DEGREES OF MOTOR PROGRAM CONTROL

by

Barry C. Noble

Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfullment of the requirements for the degree of

MASTER OF SCIENCE
in
Psychology

APPROVED:

Lam C Perlmuter
Lawrence C. Perlmuter, Chairman

HL Snyder
Harry L. Snyder

A. M. Prestrude
Albert M. Prestrude

November, 1975

Blacksburg, Virginia

ACKNOWLEDGEMENTS

The author is grateful to Dr. Lawrence Perlmuter for his guidance and patience in the preparation of this manuscript.

Thanks are also due to Mark Cross who helped in the collection and analysis of the data discussed in this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

William James in his chapter about the will in the Principles of Psychology (1890) outlined a mechanism for the control of movements. The central theme of his proposal was that voluntary movements are elicited by an image of the directed sensorial consequences. This statement of ideo-motor theory has been discussed by Greenwald (1970) and Kimble and Perlmuter (1970). Perhaps the most salient feature of James' movement control theory was the idea that voluntary behaviors are goal directed. James (1890) wrote:

> An anticipatory image, then, of the sensorial consequences of a movement, plus (on certain occasions) the fiat that these consequences shall become actual, is the only psychic state which introspection lets us discern as the forerunner of our voluntary acts. (p. 287)

The existence of an image of the anticipated consequences of an act was supported in James' thinking by the occurrence of a phenomenological experience commonly known as surprise. The question of primary importance for James appears to have been; How could surprise exist unless a detectable discrepancy between the directed sensory consequence and a resulting consequence occurred? Implicit in this question is the idea that a comparison of the directed sensory consequences and those sensory consequences resulting from movement occurs.

James adamantly insisted that the anticipatory images developed through experience. Hence, as early as 1890 three hypotheses concerning voluntary behavior were evident: 1) a voluntary act begins with an image of the directed sensorial consequences, 2) voluntary behavior is learned, 3) some sort of comparison of the directed sensory consequences of movement with the resulting sensory consequences takes place. More recently Kimble and Perlmuter (1970) pointed out that the goal of the classical theory of volition "has been to replace the concept of the will with a mechanism that could be subject to experimental test and conceivably reduced to neurophysiological status." (p. 515). In the four score and five years which have elapsed since the Principles of Psychology was published, considerable progress has been made toward developing a movement control model which could be subject to experimental test. Substantiating the conclusion that progress has been made requires a review of the development and distinguishing characteristics of two current movement control models, viz. open and closed-loop regulation.

With the advent of computer technology and information processing systems two mechanisms applicable to the control of movements became popular. The first of these is closed-loop regulation. Numerous versions of the closed-loop model have been proposed. Closed-loop regulation has been discussed by Adams (1971), Anokhin (1969), Greenwald (1970), Keele (1968), Konorski (1967), and Laszlo (1967).

Basically, the idea behind the closed-loop model is that feedback resulting from movement is or can be utilized during the performance of a movement. Through the utilization of feedback information it is possible for a performer to detect an error, a discrepancy between the directed sensory consequences and those arising from movement. As a result of the comparison between the directed consequences and those actually resulting from movement, appropriated error-correcting commands can be issued insuring that the directed sensory consequences are attained. Deviations possibly resulting from an unexpected load, or an incorrect assessment of the initial position of a limb, could thus be compensated for while the movement was in progress. In essence, this formulation was proposed by Adams (1968).

> If a movement segment is recognized as correct we go on to the next stage, but if it is incorrect an error signal is generated and we take corrective action in the hopes of finding a movement pattern that will be recognized as correct. (p. 499)

The recognition of feedback as correct requires a comparison between the directed sensory consequence and the sensory consequence which results from movement.

Two versions of the closed-loop hypothesis have been discussed by Paillard and Brouchon (1968). From the inflow point of view patterns of afference produced by movement are compared to a central representation of the directed system output. The outflow version, on the other hand, maintains that patterns of efference, or the commands to the peripheral effectors themselves, are compared centrally to the directed system output. Both versions require a comparison and hence a comparator. The major differences between these two versions of the closed-loop model are: 1) the length of the feedback loop, and 2) the type of information conveyed to the comparator. That to which feedback information is compared has received numerous titles: for James (1890) and Von Holst (1954) it was an image; Miller, Galanter and Pribram (1960) termed it a plan; and for Luria (1966) it was a motor plan.

The concept of a central efferent loop has a long history. As Festinger and Cannon (1965) pointed out it was the center of a debate between James and Helmholtz. Helmholtz (1962) demonstrated that if the external rectus of the right eye was paralized and the patient attempted to move the eye to the right, objects in the visual field moved to the right even though the eye did not move. On the basis of this demonstration Helmholtz concluded that there must have been a feeling of innervation, i.e., a central efferent feedback loop. James (1950) countered by asserting that the left covered eye moved and hence there was afferent stimulation necessary for the perception of movement present.

However, Lashley (1917) interpreted the fact that individuals in which kinesthetic feedback from leg movements was lost through injury were able to quite accurately reproduce active, but not passive, leg movements as due to the operation of a central efferent loop. Perhaps the most frequently cited evidence in support of a central efferent loop, however, is the work of Taub and his associates: Taub, Bacon, and Berman (1965), Taub and Berman (1968), and Taub, Ellman, and Berman (1966). Taub and Berman (1968) stated:

> The former mechanism requires the existence of a purely central feedback system that could in effect, return information concerning future movements to the CNS before impulses that will produce these movements have reached the periphery. An animal could thus determine the general position of its limbs in the absence of peripheral sensation. Indeed, just such a mechanism has been demonstrated electrophysiologically, first by Chang (1935) and Li (1958) and subsequently by a large number of other investigators, . . .
>
> Indeed, if central feedback is of significance for behavior following deafferentation, it seems reasonable to assume that not one but several "loop" pathways would be involved. That is, if one were

> to set out a priori to construct a servo-mechanism that would be maximally sensitive to control, one would certainly establish a feedback loop at <u>each</u> level of the system from command to output. (p. 188-189)

Paillard and Brouchon (1968) reached conclusions similar to those of Taub and Berman (1968) on the basis of their own research.

The second movement control model applicable to the control of movements is open-loop regulation. While the closed-loop model emphasizes the importance of feedback of one type or another in the control of movements, the open loop model discussed by Schmidt (1972), Schmidt and Russell (1972), and Keele (1973) contends that short duration movements are controlled by stored motor programs. The motor program model is based on the assumption that a certain amount of time is required to process feedback from movement. Chernikoff and Taylor (1952) measured kinesthetic reaction time resulting from sudden passive arm displacement and concluded that between 118.9 and 129.4 msec <u>were</u> required to process kinesthetic feedback. Keele and Posner (1968), employing a task in which on half of the trials subjects made lateral arm movements in the dark, estimated that the minimum amount of time required to process visual feedback was between 190 and 260 msec. An implicit assumption in the motor program model is that movements with durations close to these estimates are probably too short for extensive feedback involvement.

Pew (1974) emphasized that the idea of a motor program is largely a default argument. If motor programs are not postulated it is difficult to explain how it is possible for humans to execute movements with durations shorter than the time required to process feedback. Schmidt (1975) correctly asserted that, strictly speaking, neither of the two conditions necessary to support the postulation of motor program control have been met. According to Schmidt these conditions are: 1) that feedback is present, but is not utilized, 2) that movement can still occur when feedback is not present.

Despite the fact that these requirements have not been met, numerous investigators have been content to retain the model. Among these investigators McLaughlin (1967) demonstrated that what he termed "parametric adjustments" in saccadic eye movements occur if during such movements a target initially 10 degrees from the fovea is displaced to 9 degrees. Moving the target dot after the eye began to move initially had no effect on the terminal position of the eye. The eye passed the target dot and moved to the point at which the dot had been located prior to beginning of movement. After successive overshoots caused by the displacement procedure, a target initially 10 degrees from the fovea elicited a 9 degree change of fixation. Presumably the duration of saccadic eye movements is too short for the efficient operation of a feedback loop which could modify the movement in response to target displacement. Similarly, Mittelstaedt (1957) found that the extremely rapid short duration prey capture movements of mantids are not modified in response to target displacement if the displacement occurs after the movement is initiated.

Schmidt (1972) and Schmidt and Russell (1972) have developed what they termed the index of preprogramming (IP). The IP is essentially a within-subjects correlation of start and stop errors in a receptor anticipation task. Subjects were pretrained to move a certain distance in a specified amount of time, either 160 or 760 msec. Then subjects were allowed to view an external clock during movement. Each trial began when the experimenter started the clock. The subjects' task was to begin movement when the clock hand was either 160 or 760 msec from the vertical and to stop the hand of the clock at the vertical position by hitting the target block. Hence, if a subject was to make a movement lasting 160 msec and actually began to move when the hand of the clock was 200 msec from the vertical position, and the movement was preprogrammed for a duration of 160 msec, there should be no correction for the 40 msec start error. The hand of the clock would be stopped by the arrival of the subject's hand at the target 40 msec before reaching the vertical position. Therefore, a high correlation between start and stop errors indicates preprogramming.

Schmidt and Russell's (1972) prediction that the IP would decrease with increases in movement time (MT) were supported by their data. In fact, MT and not the rate of movement was the primary determinant of the degree of preprogramming. The rate of movement was manipulated by changing the distance traversed while holding instructed movement time (IMT) constant. The manipulation of distance was necessary. If only one distance were employed at each IMT the rate of movement and the time required would be confounded. The motor program model proposed by Schmidt and Russell, however, asserts that MT will be the primary determinant of the degree of program control. As movement duration increases the probability that feedback loops will have time to operate and thereby alter the process of movement control increases. Klapp

(1975), however, concluded that long 336 mm movements were under feedback control and that extremely short 2 mm movements were not. Roy and Marteniuk (1974) reached the conclusion that fast, as opposed to slow responses,were guided by motor programs.

At this point in the discussion it should be clear that once a movement controlled by a motor program is initiated it is virtually unalterable. The necessity of processing feedback during movement is diminished as movement parameters are specified prior to the beginning of movement. In a sense, movement control is internalized, as changes in environmental conditions should have no apparent effect on the course of movement.

Moreover, it should be made explicit that the open- and closed-loop control mechanisms are two mutually exclusive behavioral models of movement control. The fact that Granit (1970) has demonstrated that spindle initiated feedback loops operate in as little as 30-50 msec is more or less irrelevant in terms of the motor program as a behavioral model. Physiologically speaking, as the earlier quotation from Taub's writing was intended to emphasize, hierarchical organization is probably the rule in the central nervous system. "Loops" may exist at innumerable "levels".

These statements should not be construed as implying that an integration of behavioral and physiologic laws is not desirable, to the contrary, such an integration is viewed as the goal of parallelistic science. However, as Skinner (1938) recognized, behavioral and physiologic regularities are prerequisites of an eventual synthesis.

Skinner (1938) wrote:

> What is generally not understood by those interested in establishing neurological bases is that rigorous description at the level of behavior is necessary for the demonstration of a neurological correlate. The discovery of neurological facts may proceed independently of a science of behavior if the facts are directly observed as structural or functional changes in tissue, but before such a fact may be shown to account for a fact of behavior, both must be quantitatively described and shown to correspond in all their properties. This argument becomes more cogent as independent techniques are developed in neurology and hence applies more directly to physio-chemical neurology than to a conceptual (sic). That is to say, a demonstration of a correlation comes to demand greater rigor as neurology and a science of behavior begin to deal with different methods and subject matters. (p. 422)

The problem as to where motor programs reside may have been alleviated as Schmidt (1975) proposed a purely behavioral definition of the motor program.

> What is meant by this definition of the motor program is that when the program is initiated, it carries itself out as planned, correcting for deviations from the intended path of movement, but that if something happens in the environment that requires that some new movement be planned, the performer can not accomplish such changes until the program has run its course for approximately 200 msec. (p. 232)

This definition of motor program control should foster experiments employing methodologies similar to McLaughlin's (1967) or Henry and Harrison's (1961). Henry and Harrison required subjects to make a forward arm swing movement at maximal speed starting downward in the sagital plane in response to a visual stimulus (S1). A second visual stimulus (S2) was presented either .10, .19, .27, or .35 sec after S1.

