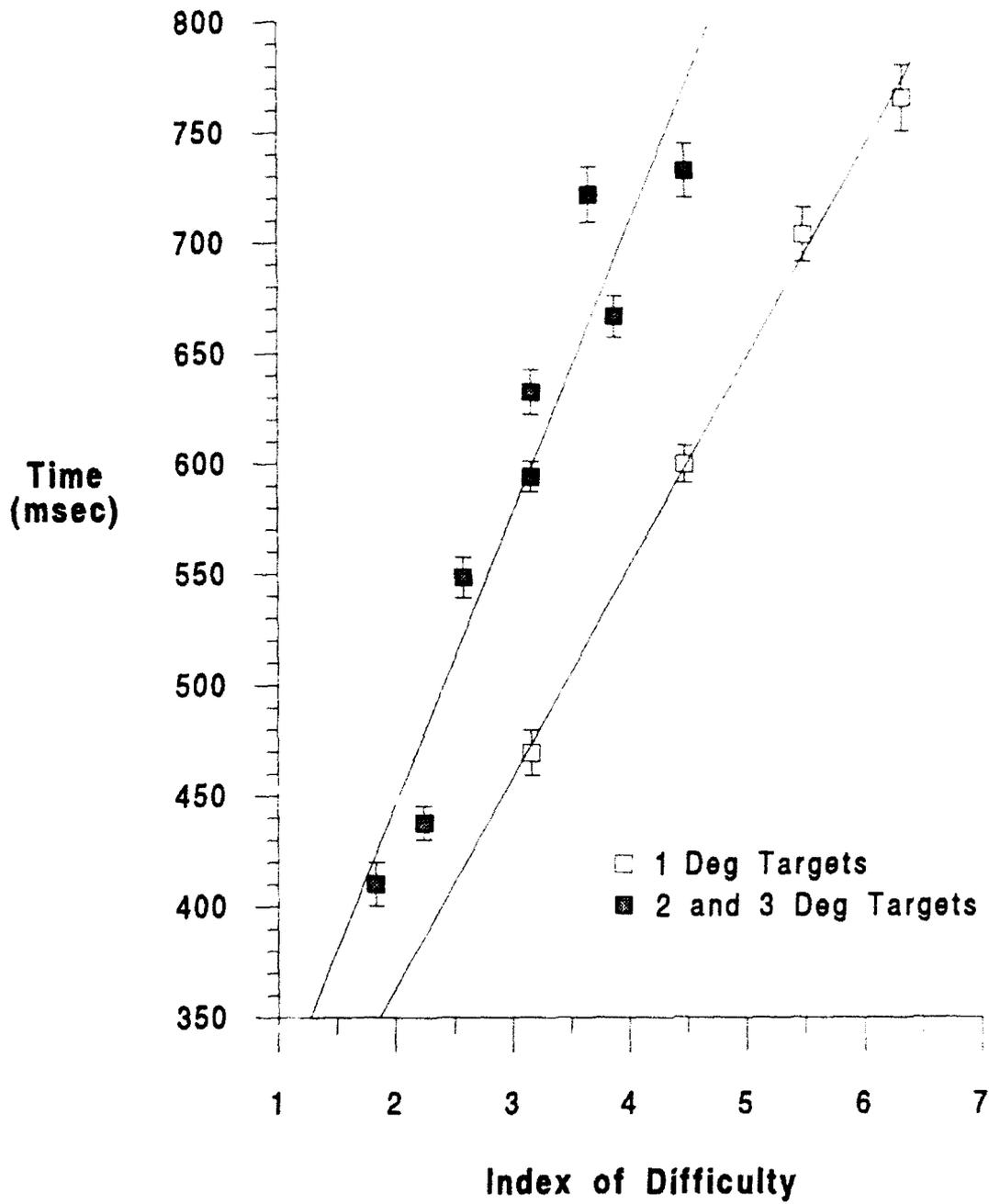
Table 6.4: Movement Time by Hand and Day

Hand	Day 1	S.E.	Day 2	S.E.
Left	610 ms	15.5 ms	610 ms	14.3 ms
Right	593 ms	15.2 ms	614 ms	14.3 ms

The interaction between hand, target direction, and target distance appears again to stem from an interaction between supination/pronation and target distance. As the square root of the target distance increased, the differences in movement for pronations and supinations became progressively larger in a linear fashion (r^2_{sup}=.997 and r^2_{pro}=.995), with pronation being the faster of the two (Figure 6.10). The difference in slopes is not significant, but the trends are clear (x_{sup}=99.1 and x_{pro}=90.5).

Standard deviation of total movement distance. For this measure, the main effect of total movement distance was significant [$F(3,6)$=52.45, $p \leq .0001$], as were the interactions of hand by target-width and day by target-width [$F(2,4)$=9.62, $p \leq .0296$, and $F(2,4)$=9.19, $p \leq .0320$, respectively]. The target-width effect also approached significance [$F(2,4)$=5.54, $p \leq .0704$].

Here, the distance and width effects were both linear functions; the dependent variable increased with the square root of target width (r^2=.856) and decreased with the square root of target distance (r^2=.848) [Figures 6.11 and 6.12].

When this metric was plotted versus the calculated index of difficulty for each distance/width combination, however, another inconsistency arose. The correlation was substantially worse with all targets (r^2=.53), than when the two most outlying indices of difficulty were dropped (the 3° target at the 10° distance and the 1° target at the 40° distance). For the smaller subset, the fit was substantially better (r^2=.842) [Figure 6.13]. The open squares in this figure represent the outlying indices of difficulty, while the filled squares represent the remaining targets. Unsurprisingly, the standard deviation of total movement distance decreased with increased movement difficulty.

The hand by target width interaction occurred because the left hand was more variable than the right for the wider targets (2° and 3°) with the difference diminishing on the narrowest target (d_T=.0341 deg, $p \leq .05$) [Table 6.5]. This was surprising, since the exact opposite pattern had been predicted by the background-noise hypothesis. The day by target-width interaction occurred because the subjects performed slightly better on the second day with the narrower targets and slightly worse with the widest target (Table 6.6).

Table 6.5: Standard Deviation of Total Movement Distance by Hand and Target Width

Target Width	Left Hand	S.E.	Right Hand	S.E.
1 deg	.76 deg	.04 deg	.69 deg	.03 deg
2 deg	.81 deg	.03 deg	.68 deg	.02 deg
3 deg	.92 deg	.04 deg	.81 deg	.04 deg

Movement Time by Supination/Pronation and Square Root of Target Distance
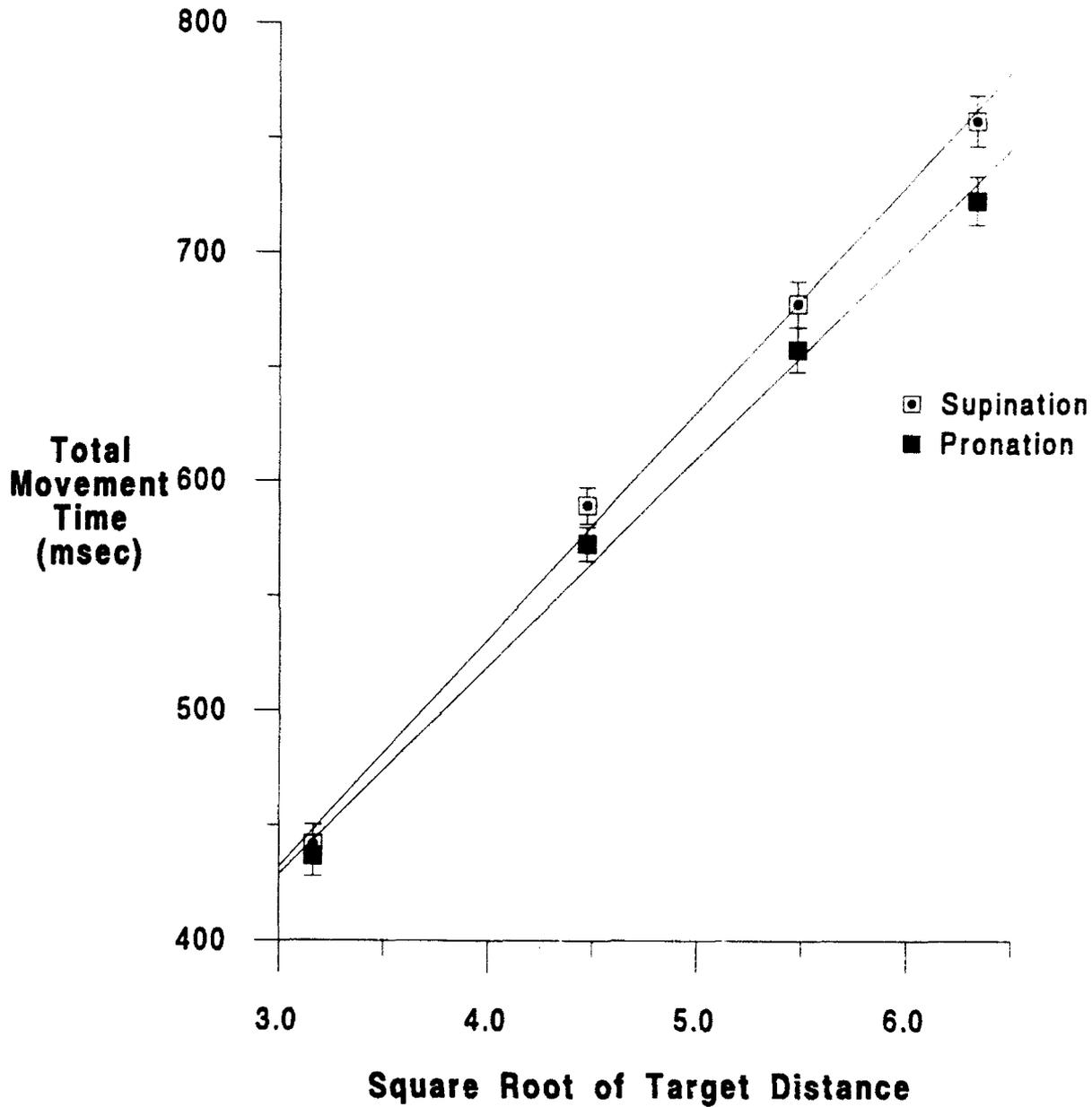
FIGURE 6.10

Standard Deviation of Complete
Movement Distance by Target Width
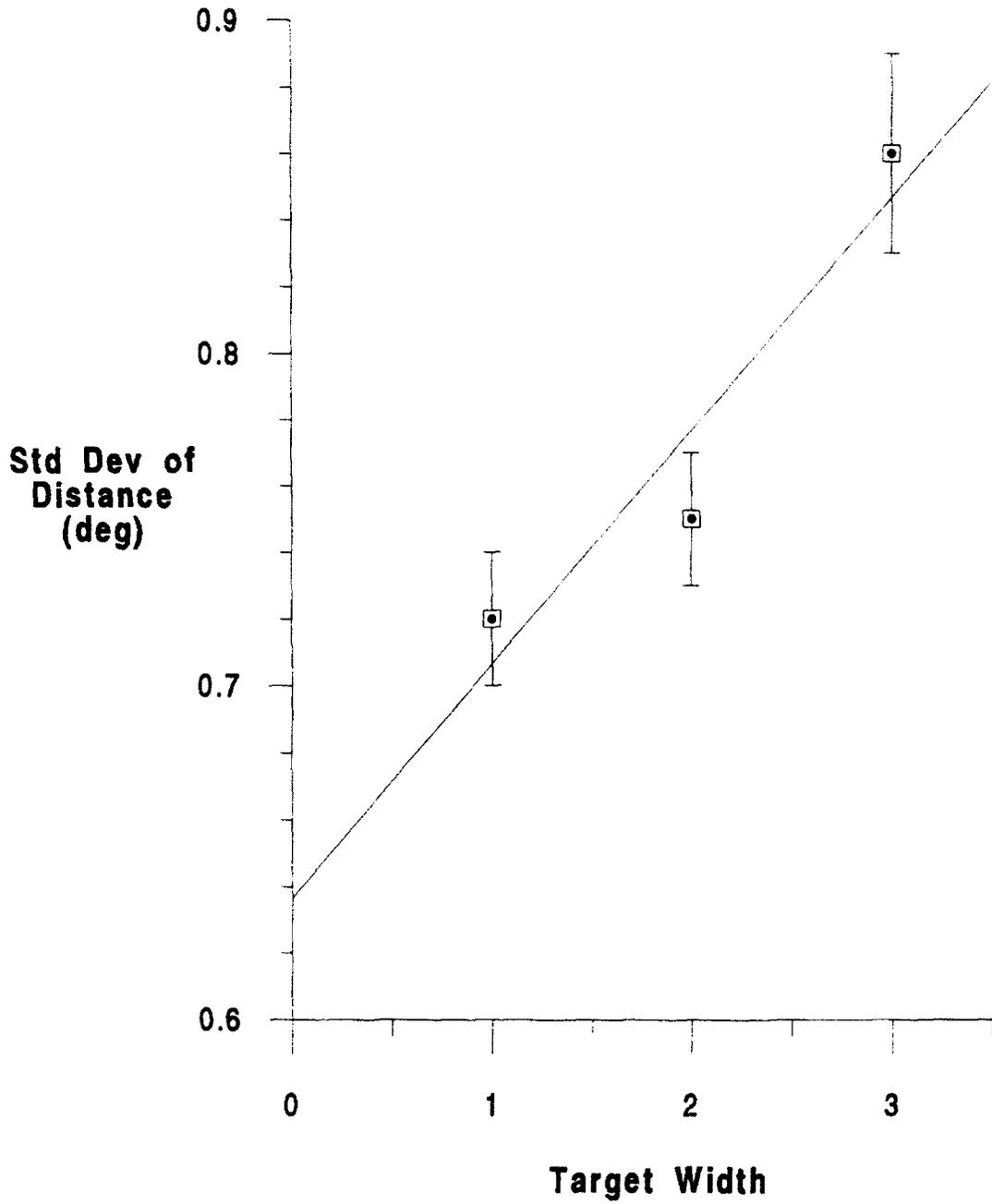
FIGURE 6.11

Standard Deviation of Total Movement Distance by Square Root of Target Distance
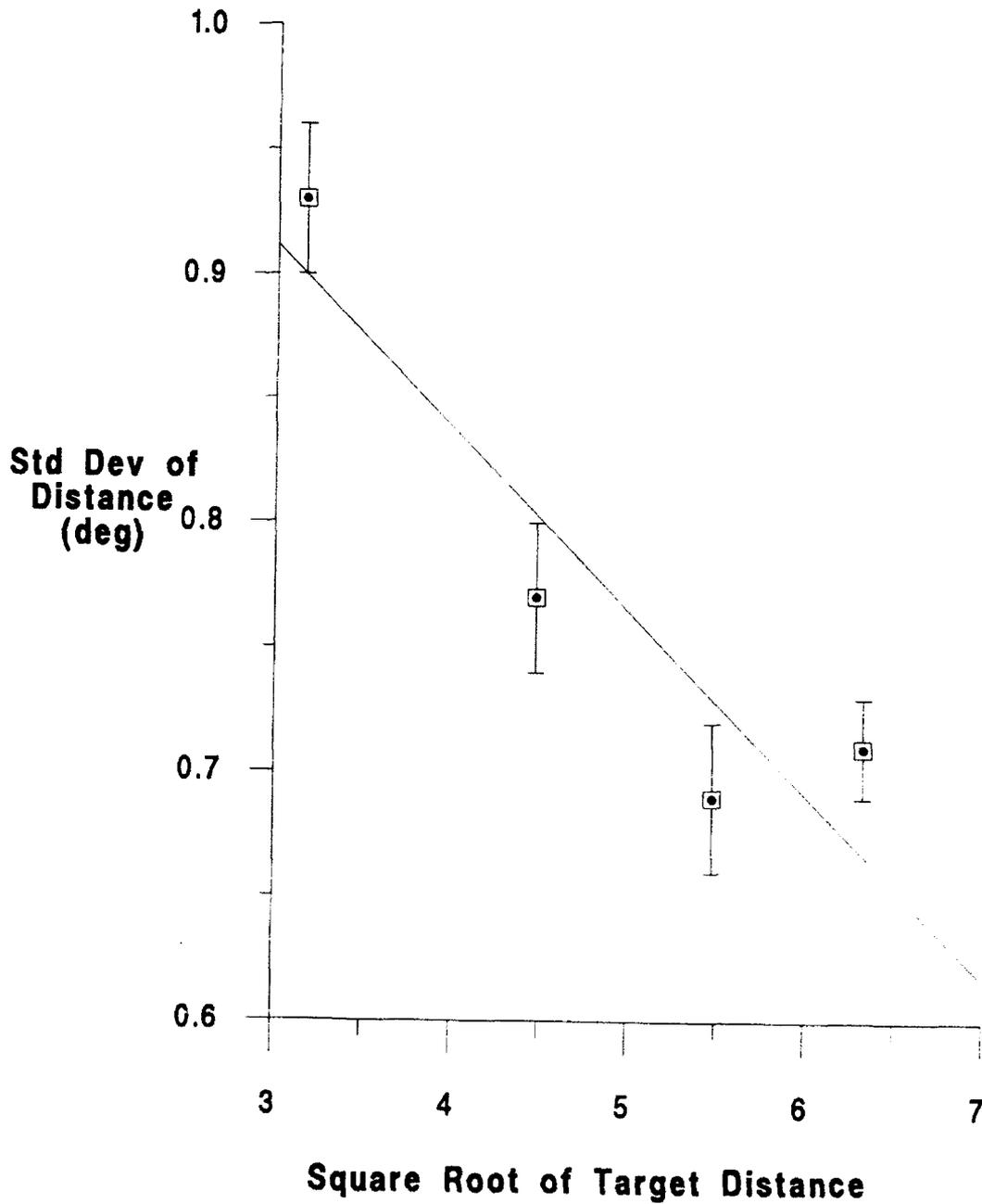
FIGURE 6.12

Standard Deviation of Total Movement
Distance by Index of Difficulty
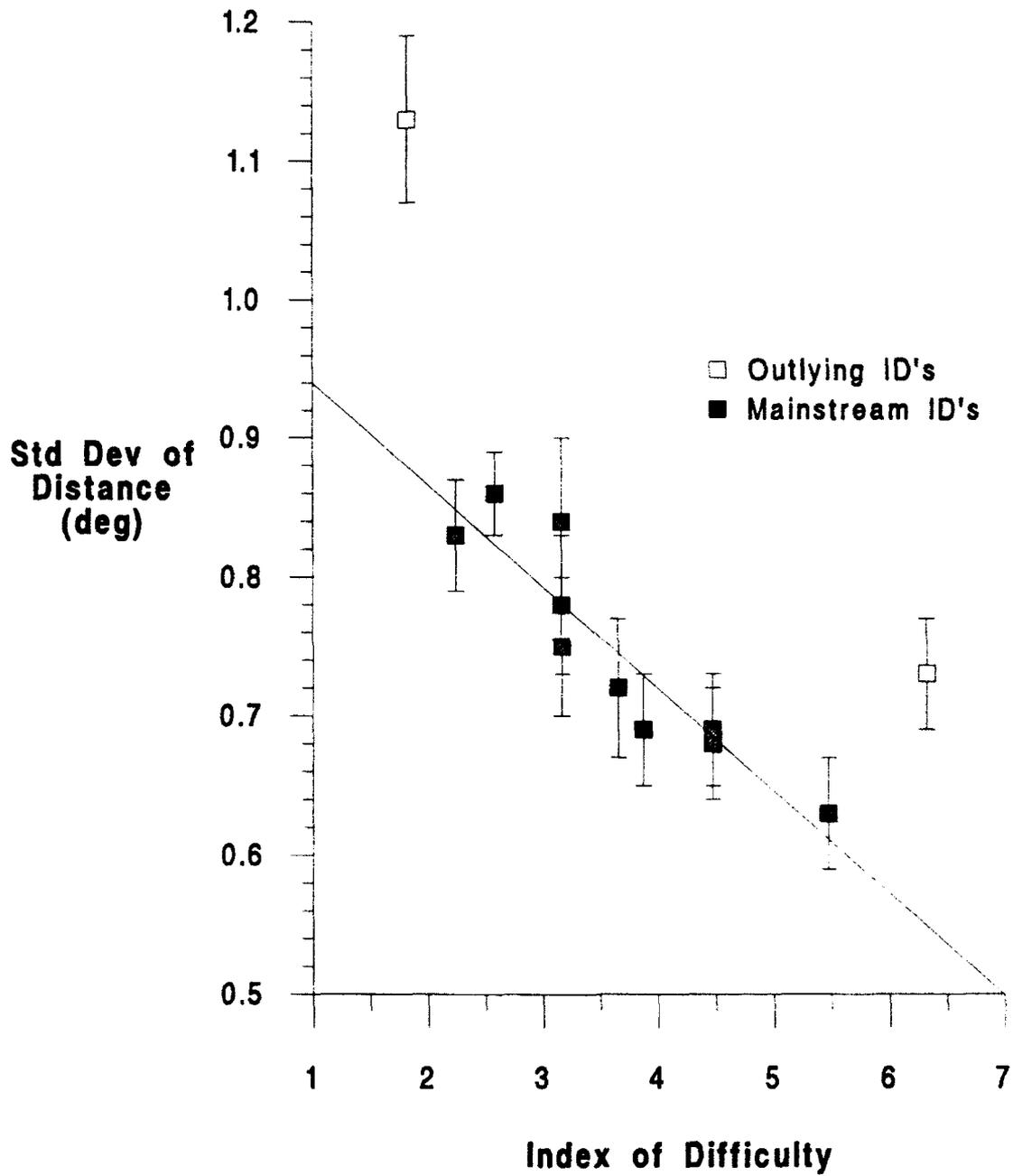
FIGURE 6.13

Table 6.6: Standard Deviation of Total Movement Distance by Day and Target Width

Target Width	Day 1	S.E	Day 2	S.E
1 deg	.74 deg	.03 deg	.71 deg	.03 deg
2 deg	.78 deg	.03 deg	.71 deg	.03 deg
3 deg	.83 deg	.04 deg	.90 deg	.03 deg

Constant error of total movement distance. Only target distance significantly affected the constant error of total movement distance $[F(2,4)=12.51, p \leq .0054]$. The target-distance effect was caused by movements to the farthest and nearest target distances exhibiting significantly more extreme (negative) errors than those to the other targets $(d_T=.132$ deg, $p \leq .05)$ [Table 6.7].

Table 6.7: Constant Error of Total Movement Distance by Target Distance

Target Distance	Constant Error of Complete Movement	S.E.
10 deg	-0.18 deg	.04 deg
20 deg	0.00 deg	.03 deg
30 deg	0.04 deg	.03 deg
40 deg	-0.23 deg	.04 deg

The interaction between hand and target width also approached significance $[F(2,4)=4.91, p \leq .0838]$. This is interesting because it involves one of the cases where a difference should have occurred between hands if the background-noise hypothesis had been true. As Table 6.8 shows, the preferred hand tended to perform more accurately for the narrower targets, with this trend becoming more pronounced as the targets became smaller $(d_T=.0995$ deg, $p \leq .05)$. However, the superiority of the nonpreferred hand for the widest target raises questions about the viability of this hypothesis.

Table 6.8: Constant Error of Total Movement Distance by Hand and Target Width

Target Width	Left Hand	S.E.	Right Hand	S.E
1 deg	-.14 deg	.05 deg	-.07 deg	.04 deg
2 deg	-.13 deg	.04 deg	-.08 deg	.04 deg
3 deg	-.10 deg	.06 deg	-.15 deg	.05 deg

Probability of missing. When the probability of missing the target was examined, the main effect of target width $[F(2,4)=101.13, p \leq .0004]$, and the hand by target-direction interaction $[F(1,2)=61.16, p \leq .0160]$ were significant. Here, the target-width effect involved an inverse linear relationship

(r^2=.938) between the square root of the target width and the subject's ability to halt his motion within it (Figure 6.14). The hand by target-direction interaction again involved a supination/pronation effect, with pronations being 2.5% more likely to hit the target than were supinations (24% vs 21.5%).