The subjects' task was to reverse the direction of movement upon presentation of S2 before striking the target string. This task proved to be rather difficult at all inter-stimulus intervals but .10 and .19 sec.

Schmidt's (1975) new definition of motor programming represents an advance as it is purely behavioral and makes explicit an idea which was implicit in the motor program model proposed by Schmidt and Russell (1972). However, the concept behind the IP was potentially a more constructive contribution than emphasizing the unalterability of movements controlled by motor programs. Alterable versus unalterable suggests a dichotomy. The IP represented a change from a conceptualization of movement control in terms of a dichotomy, viz., open vs. closed-loop control. The classificatory dichotomy was replaced by the idea of a continuum ranging from near zero feedback involvement, motor programming, to almost complete feedback utilization.

Pew (1966) foreshadowed the adoption of a continuum ranging from near zero feedback involvement to almost complete feedback utilization in the control of movements when he suggested that as a result of practice the necessity of continually monitoring feedback in order to maintain performance may diminish. Pew employed an acceleration tracking task in which subjects attempted to keep a dot on an oscilloscope centered at the intersection of two crosshairs by sequentially alternating between two keys. When the right key was depressed the dot accelerated to the right. When the left key was depressed the dot accelerated to the left. On the basis of the results obtained Pew (1966) concluded:

> The underlying theme of these proposals is the hierarchical nature of control of skilled acts which develop with strict closed loop control and reaching levels of highly automitized action with occasional "executive" monitoring. (p. 771)

In addition, Fleishman and Rich (1963) demonstrated that over half of the variance of total time on target scores in a two hand tracking task was accounted for in terms of two ability traits developed prior to practice at the task. Subjects with high scores on a spatial sensitivity measure demonstrated initially superior performance as compared to subjects receiving lower scores. However, late in practice subjects receiving high scores on a kinesthetic sensitivity measure showed superior performance to subjects receiving low scores on the kinesthetic measure. The correlation between the two sensitivity measures was not significant. The implication of the Pew (1966) and Fleichman and Rich (1963) studies is that quantitative as well as qualitative differences in feedback involvement in the control of movements may develop with practice. As previously noted, Schmidt and Russell (1972) proposed that another variable, movement duration, also influences the degree of feedback involvement in the control of movements. Short duration movements are supposedly under motor program control. Which is to say, that the degree of feedback involvement is nominal. Therefore, at least two variables, movement duration, and the extent of practice, probably influence the degree of feedback involvement in the control of movements.

Several testable predictions can be derived from the proposal that the degree of feedback involvement increases as movement duration increases. In developing these predictions it is imperative to consider the obvious analogy between motor programs and computer programs. First of all, the output from a computer program will be invariant provided, of course, that the input remains constant. Therefore, continuing the analogy, movements controlled by motor programs should be relatively invariant. Now, if the degree of feedback involvement increases as MT increases, it follows that the variability of MT scores should increase as MT increases. It is as if the "degrees of freedom" increase with increases in MT.

Specifically, if subjects are instructed to make a lateral arm movement from point A to point B in either 200, 500, or 800 msec, and knowledge of results in terms of the total elapsed time from the beginning to the end of movement is provided after the completion of each movement, the variability of MT scores should increase with increases in instructed movement time (IMT). In fact, Keele and Posner (1968) and Schmidt and Russell (1972) have presented data which support this prediction of the proposed model.

If the potential for feedback utilization in the control of movements increases as IMT increases, it should be possible to demonstrate at some IMT that the variability of MT scores could be reduced by providing subjects with a visual display which could be utilized to regulate the progress of movements. The display would have to be such that the subject, having begun movement could compare the amount of time remaining before the IMT expired with the distance which remained to be traversed in that amount of time. By virtue of the comparison between the amount of time remaining and the distance remaining, subjects should be capable of regulating the progress of movements at longer IMTs. If there is a small distance remaining and a long time, subjects should decrease the rate of movement. Conversely, if there is a large distance remaining to be traversed before the IMT expires and a small amount of time, subjects should increase the rate of movement. The result of such regulation, which is normally categorized as closed-loop, should be a reduction in the variability of MT scores when the display is provided and the duration of movement is such that the comparison process can occur. The duration of movement and the presence of a visual display should, therefore, be the primary determinants of the variability of MT scores.

The primary purpose of the experiments which follow was to verify the following predictions: 1) the standard deviations of MT scores will increase as IMT increases, 2) at short IMTs the presence of a visual display during movement will not affect the standard deviations of MT scores, 3) at longer IMTs the presence of a visual display will decrease the standard deviations of MT scores, 4) manipulating distance while holding IMT constant will not affect the standard deviations of MT scores. All of these predictions follow from the proposed movement control model which states that the duration of movement, and not the rate of movement, is the primary determinant of the degree of motor program control.

Experiment I

Method

Subjects. Twelve female and eight male right handed undergraduate volunteers attending Virginia Polytechnic Institute and State University served as subjects. They were given additional course credit for their participation in the experiment.

Apparatus. The apparatus consisted of a microswitch, a carriage to which was attached a handle, and a photo-resister embedded in the metal base under the finish position. The diameter of the cylindrical handle was 2 cm. The height of the handle was 15.24 cm.

The handle was mounted in the carriage and two axles were attached to the underside of the carriage. Precision roller bearings were mounted on the ends of the axles. These bearings served as wheels. The carriage was guided by a steel rod running through lubricated bushings in a channel drilled lengthwise through the center of the carriage.

The carriage wheels and the microswitch were hidden from the subject's view by a cover which contained a slot 66 cm long and 3 cm wide. The handle moved inside this slot. This construction allowed only the handle, the steel rod, and part of the cart to be visible to the subject.

The clock which measured MT was started by the subject moving the carriage away from the left hand white line which demarcated the start position. The arrival of the handle at the right hand white line, the finish position, interrupted the source of ambient light causing the photoelectric relay to stop the MT clock.

The illumination of a disc 2.9 cm in diameter was the signal to the subject to begin movement. This visual stimulus is referred to as the go signal. Start time (ST), the first temporal component of the response, was the time from the presentation of the go signal until the subject began to move. The disc which served as the go signal was directly in front of the subject at a height of 24 cm above the surface of the table and an average distance of 72 cm from the subject's forehead. The speaker from which auditory feedback and warning signals emanated was directly below the disc. The duration of the go signal was controlled by a Hunter timer (model 100 B series D).

The auditory stimulus which was paired with the subject's movement was produced by a Hewlett Packard audio oscillator (model 200 AB) set at 1200 Hz. The duration of the auditory warning and feedback signals were controlled by two Hunter timers (model 100 C series B).

Task. The subject was required to move a carriage from left to right with the right hand. The start and finish positions were designated by two white lines 3 and 5 cm wide respectively. Subjects were instructed to move from the start to the finish position in either 160 or 760 msec. Subjects were required to stop movements at the finish position. The distance from start to finish, white line to white line, was 35.5 cm. Subjects were to begin movement as quickly as possible following the illumination of the go signal. The go signal was illuminated for 250 msec. As soon as the subject began to move, an auditory feedback stimulus was presented. The duration of this auditory feedback stimulus was equal to the IMT, either 160 or 760 msec. Subjects were not informed that the duration of the auditory feedback stimulus was equal to that of the IMT.

Procedure. The experimental room was divided by a partition which contained a one-way mirror. This mirror was used by the experimenter to monitor the subject's behavior. The height of the subject's chair was adjusted so that the right elbow was approximately 5.08 cm above the apparatus cover when the handle was held in the start position. This was achieved by adjusting the distance of the seat of the chair from the floor. Subjects were seated so that their sternum was half way between the start and finish position. When holding the handle in the start position, the subject's right arm crossed their chest. Following the positioning of the subject, the experimenter read the instructions which included a practice movement to insure understanding of the task.

The inter-trial intervals were 10, 12, 14, and 16 sec. The mean inter-trial interval was 13 sec. After each block of 25 trials there was a 2 min rest period. Following each movement for which an MT score was available, the experimenter announced the resulting MT to the subject. The subject then returned the handle to the start position to await the presentation of the next go signal.

Upon returning on the second day subjects were asked to report their IMT, in order to insure that they had not forgotten it. Following 25 additional Phase I trials on the second day, Phase II began. On half of the trials in Phase II an auditory signal identical to the auditory feedback signal was presented for either 160 or 760 msec immediately prior to the go signal. This auditory warning signal terminated simultaneously with the presentation of the visual go signal.

Design. The experiment consisted of two distinct phases. In Phase I two groups of ten subjects were instructed to make a lateral left-to-right arm movement in either 160 or 760 msec. Each subject was given 125 training trials in Phase I. Hence, the experimental design in Phase I was a mixed model factorial, 2 (IMT) & 25 (trial blocks). There were five trials in each trial block. There were six female and four male subjects in each IMT condition.

In Phase II, trials 126-195 inclusive, each of the two IMT groups were subdivided into two groups of five subjects. There were three female and two male subjects in each of the four resulting groups. The four resulting groups were designated: 160-160, 160-760, 760-760, and 760-160. The first number in the group designation refers to the IMT used in Phase I. The second number in the group designation refers to the duration of the auditory warning signal which preceded the visual go signal on half of the trials in Phase II. The auditory warning signal occurred on half of the trials in Phase II. The presence or absence of the warning signal is referred to as trial type.

The trial type sequence was randomly assigned with the restriction that the ratio of warning signal present to warning signal absent, or vice-a-versa, could not exceed .66 in any block of ten trials. In addition, no more than three trials of either type could occur sequentially. These restrictions insured that trials on which the warning signal was present occurred throughout Phase II.

The analyses of mean trial block ST and MT scores in Phase II were 2(IMT) X 2(warning signal duration) X 2(trial type) X 7(trial blocks) mixed model factorials. Trial type and trial blocks were repeated measures variables.

Results

Phase I start time. The 160 IMT condition produced shorter and less variable ST scores than did the 760 IMT condition. The mean ST of the 160 IMT condition was 253.8 msec, SD = 55.5 msec. The mean ST of the 760 IMT condition was 409.5 msec, SD = 96.8 msec. A Hartley's F-max test revealed that the associated variances of the two IMT conditions differed significantly, F(1248, 1250) = 3.04, $p < .05$. Figure 1 depicts the total variance of ST and MT scores of the two IMT conditions in Phases I and II. Phase I variances are depicted by open bars. In other words, the variance of the 160 IMT condition's Phase I MT scores shown in Figure 1 is the variance of the 1248 scores obtained when 10 subjects made 125 movements each.

In order to assess the effect of IMT on the variance of ST scores after performance became more stable, the within subjects standard deviations of ST scores were computed over trials 52-125 inclusive. The mean standard deviation of ST scores in the 160 IMT condition was 34.7 and 64.0 msec in the 760 IMT condition. A between groups t test demonstrated that this difference was significant, t (18) = 5.22, $p < .001$.

A mixed model ANOVA conducted on the mean trial block ST data revealed a significant IMT x trial blocks interaction, F(24,432) = 2.17, $p < .05$. Generally, over the first five to seven trial blocks mean ST decreased in the 160 IMT and increased in the 760 IMT condition before stabilizing. The main effect of IMT was also significant,

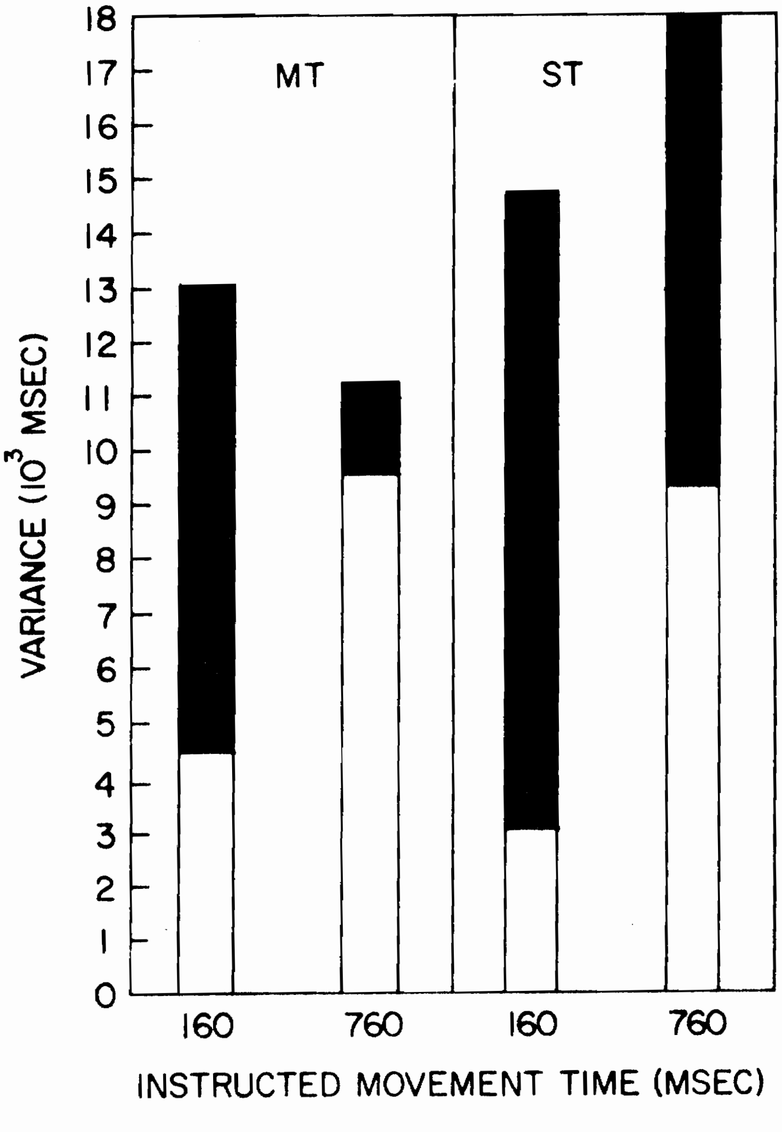

Figure 1. Variance of start time and movement time scores at each instructed movement time for both phases of Experiment 1. Phase 1 variances are depicted by open bars. Increases in Phase 2 are depicted by solid bars.

$F(1,18) = 41.44$, $p < .001$. Apparently, IMT not only influences the variance of ST scores, but also the means of ST scores.

Phase I movement time. The 160 IMT condition produced shorter and less variable MT scores than did the 760 IMT condition. The left panel of Figure 1 shows the variance of MT scores of the two IMT conditions in Phase I. The MT for the 160 IMT condition was 237.2 msec, $SD = 66.6$ msec. The mean MT in the 760 IMT condition was 762.6 msec, $SD = 97.4$ msec. A Hartley's F-max test revealed that the associated variances were significantly different, $F(1250, 1234) = 2.14$, $p < .05$.

In order to evaluate performance under more stable conditions, the within-subjects standard deviations of MT scores were computed over trials 52-125 inclusive. The mean standard deviation in the 160 IMT condition was 40.6 msec and 81.2 msec in the 760 IMT condition. The standard deviations of MT scores after performance stabilized were approximately twice as large in the 760 IMT condition as in the 160 IMT condition. A between groups t test demonstrated that this difference was significant, $t\ (18) = 4.80$, $p < .001$.

A mixed model ANOVA conducted on the mean trial block MT data revealed a significant main effect of IMT, $F(1,18) = 1606.88$, $p < .001$. The IMT x trial blocks interaction was also significant, $F(24,432) = 5.83$, $p < .001$. The mean MT scores of the 160 IMT condition decreased for approximately the first five trial blocks as the subjects' performance approached the IMT. In the 760 IMT condition, mean MT increased for approximately five trial blocks as performance in this group approached the IMT.

Phase I ratio measure- SD(ST)/SD(MT). The analysis of the ratios of the standard deviations of the two temporal components of the response represents an expedient method of assessing the effects of the independent variables on the relationship between the two temporal components of the response, ST and MT. The ratio data will enable future investigators not only to compare the effects of the independent variables on the standard deviations of the two temporal components of the response in isolation, but also the effect of the independent variables on an easily computed relationship between the two components.

The ratio of the standard deviations of the two temporal components were computed for each block of five trials. The ratios decreased as IMT increased. The mean ratio in the 160 IMT condition was 1.65. The mean ratio in the 760 IMT condition was .85. A mixed model ANOVA, 2(IMT) X 25(trial blocks), conducted on the mean trial block ratios revealed a significant main effect of IMT, $\underline{F}(1,18) = 13.34$, $p < .005$. Neither the effect of trial blocks nor the IMT x trial blocks interaction reached significance. Thus, on the average the standard deviations of MT scores at IMT 160 were of lesser magnitude than the standard deviations of ST scores. However, at IMT 760, on the average, the standard deviations of MT scores were of greater magnitude than the standard deviations of ST scores.

Additional analyses. As the two IMT groups of ten subjects were subdivided in Phase II, the hypothesis that the two groups of five subjects at each IMT were not different in Phase I was examined. The procedure employed in testing this hypothesis was to conduct a mixed model ANOVA at each level of IMT for the mean ST and MT, as well as the ratio data, comparing the performance of the two groups of five subjects in Phase I. Only one significant group difference was revealed in these analyses. The mean ST of the 160-160 IMT condition in Phase I was 231.1 msec. The mean ST score of the 160-760 group was 276.6 msec. The mean trial block ST scores of the 160-160 and 160-760 groups differed significantly in Phase I, *F*(1,18) = 6.26, $p < .025$. As a result of this difference conclusions as to the effect of warning signal duration in Phase II were limited.

Phase II start time. Geblewiczowa (1963) and Lansing, Schwartz, and Lindsley (1959) reported that when an auditory warning signal was presented reaction times to a visual signal were diminished. Therefore, the presentation of a warning signal on half of the trials in Phase II should be analogous to subtracting a constant from half of the scores in a distribution. The left panel of Figure 1 depicts the increase in the variance of ST scores in Phase II. Increases are indicated by solid bars.

The standard deviation of ST scores in the 160 IMT condition was 120.8 msec from trials 126-195 inclusive. The standard deviation of ST scores in the 760 IMT condition was 133.8 msec from trials 126-195 inclusive. The increase in the standard deviations of ST scores from Phase I to Phase II was probably not due to an initial disruption of performance caused by a change in stimulus parameters, as the standard deviations of the four groups' ST scores from trials 165-195 were: 160-160 = 113.2, 160-760 = 123.8, 760-760 = 123.6, and 760-160 = 137.3 msec.

Table 1 shows the results of a mixed model ANOVA on the mean trial block ST scores in Phase II. As noted, the spurious difference between the 160-160 and 160-760 groups in Phase I prohibits a meaningful interpretation of the significant IMT x tone duration interaction. Therefore, the mean ST scores of the four conditions will simply be reported. The mean ST of the 160-160 condition was 195.1 msec. The mean ST of the 160-760 condition was 274.8 msec. The mean ST of the 760-760 condition was 378.4 and 343.6 msec for the 760-160 condition.

The significant main effect of trial type shown in Table 1, however, indicates that on trial blocks on which the auditory warning signal was present mean ST scores were of lesser magnitude than on trial blocks on which the auditory warning signal was absent. The mean ST when the warning signal was present was 207.9 msec as compared to 389.1 msec on trial blocks on which it was absent. The decrease in ST scores when an auditory signal was presented is consistent with results reported by Geblewiczowa (1963) and Lasing, Schwartz, and Lindsley (1959).

Phase II movement time. In the 160 IMT condition the duration of the auditory warning signal produced a difference in the mean MT scores. The long warning signal produced longer mean MT scores than did the short duration warning signal. Table 2 shows the results of a mixed model ANOVA conducted on the mean trial block MT data. Figure 2 depicts the significant IMT x tone duration x trial blocks interaction.

The proposed movement control model states that an increase in mean MT should be accompanied by an increase in the standard deviations

TABLE 1

Analysis of Variance Summary of Phase II Start Time Scores

SV	df	SS	MS	F
IMT (Inst. move. time)	1	1,129,810.0	1,129,810.0	26.10***
TD (tone duration)	1	38,572.5	35,572.5	.89
IMT x TD	1	221,674.0	221,674.0	5.12*
S/IMT, TD	16	692,467.0	43,279.0	
TT (trial type)	1	2,298,900.0	2,298,900.0	412.92***
TT x IMT	1	6,025.8	6,025.8	1.08
TT x TD	1	6,330.0	6,330.0	1.14
TT x TD x IMT	1	10,275.2	10,275.2	1.85
TT, S/IMT, TD	16	89,077.9	5,567.4	
TB (trial blocks)	6	28,299.7	4,716.6	2.78*
TB x IMT	6	7,772.9	1,295.5	.76
TB x TD	6	13,763.0	2,293.8	1.35
TB x TD x IMT	6	6,234.2	1,039.0	.61
TD, S/IMT, TD	96	162,821.0	1,696.1	
TB x TT	6	4,993.7	832.3	.82
TB x TT x IMT	6	6,280.9	1,046.8	1.03
TB x TT x TD	6	7,672.9	1,278.8	1.25
TB x TT x TD x IMT	6	8,543.2	1,423.9	1.40
TT, TB, S/IMT, TD	96	97,943.5	1,020.2	

* = $p < .05$

*** = $p < .001$

TABLE 2

Analysis of Variance Summary of Phase II Movement Time Scores

SV	df	SS	MS	F
IMT (Inst. move. time)	1	21,268,200.0	21,268,200.0	586.79***
TD (tone duration)	1	38,844.0	38,844.0	1.04
IMT x TD	1	95,367.0	95,367.0	2.55
S/IMT, TD	16	598,267.0	37,391.7	
TT (trial type)	1	7,480.0	7,480.0	1.90
TT x IMT	1	4,348.0	4,348.0	1.10
TT x TD	1	1,493.0	1,493.0	.38
TT x IMT x TD	1	1,900.0	1,900.0	.48
TT, S/IMT, TD	16	63,402.2	3,962.6	
TB (trial blocks)	6	26,917.2	4,486.2	1.52
TB x IMT	6	34,210.0	5,701.7	1.93
TB x TD	6	9,659.3	1,609.9	.55
TB x IMT x TD	6	44,314.1	7,385.7	2.50*
TD, S/IMT, TD	96	283,252.0	2,950.5	
TB x TT	6	15,229.4	2,538.2	1.21
TB x TT x IMT	6	11,816.8	1,969.5	.94
TB x TT x TD	6	11,286.0	1,881.0	.90
TB x TT x TD x IMT	6	27,768.1	3,794.7	1.81
TT, TB, S/IMT, TD	96	201,330.0	2,097.2	

* = $p < .05$
*** = $p < .01$

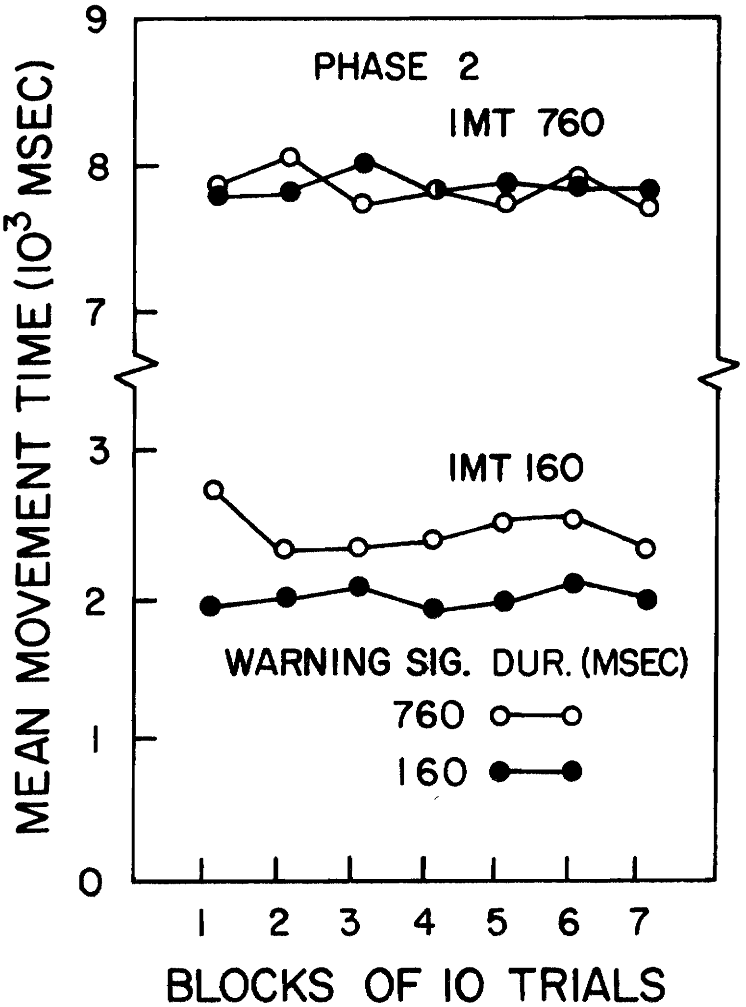

Figure 2. Mean movement times in Phase 2 as a function of trial blocks, warning signal duration and instructed movement time.

of MT scores. Interestingly enough, the computation of the standard deviations of MT scores from trials 165-195 showed the following pattern: 160-160 = 44.2, 160-760 = 101.6, 760-760 = 82.9 and 760-160 = 72.6 msec. The difference between the variances of the 160-160 and 160-760 condition's MT was significant, F-max(144,131) = 5.27, $p < .05$. However, the difference between the variances of the 760-760 and 760-160 MT scores was not significant, F-max(151,150) = 1.30, $p < .05$. The difference between the mean MT scores of the 160-160 and 160-760 conditions was accompanied by a difference in the variances which went in the same direction.