Number of submovements. Only target distance affected the number of submovements significantly [$F(3,6)$=41.80, $p\leq$.0002]. The number of submovements was a linear function (r^2=.984) of the square root of target-distance (Figure 6.15).

Summary of Current-Control Phase Measures. Again the results were somewhat surprising. None of the previously described handedness hypotheses (Table 6.1) was supported to a strong degree. The only one that achieved even limited success in its predictions was the background-noise hypothesis, which correctly predicted that the preferred hand would be more accurate than the nonpreferred hand as the target width decreased. However, this support is undermined by the fact that the widest target exhibited a **non**preferred-hand superiority in accuracy.

Probability of Missing by
Square Root of Target Width
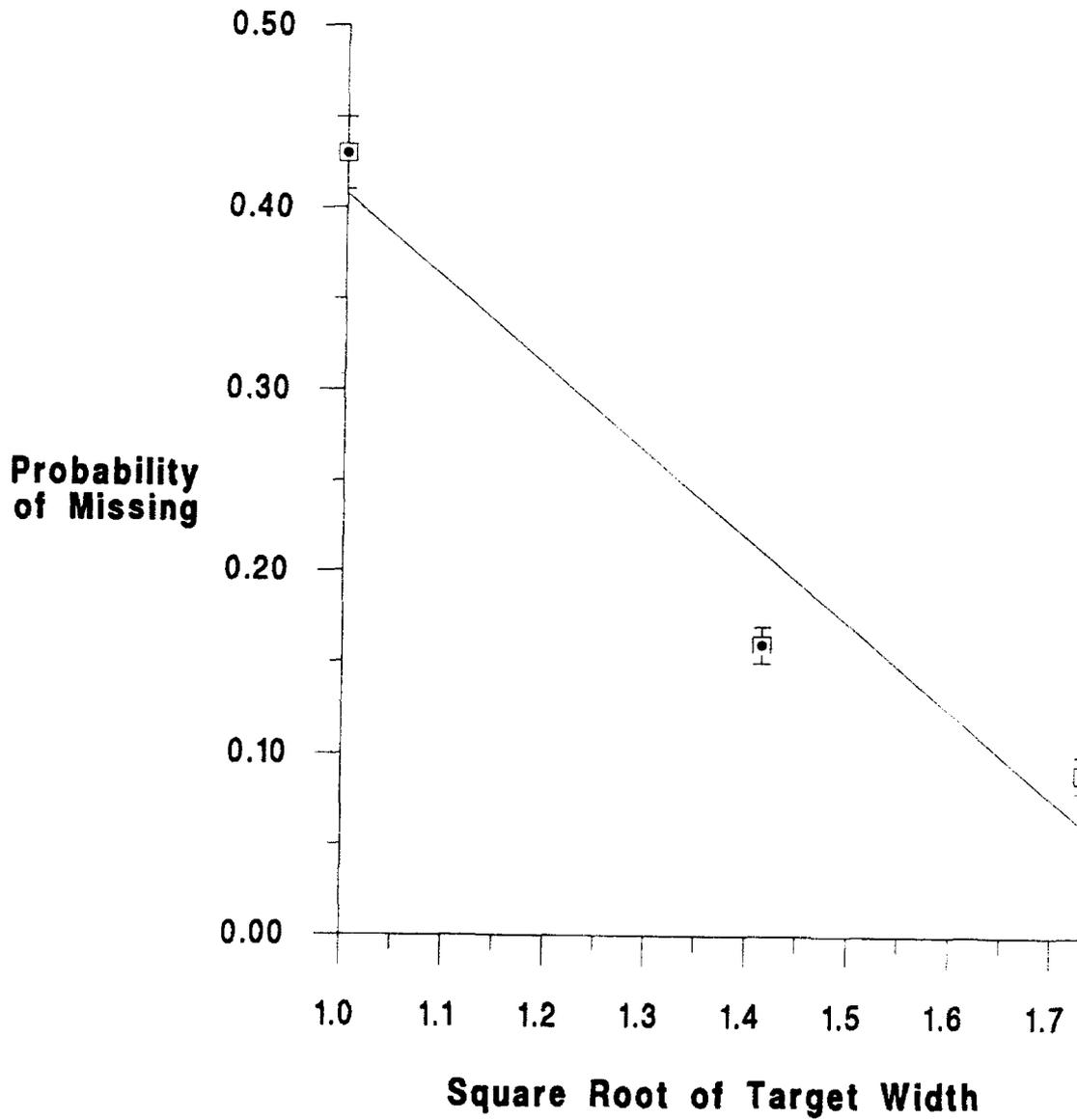
FIGURE 6.14

Number of Submovements by Square Root of Target Distance
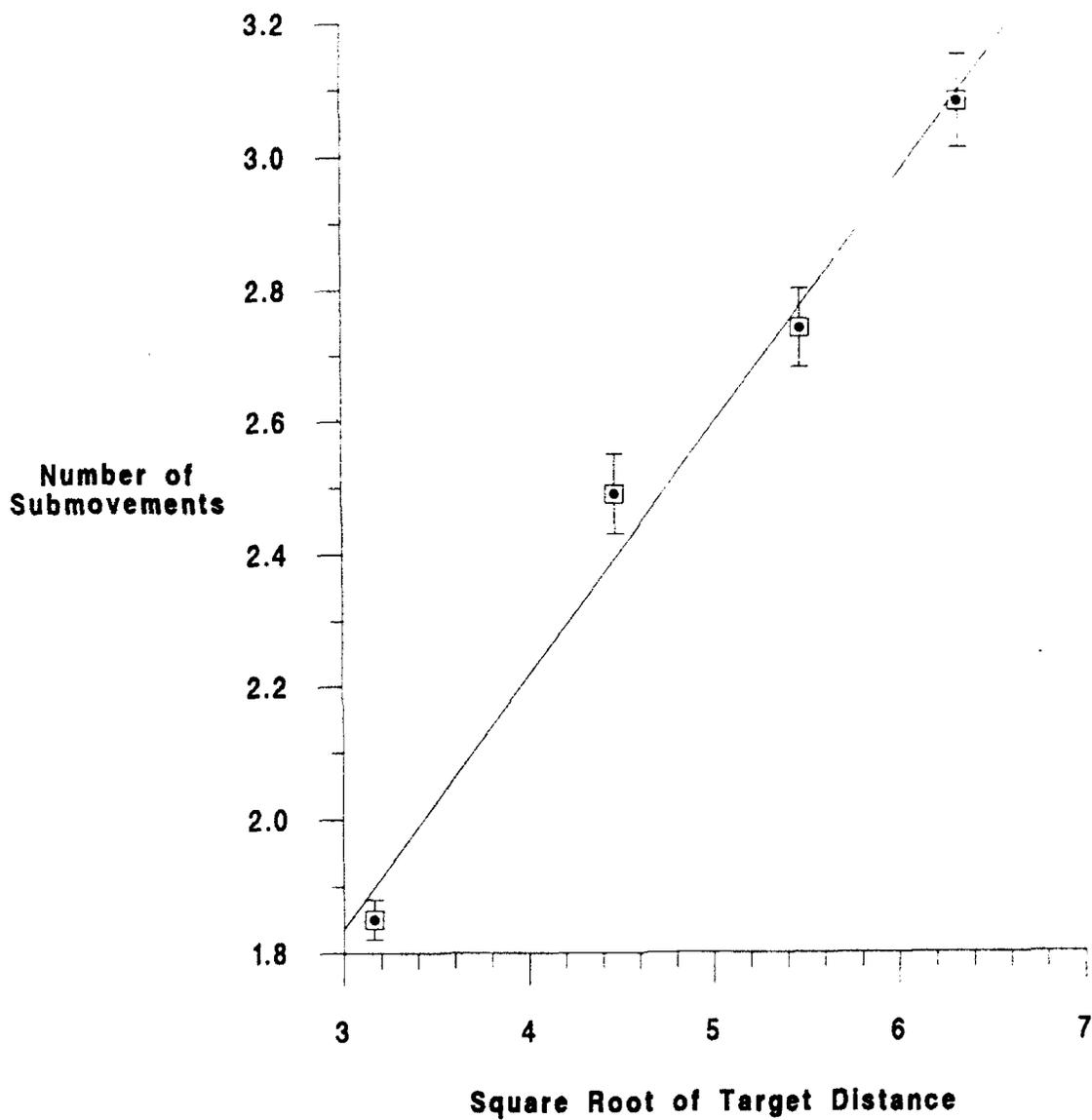
FIGURE 6.15

Discussion

The results of Experiment 1 were somewhat unexpected. A marked difference in performance between the two hands did not occur. No main effects of hand were noted for any of the dependent variables; even the interactions involving hand did not support any of the hypotheses being evaluated (cf. Table 6.1).

The supination/pronation effects were also unexpected, but far easier to explain. Pronations took less time to perform than did supinations (in terms of both the total movement time and first submovement time), but were less accurate in terms of constant error of first submovement distance. This suggests a distance-duration trade-off, with subjects preferring to make shorter, but faster pronations and longer, slower supinations.

Several handedness hypotheses can be tentatively rejected with the results of this experiment. According to the feedback hypothesis, if a preferred/nonpreferred hand difference had been present, it should have appeared as a difference between the hands during the current-control phase of movement. This would have been indicated by significant hand effects on some total movement variables such as constant error, standard deviation of total movement distance, total movement time, and number of submovements, while the corresponding first submovement variables (from the initial ballistic impulse phase) would show no difference. However, the predicted pattern was not present for any of the dependent variables, contrary to the feedback hypothesis.

If the force-variability hypothesis had been correct, a preferred-hand superiority should have occurred in the variability of the movements and the number of submovements per trial. Also, this superiority should have become more pronounced as the target widths decreased and distances increased. While such a pattern did emerge to a slight degree, no significant differences between the hands were noted. Apparently both hands were equally handicapped by the more difficult movements. On this basis, the force-variability hypothesis can be rejected.

If the practice hypothesis had been supported, significant day by hand interactions should have occurred for some or all the dependent variables, with the preferred hand performing significantly better than the nonpreferred on the first day, and the difference diminishing on subsequent days. While one day-by-hand interaction was significant, it involved a decrease in performance by the preferred hand on the second day. Because it is unlikely that practice would result in significantly worse performance for the preferred hand, the data therefore rule out the practice hypothesis as well.

Had the background-noise hypothesis been correct, a number of hand by target-width interactions should have occurred, with the preferred hand performing better than the nonpreferred only on the narrower targets. This should have appeared in the total movement time, the standard deviation of total movement distance, the number of submovements per trial, and the constant error in total movement distance. The data did indeed show a disparity between the hands in the standard deviation of total movement distance, but it was small and occurred only for the wider targets. The

constant error in total movement distance exhibited the predicted pattern for the narrower targets, but disappeared as the width increased.

One explanation for this is that subjects may have attempted to land at the exact center of the widest target, which could cause artifacts if the movement-parsing algorithm interpreted slow, minute movements as tremor or treated them as having stopped while they were still underway. Given the lack of support from the other dependent variables, however, such an account seems unlikely to have been a major cause of differences between the hands.

The analysis of the initiation-time data provided surprising results. No effects were predicted here, since all parameters of the movement were available to the subject before onset of the response signal. Previous work (Klapp and Greim, 1979) had shown that differences in reaction time caused by target width only occurred for choice, not simple, reaction time. However, Experiment 1 does not support this finding; there is a difference between the narrowest and the two widest targets in spite of the fact that the current experiment was based entirely on simple reaction time.

Since all the hypotheses about the source of differences between the preferred and nonpreferred hands in the execution of movement have been ruled out by this study, attention must now be focused on the remaining hypothesis, namely, that the left hemisphere in right-handers is somehow more attuned to making positioning movements, while the right is superior in creating motor programs. Probably the best method of investigating this hypothesis further is through a modification of Rosenbaum's (1980) movement-precuing technique, as discussed earlier (Chapter III). Selectively varying the amount and type of precue information that a subject has available before a movement could help illuminate the programming process and highlight any differences between the two sides of the brain. This technique therefore forms the basis of Experiment 2.

CHAPTER VII

EXPERIMENT 2: MOVEMENT PROGRAMMING

Rationale

Suppose the two cerebral hemispheres are differently specialized in their ability to process and use spatial information in the construction of motor programs. Then it should be possible to observe differences in positioning movements by varying the amount of precue information supplied before a movement is initiated. If one hemisphere (and consequently one hand) is better at using such information, faster programming should result. The movement-precuing technique developed by Rosenbaum (1980) is uniquely suited to pursue this possibility, so a modification of it was employed in Experiment 2.

An additional advantage of this technique is that a variety of other questions regarding movement programming can also be simultaneously addressed. These include:

1) Is a parametric or nonparametric programming model more appropriate?

2) Is programming accomplished as a serial or parallel process?

3) Is the process hierarchically organized? If so, in what order?

4) Can the Hick-Hyman Law account for observed results? In other words, are multiple response alternatives first prepared, and then selected among?

5) Can a dimension reduction hypothesis account for observed results?

Initiation-time patterns associated with positive answers to each of these questions are summarized in Table 7.1. These patterns are not necessarily always mutually exclusive, so the listing below is not meant to be exhaustive (all of the possible interactions are not detailed.) It is possible that the programming process could, for example, be both serial and hierarchical in nature.

Table 7.1: Predicted vs. Observed Effects of Precue Manipulation on Initiation Time

<u>Elements of Movement Program Provided in Precue</u>

<u>Programming Issues</u>	<u>Direction</u>	<u>Distance</u>	<u>Both</u>	<u>None</u>	<u>2-Choice</u>	<u>4-Choice</u>
Parametric	shorter	shorter	shortest	*	no effect	no effect
Serial Process	shorter	shorter	shortest	*	no effect	no effect
Parallel Process	no effect	no effect	shortest	*	no effect	no effect
Hierarchical	shorter[1]	shorter[1]	shortest	*	no effect	no effect
Non-hierarchical	shorter	shorter	shortest	*	no effect	no effect
Multiple Responses Prepared	shorter	shorter	shortest	*	equal to dist	equal to dir
Dimensional Reduction	shorter[2]	shorter[2]	shortest	*	no effect	no effect
ACTUAL RESULTS	SHORTER	NO EFFECT	SHORTEST	*	NO EFFECT	NO EFFECT

* = baseline RT

1 = depends on which is higher in hierarchy

2 = should be equal to each other

Differences between preferred and nonpreferred hands for the execution portion of the movements are predicted to be the same as those observed in the previous study. It is assumed that all movements are fully programmed before the subjects attempt to execute them.

Method

Subjects

Six right-handed males between the ages of 21 and 35 served as paid subjects. Each received $4 per hour, plus a bonus based on good performance.

Procedure

The procedure was similar to that used in the first experiment, with two major differences. First, instead of three different target widths, a single width (3 degrees) was used. Second, the movement precue did not always specify the target location fully. Instead it provided only partial information. Subjects were informed about either the direction they would have to move (left/right), the extent of the movement ($10°$, $20°$, $30°$, or $40°$ of wrist rotation), both dimensions, or no dimensions.

The precue symbol was the same as in the previous experiment except that, rather than a single radius extending from the center to specify the exact movement required, several radii were present. For the direction precue, all four radii on the selected movement side were displayed (top of Figure 7.1a). For the extent precue, the radius at the appropriate target distance on each side was displayed (middle of Figure 7.1a). For the full-information precue, a single radius appeared (bottom of Figure 7.1a). For the no-information precue condition, all eight lines were displayed (top of Figure 7.1b).
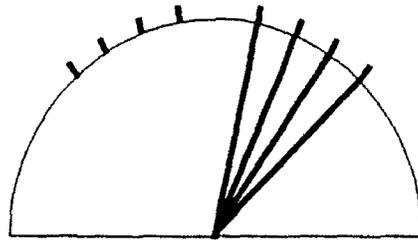
Direction
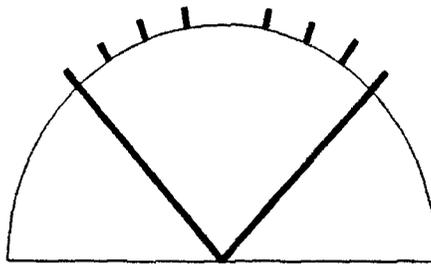
Extent
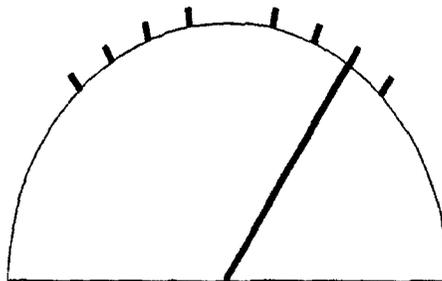
Full Information

Figure 7.1a: Movement Precues for Experiment #2
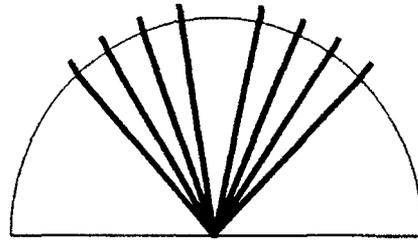
No Information
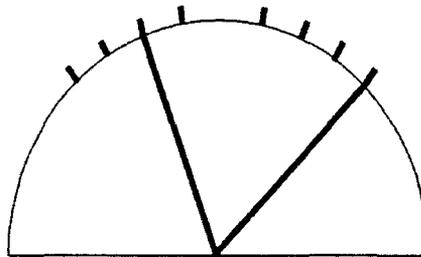
2-Choice
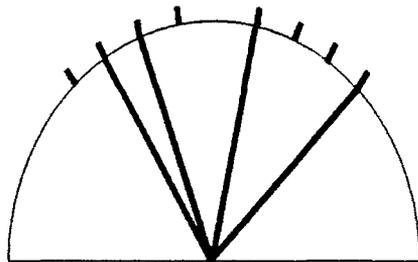
4-Choice

Figure 7.1b: Movement Precues for Experiment #2

Two additional movement precues were also included. In one of these, two targets were precued (but neither direction nor extent could be inferred). In the other, four targets were precued (such that direction and extent were still unknown) [middle and bottom of Figure 7.1b]. These precues corresponded to the number of targets indicated by the direction and distance precues. They were included to determine whether the subjects actually used the additional information available at the start of the movement to finish incomplete motor programs, or simply prepared multiple programs based on the available information. If the subjects prepared multiple programs, results should be identical when two targets were precued and when extent information was precued, since both of these precue types involve only two possible targets. The same would be true for the 4-target and direction precues.

The subjects' task involved moving a cursor from one of eight possible starting positions to a target located in the center of a display. Subjects again initiated each trial by positioning the cursor within a central alignment marker. Then they received information about the particular movement to be made, via the visual precue just described, which was presented for a period of two seconds.

The screen was blanked after the movement precue for a period of one sec. The response signal then occurred. It consisted of an audible tone and a symbol that was similar to the precue, but that specified only the final wrist position. At the onset of the response signal, subjects had to rotate the handle, moving the cursor from the starting location to the target as quickly and accurately as possible.

Scoring and feedback were identical with those used in the previous study.

Design

Each subject served in six 75 min. sessions as in the previous experiment. The movements within each session were organized into blocks of trials with type of precue, target distance, and target direction varied within blocks. A block consisted of 48 movements, one for each type of precue at each possible starting point; subjects performed six blocks per day. Movements within blocks were randomized to prevent systematic order effects. Hands were alternated across days. At the beginning of each data-collection day, subjects performed a short practice block of 15 trials.

Dependent variables for the study were initiation time, total movement and first submovement time, standard deviation of distance for total movements and first submovements, probability of missing the target, number of submovements, and the constant error in distance of both the total movement and first submovement.

Results

Significant effects for this experiment are summarized in Appendix A. Again, no main effects for preferred versus nonpreferred hand were significant.

Preparation Phase

Initiation time.   A summary of the initiation-time analysis appears in the bottom row of Table 7.1.   There were significant main effects of target distance $[F(3,9)=3.79, p\leq.05]$ and precue $[F(5,15)=31.97, p\leq.0001]$ on initiation time.   The interaction between hand, target direction, and distance was marginally reliable $[F(5,15)=2.67, p\leq.0644]$ and also important.

The target-distance effect on initiation time stemmed from the shortest movements taking significantly more time to program than did the others (Table 7.2).   The precue effect was much more complicated and appears in Table 7.3. The no-information, extent, 2-, and 4-choice precues did not produce significant initiation-time differences, while the direction precue produced significantly faster initiation times than did any of the others.   When both direction and extent were precued, the shortest initiation time occurred, significantly faster even than the direction precue alone $(d_T=33.34$ msec, $p\leq.05)$.   When extent alone was precued, the initiation time did not differ significantly from that when no information was provided $(d_T=33.34$ msec, $p\leq.05)$.

Table 7.2: Initiation Time by Target Distance

Target Distance	Initiation Time	S.E.
10 deg	364 ms	6.45 ms
20 deg	345 ms	5.53 ms
30 deg	342 ms	5.59 ms
40 deg	345 ms	5.79 ms

Table 7.3: Initiation Time by Precue

Precue	Initiation Time	S.E.
None	385 ms	5.78 ms
Direction	310 ms	6.49 ms
Extent	372 ms	5.97 ms
Both	264 ms	6.27 ms
2-Choice	379 ms	5.33 ms
4-Choice	385 ms	5.83 ms

The interaction between day and precue appears in Table 7.4.   Not surprisingly, there was an improvement in initiation time on the second day, but the only significant differences involved those for the no information, direction, and 4-choice precues $(d_T=13.86$ msec, $p\leq.05)$.   The full information precue ("both") showed the least improvement between days.   This is not

surprising, since with full information the task amounted to little more than a measure of simple reaction time. The direction precue exhibited the greatest improvement between days. This is consistent with a hierarchical structure within the movement programming process, with direction required before distance information can be made use of. Early extent knowledge in such a case would provide little helpful information to the subject, since without the appropriate direction parameter it would not be possible to begin construction of the movement program. Any practice effect on interpreting the symbols would be largely overshadowed by the greater amount of programming time required for all precues other than the first dimension. Precuing direction information would allow the subject to benefit by beginning the programming process.

Table 7.4: Initiation Time by Day and Precue

Precue	Day 1	S.E.	Day 2	S.E.
None	396 ms	7.38 ms	373 ms	8.72 ms
Direction	325 ms	8.37 ms	294 ms	9.61 ms
Extent	380 ms	7.41 ms	364 ms	9.32 ms
Both	270 ms	7.94 ms	259 ms	9.72 ms
2-Choice	384 ms	6.87 ms	374 ms	8.15 ms
4-Choice	395 ms	7.40 ms	374 ms	8.89 ms

The three-way interaction between hand, target direction, and target distance is much more difficult to interpret. Table 7.5 suggests that the right hand was much more consistent between supination and pronation movements than was the left when direction information was unavailable. This could be the result of the agonist-antagonist muscle pairs within the preferred arm being more nearly equal in strength than are those in the nonpreferred arm.

Table 7.5: Initiation Time by Hand, Target Direction, and Precue

	Left Hand				Right Hand			
Precue	Left	S.E.	Right	S.E.	Left	S.E.	Right	S.E.
None	360 ms	9.97 ms	403 ms	15.06 ms	384 ms	9.00 ms	391 ms	10.42 ms
Direction	293 ms	12.99 ms	311 ms	16.09 ms	306 ms	8.02 ms	329 ms	13.27 ms
Extent	341 ms	11.22 ms	399 ms	13.54 ms	379 ms	11.06 ms	370 ms	9.75 ms
Both	255 ms	14.73 ms	271 ms	15.38 ms	259 ms	7.62 ms	273 ms	11.14 ms
2-Choice	356 ms	10.24 ms	391 ms	12.44 ms	389 ms	7.99 ms	381 ms	10.81 ms
4-Choice	363 ms	12.85 ms	405 ms	14.33 ms	380 ms	9.14 ms	390 ms	8.62 ms

Ballistic Phase

First submovement time. Significant effects on first submovement time were found for both target distance [$F(3,9)=8.28$, $p \leq .0059$] and precue [$F(5,15)=3.79$, $p \leq .0203$]. The distance effect involved the first submovement being executed more rapidly (255 msec) for the 10° targets than for the other target distances (284, 288, and 292 msec) [$d_T=26.32$ msec, $p \leq .05$].