Ratio analysis. A mixed model ANOVA, 2(IMT) & 2(tone duration) & 14(trial blocks), was conducted on the trial block ratios of the standard deviations of ST and MT scores. As in Phase I, the ratios decreased as IMT increased. The mean ratio in the 160 IMT condition in Phase II was 6.55. The mean ratio in the 760 IMT condition in Phase II was 1.99. This difference between the IMT conditions resulted in a significant main effect of IMT, $F(1,16) = 17.94$, $p < .001$. All other main effects and interactions did not reach significance. The right panel of Figure 3 depicts the significant main effect of IMT. The increase in the ratios from Phase I to Phase II is probably attributable to the increase in the variance of ST scores in Phase II shown in the right panel of Figure 1.

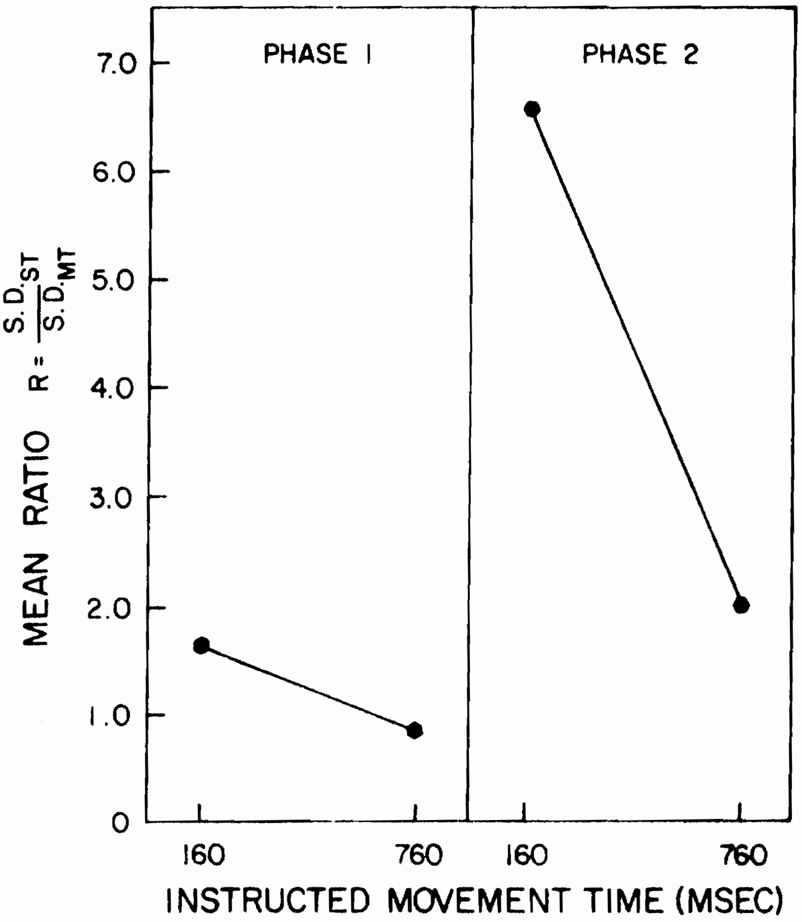

Figure 3. Mean ratios of start time and movement time scores in both phases of Experiment 1.

Experiment II

The purpose of Experiment II was twofold: 1) an assessment of the means of MT and ST scores when subjects had no prior experience with the auditory signal employed as a warning signal in Phase II, 2) replication of the pattern of ST and MT standard deviations shown in Figure 1 for Experiment I.

Method

Subjects. Six female and four male right handed undergraduate volunteers attending Virginia Polytechnic Institute and State University served as subjects. Subjects received course credit for their participation in the experiment.

Apparatus. The apparatus was the same as that employed in Experiment I.

Task. The task was the same as that in the first experiment.

Procedure. With one exception the procedure was the same as that employed in Experiment I. In Phase I of Experiment I an auditory feedback stimulus was paired with the subject's movements. However, in Phase I of Experiment II an auditory stimulus was not paired with the movements. In the second phase of Experiment II the auditory warning signal was employed and the auditory feedback stimulus was paired with the subject's movements. As in the first experiment, the duration of the auditory feedback stimulus which was paired with the movements was equal to the IMT, either 160 or 760 msec. The durations of the auditory warning signals employed in Phase II were 160 and 760 msec.

Design. Two groups of five subjects were instructed to move from the start to the finish position in either 160 or 760 msec. These groups practiced attaining the IMT for 125 trials in Phase I. There were three female and two male subjects in each condition. Phase II consisted of 70 trials.

Results

Phase I. The 160 IMT condition produced shorter and less variable ST scores than did the 760 IMT condition. The mean ST in the 160 IMT condition was 252.4 msec, SD = 52.4 msec. The mean ST in the 760 IMT condition was 434.3 msec, SD = 194.3. A Hartley's F-max test on the associated variances revealed a significant difference, $F(625,614) = 13.73$, $p < .05$.

The 160 IMT condition produced shorter and less variable MT scores than did the 760 IMT condition. The mean MT in the 160 IMT condition was 223.8 msec, SD = 82.5 msec. The mean MT in the 760 IMT condition was 746.3 msec, SD = 129.4 msec. A Hartley's F-max test revealed that the associated variances differed significantly, $F(625,614) = 2.46$, $p < .05$.

The mean ST and MT scores of the two IMT conditions in Experiment II were compared to the 160-160 and 760-760 groups in Experiment I. No significant group differences were found. Therefore, the presence of the auditory feedback stimulus which was paired with movements in the first experiment probably did not affect the mean MT or ST scores.

Phase II. The mean ST of the 160 IMT condition in Phase II was 226.6 msec, SD = 117.3 msec. The mean ST of the 760 IMT condition was 455.8 msec, SD = 199.7 msec.

In the 160 IMT condition, the presence of the auditory warning signal reduced mean ST scores. The mean ST score when the warning signal was present was 151.2 msec. When the warning signal was not present the mean ST was 302.0 msec. A mixed model ANOVA, 2(groups) X 2(trial types) X 7(trial blocks), was conducted comparing the 160-160 mean Phase II ST scores in Experiment I to those of the 160 IMT condition in Experiment II. This analysis revealed a significant main effect of trial type, $\underline{F}(1,8) = 108.34$, $P < .001$. All other main effects and interactions did not reach significance. Therefore, the reduction in mean ST scores when the warning signal is presented probably does not depend on prior exposure to the auditory signal employed as a warning signal in Phase II.

In the 760 IMT condition, mean ST scores were of lesser magnitude when the 760 msec duration warning signal was presented. The mean ST when the warning signal was presented was 369.7 msec. When the warning signal was absent the mean ST was 541.8 msec. A mixed model ANOVA, 2(groups) X 2(trial types) X 7(trial blocks), was conducted comparing the 760-760 group in Experiment I to the 760 IMT group in Experiment II. This analysis revealed a significant main effect of trial type, $\underline{F}(1,8) = 161.78$, $p < .001$. All other main effects and interactions did not reach significance. Therefore, the reduction in mean ST scores when the warning signal was presented probably does not depend on prior exposure to the auditory signal employed as the warning signal in Phase II.

The mean MT score in Phase II of the 160 IMT condition was 207.9 msec, SD = 46.4 msec. The mean MT score of the 760 IMT condition was 776.2 msec, SD = 172.9 msec. Mixed model ANOVA, 2(groups) X 2(trial types) X 7(trial blocks), comparing the mean MT scores of the 160 and 760 IMT conditions to their respective counterparts in Experiment I, groups 160-160 and 760-760, did not reveal any significant differences. Therefore, in these conditions the presence of an auditory warning signal does not affect mean MT scores.

Discussion

The major findings in Phase I of Experiment I were that IMT produced differences in the mean ST and MT scores, as well as the standard deviations of ST and MT scores. Both the means and standard deviations of ST and MT scores increased with longer IMTs. The results in Phase I of Experiment II indicate that these differences were reliable and replicable with as few as five subjects per group.

The fact that the within subjects standard deviations of MT scores increased significantly when the duration of movement increased is in line with the prediction of the proposed movement control model which maintains that the degree of motor program control decreases with increases in movement duration. Similar findings have been reported by Keele and Posner (1968) and Schmidt and Russell (1972). However, despite the apparent confirmation of the model's predictions at least three poignant criticisms of these data need to be considered. First of all, as only one distance was employed in Experiments I and II the speed of the movements and the time required were confounded. Secondly, in both experiments the mean MT of the 160 IMT condition was above

160 msec. If subjects were moving as quickly as possible, the variance of MT scores in the 160 IMT condition would necessarily be restricted. Finally, the proposed motor program model contends that the degree of feedback involvement in the control of movements increases as the duration of movement increases. Therefore, it is necessary to demonstrate that at longer IMTs providing continuous feedback which could be used to regulate the course of movements will decrease the standard deviations of MT scores. Experiment III was designed to eliminate these problems.

In the second phase of the first two studies the presence of an auditory warning signal decreased mean STs to a visual go signal. This diminutive effect has been reported by Geblewiczowa (1963) and Lansing, Schwartz, and Lindley (1959).

The analysis of mean MT scores in the second phase of Experiment I showed that the effect of a long duration warning signal was to increase the mean MT scores of the 160-760 group as compared to the 160-160 group. Furthermore, the standard deviation of the 160-760 group's MT scores was significantly greater over trials 165-190 inclusive than the standard deviation of the 160-160 group's MT scores. Although further investigation is required to determine whether or not the increase in the means and standard deviation of MT scores in the 160-760 condition was caused by the presence of a long duration warning signal, the obtained pattern is congruent with the proposed movement control model which predicts that the standard deviations of MT scores will increase with increases in movement duration.

Experiment III

The results obtained in Phase I of the first two studies were consistent with the predictions of the proposed movement control model. An increase in movement duration produced a concomitant increase in the standard deviations of MT scores. Besides providing support for the proposed model, the results of the first two studies made it possible to estimate how many trial blocks would be required before stable estimates of the standard deviations of MT scores could be obtained. In the first two studies the trial blocks effects were, for the most part, limited to the first five trial blocks. Therefore, 15 rather than 25 trial blocks were employed in the third experiment.

As a result of the fact that the rate of movement and the duration of movement were confounded in the first two studies, it was not possible to separate the potential effects of these two variables. Therefore, in Experiment III movement distance was manipulated while holding IMT constant. As previously noted, according to the proposed movement control model the duration of movement and not the rate of movement determines the degree of program control. Therefore, manipulating movement distance should not appreciably affect the standard deviations of MT scores. The manipulation of distance also helps to eliminate the vicious argument that subjects in the shortest IMT condition may be moving as quickly as possible, thereby artificially restricting the variance of MT scores for the following reason; In order to traverse 50 cm in 200 msec subjects must move as quickly as possible, subjects moving 25 cm in 200 msec could not be moving as quickly as possible.

Experiment III also included an intermediate IMT to ascertain whether or not an intermediate IMT would produce an intermediate mean standard deviation of MT scores. The proposed movement control model predicts that the standard deviations of MT scores when only knowledge of results is provided should increase as movement duration increases. The proposed model maintains that the degree of motor program control decreases as movement duration increases, or conversely, that the degree of feedback involvement in the control of movements increases as movement duration increases. Therefore, the presence of a visual display which subjects could use to regulate the progress of movements should decrease the mean standard deviations of MT scores at longer IMTs, but not at shorter IMTs.

Method

Subjects. Thirty-six female and thirty-six male right-handed undergraduate students attending Virginia Polytechnic Institute and State University served as subjects. These volunteers received additional course credit for their participation in the experiment.

Apparatus. The same event timers and clocks employed in the prior studies were used. The apparatus consisted of a microswitch which was located behind the start line. The distance between the microswitch and the start line was adjustable so that the little finger of the subject's right hand was always on the edge of the start line when the microswitch lever was pressed. The start line was 3 cm wide. A red circle 2.54 cm in diameter served as the target. A photoresister was placed in the center of the red target circle. The arrival of the subject's hand at the target circle stopped the MT clock.

Two types of information were provided by means of a msec clock (R. Cramer, Inc., No. 982700 I). This clock was adjacent to the target circle and was easily visible to the subject. The center of the feedback clock was 16.51 cm above the surface across which subjects moved the right hand. This clock began to move when the microswitch was released and stopped when the right hand arrived at the target circle. As this clock had a mechanical clutch, an audible click occurred when it was started and stopped. Three red bands were placed on the face of the clock at 200, 500, and 800 msec, respectively. An opaque plastic door was mounted on the feedback clock stand in such a way that it could be easily opened and closed.

An amber pilot light was mounted 8.89 cm above the feedback clock. A green pilot light was mounted 1.27 cm above the feedback clock. The carriage which subjects moved in Experiments I and II was eliminated. The auditory feedback signal employed in the first experiment was also eliminated.

Task. Subjects were instructed to make a lateral left to right arm movement from a white start line to a red circular target in either 200, 500, or 800 msec. Subjects were instructed to begin movement as quickly as possible following the onset of the green pilot lamp. This visual stimulus is referred to as the go signal. The go signal was initiated by the experimenter and terminated by the arrival of the subject's hand at the target circle.

As noted, the handle which subjects moved in the first two studies was eliminated. Subjects simply slid their hand across a smooth fiberboard surface, palm down. As in the previous studies, subjects were instructed not to stop movements until having reached the target where the movements terminated.

Procedure. When holding the right hand in the start position, the subject's posture differed from that of subjects in the previous studies. In Experiment I and II the subject's arm crossed the chest when the carriage handle was held in the start position. However, when the subject's right hand was at the start position in the present study the right arm did not cross the chest. The subject's arm was extended in front of him/her and the elbow was not bent. The height of the subject's chair was adjusted so that the elbow was approximately 5.02 cm above the surface across which the subject's hand moved.

On each trial, the illumination of the amber pilot light signalled the subject to press the microswitch lever with the outside edge of the thumb of the right hand. The microswitch closure turned on an indicator in the control room and 4, 6, or 8 sec later the experimenter presented the go signal. The interval from the press to the presentation of the go signal was randomly assigned to prevent subjects from anticipating the presentation of the go signal. The time from the presentation of the go signal until the beginning of movement was defined as the ST. The time from the beginning of movement until the subject's right hand reached the target circle was defined as MT.

The feedback clock began to move when the subject released the microswitch lever and stopped when the right hand reached the target circle. In the knowledge of results condition subjects were not allowed to view the feedback clock during movement. The opaque door was closed. After each movement subjects in the knowledge of results condition:

reached over with their left hand, opened the door, noted the terminal position of the hand of the clock in relation to their particular target time, reset the feedback clock, and closed the door. When the subject closed the door, the experimenter turned off the amber light. This was the signal to the subject to return the right hand to the start position. Subjects were instructed that the right hand was to remain at the target circle until the amber light was turned off.

Subjects in the feedback condition had the opportunity to view the feedback clock during and after each movement. Hence, subjects in the feedback condition not only had continuous feedback during movements, but also knowledge of results. The sequence of events on each trial was the same for subjects in the feedback and knowledge of results conditions, with the exception that subjects in the feedback condition did not manipulate the opaque door. The door remained open in the feedback condition.

Design. In the present experiment movement distance, IMT, and the type of information subjects received about performance were manipulated. There were two movement distances, 25 and 50 cm. At each movement distance there were three IMTs 200, 500, and 800 msec. At each IMT there were two information conditions-feedback and knowledge of results. The difference between the feedback and knowledge of results conditions was that subjects in the feedback condition were provided with continuous visual feedback during movement while subjects in the knowledge of results condition were not. There were 15 blocks of 5 trials. Trial blocks was the only repeated measures variable.

There were three female and three male subjects in each of the twelve groups in the experiment.

Results

Figures 7 and 8 show the effects of IMT, information, and trial blocks on the mean standard deviations of MT scores at distances 50 and 25 cms respectively. Since the predictions of the proposed movement control model, as to the effects of IMT and information on the standard deviations of MT scores pertain to stable performance, the decision was made to restrict the analyses conducted on the standard deviations of MT scores to trial blocks 6-15 inclusive. For consistency, all other analyses conducted were also restricted to trial blocks 6-15 inclusive. Graphs depicting changes in performance across trial blocks 1-15 inclusive, which may be of general interest, have been provided.

Specifically, Figure 4 shows the effects of IMT, information, and trial blocks on the mean ST scores from trial blocks 1-15 inclusive, and Figure 10 shows the effects of IMT on the ratios of the standard deviations of the two temporal components- ST and MT - from trial blocks 1-15 inclusive.

Start time. An ANOVA, summarized in Table 3, conducted on the mean ST socres from trial blocks 6-15 inclusive, revealed a significant IMT x information interaction.

Figure 4 shows that at each IMT feedback increased mean STs. However, the Newman-Keuls multiple comparison procedure conducted on the six means involved in the IMT x information interaction showed that feedback as compared to knowledge of results significantly increased

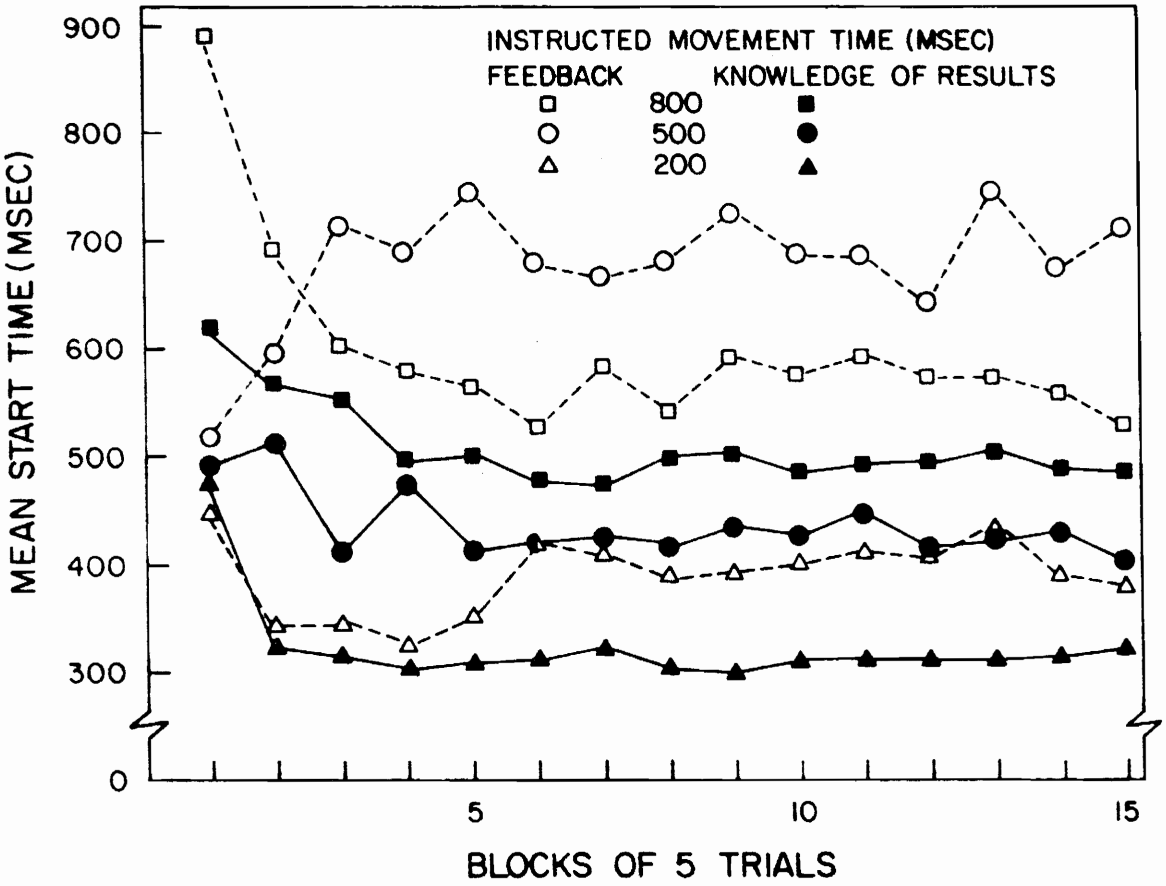

Figure 4. Mean start times as a function of trial blocks, information, and instructed movement time.

TABLE 3

Analysis of Variance Summary of Mean Start Time Scores Over Trial Blocks 6-15 Inclusive in Experiment III

SV	df	SS	MS	F
D (distance)	1	363,426.0	363,426.0	2.01
IMT (Inst. move. time)	2	5,716,090.0	2,858,050.0	15.87***
D x IMT	2	682,694.0	341,347.0	1.89
I (information)	1	3,940,630.0	3,940,630.0	21.88***
I x D	1	2,892.6	2,892.6	.01
I x IMT	2	1,274,740.0	637,386.0	3.54*
I x D x IMT	2	375,408.0	187,704.0	1.04
S/D, IMT, I	60	10,802,500.0	180,041.0	
TB (trial blocks)	9	56,460.9	6,273.4	1.57
TB x D	9	29,690.2	3,298.9	.82
TB x IMT	18	67,140.1	3,730.0	.93
TB x D x IMT	18	58,894.8	3,271.9	.81
TB x I	9	38,912.8	4,323.6	1.08
TB x I x D	9	27,566.5	3,062.9	.76
TB x I x IMT	18	79,179.8	4,398.8	1.01
TB x I x D x IMT	18	30,781.9	1,710.1	.42
TB, S/D, IMT, I	540	2,158,320.0	3,996.8	

* = $p < .05$
*** = $p < .001$

mean STs only at IMT 500. The results of the Newman-Keuls test on the differences among means involved in the IMT x information interaction are summarized in Table 4.

Table 4 also shows that, in the knowledge of results condition, the mean ST of the IMT 800 condition differed significantly from the mean ST of the IMT 200 condition. However, the mean ST at IMT 500 was not significantly different from the mean STs at IMTs 200 and 800.

An ANOVA, summarized in Table 5, conducted on the standard deviations of ST scores from trial blocks 6-15 inclusive, revealed significant main effects of IMT and information. Figure 5 shows the mean standard deviations of ST scores as a function of IMT over trial blocks 1-15. Over trial blocks 6-15 inclusive, IMT 200 produced the least variable STs. The Newman-Keuls multiple comparison procedure conducted on the differences among the mean standard deviations of ST scores revealed that the main effect of IMT was due to significant differences between the mean standard deviations of STs at IMTs 200 and 800, and IMTs 200 and 500, $p < .05$. The difference between the mean standard deviations of STs at IMTs 500 and 800 was not significant, $p > .05$.

Figure 6 depicts the significant main effect of information. As Figure 6 shows, feedback increased the mean standard deviations of ST scores. The mean standard deviations of STs in the feedback and knowledge of results conditions at IMTs 800, 500, and 200 were, respectively: 116.7 - 69.7, 149.2 - 70.6, 77.7 - 39.4 msec.