The precue effect occurred because the directionally precued movements had significantly longer first submovements than those obtained with the other precues (d_r=19.53 msec, $p \leq .05$). None of the other precues yielded times that differed significantly from one another. The data are contained in Table 7.6.

Table 7.6: First Submovement Time by Precue

Precue	Movement Time	S.E.
None	272 ms	6.83 ms
Direction	299 ms	8.26 ms
Extent	273 ms	6.83 ms
Both	280 ms	7.14 ms
2-Choice	275 ms	7.01 ms
4-Choice	281 ms	6.74 ms

Standard deviation of first submovement distance. Significant effects on this measure were found for target distance [$F(3,9)$=29.32, $p \leq .0001$], the interaction between hand and target direction [$F(1,3)$=12.33, $p \leq .0392$], and the interaction between hand, target direction, and target distance [$F(3,9)$=3.84, $p \leq .05$]. The standard deviation of movement distance again increased linearly with the distance to the target (r^2=.996) [Figure 7.2].

The interaction between hand and target direction stemmed from the preferred hand exhibiting less difference between supinations and pronations than did the nonpreferred hand. This effect is shown in Table 7.7.

Table 7.7: Standard Deviation of First Submovement Distance by Hand and Target Direction

	Left Hand	S.E.	Right Hand	S.E.
Supinating	6.66 deg	.27 deg	6.08 deg	.24 deg
Pronating	5.49 deg	.22 deg	5.79 deg	.22 deg

The three-way interaction is actually a two-way interaction between supination/pronation and target distance. The standard deviation of the first submovements for both supinations and pronations increased linearly with the target distance (r^2_{sup}=.9996, and r^2_{pro}=.985). Supinations became increasingly more variable than pronations as the target distance increased. This relationship is depicted in Figure 7.3 (the slopes in this relationship are significantly different (z=3.24, z_{crit}=1.96)].

Constant error of first submovement distance. Significant effects were found on this measure for target distance [$F(3,9)$=91.27, $p \leq .0001$] and precue [$F(5,15)$=2.98, $p \leq .0461$]. The distance effect occurred because the constant error of the first submovement distance was an inverse linear function of target distance (r^2=.9999) [Figure 7.4]. The precue effect occurred because both precues involving direction information (the direction and full-information precues) produced substantially smaller constant errors than did the other four precues (d_r=1.566, $p \leq .05$). Neither the two directional

Standard Deviation of First Submovement Distance by Target Distance
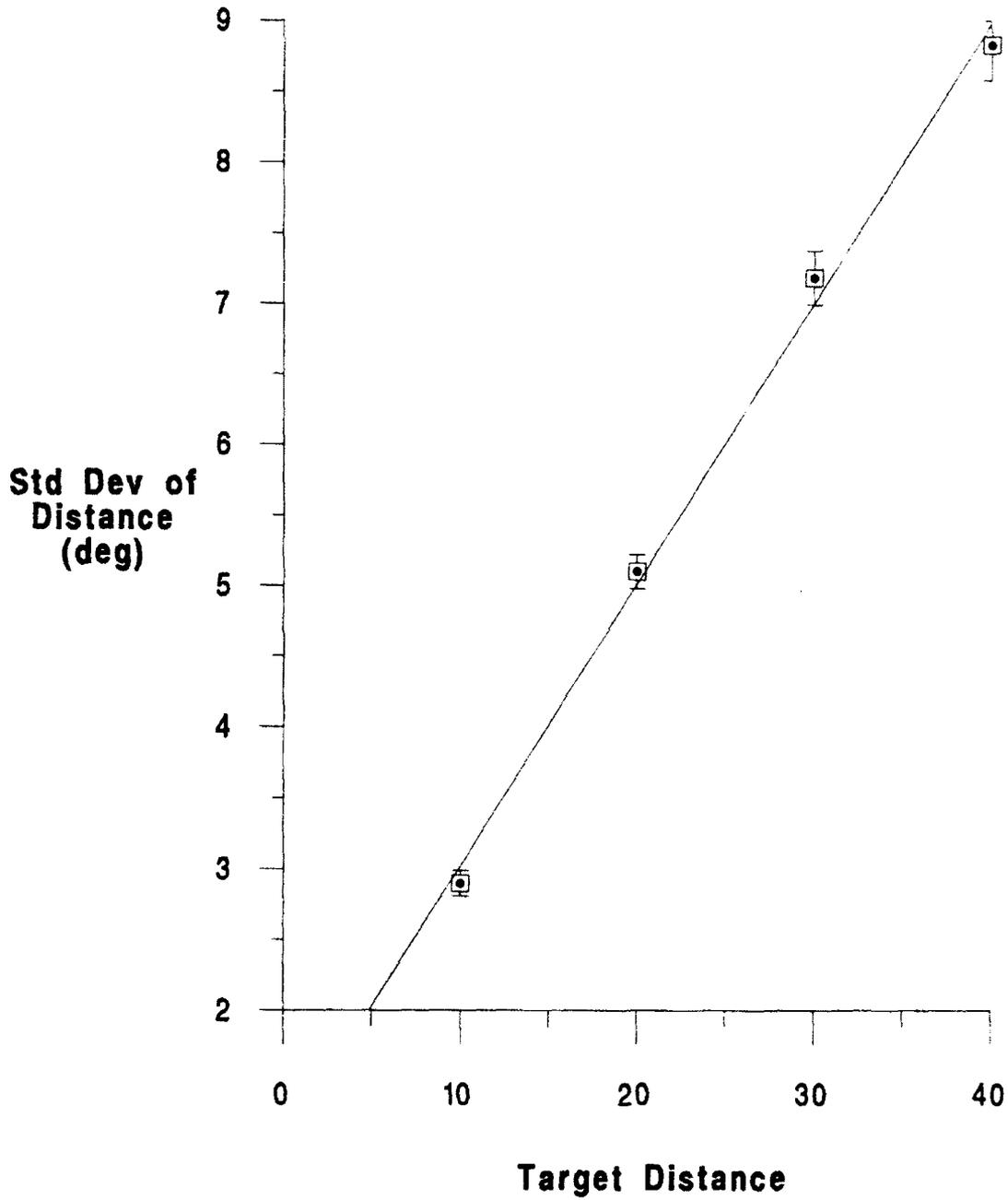
FIGURE 7.2

Standard Deviation of First Submovement Distance by Supination/Pronation and Square Root of Target Distance
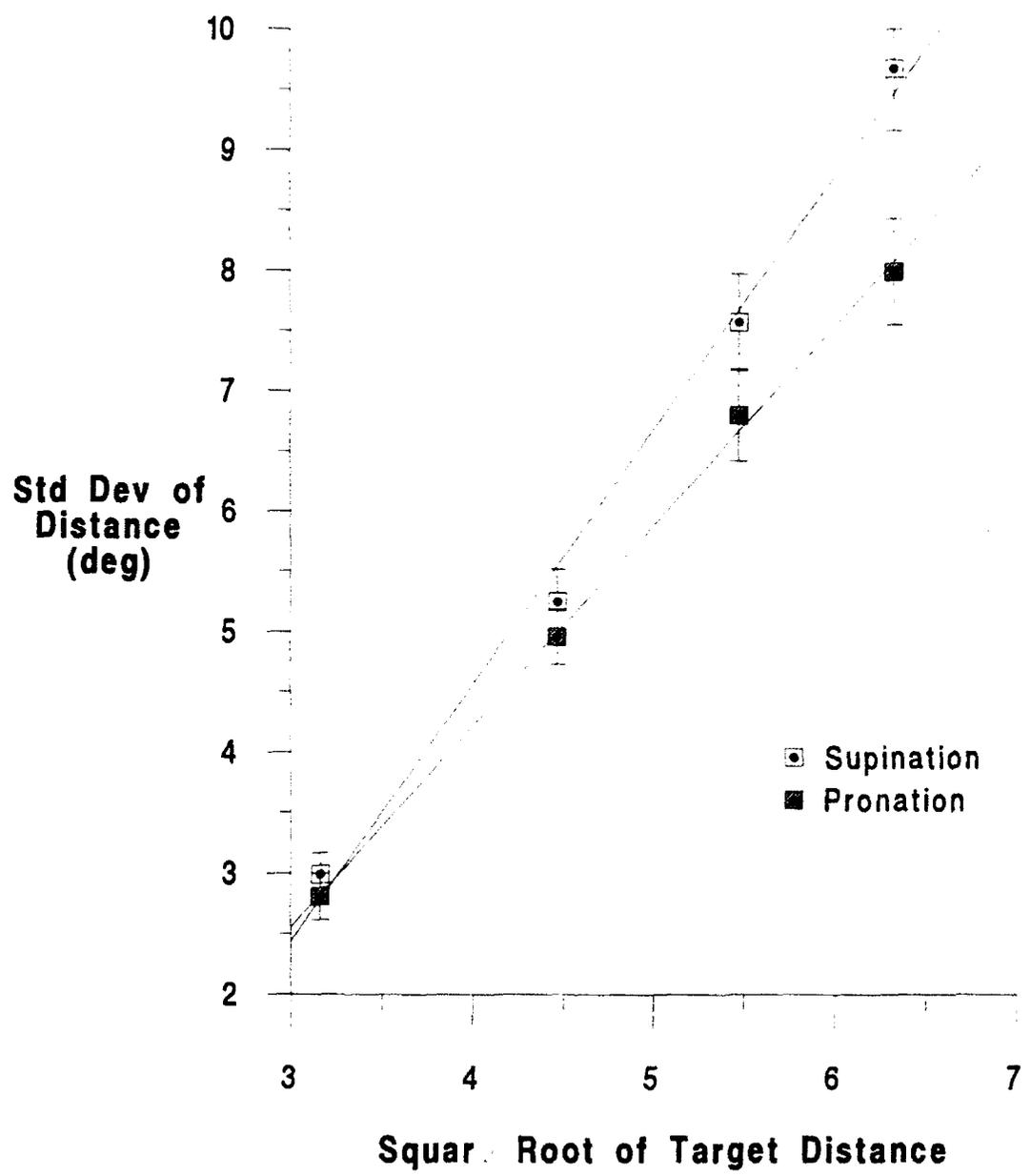
FIGURE 7.3

Constant Error of First Submovement
Distance by Target Distance
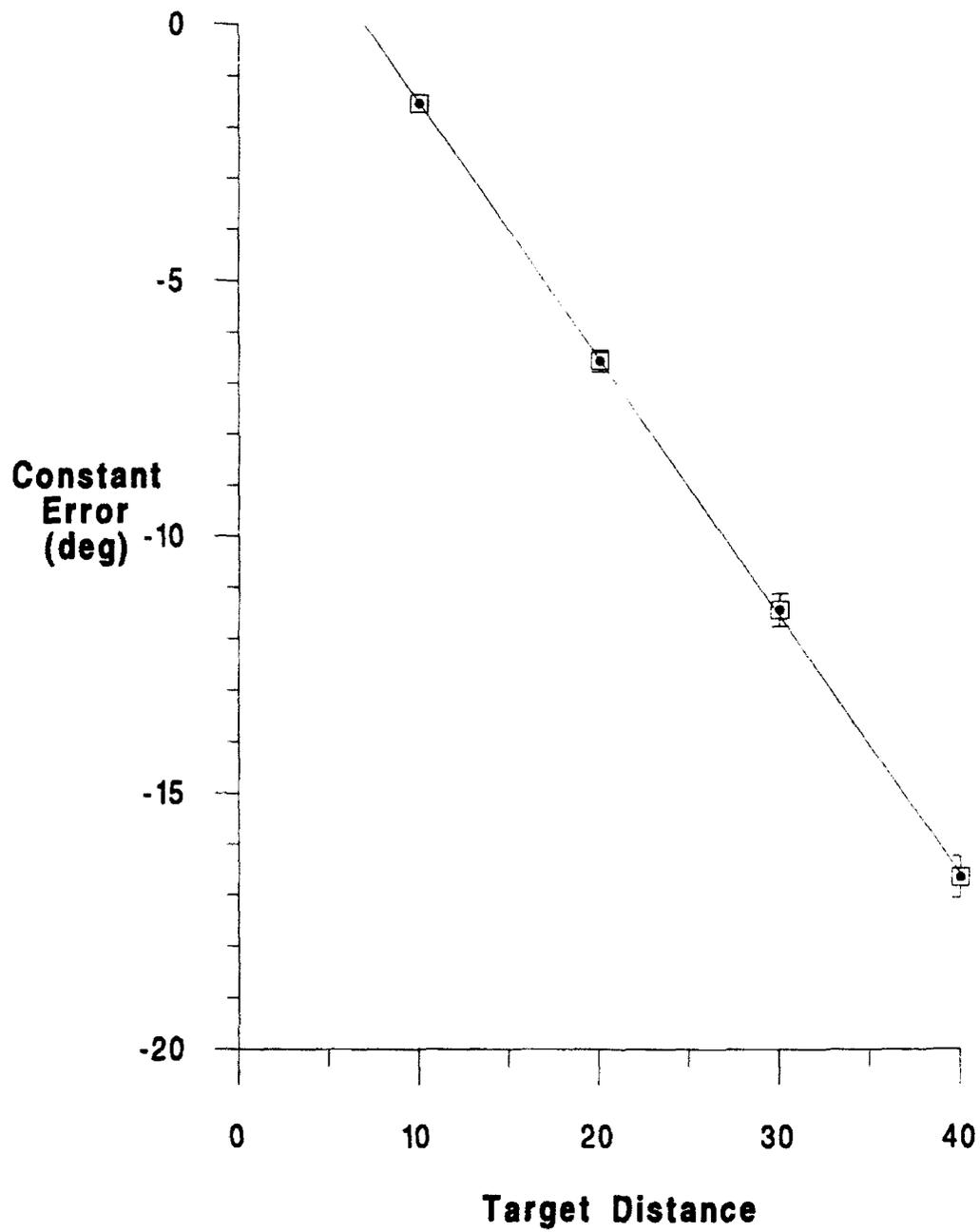
FIGURE 7.4

precues nor the other four precues differed significantly from each other in their effects (Table 7.8).

Table 7.8: Constant Error of First Submovement Distance by Precue

Precue	Constant Error	S.E.
None	-9.75 deg	.63 deg
Direction	-8.32 deg	.58 deg
Extent	-9.24 deg	.64 deg
Both	-7.99 deg	.56 deg
2-Choice	-9.44 deg	.62 deg
4-Choice	-9.57 deg	.63 deg

Summary of ballistic-phase measures. As in Experiment 1, none of the hypotheses regarding hand differences in the ballistic phase of movement was supported by the present data. The persistence of some hand by target-direction by target-distance interactions is quite interesting, however, and will be further developed later.

Current-Control Phase

Total movement time. Total movement time exhibited significant effects only for target distance [$F(3,9)=31.66$, $p \leq .0001$]. The interactions between hand and precue, and between hand, target direction, and target distance were also marginally reliable and of interest [$F(5,15)=2.51$, $p \leq .0768$; and $F(3,9)=3.77$, $p \leq .00531$, respectively].

The distance effect again stemmed from a linear relationship between the square root of target distance and movement time ($r^2=.997$). This effect is presented in Figure 7.5.

The interaction between hand and precue resulted from a tendency for the preferred hand to be faster when only extent was known [$d_T=17.65$ msec], while the nonpreferred hand was faster with all the other precues (though not significantly so) [Table 7.9]. This does **not** support the hemispheric-processing hypothesis, because that hypothesis predicts that the **programming**, not **execution**, of the movement should be facilitated.

Table 7.9: Movement Time by Hand and Precue

Precue	Left Hand	S.E.	Right Hand	S.E.
None	571 ms	17.08 ms	566 ms	14.76 ms
Direction	569 ms	16.20 ms	588 ms	15.86 ms
Extent	576 ms	15.74 ms	561 ms	15.82 ms
Both	566 ms	17.60 ms	570 ms	16.31 ms
2-Choice	562 ms	16.98 ms	574 ms	15.17 ms
4-Choice	572 ms	15.18 ms	584 ms	16.60 ms

Total Movement Time by
Square Root of Target Distance
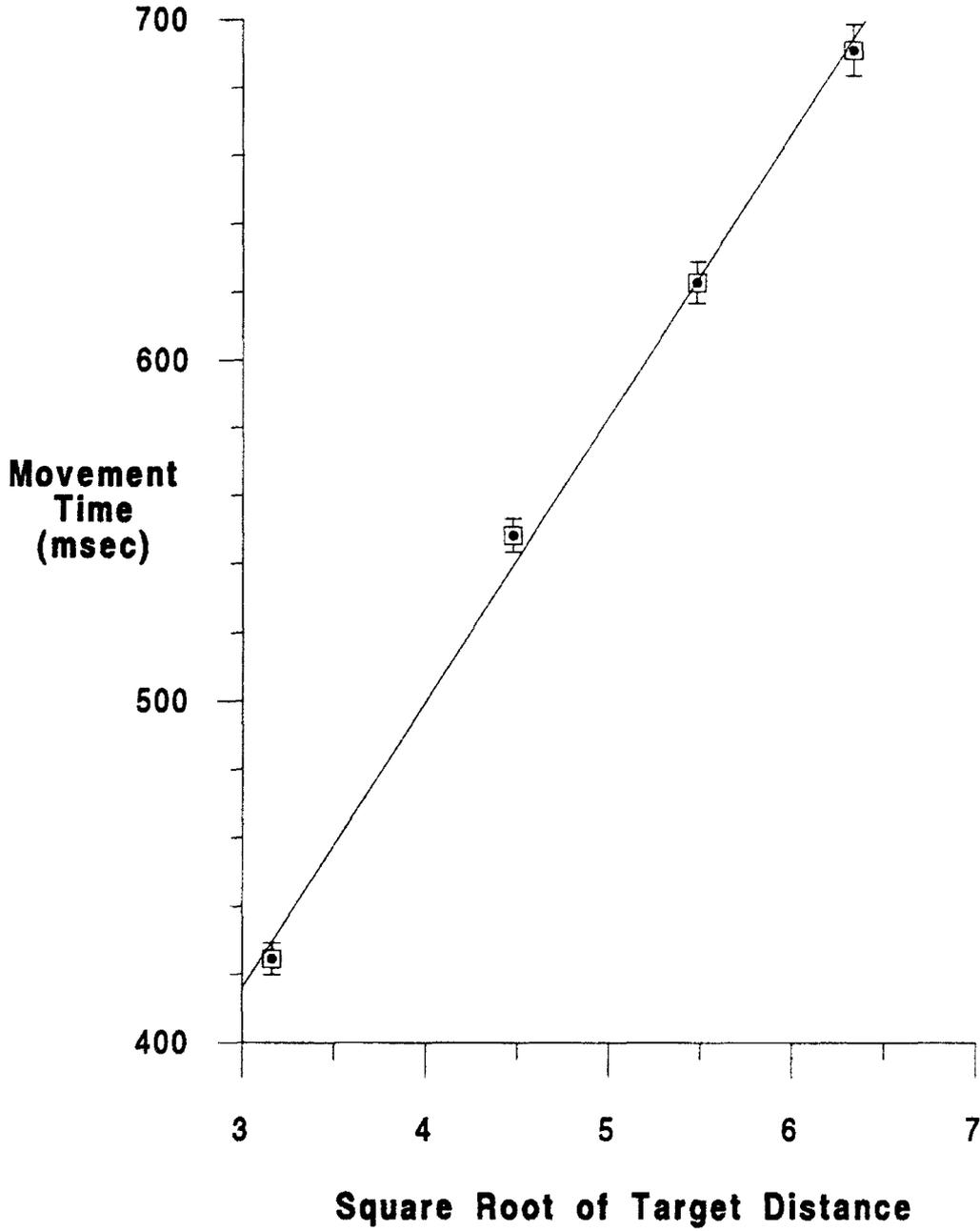
FIGURE 7.5

The interaction between target direction, target distance, and hand appears to involve another supination/pronation effect. Both supination and pronation movement times increased linearly with the square root of target distance (r^2_{sup}=.999 and r^2_{pro}=.995). The disparity between the two was greatest with the shortest target distance, decreasing for the longer movements (Figure 7.6). The difference between the slopes comes very close, but does not quite reach significance (z=1.82, z_{crit}=1.96).

These results are somewhat surprising when compared to those in the first experiment. While pronations were slower in both cases, the two types of movement progressively **diverged** with increasing movement distance in Experiment 1; here the opposite pattern emerged.

Probability of missing. Only target distance affected this measure significantly [$F(3,9)$=10.29, $p\leq$.0029]. This was caused by the shortest distance yielding an error rate approximately 4% higher than that found with the other targets (16% vs 12%, 11%, and 12%). Although, the nonpreferred hand did tend to miss more often than the preferred hand (Table 7.10), the interaction between hand and precue condition was not significant [$F(5,15)$=0.39, $p\leq$.8462]. Since the preferred hand also exhibited longer movement times **in general** for both complete movements and first submovements, possibly this represents a speed-accuracy trade-off. Unfortunately, there seems to be no consistent pattern relating the difference in miss rate to the difference in movement times.

Table 7.10: Probability of Missing by Hand and Precue

Precue	Left Hand	S.E.	Right Hand	S.E.
None	.15	.02	.12	.02
Direction	.15	.02	.13	.02
Extent	.12	.02	.12	.02
Both	.16	.02	.13	.02
2-Choice	.11	.02	.12	.02
4-Choice	.14	.02	.10	.02

Number of submovements. This measure showed a significant main effect of target distance [$F(3,9)$=83.37, $p\leq$.0001], and a three-way interaction between hand, target direction, and target distance [$F(3,9)$=6.74, $p\leq$.0112].

The distance effect is easily described; the number of submovements was a linear function of the square root of the target distance (r^2=.992) [Figure 7.7]. The three-way interaction between hand, direction, and distance is somewhat more difficult to understand. The preferred hand was somewhat more consistent in the number of submovements required for both supinations and pronations than the nonpreferred hand was, but a second pattern also emerged from the data. Movements over the shortest target distance required more submovements for supinations, while differences between the two disappeared at the 20° distance. For the longest movements, the trend reversed itself. These data are presented in Table 7.11.

Movement Time by Supination/Pronation and Square Root of Target Distance
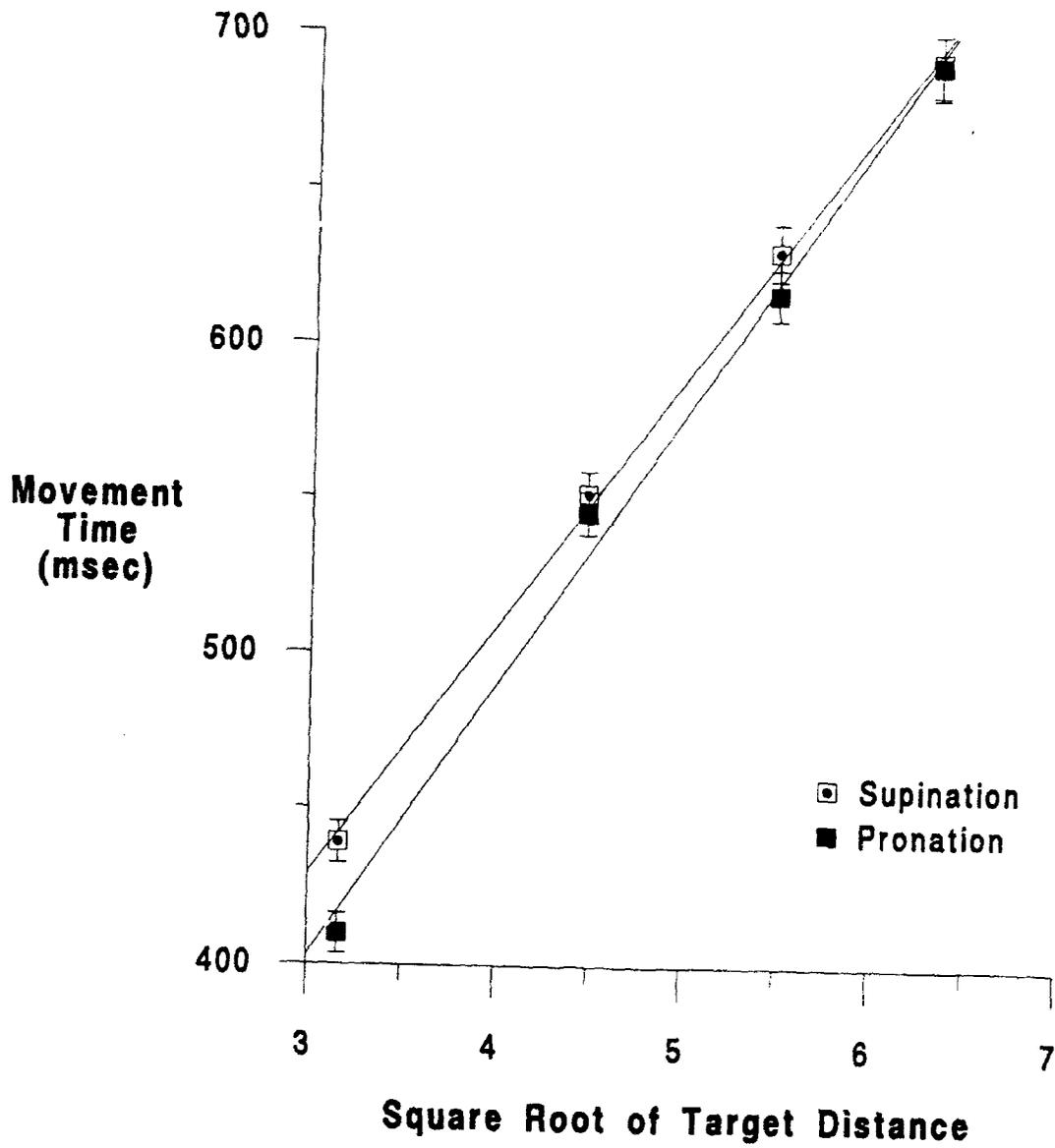
FIGURE 7.6

Number of Submovements by
Square Root of Target Distance

FIGURE 7.7

71
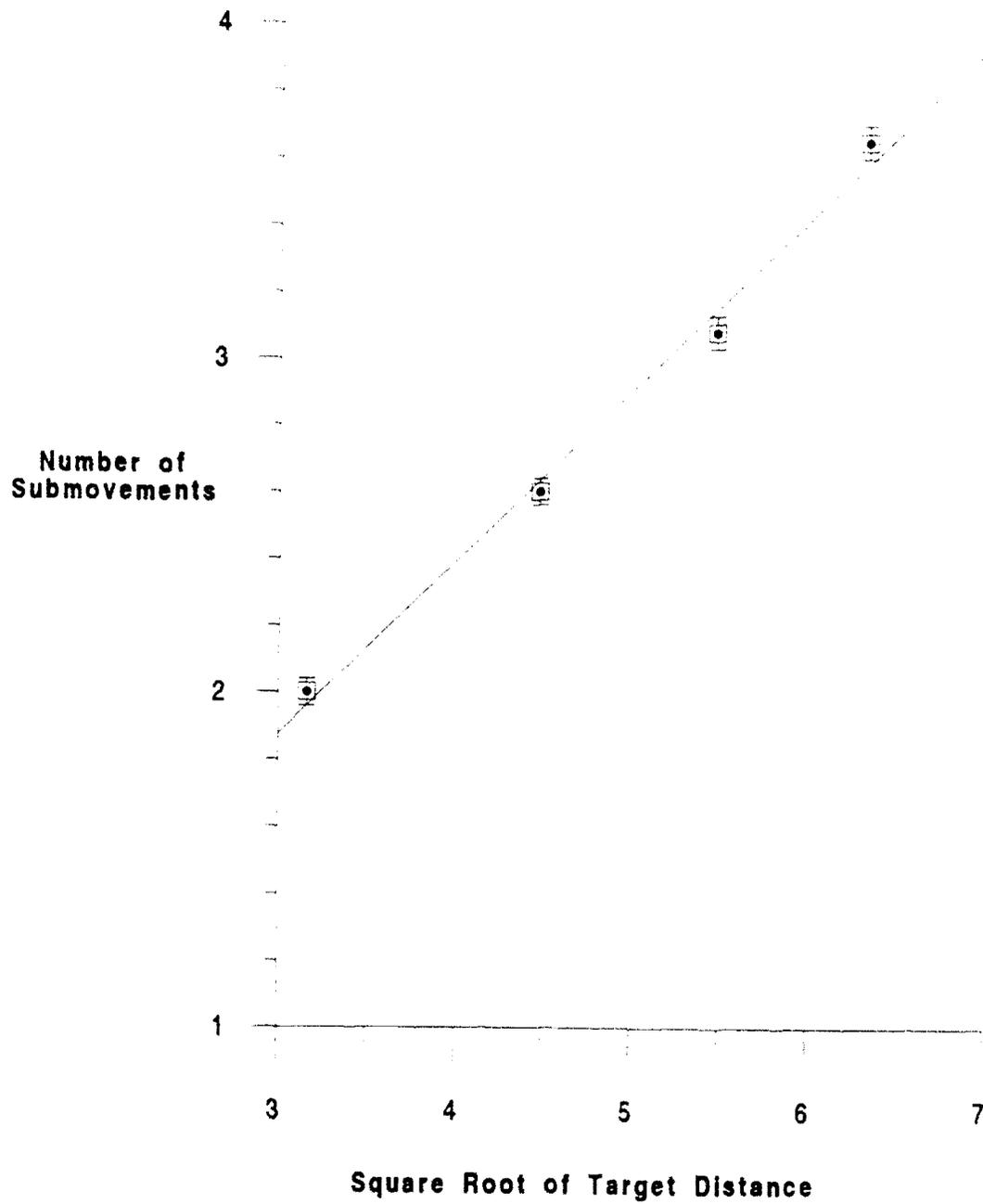
Table 7.11: Number of Submovements by Hand, Distance, and Target Direction

Target Distance	Left Hand				Right Hand			
	Left	S.E.	Right	S.E.	Left	S.E.	Right	S.E.
10 deg	2.18	.09	1.90	.08	1.90	.07	2.03	.07
20 deg	2.62	.08	2.63	.10	2.54	.07	2.60	.08
30 deg	2.82	.09	3.16	.09	3.25	.09	3.09	.08
40 deg	3.19	.09	3.93	.12	3.86	.10	3.63	.08

Summary of current-control phase measures. None of the hypotheses that attribute the performance difference between the hands to the current-control phase was supported. In this respect, the present results paralleled those of the previous experiment.

Discussion

The lack of any substantial performance differences between the preferred and nonpreferred hands in this experiment was surprising. The only effects of hand were the hand by target-direction interactions for initiation time, number of submovements, and standard deviation of first submovement distance. These variables suggest that differences between the preferred and nonpreferred hands might not be due to less variation within the preferred hand *per se*, but to greater consistency between opposite movements by the preferred hand. Perhaps the supination/pronation movements with the preferred hand are more similar to each other in terms of execution speed and other parameters than are those with the nonpreferred hand.

The superiority of the nonpreferred hand in total movement time with most precues is also quite surprising. Had the hemispheric-processing hypothesis been supported, one would have expected the initiation time for the movement to be lower for the nonpreferred hand, given the previously discussed superiority of the right hemisphere in processing spatial information such as the full-information precue provides. Overall movement time (a sequential, feedback-driven process) would have been faster for the preferred hand because of the left cerebral hemisphere's superiority in this type of information processing. However, no such differences arose in this study.

A possible explanation for this might be that the difference between the preferred and nonpreferred hands (and their controlling hemispheres) lies not in the initial construction of the motor program, but rather in a greater facility at **adapting** existing programs to account for new information. There could be a variety of reasons for this, including greater automaticity within the motor program for the preferred hand due to the left hemisphere's weaker spatial information processing ability. Perhaps the right (spatial processing) hemisphere is more facile at manipulating rapidly changing inf .mation than is the left. This would result in the nonpreferred hand being more adaptable once an initial motor program is constructed.

The most interesting aspect of the present experiment is that the effects of precuing differed from those found by Rosenbaum (1980). He found that

prior specification of hand, direction, or extent in any order decreased the reaction time of his subjects, leading him to postulate a serial, but not necessarily hierarchical organization within the motor program. This was not the case in Experiment 2.

Experiment 2 shows that information about movement extent was only valuable when coupled with direction information, while direction information alone was more valuable than no information. The combination of direction and extent information was more valuable than direction information alone, while extent information alone was not more valuable than no information. This suggests that direction and extent information **are** hierarchically organized in the motor program, with direction information being required before encoding extent. While these results agree with those of Larish and Frekany (1985), other aspects of their final conclusions were not supported here. Since precuing both direction and extent produced significantly faster initiation times than precuing direction alone (and direction was more valuable than no information), parallel processing can be ruled out. Had there been parallel processing, there should have been no difference between precuing either of the pertinent dimensions and providing no precues at all, while precuing both dimensions should have resulted in a significant decrease in initiation time over either one.

Although precuing successively more movement dimensions resulted in progressively lower initiation times, the dimension-reduction hypothesis can also be rejected with the results of Experiment 2. If this hypothesis were correct, precuing either extent or direction should have resulted in **equivalent** initiation times, since in either case only one dimension remained to be specified afterwards. However, this did not occur.

The contention by both Goodman and Kelso (1980) and Lepine et al. (1989) that the Hick-Hyman Law accounts for the observed precuing differences did not hold either. Unlike most previous experiments in this area, precuing of movement extent **did not** reduce the number of response alternatives here to the same degree that precuing of movement direction did (extent precues left 2 possible targets, while direction precues left 4 targets). Had subjects been preparing multiple motor programs when the number of response alternatives was small, precuing of extent should have yielded shorter initiation times than did precuing of direction (since the choice was between two rather than four alternatives). The two-choice and extent precues should have produced equal initiation times, as should the four-choice and direction precues. None of these predicted outcomes occurred. The only hypothesis that fits the observed data is that motor programming proceeds in a parametric, hierarchically-organized, serially-executed fashion.

This is not to say that all of the previous investigators' findings were totally unsupported here. Like Rosenbaum's (1980) findings, omitting direction information from the precue did result in greater increase in initiation time than did omission of extent information. Rosenbaum's original findings also admitted that there was some tendency for some extent decisions to be made following the determination of hand and direction. Considering the confusing nature of his precue, it is unsurprising that the results obtained here did not parallel those found in his study. Since Goodman and Kelso (1980) used an identical precue in their replication of Rosenbaum's study, the

same criticism can be made of their results as well (a fact that they point out).

Lepine, Glencross, and Requin (1989) also found that specification of the extent parameter facilitated reaction time less than did that of direction or hand. They argued that this happened because the latter two parameters represented discrete binary decisions (forward/backward and left/right) while the former was a continuous variable. It is difficult to understand why specification of extent should affect the programming process differently than does specifying direction. **Both** are continuous variables that can assume one of two arbitrarily assigned levels in each of these studies (forward/backward and near/far.) The hand is normally free to move in **any** direction in three-dimensional space, not just fore and aft.

The results here agree better with those of Larish and Frekany (1985). It was found that direction required more time to specify than extent, and that direction information was required before extent information could be used. Unlike their results, however, those from this study do not indicate that programming proceeds in a parallel fashion. Indeed, it is difficult to understand how Larish and Frekany can postulate both a hierarchical and parallel programming process simultaneously. If direction information is necessary to use extent information, it would seem that these two parameters cannot be processed at the same time. If this were true, then the initiation time for the specification of direction information and that for the condition in which no information was provided in the precue should be equivalent. This was not confirmed in the present study.

It is possible that some of the difference in results between this study and those of most previous investigators stems from differences in the tasks involved. All of the previously cited studies used a complex movement with several muscle pairs and body linkages. The movement in the present studies employs only one set of agonist/antagonist muscles and involves only wrist rotations---a much simpler task. Additionally, with button-pressing tasks, it is not necessary for the subject to decelerate in order to stop the movement; depressing the switch ends the movement, independently of any voluntary impulse from antagonist muscles. The wrist rotation task used here requires both an accelerative and decelerative impulse from the subject. This would seem to be more representative of real-world tasks.

CHAPTER VIII

EXPERIMENT 3: MOVEMENT REPROGRAMMING

Rationale

Experiment 3 was designed to test a possibility raised in Experiment 2. Perhaps the unexpected superiority of the nonpreferred hand on manual aiming tasks with limited information stems from its adaptability to new information during the construction of a motor program (reprogramming). Here, it was decided to use the response-priming technique developed by Meyer et al. (1978). Rather than giving the subject only part of the information that he needed to construct the motor program, the precue provided complete information. Sometimes, however, this information was incorrect, thus forcing the subjects to modify their prepared program.

Using this method, it was also possible to examine the nature of the motor program further. If the non-hierarchical program structure proposed by Rosenbaum (1980) is correct, and if it is possible (and parsimonious) to modify existing motor programs, incorrect precues should result in slower initiation times than do correct precues. Miscuing successively more movement dimensions should result in increasingly worse performance. If, on the other hand, the programming process is hierarchical, as suggested in Experiment 2, this should still hold true, but the degree of degradation would vary with the dimensions miscued.

For Experiment 3, various predictions can also be made on the basis of hypotheses about sources of performance differences between the preferred and nonpreferred hands. If there is a hemispheric superiority in terms of motor reprogramming, the nonpreferred hand (and right cerebral hemisphere) should exhibit faster initiation times than does the preferred hand when the initial primed response is incorrect, but no differences should appear when the primed response is completely accurate. This is a function of the processing mode employed by the contralateral (controlling) cerebral hemisphere. Consistent with the results of the previous studies, it is predicted that no main effects of hand will result here on any of the dependent measures for movement execution.

For the aspects of movement programming investigated in Experiment 2, the response-priming technique provides a unique opportunity to cross-check previous conclusions. The initiation-time data associated with positive answers to the questions addressed earlier should exhibit the patterns shown in Table 8.1, depending on the nature of the programming process.

Table 8.1: Predicted Effects on Initiation Time for Programming Issues

	Elements of Movement Program Changed from Primed Stimulus				
Programming Questions	Direction	Distance	Both	Neither	No Information
Parametric	slower	slower	slowest	Fastest	*
Serial Process	slower	slower	slowest	Fastest	*
Parallel Process	slower[1]	slower[1]	slower[1]	Fastest	*
Hierarchical	slower[2]	slower[2]	slowest[3]	Fastest	*
Non-hierarchical	slower	slower	slowest	Fastest	*
ACTUAL EFFECTS	SLOWEST	SLOWER	SLOWEST	FASTEST	*

* = baseline RT

1 = should all be equal to each other

2 = higher in hierarchy will result in same time as switching both,
    lower equal result in slight decrease

3 = should be equal to time for higher element in hierarchy

Method

Subjects

Six right-handed males between the ages of 21 and 30 served as paid subjects. Each received $4 per hour, plus a bonus based on good performance.

Procedure

The procedure was similar to that used in the previous experiments, with several modifications. First, rather than precuing partial, but always correct, dimensions of the movement to be made (direction, extent, or both) as was done previously, the current precue did not always provide correct information. Five types of precues were used:

1) "NONE"--in which none of the movement dimensions was switched after the precue (i.e., completely correct information was provided in the precue). This made up about 3/7 of the trials.

2) "BOTH"--indicating that both the direction and extent of the movement were switched after the precue (i.e., totally incorrect information was provided originally). These composed 1/7 of the trials.

3) "DIRECTION"--indicating that this dimension of the precued movement was switched (i.e., only the original distance information was correct). These amounted to 1/7 of the trials.

4) "DISTANCE"--indicating that the precued movement distance was incorrect, but that the direction was proper. This again amounted to 1/7 of the trials.

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5) "NO INFORMATION"--indicating that no useful information was provided in the precue. These composed the final 1/7 of the trials.

About 71% of the precues contained at least some valid information, and the precue was either at least partially valid or neutral in about 85% of the cases. Totally misleading precues made up only 14% of the trials.

The form of the precue is depicted in Figure 8.1. Here, the number in the center of the display gave the distance from the starting position to the target, with the arrow representing the direction of the wrist rotation to be made. For the NO INFO precue, the number was replaced by two "X"'s, and arrows pointing in both directions were displayed.

The subjects' task again involved moving the cursor from one of eight possible starting positions to a target located in the center of the display. The subjects initiated each trial by aligning the cursor with the alignment marker in the center of the display for a period of one-half second. They were then precued about the particular movement to be made. The precue appeared on the display for a period of two sec.

The screen was blanked after the precue for a period of one sec. The response signal then appeared, and an audible tone sounded. Following invalid precues, response signals consisted of the same symbols as were used in the previous two experiments, i.e., a semicircle with a single radius extending from the center to the edge of the circle, corresponding to the required direction and extent of the movement. When the movement precue was totally valid, the response signal was the precue that had previously been used in Experiment 2 to provide no information (all eight targets cued). This forced subjects to attend fully to the precue and keep it in memory. (If they did not, then they would not have known where to move on such trials.)

At the onset of the response signal, subjects had to rotate the handle and move the cursor from the starting location to the target region as quickly and accurately as possible. Here, the movement initiation requirements were modified somewhat. Rather than giving the subject some liberal time limit (i.e., 1 sec) to commence his movement, a more stringent individual time limit was established for each subject.

The new time limit was based on performance during practice sessions, and was set to a value that equaled the time at which only the fastest 33% of the practice movements had been initiated. This was done to place time stress on the subjects; they were not informed about the impending stress until after the practice sessions. If movement preceded the response signal or had not commenced within the preset time limit, then a message was presented to the subject ("STARTED TOO SOON" or "STARTED TOO LATE"), and the trial was repeated at the end of the block.

Scoring and feedback were identical to those used in the previous experiments. Subjects were told that speed and accuracy were equally important on the task, and that their best score would result from making rapid, controlled movements.

40 >
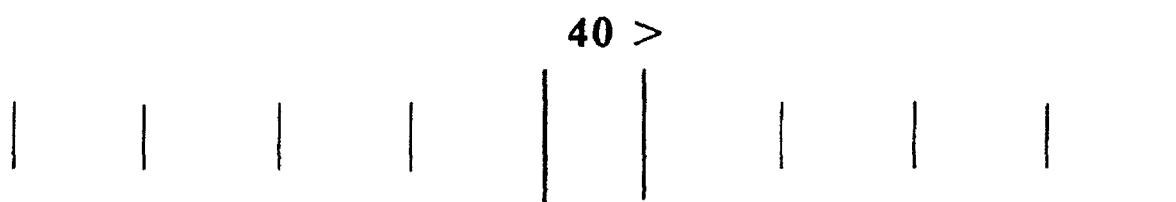
Figure 8.1: Response Priming Display for Experiment #3

Design

Each subject served in five 90-min. sessions on separate days over a one-week period. The first session was practice and is not reported here. In the first half of the practice session, the procedure was introduced, and the subject performed all movements with only their left (or right) hand. In the second half of the practice session, the other hand was used.

The movements within each session were organized into blocks of trials with type of precue, target distance, and target direction all varying within the block. Each block consisted of 168 movements, which included an equal number of trials from each starting point, subject to the precue distribution detailed earlier.

Subjects performed two blocks of trials per day. Movements within blocks were randomized to eliminate systematic order effects. The same hand was used on all blocks within a day, and hands were alternated across days. At the beginning of each data-collection day, subjects performed a short practice block of 15 trials. Dependent variables were the same as those measured in the previous experiments.

Results

Significant effects for this experiment are summarized in Appendix A. As in the previous studies, there were no significant main effects of preferred versus nonpreferred hand for any of the dependent measures.

Preparation Phase

Initiation time. Initiation time data are presented in Table 8.2. Only the precue condition had a significant effect on initiation time $[F(4,12)=8.66, p\leq.0016]$. The relationship between these results and the theoretical issues discussed earlier are summarized in words in the bottom line of Table 8.1.

Table 8.2: Initiation Time by Precue Changed

Precue Changed	Initiation Time	S.E.
None	268 ms	3.61 ms
Direction	340 ms	6.13 ms
Extent	318 ms	7.03 ms
Both	344 ms	5.49 ms
No Information	327 ms	5.41 ms

Changing movement extent produced a significantly shorter initiation time than did changing either direction or both extent and direction ($d_-=21.08$ msec, $p\leq.05$). When direction alone or both direction and extent were changed, initiation time did not differ significantly from that of the no-information precue. When direction alone was changed, the results were not significantly

different than those obtained when no information was provided. The no-change precue yielded significantly faster times than did all other conditions.

Ballistic-Phase Measures

First submovement time. Only the main effect of target distance reached significance for this measure $[F(3,9=4.54, p \leq .0336]$. Movement time once again increased linearly with the square root of target distance ($r^2 = .973$). These data appear in Figure 8.2.

Standard deviation of first submovement distance. This measure was also significantly affected only by target distance $[F(3,9) = 14.68, p \leq .0008]$. Once again, there was a linear relation between the target distance and the standard deviation of the movement distance ($r^2 = .965$), as shown in Figure 8.3.

Constant error of first submovement distance. For this measure, there were main effects of target distance $[F(3,9) = 20.23, p \leq .0002]$ and precue $[F(4,12) = 3.42, p \leq .0437]$, and an interaction between target distance and precue $[F(12,36) = 2.08, p \leq .0450]$. The interaction between hand and target direction also approached significance $[F(1,3) = 6.94, p \leq .0780]$.

The distance effect again stemmed from constant error increasing linearly with target distance ($r^2 = .994$) [Figure 8.4]. The precue effect occurred when the direction and direction-extent combinations were switched between the precue and response signal. As Table 8.3 shows, these two switches increased constant error substantially compared to those for the no-information precue $[d_T = 3.631^\circ, p \leq .05]$.

Table 8.3: Constant Error of First Submovement Distance by Precue Changed

Precue Changed	Constant Error of 1st Submovement	S.E.
None	-3.23 deg	.64 deg
Direction	-5.98 deg	.78 deg
Extent	-4.02 deg	.65 deg
Both	-5.88 deg	.66 deg
No Information	-2.17 deg	.59 deg

The interaction between precue and target distance for constant error was somewhat confusing. For each precue, the constant error of first submovements was a linear function of the target distance ($r^2_{none} = .985$, $r^2_{dir} = .987$, $r^2_{ext} = .9999$, $r^2_{both} = .907$, and $r^2_{no-info} = .933$). It appears that as the target distance increased, all the precues that contained any valid information tended to yield constant errors that converged at the 40° distance. This effect is shown in Figure 8.5.