Movement time. Mean MTs increased as IMT increased. An ANOVA, summarized in Table 6, conducted on the mean MT scores from trial

TABLE 4

Summary of Comparisons of Differences Among Mean Start Time

	200 KR	200 F	500 KR	800 KR	800 F	500 F
200 KR = 314.0	---	92.0	112.5	179.2*	264.2*	379.4*
200 F = 406.1		---	20.5	87.2	172.1*	287.3*
500 KR = 426.6			---	66.7	151.6*	226.8*
800 KR = 493.3				---	84.9	200.1*
800 F = 578.2					---	115.2*
500 F = 693.4						---

* = $p < .05$

<u>NOTE</u>.

[a] Numbers in mean designations indicate the instructed movement time.

[b] Symbols F and KR indicate feedback and knowledge of result conditions.

TABLE 5

Analysis of Variance Summary of Standard Deviations of Start Time Scores Over Trial Blocks 6-15 Inclusive in Experiment III

SV	df	SS	MS	F
D (distance)	1	37,039.4	37,039.4	2.00
IMT (Inst. move. time)	2	327,291.0	163,645.0	8.87***
D x IMT	2	68,064.9	34,032.4	1.84
I (information)	1	549,046.0	549,046.0	29.77***
I x D	1	2.1	2.1	.00
I x IMT	2	52,452.1	26,226.0	1.42
I x D x IMT	2	23,532.4	17,766.2	.63
S/D, IMT, I	60	1,106,420.2	18,440.4	
TB (trial blocks)	9	44,014.2	4,890.4	1.10
TB x D	9	22,963.2	2,551.4	.57
TB x IMT	18	84,205.9	4,678.1	1.05
TB x D x IMT	18	85,640.1	4,757.7	1.07
TB x I	9	40,006.0	4,445.1	1.00
TB x I x D	9	23,375.9	2,597.3	.58
TB x I x IMT	18	88,627.4	4,923.7	1.10
TB x I x D x IMT	18	38,353.8	2,130.7	.47
TB, S/D, IMT, I	540	2,400,830.0	4,445.9	

*** = $p < .001$

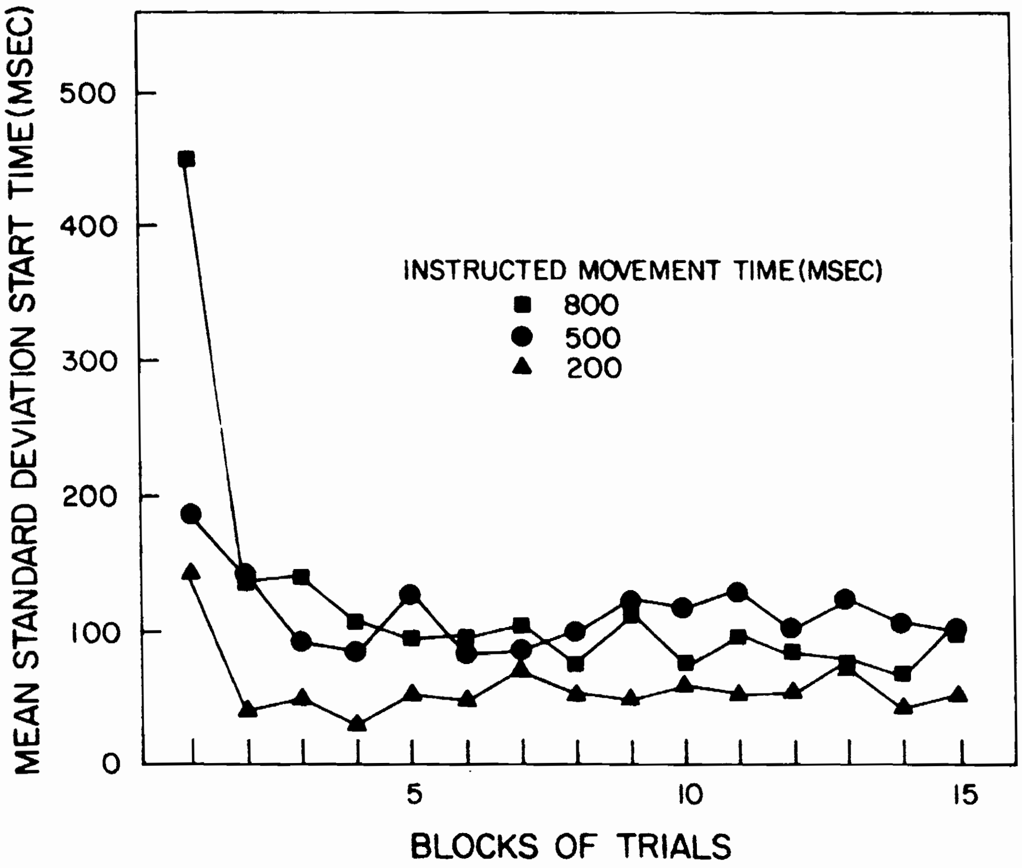

Figure 5. Mean standard deviations of start time scores as a function of trial blocks and instructed movement time.

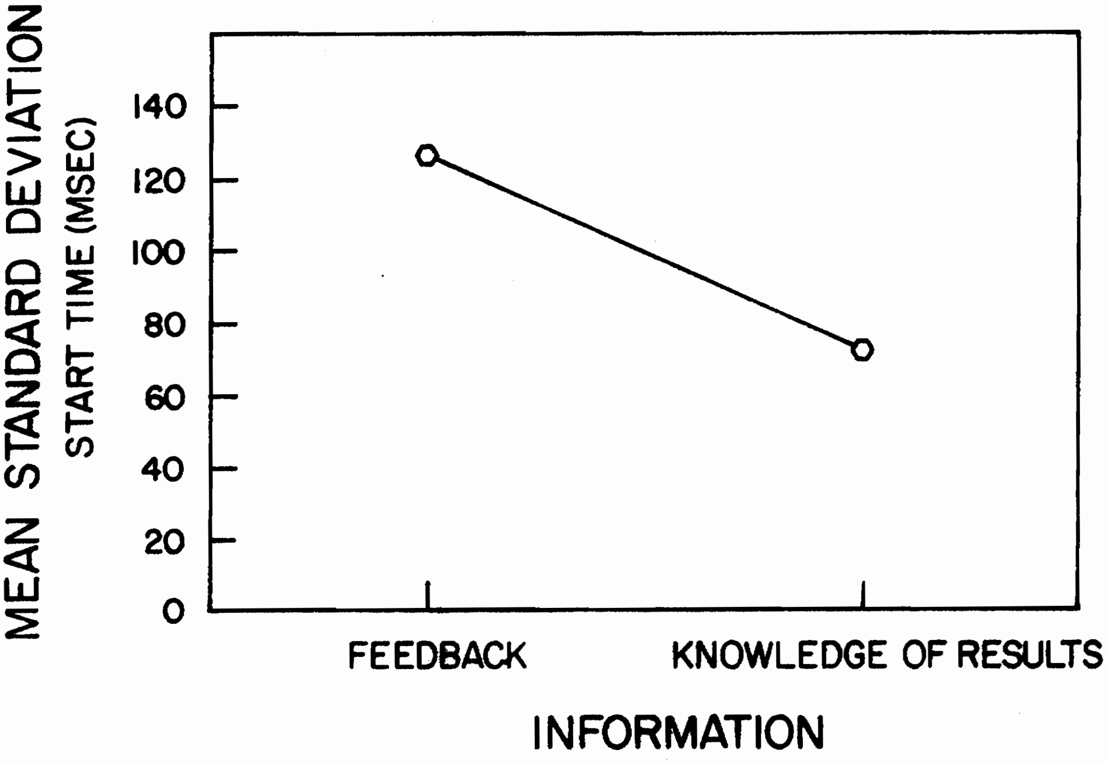

Figure 6. Mean standard deviations of start time scores for the two information conditions.

TABLE 6

Analysis of Variance Summary of Mean Movement Times Over Trial Blocks 6-15 Inclusive in Experiment III

SV	df	SS	MS	F
D (distance)	1	14.4	14.4	.00
IMT (Inst. move time)	2	43,925,800.0	21,962,800.0	3,547.59***
D x IMT	2	23,023.0	11,511.5	1.85
I (information)	1	29,801.6	29,801.6	4.81*
I x D	1	727.3	727.3	.12
I x IMT	2	2,817.0	1,408.5	.23
I x D x IMT	2	22,506.0	11,253.0	1.82
S/D, IMT, I	60	371,455.0	6,190.9	
TB (trial blocks)	9	12,630.0	1,403.4	1.04
TB x D	9	1,253.1	139.2	.10
TB x IMT	18	25,600.0	1,422.2	1.06
TB x D x IMT	18	11,958.0	664.3	.49
TB x I	9	7,726.0	858.4	.64
TB x I x D	9	6,576.2	730.6	.54
TB x I x IMT	18	16,088.0	893.7	.67
TB x I x D x IMT	540	16,688.3	927.1	.69
TB, S/D, IMT, I		725,616.0	1,343.7	

* = $p < .05$
*** = $p < .001$

blocks 6-15 inclusive revealed significant main effects of IMT and information. The mean MT in the IMT 800 condition was 818.4 msec. The mean MT in the IMT 500 condition was 511.8 msec and the mean MT in the IMT 200 condition was 213.4 msec. The Newman-Keuls multiple comparison procedure conducted on the differences among mean MTs revealed that all pairwise comparisons among mean MTs of the three IMT conditions were significant, $p < .05$.

The mean MT in the IMT 200 knowledge of results condition was 209.0 msec and 217.7 msec in the IMT 200 feedback condition. The mean MT in the IMT 500 knowledge of results condition was 504.5 msec and 519.1 msec in the IMT 500 feedback condition. The mean MT in the IMT 800 knowledge of results condition was 810.7 msec and 826.0 msec in the IMT 800 feedback condition. Although the magnitude of the difference between the mean MTs of the feedback and knowledge of results condition increased at longer IMTs, the IMT x feedback interaction was not significant. However, as Table 6 shows, the main effect of information was significant.

Figures 7 and 8 depict the effects of IMT and information on the standard deviations of MT scores from trial blocks 1-15 inclusive at movement distances 50 and 25 cm. Figures 7 and 8 show that across trial blocks 6-15 inclusive in the IMT 800 condition feedback reduced the mean standard deviations of MTs as compared to the IMT 800 knowledge of results condition. An ANOVA, summarized in Table 7, conducted on the standard deviations of MT scores from trial blocks 6-15 inclusive, revealed a significant IMT x information interaction. Figure 9 depicts

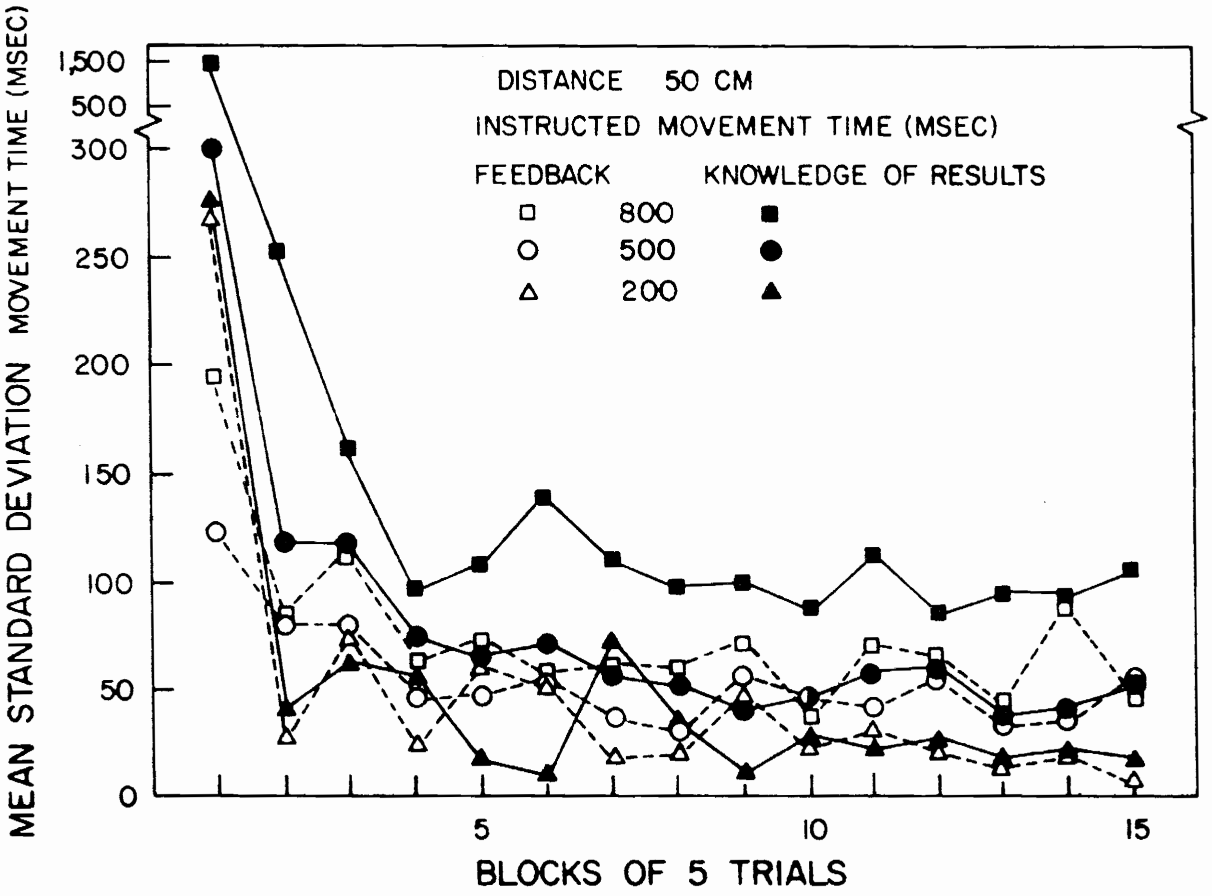

Figure 7. Mean standard deviations of movement time scores at distance 50 cm as a function of trial blocks, information and instructed movement time.