Finally, the hand by target-direction interaction reveals that movements by the preferred hand were again more consistent than those by nonpreferred hand for rotations in either direction. The difference in constant error between supinations and pronations by the preferred hand was approximately

First Submovement Time by Square Root of Target Distance
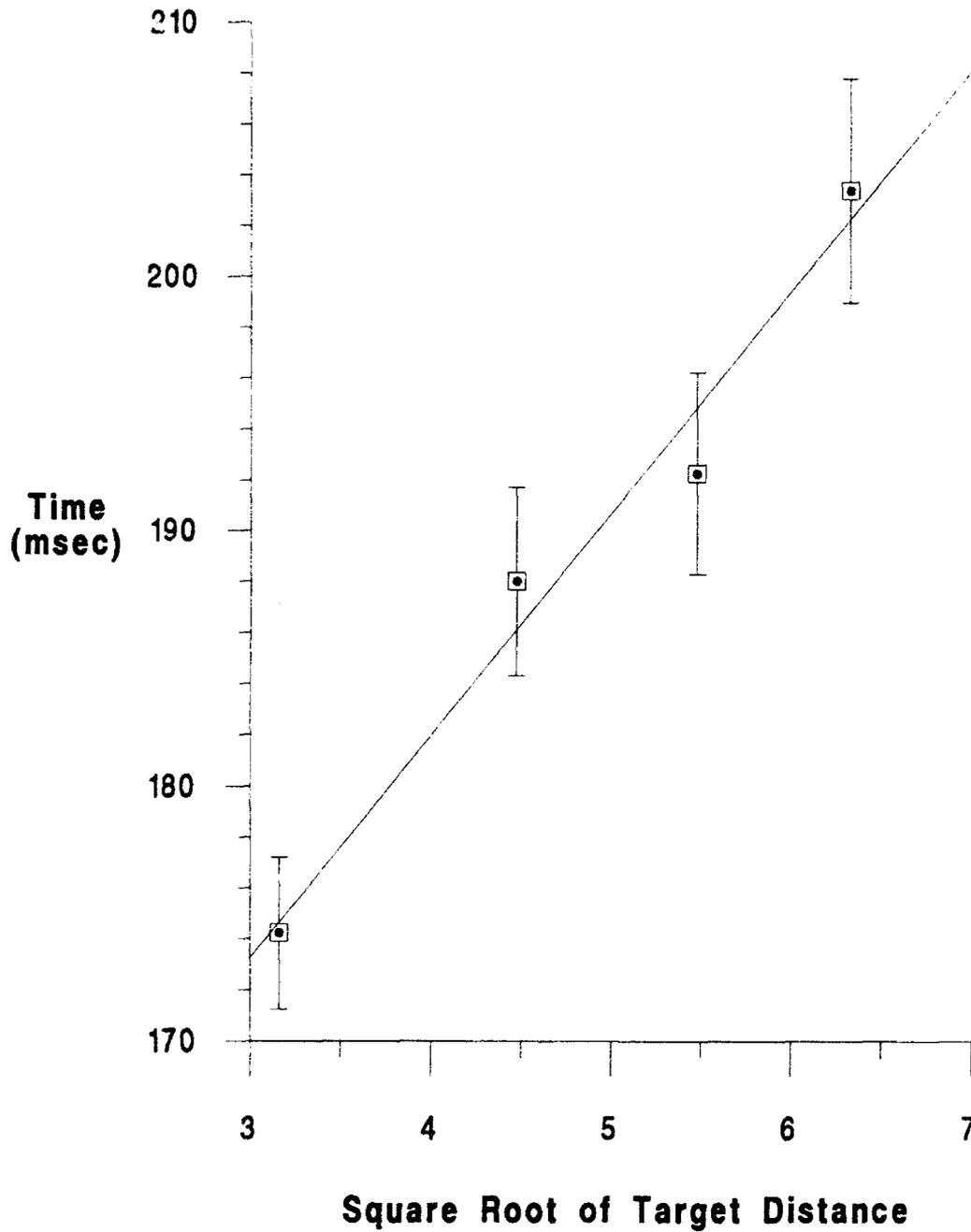
FIGURE 8.2

Standard Deviation of First Submovement Distance by Target Distance
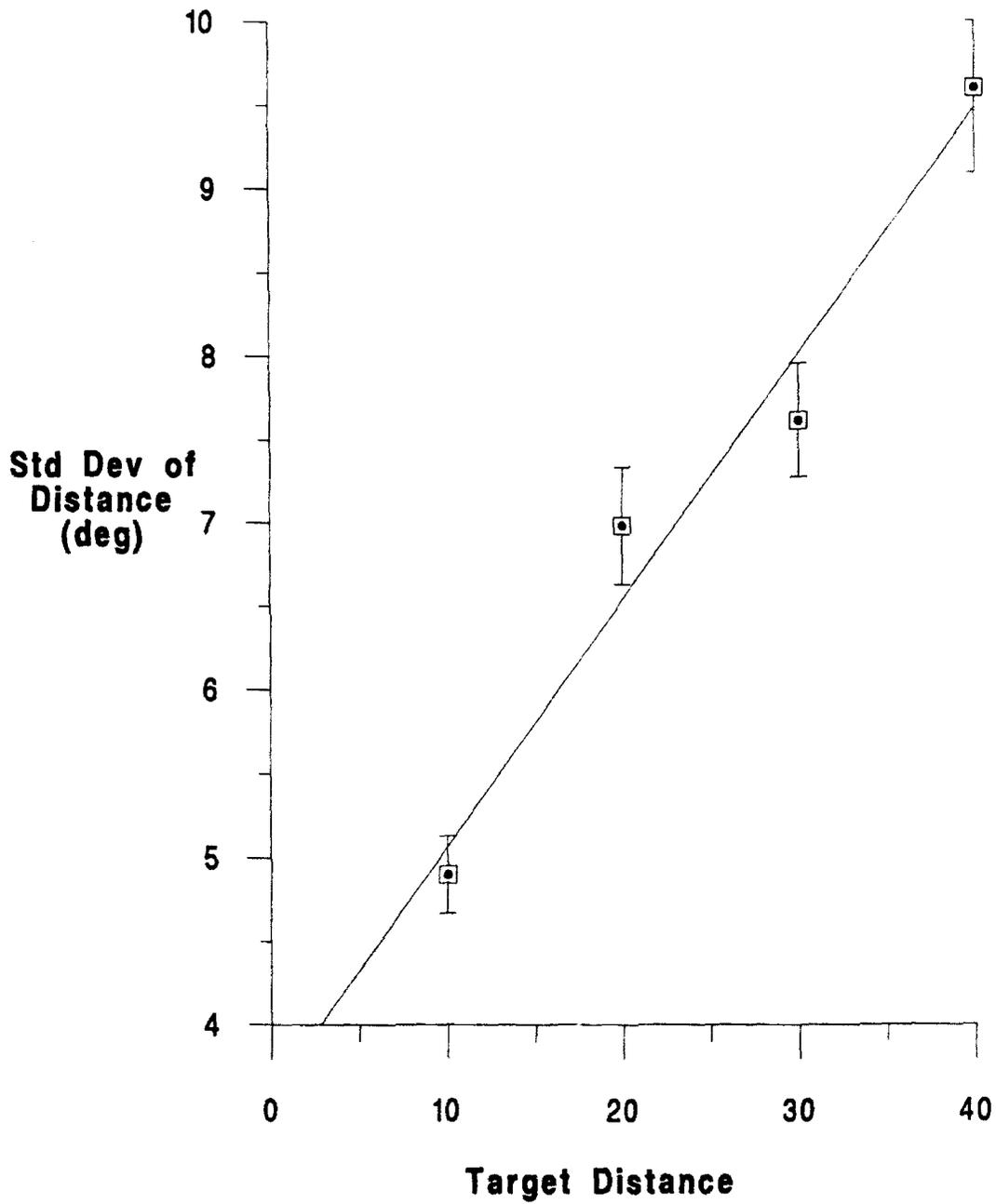
FIGURE 8.3

Constant Error of First Submovement
Distance by Target Distance
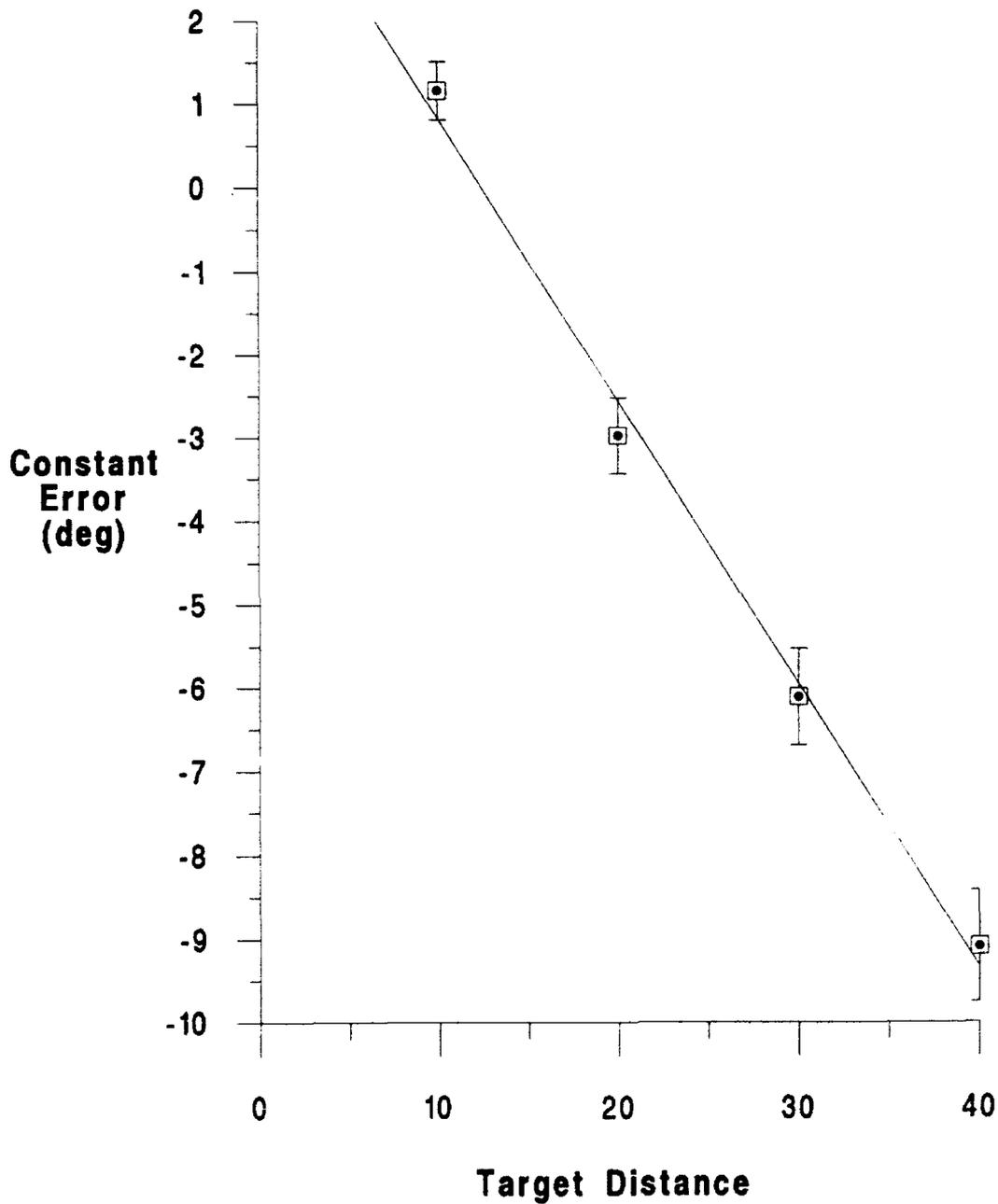
FIGURE 8.4

Constant Error of First Submovement Distance by Target Distance and Precue Switched

Legend:
- × None
- ◇ Direction
- ◆ Extent
- □ Both
- ■ No Info

Y-axis: Constant Error (deg)

X-axis: Target Distance
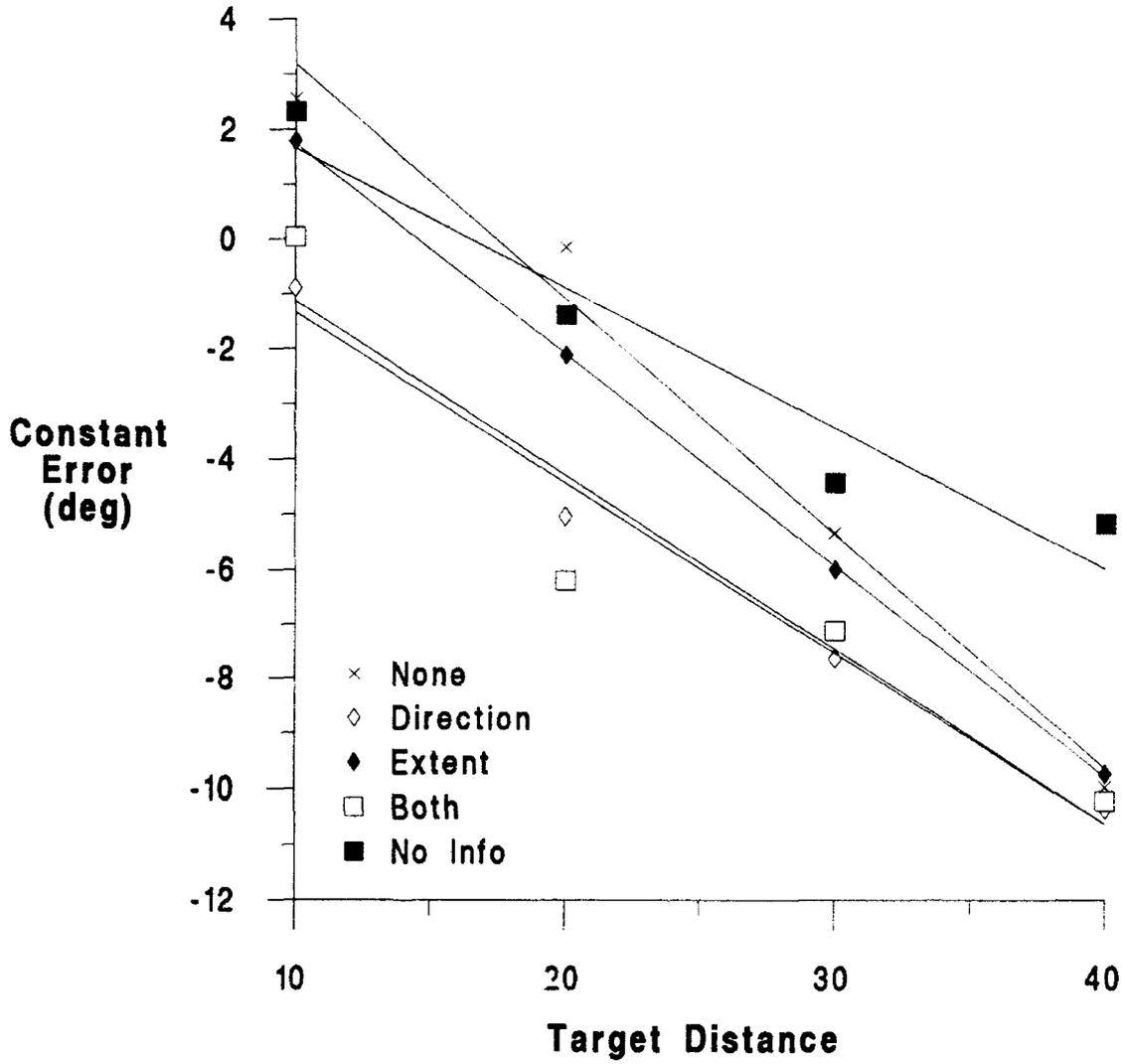
FIGURE 8.5

$0.25°$ (-4.53 vs -4.30), while the nonpreferred hand exhibited a difference of almost $1.5°$ (-4.80 vs -3.38).

Summary of ballistic measures. As in the previous experiments, none of the hypotheses about performance differences between the hands was supported by data from the ballistic movement phase. The general trend toward greater consistency of supinations and pronations by the preferred hand, however, does seem to persist across the studies.

Current-Control Phase

Total movement time. This measure was significantly affected only by target distance [$F(3,9)=10.81$, $p \leq .0024$]. Total movement time again increased linearly with the square root of the target distance ($r^2=.999$), as shown in Figure 8.6.

Standard deviation of total movement distance. This measure was significantly affected only by the day-by-precue interaction [$F(4,12)=3.70$, $p \leq .0348$]. This occurred because there was no significant difference [$d_T=.077°$, $p \leq .05$] between the two days except with the no-information precue, which produced substantially less variation on the second day ($.88°$ vs $.98°$).

Constant error of total movement distance. Only target distance affected this measure significantly [$F(1,3)=7.18$, $p \leq .0092$]. Constant error was a linear function of the square root of target distance ($r^2=.967$) [Figure 8.7].

Number of submovements. This measure was affected by target distance [$F(3,9)=13.15$, $p \leq .0012$] and the hand-by-precue interaction [$F(4,12)=3.30$, $p \leq .0483$]. In the distance effect, the number of submovements increased linearly with the square root of target distance ($r^2=.994$) [Figure 8.8].

The hand-by-precue interaction is somewhat more difficult to characterize. It may have occurred because the preferred hand required more submovements for the precues in which only extent was switched or no information was presented [$d_T=.168$ submovements, $p \leq .05$] (Table 8.4). An alternative view is that the nonpreferred hand requires fewer submovements overall, except in cases where only the direction information was invalid.

Table 8.4: Number of Submovements by Hand and Precue Changed

Precue Changed	Number of Submovements			
	Left Hand	S.E.	Right Hand	S.E.
None	3.14	.10	3.28	.10
Direction	3.22	.11	3.13	.09
Extent	3.13	.12	3.32	.11
Both	3.21	.13	3.28	.10
No Information	2.98	.11	3.22	.10

Total Movement Time by
Square Root of Target Distance
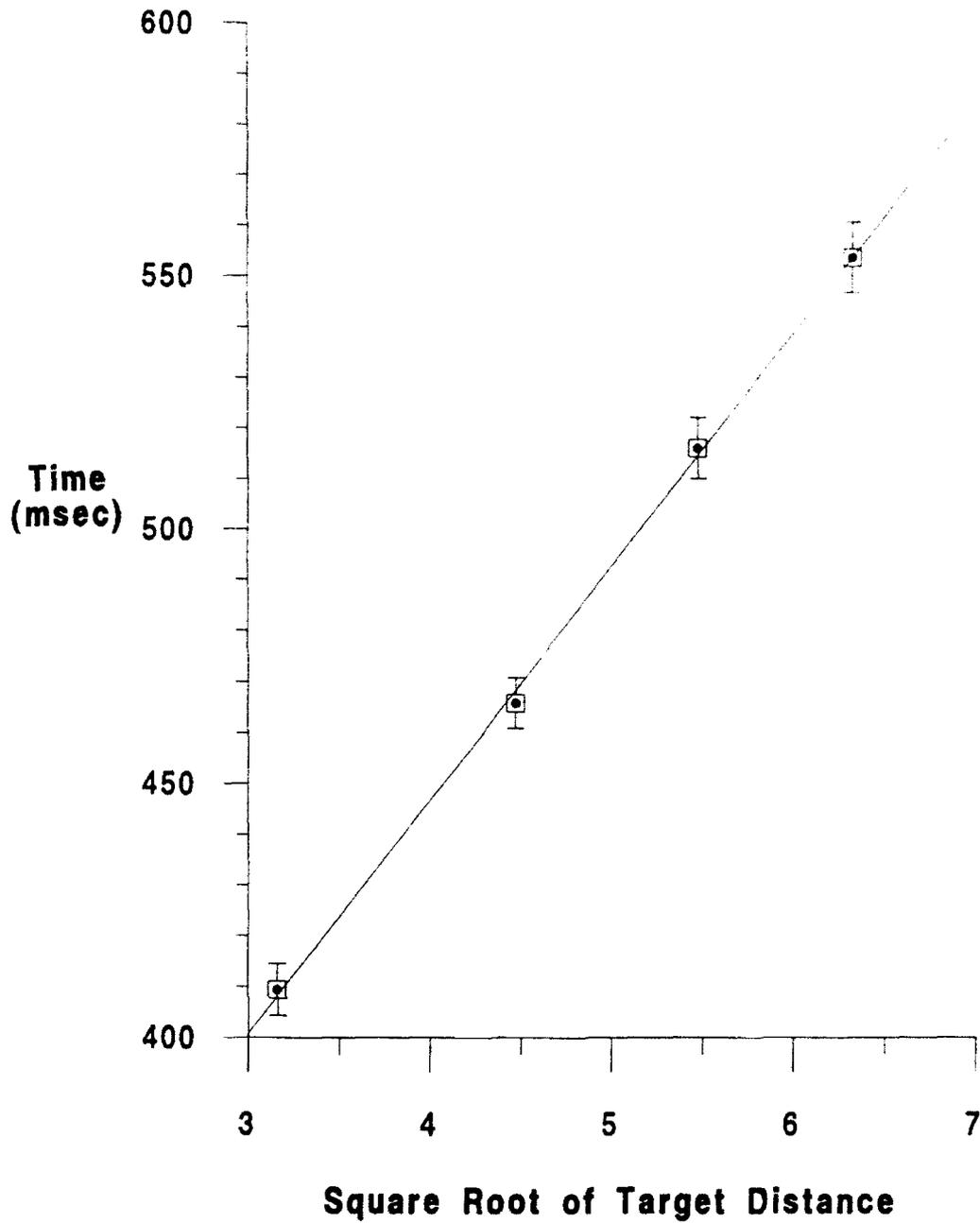
FIGURE 8.6

Constant Error of Total Movement
Distance by Target Distance
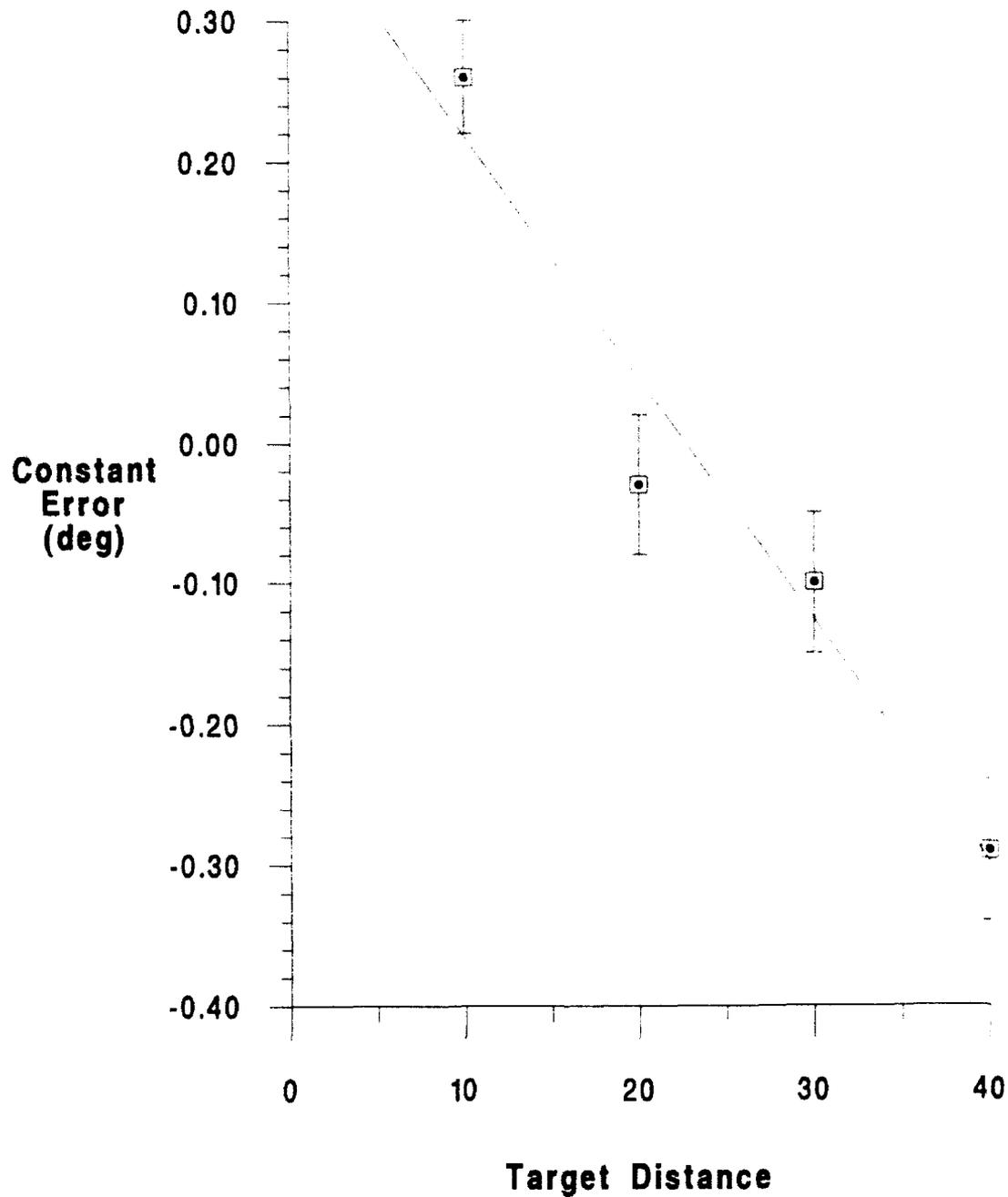
FIGURE 8.7