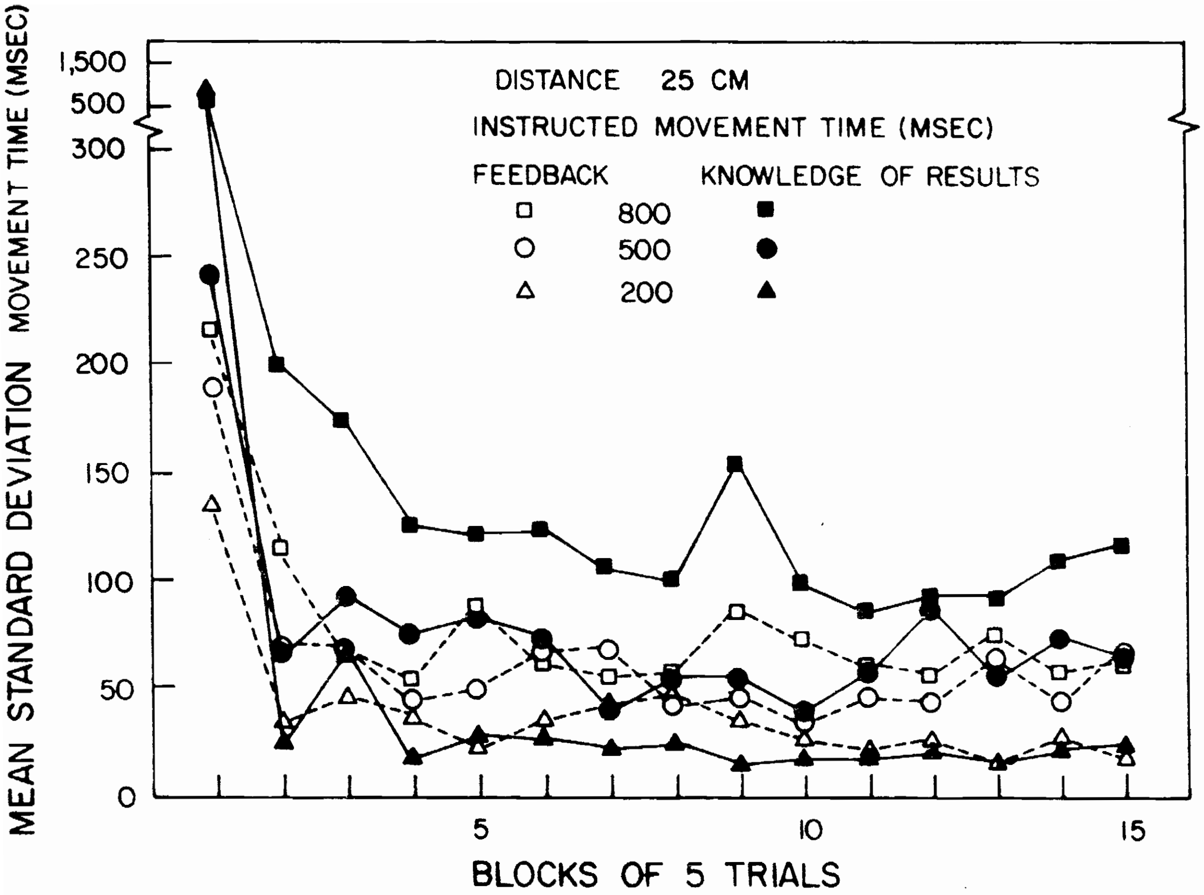

Figure 8. Mean standard deviations of movement time scores at distance 25 cm as a function of trial blocks, information, and instructed movement time.

TABLE 7

Analysis of Variance Summary of Standard Deviations of Movement Time Scores Over Trial Blocks 6-15 Inclusive in Experiment III

SV	df	SS	MS	F
D (distance)	1	1,913.9	1,913.9	.54
IMT (Inst. move. time)	2	359,395.0	197,698.0	55.65***
D x IMT	2	1,751.1	875.6	.25
I (information)	1	39,772.0	39,772.0	11.20**
I x D	1	105.0	105.0	.03
I x IMT	2	77,362.6	38,681.3	10.89***
I x D x IMT	2	993.7	496.8	.14
S/D, IMT, I	60	213,165.0	3,552.8	
TB (trial blocks)	9	19,681.1	2,186.7	1.66
TB x D	9	6,513.2	723.6	.55
TB x IMT	18	21,862.9	1,214.6	.92
TB x D x IMT	18	15,031.5	835.0	.64
TB x I	9	8,547.1	949.6	.72
TB x I x D	9	10,774.5	1,197.1	.91
TB x I x IMT	18	18,475.8	1,026.4	.78
TB x I x D x IMT	15	17,731.4	985.0	.75
TB, S/D, IMT, I	540	710,695.0	1,316.1	

** = $p < .005$
*** = $p < .001$

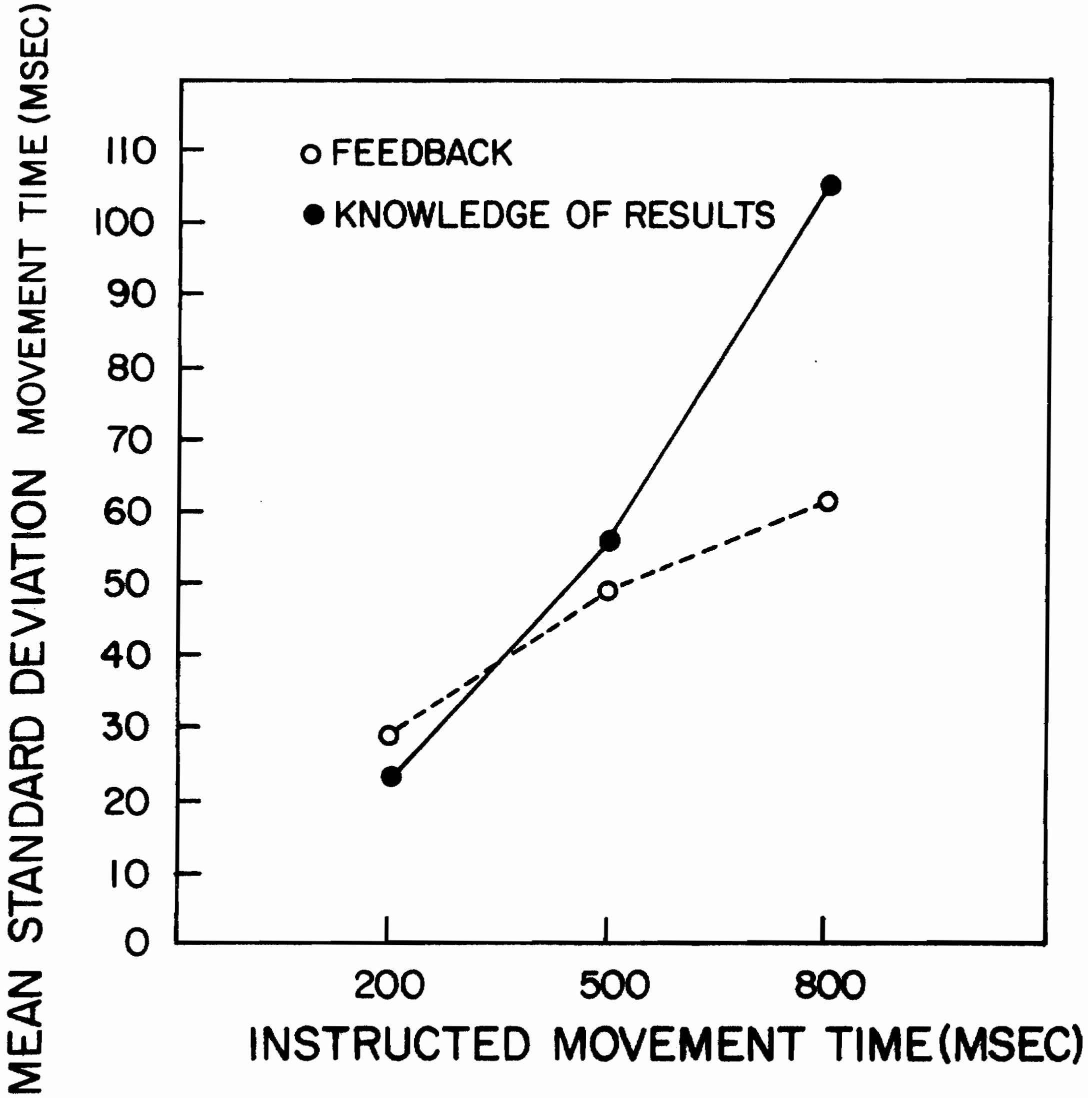

Figure 9. Mean standard deviations of movement time scores from trial blocks 6-15 inclusive as a function of instructed movement time and information.

the effects of IMT and information on the mean standard deviations of MT scores.

Table 8 summarizes the results of the Newman-Keuls multiple comparison procedure conducted on the differences among the six means involved in the IMT x information interaction. As Table 8 shows, the mean standard deviations of MT scores increased as IMT increased in the knowledge of results condition. However, in the feedback condition the mean standard deviations of MTs did not differ significantly at IMTs 500 and 800. Table 8 shows that feedback significantly reduced the mean standard deviations of MT scores only at IMT 800.

Ratios SD(ST)/SD(MT). A mixed model ANOVA, summarized in Table 9, conducted on the ratio data across trial blocks 6-15 inclusive revealed significant main effects of information and IMT.

Figure 10 shows the effect of IMT on the mean ratios across trial blocks 1-15 inclusive. The Newman-Keuls multiple comparison procedure conducted on the differences among the mean ratios of the three IMT conditions revealed that the main effect of IMT was due to significant differences between the mean ratios at IMTs 200 and 800, and IMTs 200 and 500, $p < .05$. The difference between the mean ratios at IMTs 500 and 200 was not significant, $p > .05$.

Figure 11 shows the significant main effect of information. The difference between the mean ratio in the feedback and knowledge of results condition is probably in part due to the fact that the presence of a feedback display increased the standard deviations of STs.

TABLE 8

Summary of Comparisons of Differences Among Mean Standard Deviations of Movement Times

	200 KR	200 F	500 F	500 KR	800 F	800 KR
200 KR = 23.5	---	5.4	25.7*	32.3*	38.4*	82.0*
200 F = 28.9		---	20.3*	26.9*	33.0*	76.6*
500 F = 49.2			---	6.6	12.7	56.3*
500 KR = 55.8				---	6.1	49.7*
800 F = 61.9					---	43.6*
800 KR = 105.5						---

* = $p < .05$

NOTE.