Number of Submovements by Square Root of Target Distance
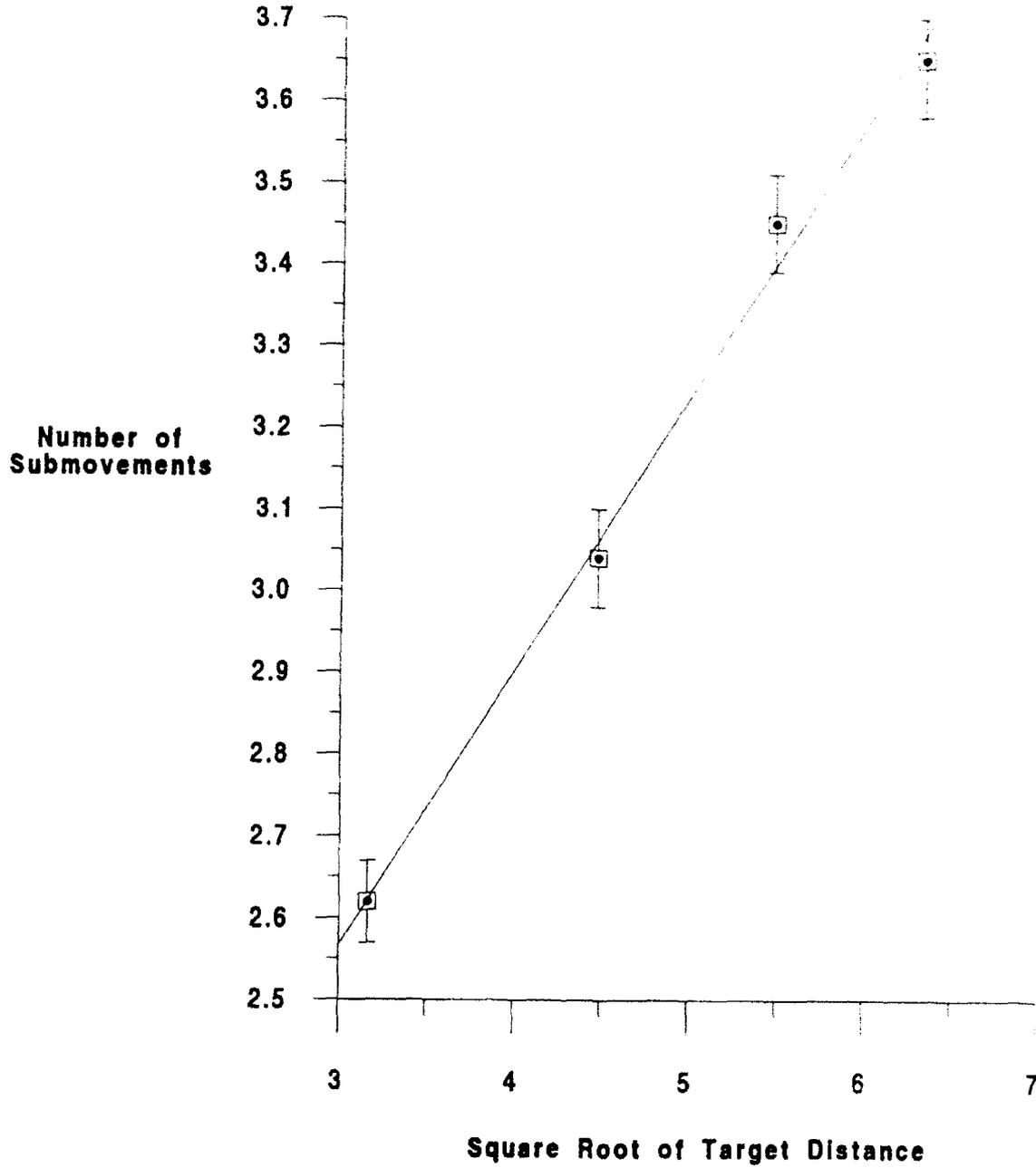
FIGURE 8.8

Probability of missing. This measure was affected by precue
$[F(4,12)=5.47, p \leq .0096]$, as well as the hand-by-precue interaction
$[F(4,12)=3.87, p \leq .0303]$. The precue effect involved large differences in
error rate across the various precues, and is summarized in Table 8.5.
Direction changes produced significantly more errors $[d_{,}=.0535, p \leq .05]$ than
did completely valid precues. Changing extent information alone, or changing
both direction and extent together, also yielded relatively low error rates,
while the no-information precue yielded intermediate error rates. Oddly,
changing both direction and extent produced significantly fewer errors than
providing the subject with no information at all. This may or may not have
been due to a priming effect similar to that found in the Hawthorne studies
(Gilmer, 1971).

Table 8.5: Probability of Missing by Precue Changed

Precue Changed	Probability of Missing	S.E.
None	.16	.01
Direction	.22	.02
Extent	.15	.02
Both	.13	.02
No Information	.18	.02

The hand-by-precue interaction occurred because the right hand was
significantly $[d_{T}=.0565, p \leq .05]$ more accurate than the left hand for most
precues, except when direction was switched (both the DIRECTION and BOTH
precues). With the latter two precues, the difference between hands was not
significant. These data for both hands are presented in Table 8.6. If a
hierarchical control structure for motor programs in which direction
information is required prior to make use of extent information exists, this
may indicate that the left cerebral hemisphere (right hand) is better able to
modify existing programs. Neither hemisphere seems to be superior when a
total reconstruction of such programs is required, eliminating some support
for the hemispheric specialization hypothesis.

Table 8.6: Probability of Missing by Hand and Precue Changed

Precue Changed	Probability of Missing			
	Left Hand	S.E.	Right Hand	S.E.
None	.18	.01	.13	.02
Direction	.22	.02	.22	.03
Extent	.22	.03	.05	.02
Both	.15	.02	.12	.02
No Information	.21	.02	.15	.02

Summary of current-control phase measures. As in both previous
experiments, there was no significant support for any of the hypotheses about
the source of hand difference per se. Possibly the most interesting aspect of
the current-control phase measures here is the relatively poorer performance
(in terms of missing the target) of the preferred hand when movement direction

or both direction and extent had to be altered before the movement began. The preferred hand exhibits significantly better performance than the nonpreferred under all conditions in which direction information is not present or is not altered, suggesting that the left cerebral hemisphere may be better able to update existing motor programs in these cases. Interestingly, the cases in which direction was switched were also the cases in which the nonpreferred hand was not significantly lower in terms of number of submovements required to hit the target. This suggests that the superiority of the preferred hand does not lie in being able to execute faster corrective submovements than the nonpreferred hand (the sequencing hypothesis).

Discussion

As before, the lack of any substantial hand effects is surprising, but there are several other general trends in these data that bear noting. The probability of hitting the target was higher for the preferred hand, except when the precued direction information was invalid. This may indicate that motor programs for the preferred hand are more difficult to change when the more significant portions of the information therein are incorrect. It could be that the motor program for the preferred hand is more firmly automated than for the nonpreferred hand. Perhaps the preferred hand is more resistant to outside interference or extraneous input once a motor program has been constructed.

It is possible, however, that by trying to simplify the movement task as much as possible (unidimensional movements, very little friction on the handle, etc.), the experimental manipulation used in Experiment 3 may have actually minimized the difference between the two hands. If one accepts this position, the "sequences of action" hypothesis discussed in Chapter II is still viable. Perhaps the preferred hand is more attuned to making sequences of actions, not because of any superiority in the programming process itself, but rather because once programming is complete, the program is "hardwired" into the motor system and requires less conscious attention unless some outside agent interferes. A series of movements may thus be queued into the system more effectively because each element of the complex movement is basically a subprogram, not requiring continuous conscious control.

Viewed in this light, the quicker transitions between the upward and downward strokes of rhythmic tapping cited earlier do not result because the preferred hand can switch more rapidly between the two types of movements. They simply represent a degradation in performance by the nonpreferred hand because of interference to the system from the "real world" (the impact of the stylus on the tabletop). The preferred hand may simply continue its existing automated movement, ignoring the "noise" caused by the impact.

Perhaps the best way to test this hypothesis would be to introduce various levels of "noise" systematically into the positioning movement. One could have subjects practice on the movement task in a neutral condition, then vary the friction of the handle randomly before the start of a movement, or introduce some jiggle into the handle. If the preferred hand is more affected

by these extraneous elements, because of inflexibility resulting from movement automaticity, then this would support the automaticity hypothesis.

Regarding the motor-programming issues raised earlier, the present results confirm the findings of the previous study. Initiation time for switching direction (after the "direction" and "both" precues) was about the same regardless of whether extent information was also switched. When extent information was switched, but direction information was not, subjects were significantly faster than when both types of information were switched simultaneously. This agrees with the results obtained by Larish and Frekany (1985).

The data are consistent with a hierarchical control structure that requires direction information in order to use extent information. Apparently, when extent information alone is switched, the programming process must backtrack only one step in the hierarchy and change the appropriate distance parameter (a gain change within previously selected agonist-antagonist muscles). This occurs significantly faster than when both direction and extent information must be switched.

The present data are also consistent with a nonhierarchical, serial-programming model such as that proposed by Rosenbaum (1980). If a nonhierarchical model was correct, extent switches should yield about the same pattern of results as direction switches, producing initiation times that are slower than those obtained with full information, yet still significantly faster than when both direction and extent information are changed together. This pattern failed to occur in Experiment 3. Also, initiation times for direction switches were almost identical with those for movements in which both direction and extent were switched simultaneously. It appears that rather than simply backtracking one stage in the programming process and changing the motor program, an individual must go back to the very beginning of the process and program a new movement from scratch when direction information changes.

There is also another related possibility that may have occurred in Experiment 3. Subjects may have incorrectly started moving toward an invalidly precued target, and then changed the movement into one toward the correct target after the start of the trial. If so, then the initiation-time measure would not represent the actual time required by subjects to update their existing motor programs, and no difference between the hands would be anticipated on this measure (and would explain why none was found).

CHAPTER IX

EXPERIMENT 4:   MOVEMENT REPROGRAMMING II

Rationale

Experiment 4 was performed to eliminate the last possibility raised at the end of Experiment 3. It required the subjects to prepare each precued movement, and then upon learning the actual target, to modify their existing motor programs before initiating the movement. Here, the predicted results correspond exactly to those obtained in Experiment 3, assuming that the original (hierarchical programming) account of Experiment 3's outcome is correct. On the other hand, if the outcome of Experiment 3 stemmed from subjects attempting to reverse their movements on the fly, then Experiment 4 may yield different results than those obtained previously.

Method

Subjects

Five of the six subjects from Experiment 3 participated in this experiment as paid subjects. All were right-handed males between the ages of 21 and 27. Each received $4 per hour, plus a bonus based on good performance.

Procedure

The procedure was the same as in Experiment 3, with one major modification. For each trial on which the subject began moving in the wrong direction, a score of 0 points was awarded. These trials were not repeated, and the data from them were not included in the analysis. Since each subject's bonus was based on his average score per trial, dividing the total points awarded by the total number of trials per block (including those in which no points were earned) substantially reduced the payoff if wrong-direction movements occurred. In practice, the number of such movements was relatively small (0.6% when no changes were made, 9.5% when direction was changed, 2.1% when extent was changed, 10.8% when both dimensions were changed, and 2.1% when no information was provided). These percentages are somewhat misleading in that in the case of the DIRECTION and BOTH switches, two subjects accounted for approximately half of the total errors. Each of the two subjects was well above the average number of incorrect starts with only one hand, but not with the **same** hand (one of the two subjects had difficulty with the left hand, and the other with the right).

The distribution of precues was the same as in Experiment 3. Four target distances (10°, 20°, 30°, and 40°) and one target width (3°) were employed.

Design

Each subject served in five 90 min. sessions on separate days over a one week period, using the same practice schedule as in Experiment 3. The movements in each session were organized in the same manner as those in the previous study. Dependent variables were identical to those used in the previous three experiments.

Results

Significant effects for Experiment 4 are summarized in Appendix A and, for the most part, agreed with those found in Experiment 3. For the first time, however, a significant main effect of hand occurred.

Preparation Phase

Initiation time. Only the main effect of precue reached significance [$F(4,16)=22.34$, $p\leq.0001$] for this measure. As expected, the valid precue (no dimensions switched) again yielded significantly faster initiation times than did all other precues. The precues followed by a change of either direction or both direction and extent information yielded times significantly slower than those for which only extent was changed ($d_T=24.61$ msec, $p\leq.05$). Initiation times for each precue appear in Table 9.1.

Table 9.1: Initiation Time by Precue Changed

Precue Changed	Initiation Time	S.E.
None	239 ms	2.20 ms
Direction	316 ms	3.57 ms
Extent	287 ms	3.80 ms
Both	312 ms	3.70 ms
No Information	298 ms	2.59 ms

Ballistic-Phase Measures

First submovement time. The main effect of target distance, and the three-way interaction between hand, target direction, and target distance were significant for this measure [$F(3,12)=19.99$, $p\leq.0001$, and $F(3,12)=3.84$, $p\leq.0387$, respectively]. As before, the distance effect stemmed from movement time being a linear function of the square root of target distance ($r^2=.996$) [Figure 9.1].

The hand by target-direction by target-distance interaction was interesting. It apparently stemmed from the left-hand movements to the outer targets being slightly longer for supinations than pronations, whereas the

First Submovement Time by Square Root of Target Distance

Time (msec)

Square Root of Target Distance

FIGURE 9.1

94
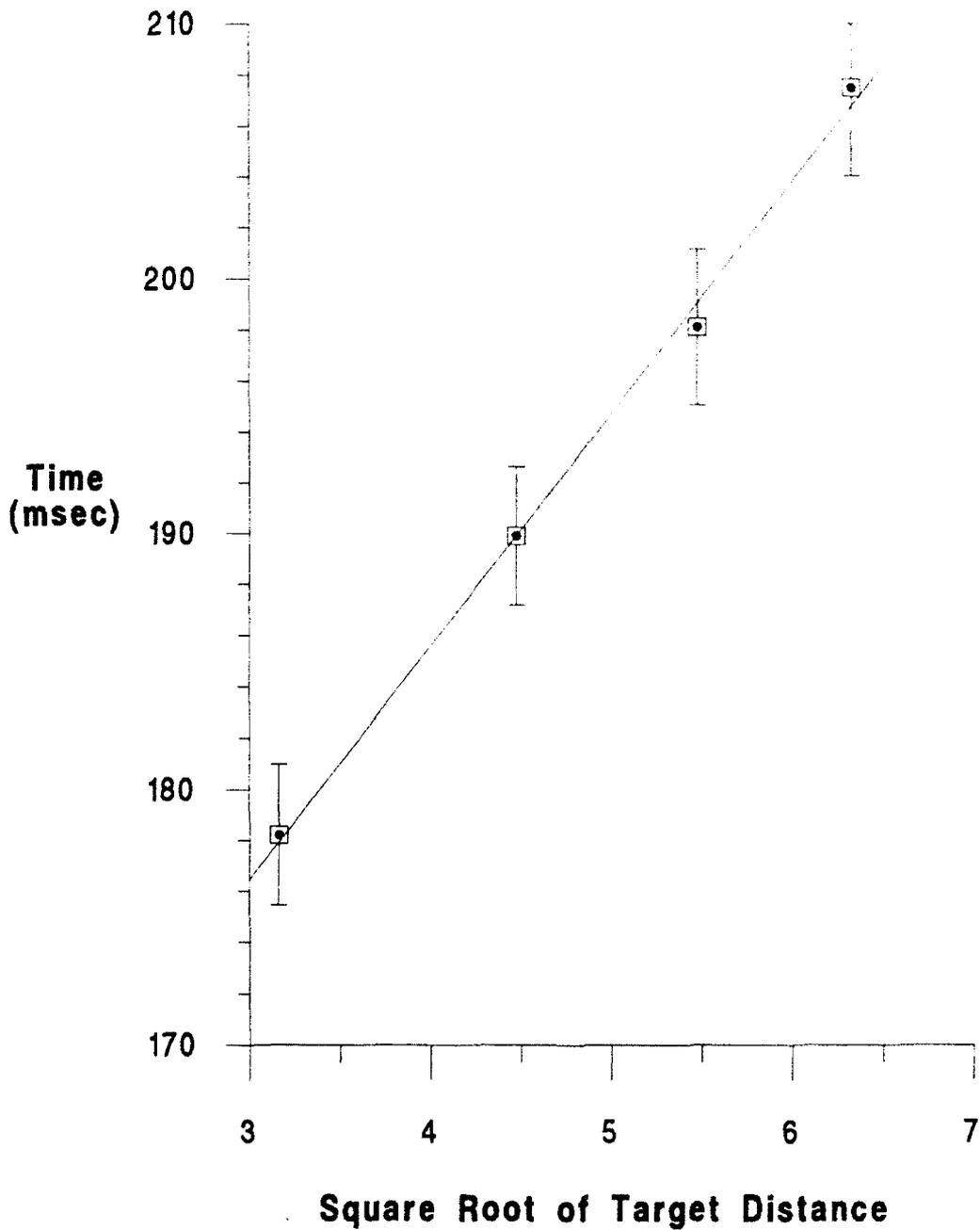
right hand exhibited the opposite pattern (with a difference only appearing at the shortest distance). This trend appears in Table 9.2.

Table 9.2: Movement Time Interaction for Hand, Distance, and Target Direction

Target Distance	Left Hand				Right Hand			
	Left	S.E.	Right	S.E.	Left	S.E.	Right	S.E.
10 deg	181 ms	6.1 ms	178 ms	5.6 ms	183 ms	5.8 ms	171 ms	4.7 ms
20 deg	189 ms	5.1 ms	181 ms	5.4 ms	196 ms	6.0 ms	194 ms	5.3 ms
30 deg	202 ms	6.4 ms	192 ms	6.6 ms	198 ms	5.5 ms	201 ms	5.9 ms
40 deg	213 ms	7.6 ms	200 ms	6.7 ms	208 ms	6.8 ms	209 ms	6.9 ms

Standard deviation of first submovement distance. A significant effect of target distance [$F(3,12)=13.60$, $p \leq .0004$] and a hand-by-target-distance interaction [$F(3,12)=3.59$, $p \leq .0464$] occurred for this measure. The interaction between hand, target direction, and target distance was almost significant, and is also worth noting [$F(3,12)=2.95$, $p \leq .0757$].

The standard deviation of first-submovement distance increased linearly with target distance ($r^2 = .9966$), as shown in Figure 9.2. The hand by target-distance interaction stemmed from all movements longer than ten degrees being less variable with the preferred hand than with the nonpreferred. However, this difference was only significant for the 20° target distance ($d_r = .995$ de~, $p \leq .05$) [Table 9.3].

Table 9.3: Standard Deviation of First Submovement Distance by Hand and Target Distance

Target Distance	Left Hand	S.E.	Right Hand	S.E.
10 deg	4.18 deg	.29 deg	4.17 deg	.23 deg
20 deg	6.39 deg	.38 deg	4.80 deg	.29 deg
30 deg	7.56 deg	.43 deg	6.94 deg	.39 deg
40 deg	8.71 deg	.55 deg	8.19 deg	.52 deg

The interaction between hand, target direction, and target distance stemmed from movements to the nearer targets being less variable for supinations, while movements to the farthest target were essentially the same with supinations and pronations [see Table 9.4].

Table 9.4: Standard Deviation of First Submovement Distance By Target Distance and Supination/Pronation

Target Distance	Supination	Pronation
10 deg	3.78 deg	4.58 deg
20 deg	5.22 deg	5.97 deg
30 deg	6.41 deg	8.09 deg
40 deg	8.59 deg	8.31 deg

Standard Deviation of First Submovement Distance by Square Root of Target Distance
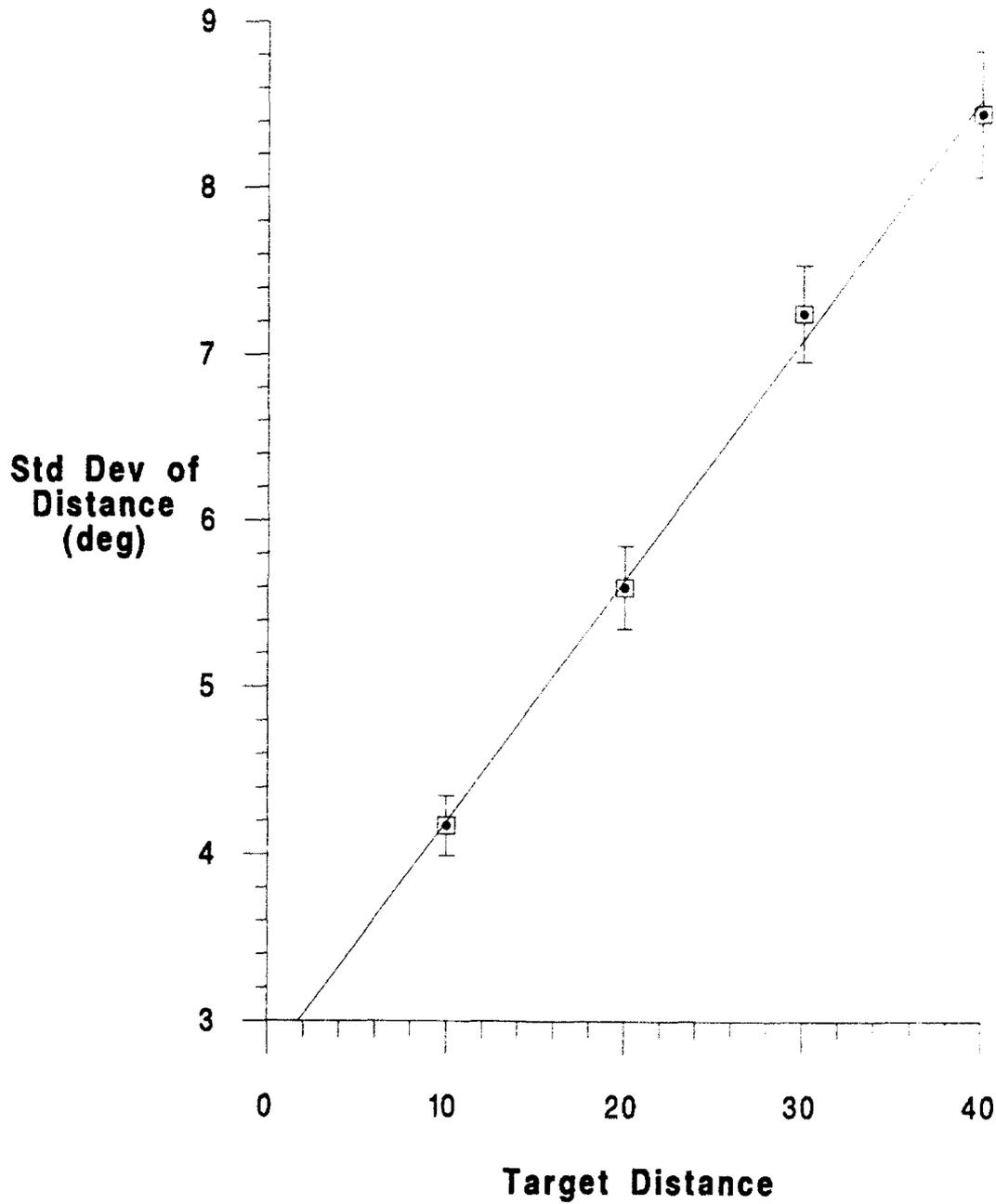
FIGURE 9.2

***Constant error of first submovement distance***. This variable was affected significantly by target distance [$F(3,12)=29.75$, $p \leq .0001$], precue [$F(4,16)=3.45$, $p \leq .0325$], and the interaction between precue and target distance [$F(12,48)=2.29$, $p \leq .0211$]. The interaction between hand and target direction was again almost significant [$F(1,4)=6.22$, $p \leq .0671$].

The distance effect here, as in most other cases, stemmed from constant error being a linear function of target distance ($r^2=.996$) [Figure 9.3]. The precue effect arose from cases in which direction information was incorrectly precued (the "both" and "direction" switches), which yielded significantly ($d_T=2.988°$, $p \leq .05$) larger constant error than did the other three precues (which did not differ from one another). The constant errors when both direction and extent were changed, and when only direction was changed, did not differ significantly. This effect appears in Table 9.5.

Table 9.5: Constant Error of First Submovement Distance by Precue

Precue Changed	Constant Error	S.E.
None	-3.15 deg	.44 deg
Direction	-5.18 deg	.48 deg
Extent	-4.01 deg	.49 deg
Both	-6.42 deg	.64 deg
No Information	-3.88 deg	.47 deg

The precue by target-distance interaction stemmed from the constant errors being linear functions of the square root of target distance, but not having the same slopes or intercepts for each precue. As in the previous experiment, differences between constant errors for four of the five precues decreased as target distance increased, converging almost completely at the $40°$ target. Unfortunately, the functions that converged here were not the same as those in Experiment 3. In Experiment 3, all functions except that for the "no-information" precue converged, while in Experiment 4, the divergent function was that for the "both" precue. These data appear in Figure 9.4.

Finally, when the hand by target-direction interaction was examined, a pattern similar to that in the previous experiments again emerged. The constant error for the first submovement of the preferred hand was almost identical for both supinations and pronations ($-4.51°$ vs $-4.38°$), while the nonpreferred hand exhibited a substantial difference between the two (-5.14 vs -4.09) [$d_T=1.28$, $p \leq .05$].

Summary of ballistic-phase measures. As in the previous experiments, no main effects of hand were apparent here. Several interesting interactions with the hand variable did occur, however. A greater consistency for the preferred hand across measures was again noted.

Constant Error of First Submovement
## Distance by Target Distance

FIGURE 9.3

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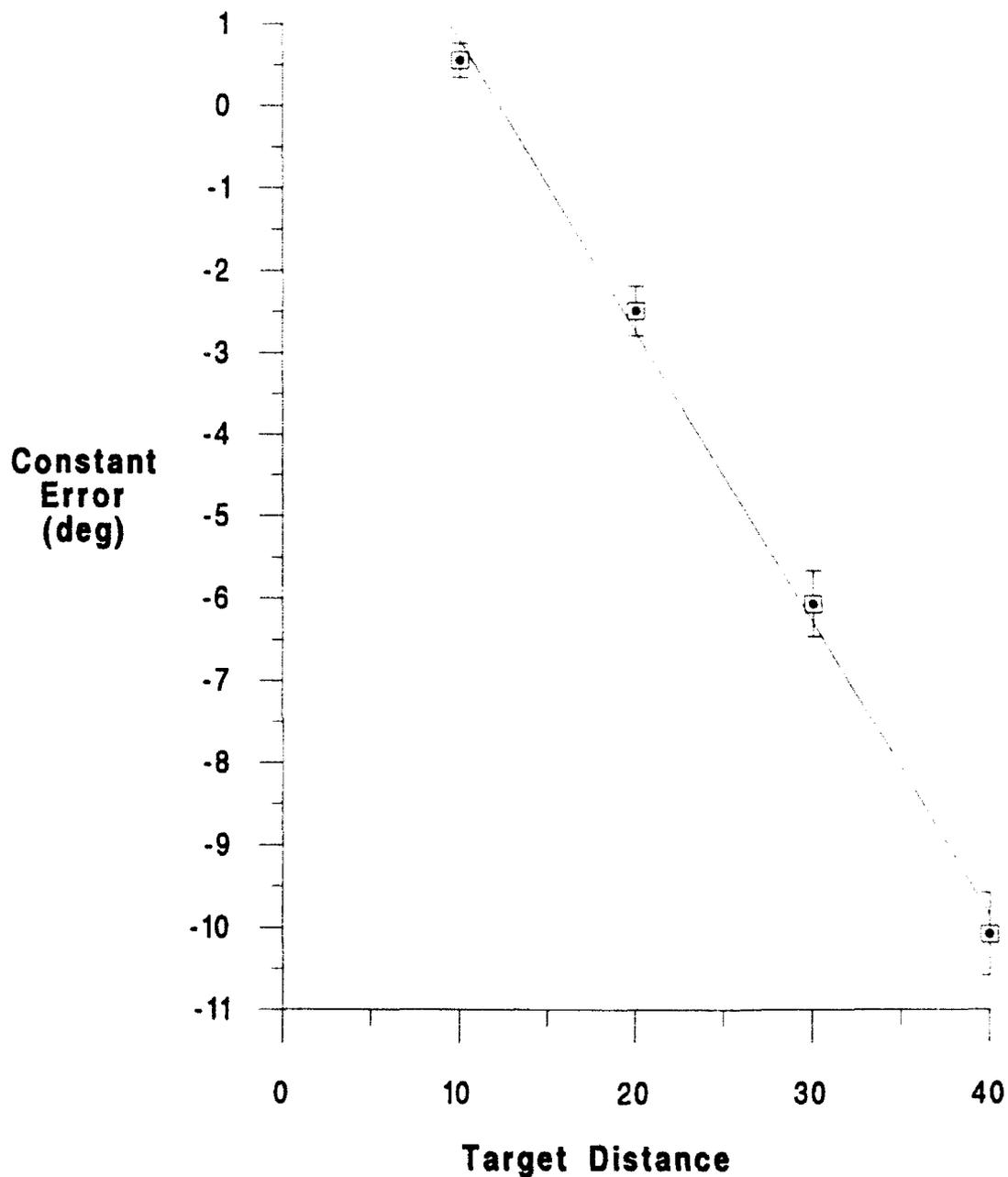
Constant Error After First Submovement
# by Target Distance and Precue Switched
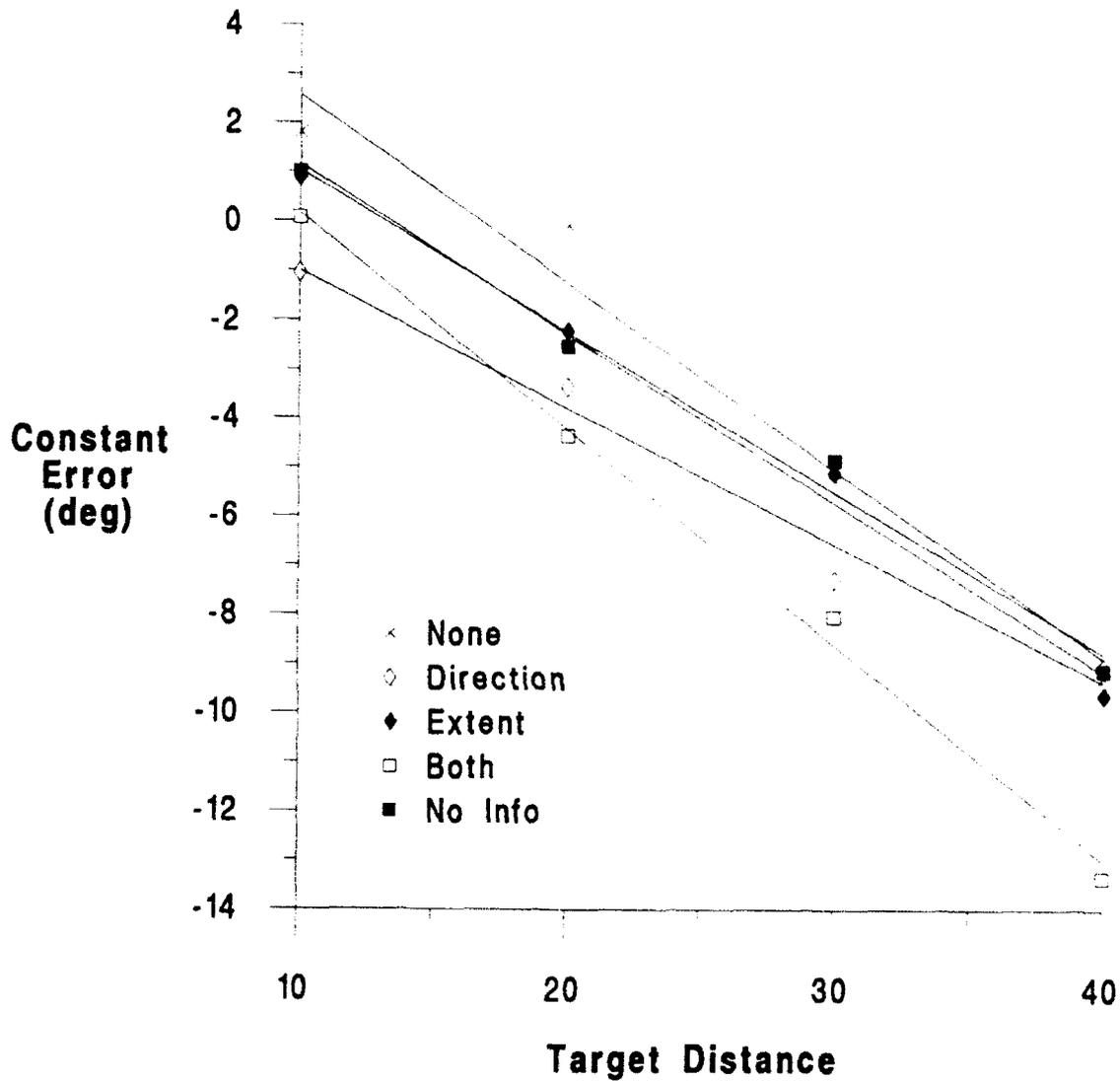
FIGURE 9.4

Current-Control Phase Measures

Total movement time. The main effect of target distance $[F(3,12)=25.45, p \leq .0001]$ was significant for this measure, as was the interaction between hand and target direction $[F(1,4)=12.11, p \leq .0254]$. As in the previous three experiments, total movement time increased linearly with the square root of target distance $(r^2=.994)$ [Figure 9.5]. The hand by target-direction interaction was actually a supination/pronation effect; supinations were performed more rapidly than pronations (456 msec vs 479 msec).

Standard deviation of total movement distance. Hand was the only independent variable that significantly affected this measure $[F(1,4)=11.09, p \leq .0291]$, with the nonpreferred hand being slightly more variable than the preferred hand $(.88°$ vs $.79°)$. This is the first case in these experiments where a main effect of hand has been found.

Constant error of total movement distance. This measure was significantly affected only by the precue $[F(4,16)=3.33, p \leq .0364]$. The effect stemmed entirely from movements with extent changes being consistent undershoots, while all other movements were slight overshoots. The difference between both extremes was less than .20 degrees (extent$=-.07°$, direction$=.11°$).

Number of submovements. The main effect of target distance $[F(3,12)=25.82, p \leq .0001]$ and the interaction between hand, target direction, and target distance $[F(3,12)=3.90, p \leq .0372]$ were significant for this measure. The interaction between hand and target direction also approached significance $[F(1,4)=5.65, p \leq .0762]$. The number of submovements again increased linearly with the square root of the target distance $(r^2=.983)$ [Figure 9.6]. The hand by target-direction interaction was actually a supination/pronation effect. Pronations required slightly more submovements on average to reach the target than did supinations (3.36 vs 3.03).

The three-way interaction stemmed from a supination/pronation by target-distance interaction. In this case, there was no difference between the two types of movement at the smallest target distance, but pronations required progressively more submovements than did supinations as the target distance increased. These data appear in Table 9.6 and Figure 9.7. The difference between the slopes of the two functions was significant at the .05 level $(z=2.43)$.

Table 9.6: Number of Submovements by Supination/Pronation and Target Distance

Target Distance	Supinations	Pronations
10 deg	2.50	2.49
20 deg	2.92	3.31
30 deg	3.28	3.70
40 deg	3.45	3.93

Total Movement Time by
## Square Root of Target Distance
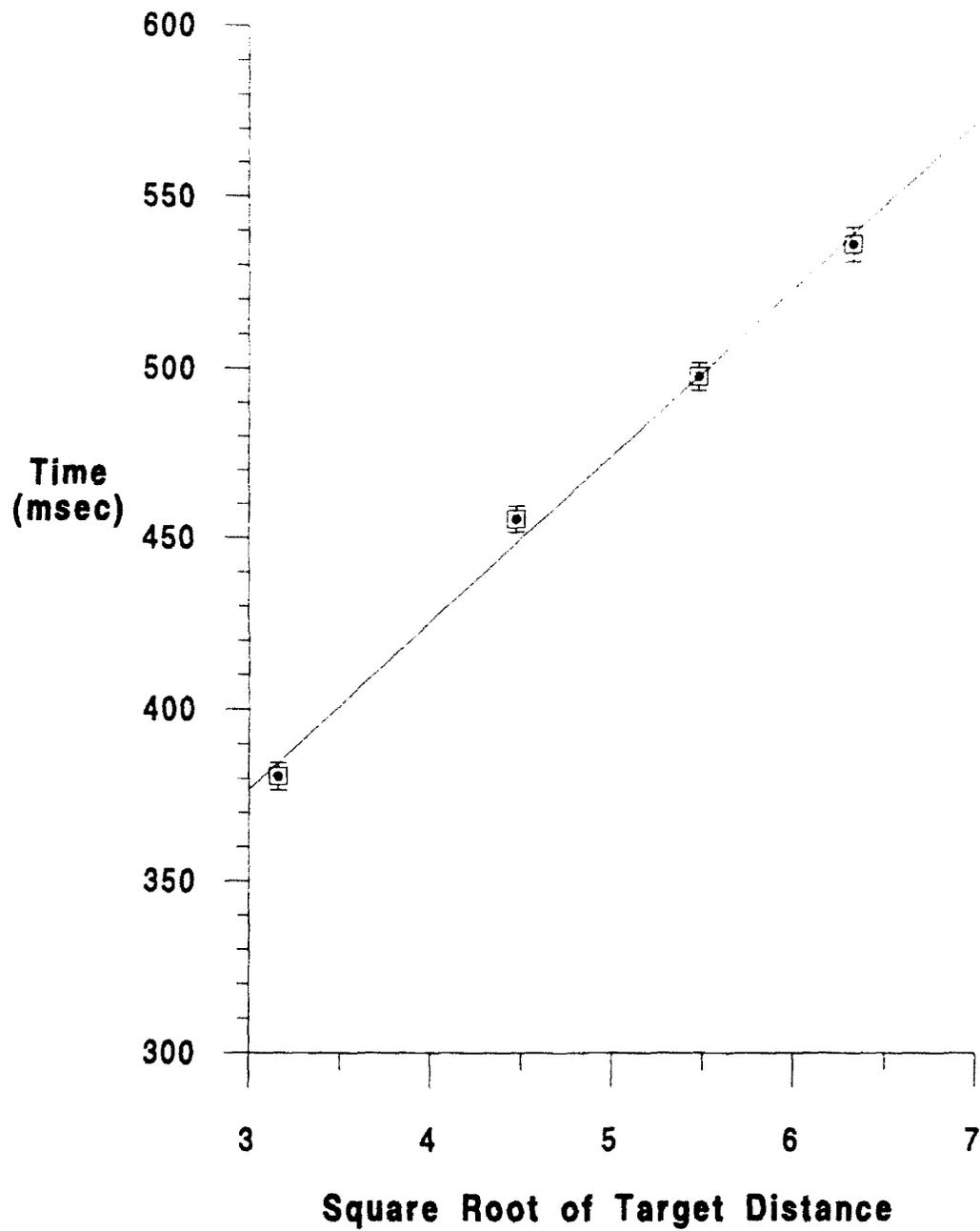
FIGURE 9.5

Number of Submovements by
# Square Root of Target Distance
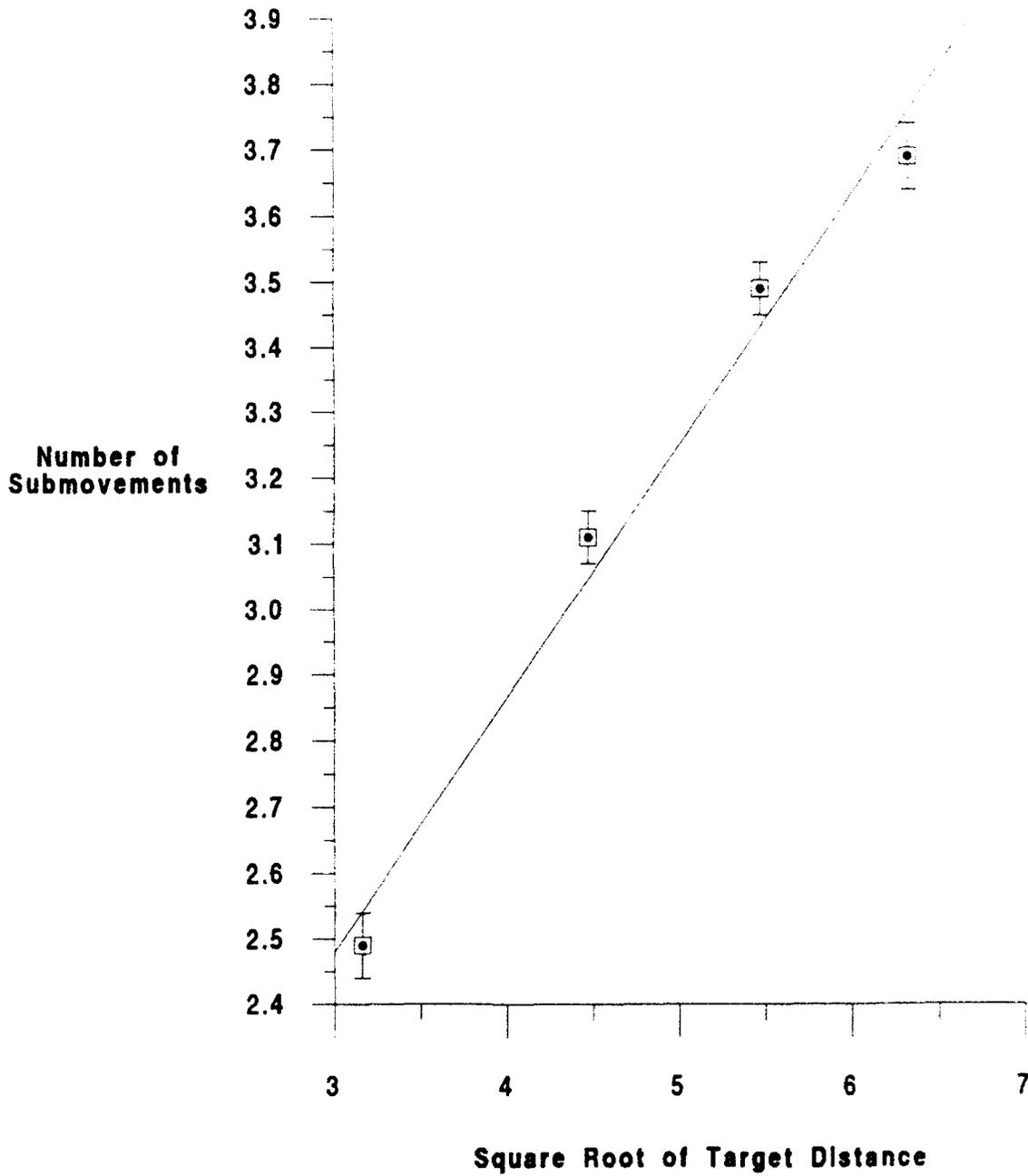
FIGURE 9.6

# Number of Submovements by Supination/Pronation and Square Root of Target Distance
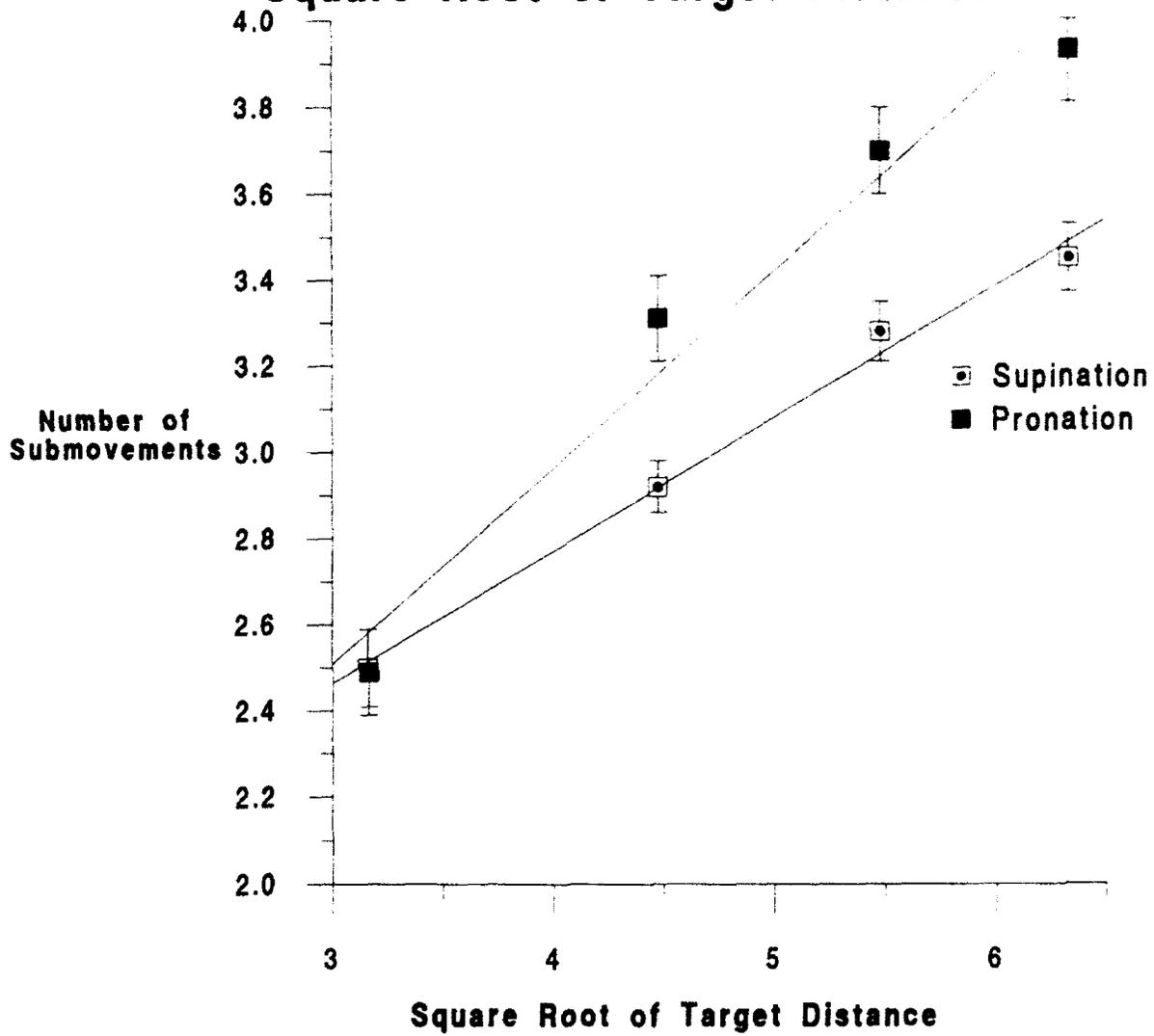
FIGURE 9.7

Probability of missing. Unlike in Experiment 3, the hand-by-precue interaction did not reach the .05 level of significance here [$F(4,16)=2.35$, $p \leq .0969$]. However, a pattern did emerge in the data. In all cases except when direction information was switched, the hands were essentially equal. When direction switches occurred, the nonpreferred hand was substantially more apt to miss the target than was the preferred hand. This differs somewhat from the pattern exhibited in the previous experiment, where the preferred hand was **superior** except for those cases when direction was switched (when the hands were equivalent). In both cases, however, the preferred hand did tend to improve its performance relative to the nonpreferred hand when direction information was switched. This tends to undermine the hemispheric processing hypothesis, which predicts virtually the opposite. These data are presented in Table 9.7.

Table 9.7: Probability of Missing by Hand and Precue Changed

| | Probability of Missing | | | |
Precue Changed	Left Hand	S.E.	Right Hand	S.E.
None	.11	.01	.11	.01
Direction	.16	.02	.10	.02
Extent	.11	.01	.13	.02
Both	.15	.02	.08	.02
No Information	.11	.02	.10	.02

Summary of current-control phase measures. The sudden appearance of a main hand effect at this point was surprising. The greater variability of the total movement distance does not, however, fit with any of the previously discussed hypotheses about the sources of hand performance differences. The remaining data still do not provide much support for any of the existing hypotheses.

Discussion

On the whole, results from Experiment 4 were consistent with those obtained in Experiment 3. It was also encouraging finally to find a significant difference between the two hands (in the standard deviation of total movement distance), but it is still difficult to explain why no differences were observed in the previous experiments. Possibly, performance by the two hands is equivalent at lower levels of difficulty, but when significant reprogramming or time stress is imposed, the superiority of the preferred hand becomes more apparent.

The advantage of the preferred over the nonpreferred hand may lie not in an overwhelming difference on any one measure, but in greater consistency between the production of various types of movements (in this case, supinations and pronations). This is suggested by the hand by target-direction interaction for the constant error of first submovement distance. Since the preferred hand displays little if any difference between supinations and pronations, it may be simpler for individuals to program such movements and accurately predict their current status at any point in time when the

preferred hand is involved. If this greater consistency between pronations and supinations extends to other types of movements as well, the net result might be a general superiority for the preferred hand in performing all tasks that require a series of movements. The key to this superiority would rest not on lesser variability within a given movement, but on the greater consistency of the preferred hand across movement types.

Regarding the nature of motor programming, the results of Experiment 4 support the previous conclusions from Experiment 3. It appears that the motor program is hierarchically organized, with information about movement direction being required at an earlier stage of preparation than is information about extent. Changing extent information had a much smaller effect on initiation time and constant error than did changing direction information. The fact that changing direction information had as much effect as changing both direction and extent information is further evidence that in such cases, the movement had to be completely reprogrammed. Extent information was useless without direction information, but direction information alone was still beneficial to the subject.

CHAPTER X

CONCLUSION

Preferred/Nonpreferred Hand Differences

The lack of solid support for any of the hypotheses about performance differences between the preferred and nonpreferred hand is intriguing. It was initially anticipated that all but one of the competing hypotheses would be systematically eliminated during the course of these experiments, or that the data would show a pattern suggestive of a new and coherent theory. What occurred, however, was that a majority of the competing hypotheses were eliminated, but no strong support emerged for the remaining ones.

The practice hypothesis was tentatively rejected based on the results of Experiment 1. There were no significant hand-by-day interactions for any of the dependent measures that would indicate improved performance by the nonpreferred hand, and thus no evidence that with practice, the nonpreferred hand achieved the same level of performance as the preferred hand. The only significant interaction of this type was one in which the preferred hand performed significantly **worse** than the nonpreferred on the second day of testing. This reasoning assumes that the preferred hand is sufficiently more practiced on wrist rotation tasks than the nonpreferred hand that such differences would appear in this study. This may or may not be a reasonable assumption depending upon the amount of time subjects have spent adjusting knobs and verniers, playing video games, etc. If both hands were equally unskilled at this type of task, no difference would be expected between the hands (as was the case in these experiments). This seems to be an unlikely possibility, but it cannot be dismissed out of hand.

The force-variability hypothesis was also substantially rejected by the first study. There were no systematic differences between the hands on any of the variability measures (standard deviation of total movement distance, standard deviation of first submovement distance, or, to a lesser extent, number of submovements).

The visual-feedback hypothesis was also discredited by the first experiment. If this hypothesis had been correct, there should have been definite superiority for the preferred hand during the current-control (feedback-driven) phase of the movement. This would have appeared in the number of submovements, the total movement time, and the probability of missing. However, no such pattern emerged.

If one assumes that any positioning movement also involves a sequence of actions (its various submovements), then the movement-sequencing hypothesis also lost credibility during these experiments. According to this hypothesis,

the total movement time for the preferred hand should have been substantially shorter than for the nonpreferred hand, because of smaller intervals occurring between successive corrective submovements. However, again no such pattern materialized.

Still, it is difficult to rule out the movement-sequencing hypothesis completely. The pattern of results expected under this hypothesis may only be displayed in a series of ballistic movements or several movements with ballistic phases. Most of the experimental evidence for superior movement sequencing by the preferred hand comes from data on rhythmic tapping, involving variables such as intertap interval and time to shift between upward and downward movements. Since these latter movements only consist of ballistic phases, movements involving current-control phases may not exhibit the same pattern of results.

Support for the background-noise hypothesis was mixed. The preferred hand did tend to exhibit a superiority over the nonpreferred hand as the target width decreased, but this was coupled with an advantage for the nonpreferred hand on the widest target. One would have expected little or no difference between the hands for the largest width, and increasingly superior performance by the preferred hand as the widths decreased. This pattern should have been manifested most strongly at the smallest target distance, but it was not. Perhaps the movement distances (and the required force pulses) were too large here in relation to the hypothesized background-noise level for any significant results to emerge. Another study with temporally-constrained movements (Schmidt et al., 1979) and increasingly slow movement velocities might prove enlightening in this regard.

Experiment 2 substantially discredited the hypothesis that the right hemisphere is more specialized in terms of spatial ability and should therefore exhibit a superiority at constructing motor programs given partial information. There did not seem to be any consistent pattern of results favoring either hand following the presentation of partial information (precues) about forthcoming movement dimensions.

Instead, the data from all four experiments suggest that one difference between the preferred and nonpreferred hands may be a greater consistency between similar movements made by the preferred hand; for both pronations and supinations, the preferred hand was substantially the same in terms of the standard deviation of movement endpoints and constant error. This outcome can be interpreted in several ways.

First, if preferred-hand consistency holds across movements other than wrist rotations, this might result in a superiority of the preferred hand, stemming from an ability to predict more accurately its position at any future point in a sequence of movements. Because similar movements by the preferred hand are equally variable and require the same amount of time to complete regardless of direction, it is possible that one less control parameter must be processed in a predictive "equation" for this hand. With the nonpreferred hand, a separate parameter may be needed to represent movements in opposite directions, making each "calculation" of final position more complex.

Another possibility is that the strength of the opposing muscle groups used for pronations and supinations are more equally balanced within the

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preferred hand than within the nonpreferred hand. This equality results in greater consistency between movements in opposite directions with the same muscle pairs. This hypothesis is not necessarily incompatible with the previous one, and it is possible that the true answer involves elements of both.

A final alternative is that the preferred hand makes slightly (not necessarily significantly) more corrective submovements, allowing for a marginally higher hit rate than the nonpreferred, though the total and first submovement time is the same for each. This would mean that the primary ballistic impulse is essentially identical for each hand in terms of amplitude and velocity, but that the subsequent corrective movements were executed more quickly. This possibility was somewhat supported by the data from Experiment 3, but not from Experiment 4. This indicates that the greater number of submovements in the earlier study may have been a function of subjects incorrectly starting their movements based on the precue data, and not on that of the response signal (the possibility that caused the changes between Experiments 3 and 4). The more restrictive controls on movement in Experiment 4 seems to have eliminated this effect, and disproved this hypothesis.

Probably the best way to investigate the hand-consistency hypotheses further would be to perform a pair of studies, one with sequences of movements, and one with reprogramming after a movement has been initiated. If the superiority of the preferred hand stems from its consistency across different but similar movements, the right hand should be better at all points during a sequence, both in terms of speed and accuracy, unless the existing "hardwired" programs are interrupted. After interruption, the nonpreferred hand, being more accustomed to changing movements on the fly because of inaccurate predictions about future location, should prove superior.

Motor Programming

The most surprising results of these experiments concerned the nature of the motor-programming process. Contrary to the results obtained by Rosenbaum (1980), it appeared here that the programming process **is** hierarchically organized, with direction information being necessary before extent information. It also appeared that the process proceeds in a **serial**, not parallel fashion. The dimension-reduction hypothesis (Larish and Frekany, 1985) thus can be rejected in a strict sense, since it relies on a nonhierarchical motor programming process as one of its fundamental assumptions. This hypothesis basically treats the motor program as an incomplete schema with the prespecified dimensions "plugged in" and with an "X" representing the missing parameter. This implies that the program can be preconstructed with either dimension prespecified, and then implemented immediately after the missing parameter is supplied. The present experiments demonstrate that this is **only** possible if the prespecified dimension is direction; this is the essence of a **hierarchical** processing structure. This does **not** suggest that motor programming is non-dimensional. On the contrary, a hierarchical process implies some type of dimensionsal structure, since each dimension represents a level in the hierarchy. What the data here show is that simply supplying progressively more movement dimensions does not lower initiation time unless the dimensions are specified in the order in which they

are found in the programming hierarchy. The question is not one of **how many** parameters remain, but rather **which** parameters remain.

The present experiments also substantially discredit the hypothesis that subjects normally prepare multiple motor programs when the number of response alternatives is small, as predicted by the Hick-Hyman Law. When subjects were presented with multidimensional 2- and 4-choice movement precues, performance was **not** equivalent to what occurred when either distance or direction information was provided (alternatives in which an equal number of possible movements would be preprogrammed). If one theorizes that multiple programs are only prepared when one dimension of the motor program is definitely known (e.g., direction or extent), this conjecture basically collapses into the dimension reduction hypothesis which was discredited above. The **only** structure for the motor program that fits the data from these studies is a **serial, hierarchically-organized process**.

Perhaps Rosenbaum's (1980) different results were a function of the methodology he employed or his experimental design. His movement precues required some degree of verbal processing (relating the displayed letters to the appropriate movement dimensions), while those used here were pictorial and spatial in nature. Why this should have caused extent information to be useful even without direction information in Rosenbaum's (1980) study remains unknown. Perhaps subjects processed his precues serially in an order corresponding to the letters' position on the screen.

Another difference between Rosenbaum's (1980) experiments and those presented here concerns the nature of the response signal. His studies used lights that corresponded in color to the various response buttons. At best, this is not a highly compatible cue for an aimed movement. His subjects were forced to perform a mental search to remember which target was assigned to each color before the motor program could be completed. This may have affected the nature of the response timing. In the present experiments, the precue and the response signal were essentially identical, as well as being more compatible with the movement to be made.

The fact that the results obtained in Experiment 2 were confirmed with the response-priming task in Experiments 3 and 4 adds credibility to the present conclusions. The motor-programming process definitely is hierarchically organized and serially executed, at least insofar as movement extent and direction information are concerned. This is consistent with the movement model proposed by Larish and Frekany (1985). According to it, the first step in producing a given movement is the selection of a particular agonist-antagonist pair. The second step is the determination of the relative gains required for the force pulses produced by each of the muscles involved.

The data obtained in these experiments do not contradict all results obtained by earlier investigators. Often, the current results confirm their data, while extending their findings and eliminating some hypotheses that have been proposed to explain the observed phenomena. The differences often lie in the interpretation of the results based upon a single aspect of the programming process.

For example, Lepine et al. (1989) reject a serial programming process because response time is not additive across all three movement dimensions

(arm, direction, and extent in their case). This is a logical conclusion based upon their data, which showed no difference between the precuing of hand and direction, leading them to reject the notion of a hierarchical programming process. If, however, their results were an artifact of either the precuing technique that they employed or the complex movement that their subjects made involving several body segments (as discussed earlier), a hierarchical structure such as in the present experiments could still exist. If so, additivity would not be expected across dimensions, unless the dimensions were precued in the same order as they were processed within the programming hierarchy. The existence of a hierarchical structure basically invalidates both the concept of a parallel programming process and the dimension-reduction hypothesis.

Goodman and Kelso's results (1980) are more difficult to explain. Using a highly compatible stimulus-response mapping, they found no serial effect for precuing any of the movement parameters. This led them to speculate that serial processing only occurred when the stimulus and response were highly incompatible (such as Rosenbaum's [1980] studies). These results have been contradicted by other researchers (e.g., Larish & Frekany, 1985) who have obtained indications of serial processing with highly compatible cues and responses. The results of Glencross and Requin (1985) again could have stemmed from a confusing precue or the nature of the movement used in their research.

The results found here dovetail greatly with those of Larish and Frekany (1985). In both cases, movement direction required longer to specify than did movement extent, and direction information was essential before extent information could be effectively utilized. Both also found that the nature of the reprogramming task was affected by the particular dimension that had to be reprogrammed. Direction changes entailed a complete reprogramming of a planned movement, while extent changes only required a modification of it.

The only difference between the results of the two sets of experiments lies in whether the programming process proceeds in a serial or parallel fashion. It is possible that the disagreement between the two studies is a function of either the type of precue used, the nature of the movement made (button-pressing versus wrist rotations), and the number of agonist-antagonist muscle pairs involved (the entire arm versus only those involved in wrist rotations).

Impact on Equipment Design

The original question that prompted the research in this dissertation concerned whether aircraft could be equally well controlled by either hand with side-stick controllers. Contrary to previous expectations, the results of this study indicate that there is probably little difference between the hands under normal circumstances.

The only condition under which there was any type of significant superiority for the preferred hand involved changes in movement direction. In these cases, the preferred hand did significantly better than the nonpreferred (the probability of missing metric in Experiment 4). In all other conditions, the hands were essentially identical. This indicates that for normal flying

tasks, it probably makes little difference whether the preferred or nonpreferred hand is used for flight control. It may also indicate, however, that when movements have to undergo rapid update in terms of direction (e.g., flying in extreme turbulence during a thunderstorm), the preferred hand is superior. Further investigation in this area with increasing task and time stress as well as subjective workload measures is necessary to draw any positive conclusions. However, it may not be necessary to avoid nonpreferred hand flight with side-stick controllers.

Future Research

Some previous studies involving three parameters in the programming process (hand, direction, and extent) have indicated that specification of the required effector occurs after specification of direction. This is also explainable by the hierarchical model of Larish and Frekany (1985). Since the same agonist-antagonist pair is used by either hand to accomplish a particular movement, it is possible that the muscles in **both** hands are primed at the same time, and selection of the particular hand occurs **after** this point, rather than before it. A modification of the second and third experiments in this series could be conducted to test this possibility by using electromyographic equipment and having subjects prepare both hands simultaneously.

APPENDICES

APPENDIX A: SUMMARY OF SIGNIFICANT RESULTS

Experiment #1

Dependent Measure	Significant Effects	F-value	Signif.
First Submovement Time	Hand X Target Direction x Target Distance*	F(3,6)=3.80	.0772
Standard Deviation of First Submovement	Target Distance	F(3,6)=57.17	.0001
	Target Width x Day	F(2,4)=9.45	.0305
Constant Error of First Submovement	Day	F(1,2)=37.85	.0254
	Target Distance	F(3,6)=27.99	.0006
	Target Width	F(2,4)=8.96	.0333
	Hand x Target Direction x Target Distance*	F(3,6)=4.18	.0644
Movement Time	Target Distance	F(3,6)=61.87	.0001
	Target Width	F(2,4)=10.37	.0262
	Day x Hand	F(1,2)=45.63	.0212
	Hand x Target Direction x Target Distance*	F(3,6)=3.69	.0816
Standard Deviation of Total Distance	Target Distance	F(3,6)=52.15	.0001
	Hand x Target Width	F(2,4)=9.62	.0296
	Day x Target Width	F(2,4)=9.19	.0320
	Target Width*	F(2,4)=5.54	.0704
Constant Error of Complete Movement	Target Direction	F(1,2)=53.45	.0182
	Hand x Target Width*	F(2,4)=4.91	.0838
Probability of Missing	Target Width	F(2,4)=101.13	.0004
	Hand x Target Direction	F(1,2)=61.16	.0160
Number of Submovements	Target Distance	F(3,6)=41.80	.0002
Initiation Time	Target Distance	F(3,6)=11.78	.0063
	Target Width	F(2,4)=11.62	.0216
	Day x Target Width	F(2,4)=26.94	.0048

* = approached significance (p≤.10)

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Experiment #2

Dependent Measure	Significant Effects	F-value	Signif.
Initiation Time	Target Distance	$F(3,9)=3.79$	.0500
	Precue	$F(5,15)=31.97$	.0001
	Day x Precue	$F(5,15)=3.15$	.0384
	Hand x Target Direction x Target Distance [*]	$F(5,15)=2.67$	.0644
First Submovement Time	Target Distance	$F(3,9)=8.28$	.0059
	Precue	$F(5,15)=3.79$	.0203
Standard Deviation of First Submovement	Target Distance	$F(3,9)=29.32$	.0001
	Hand x Target Direction	$F(1,3)=12.33$	.0392
	Hand x Target Direction x Target Distance	$F(3,9)=3.84$	.0500
Constant Error of First Submovement	Target Distance	$F(3,9)=91.27$	.0001
	Precue	$F(5,15)=2.98$	.0461
Movement Time	Target Distance	$F(3,9)=31.66$	.0001
	Hand x Precue [*]	$F(5,15)=2.51$	.0768
	Hand x Target Direction x Target Distance [*]	$F(3,9)=3.77$	.0531
Probability of Missing	Target Distance	$F(3,9)=10.29$	.0029
Number of Submovements	Target Distance	$F(3,9)=83.37$	.0001
	Hand x Target Direction x Target Distance	$F(3,9)=6.74$	.0112

[*] = approached significance ($p \leq .10$)

Experiment #3

Dependent Measure	Significant Effects	F-value	Signif.
Initiation Time	Precue	$F_{(4,12)}=8.66$	.0016
First Submovement Time	Target Distance	$F_{(3,9)}=4.54$	.0336
Standard Deviation of First Submovement	Target Distance	$F_{(3,9)}=14.68$	.0008
Constant Error of First Submovement	Target Distance	$F_{(3,9)}=20.23$	.0006
	Precue	$F_{(4,12)}=3.42$	.0432
	Target Distance x Precue	$F_{(12,36)}=2.08$	.0450
	Hand x Target Direction*	$F_{(1,3)}=6.94$	.0708
Movement Time	Target Distance	$F_{(3,9)}=10.81$	.0024
Standard Deviation of Total Distance	Day x Precue	$F_{(4,12)}=3.70$	.0348
Constant Error of Complete Movement	Target Distance	$F_{(3,9)}=7.18$	.0092
Number of Submovements	Target Distance	$F_{(3,9)}=13.15$	.0012
	Hand x Precue	$F_{(4,12)}=3.30$	.0483
Probability of Missing	Precue	$F_{(4,12)}=5.47$	.0096
	Hand x Precue	$F_{(4,12)}=3.87$	.0303

* = approached significance ($p \leq .10$)

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Experiment #4

Dependent Measure	Significant Effects	F-value	Signif.
Initiation Time	Precue	F(4,16)=22.34	.0001
First Submovement Time	Target Distance	F(3,12)=19.99	.0001
	Hand x Target Direction x Target Distance	F(3,12)=3.84	.0387
Standard Deviation of First Submovement	Target Distance	F(3,12)=13.60	.0004
	Hand x Target Distance	F(3,12)=3.59	.0464
	Hand x Target Distance x Target Direction*	F(3,12)=2.95	.0757
Constant Error of First Submovement	Target Distance	F(3,12)=29.75	.0001
	Precue	F(4,16)=3.45	.0325
	Target Distance x Precue	F(12,48)=2.29	.0211
	Hand x Target Direction*	F(1,4)=6.22	.0671
Movement Time	Target Distance	F(3,12)=25.45	.0001
	Hand x Target Direction	F(1,4)=12.11	.0254
Standard Deviation of Total Distance	Hand	F(1,4)=11.09	.0291
Constant Error of Complete Movement	Precue	F(4,16)=3.33	.0364
Number of Submovements	Target Distance	F(3,12)=25.82	.0001
	Hand x Target Direction*	F(1,4)=5.65	.0762
	Hand x Target Direction x Target Distance	F(3,12)=3.90	.0372
Probability of Missing	Hand x Precue	F(4,16)=2.36	.0969

* = approached significance (p≤.10)

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APPENDIX B: THE TUKEY TEST

     The Tukey test is a multiple-comparison procedure based on the studentized-range statistic. The procedure, often called the HSD (honestly significant difference) test, determines the critical value for all possible pair-wise comparisons between means while maintaining the experiment-wise error rate (α_E) at the pre-established α level (Montgomery, 1984). The null hypothesis in this case is that all population means are equal (H_0: $\mu_i = \mu_j$ for $i \neq j$). The test statistic is d_T, which is computed with the formula:

$$d_T = q_T (MS_{S/A})^{1/2}/(s)^{1/2}$$

where q_T is the appropriate entry in the table of the studentized range statistic, $MS_{S/A}$ is the error term from the overall analysis of variance, and s is the sample size for each group. The value of q_T is determined by the number of degrees of freedom in the error term (df_{error}), r the number of treatment means, and α_E (the error rate chosen for the Tukey test) [Keppel, 1982]. The value of d_T is compared to the difference between each pair of means. An example of this procedure (Keppel, 1982) is provided below.

	Levels (Ordered by size of treatment means)				
	a_3	a_2	a_4	a_5	a_1
MEANS	7.11	7.89	8.78	11.44	12.78
$\overline{A}_3$ = 7.11	—	.78	1.67	4.33	5.67
$\overline{A}_2$ = 7.89		—	.89	3.55	4.89
$\overline{A}_4$ = 8.78			—	2.66	4.00
$\overline{A}_5$ = 11.44				—	1.34
$\overline{A}_1$ = 12.78					—

     For purposes of example, let us assume that the value of q_T has been found to be equal to 4.04, that each of the means in the table were based on nine samples, and that the error term from the analysis of variance is 13.22. The calculated value of d_T would then be:

$$d_T = (4.04)(13.22)^{1/2}/(9)^{1/2} = 4.90.$$

Checking back at the table of means on the previous page reveals that only the largest difference (that between A_1 and A_3) exceeds the critical value of the Tukey test and is significant (Keppel, 1982).

     In practice, the Tukey test is more conservative (maintains a smaller type 1 error rate) than either the Newman-Keuls or Duncan tests, and is thus less powerful than either of these procedures. It is somewhat more powerful than the Scheffé test for pairwise comparisons, but less powerful for complex contrasts.

The studentized-range distributions cited on the previous page are developed by drawing k random samples from the same population and determining the difference between the highest and lowest of the sample means. Dividing these differences by $(MS_w/n)^{1/2}$, develops underlying distributions similar to that of the t-statistic. The n in the equation is the group sample size for all k groups (Hinkle, Wiersma, & Jurs, 1979).

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