[a] Numbers in mean designations indicate the instructed movement time.

[b] Symbols F and KR indicate feedback and knowledge of result conditions.

TABLE 9

Analysis of Variance Summary of Ratios Over Trial Blocks 6-15 Inclusive in Experiment III

SV	df	SS	MS	F
D (distance)	1	9.8	9.8	.39
IMT (Inst. move. time)	2	377.8	188.9	7.61**
D x IMT	2	63.7	31.8	1.28
I (information)	1	667.2	667.2	26.88***
I x D	1	6.9	6.9	.28
I x IMT	2	31.3	15.6	.63
I x D x IMT	2	5.8	2.9	.11
S/D, IMT, I	60	1,489.3	24.8	
TB (trial blocks)	9	117.5	13.0	1.61
TB x D	9	38.6	4.2	.53
TB x IMT	18	229.5	12.7	1.57
TB x D x IMT	18	143.6	7.9	.98
TB x I	9	37.3	4.1	.51
TB x I x D	9	39.8	4.4	.54
TB x I x IMT	18	122.0	6.7	.83
TB x I x D x IMT	18	130.4	7.2	.89
TB, S/D, IMT, I	540			

** = $p < .005$
*** = $p < .001$

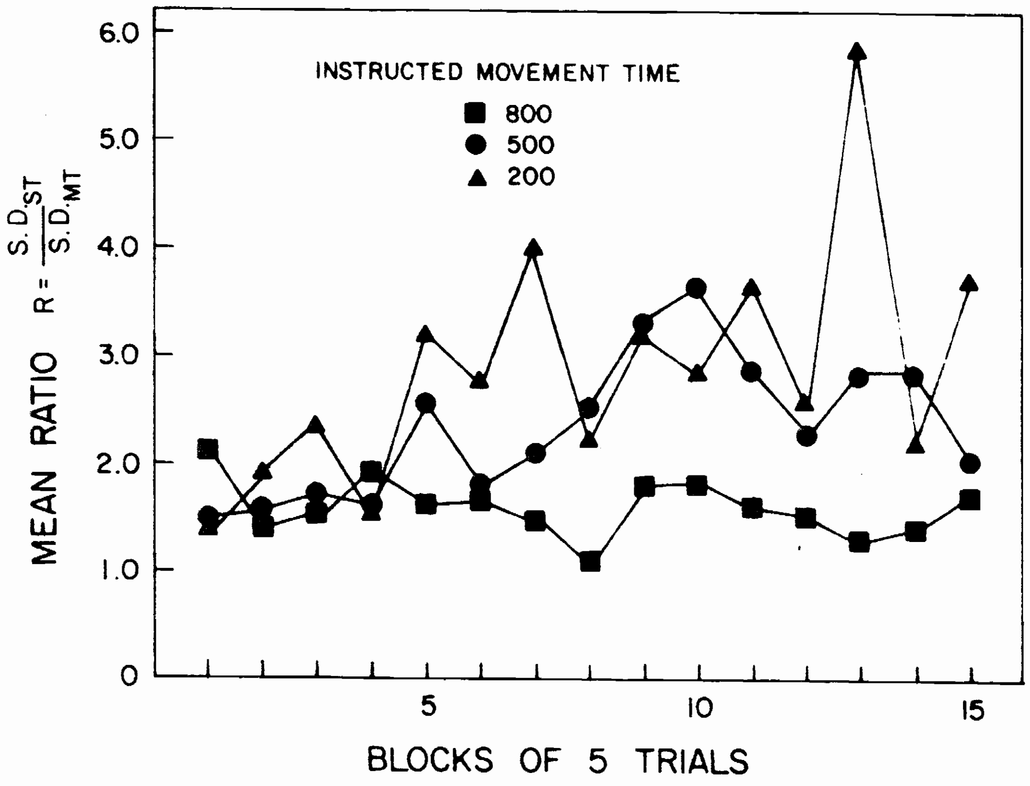

Figure 10. Mean ratios of the standard deviations of start time and movement time scores as a function of trial blocks and instructed movement time.

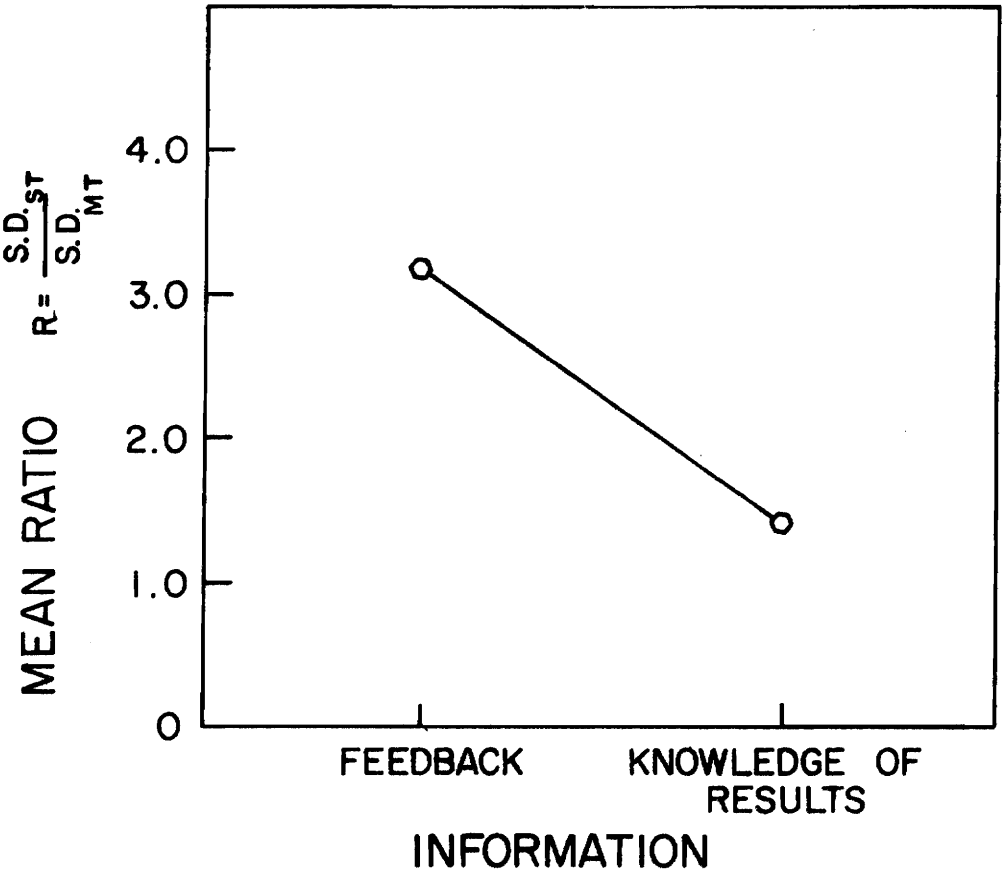

Figure 11. Mean ratio of the standard deviations of start time and movement time scores as a function of information.

Summary

Several interesting relationships were uncovered in the start time measure. In all three studies the shortest IMT condition produced the shortest and least variable ST scores. This suggests the presence of a preprogrammed ballistic start component at short IMTs, but in the absence of an assessment of movement topography, this interpretation is speculative.

A second interesting set of results was that in Experiment III, at IMT 500, the feedback condition produced longer mean ST scores than did the knowledge of results condition. However, at IMTs 200 and 800, the differences in mean STs between the feedback and knowledge of results conditions were not significant. These findings suggest that in the 500 IMT feedback condition, when the visual go signal was presented, subjects may have oriented to the display before initiating movement. However, as changes in fixation upon presentation of the go signal were not monitored, there is currently no way to ascertain whether or not the orientation explanation is correct. Furthermore, even if the orientation explanation for the difference in mean STs at IMT 500 between the feedback and knowledge of results conditions is adequate, the question as to why subjects at IMTs 200 and 800 did not "orient" before beginning movement remains unanswered.

The significant increase in the mean standard deviations of ST scores in the feedback conditions, as compared to the knowledge of results conditions, in Experiment III, may indicate that the initiation of movement in the feedback condition is "interfered" with by the presence of a feedback display. In other words, in the knowledge of results condition the initiation of movement may be more "automatic" than in the feedback conditions. A process or response component may be present between the presentation of the go signal and the beginning of movement in the feedback condition, but absent in the knowledge of results condition. However, the nature of the process or response component, at present, is unspecifiable.

The results obtained in the MT measure in Phase I of Experiments I and II supported the prediction of the proposed movement control model. The standard deviations of MT scores increased when movement duration increased. The increase in the standard deviations of MT scores at the longer IMT was attributed to a decrease in motor program control. However, an independent assessment of the effects of feedback which could be used to regulate the progress of movements was not provided and, as a result, the explanation of the increase in the standard deviations of MT scores when the duration of movements increased was perfectly circular. The standard deviations of MT scores increased with an increase in movement duration because the degree of motor program control decreases as movement duration increases because the standard deviations of MT scores increased when the duration of movements increased. In order to break this circularity it was necessary to demonstrate that at longer IMTs feedback would decrease the standard deviations of MT scores, but would not affect the standard deviations of MT scores at shorter IMTs.

In Experiment III, at IMT 800 the presence of a feedback display significantly decreased the standard deviations of MT scores. Therefore, the fact that the standard deviations of MT scores in the knowledge of results conditions increased as movement duration increased can be interpreted as indicating decreasing motor program control. Feedback decreased the standard deviations of MT scores at the longest, but not at the shorter IMTs. In short, the conclusion that the degree of program control decreases as IMT increases is based on two independent observations: 1) in the knowledge of results conditions the standard deviations of MT scores increased as movement duration increased, 2) at the longest IMT, feedback significantly reduced the standard deviations of MT scores.

However, on the basis of the present data it would not be justifiable to conclude that the significant difference between the standard deviations of the 800 IMT feedback and knowledge of results conditions was due to the fact that subjects in the feedback condition used the visual feedback display to regulate the progress of movements. The conclusion that regulation of the progress of movements is responsible for the difference in the standard deviations of MT scores of the 800 IMT feedback and knowledge of results conditions depends upon demonstrating that the topography of movements as well as the standard deviations of MT scores differ in the feedback and knowledge of results conditions at longer IMTs.

Closed-loop regulation of the progress of movements may alter the topographies in the following manner. At longer IMTs in the feedback condition subjects may, at some point after beginning movement, compare the time which remains before the IMT expires with the distance which remains to be traversed in that amount of time. On the basis of the results of the comparison between the amount of time remaining and the distance to be traversed in that amount of time, subjects may modify the rate of movement in an attempt to arrive at the target at the instant that the IMT expires. If subjects do modify the progress of movements in this discrete manner, the movement topographies would reflect such changes.

The idea of a comparison between a directed result of movement and the results which are actually occurring and a subsequent alteration of the progress of movement in order to insure that the directed result is obtained is the central theme of the closed-loop model. On the basis of the present studies, however, the most that can be said is that the reduction in the standard deviations of MT scores in the 800 IMT feedback condition is consonant with the predictions of the proposed movement control model. Assessments of movement topographies as a measure of regulation have been utilized by Brooks and his associates in a series of physiologically oriented studies: Brooks, Kozlowskaya, Atkin, Horvath, and Uno (1973), Brooks, Cooke, and Thomas (1973), and Brooks (1974).

Schmidt and Russell (1972) and Schmidt (1972) suggested that the IP, which has been discussed previously, reflected the degree of feedback involvement in the control of movements. These investigators demonstrated that the IP decreased significantly as IMT increased from 150 to 750 msec. In addition, to the decrease in the IP Schmidt and Russell found that the standard deviations of MT scores more than doubled as IMT increased from 150 to 750 msec. This finding has been replicated three times in the present studies.

Schmidt and Russell (1972) also found that doubling the distance moved while holding IMT constant and thereby affecting the rate of movement did not have a significant effect on the IP. Interestingly enough, the manipulation of distance in Experiment III did not have a significant effect on the standard deviations of MT scores after performance stabilized. This finding is interpreted as further support for the statement that the primary determinant of the degree of motor program control is the duration and not the rate of movement.

Klapp (1975) demonstrated that variables such as movement distance and target size which affect MT scores did not have significant effects on ST scores. An obvious example of an independent variable in the present studies which had different effects on the standard deviations of the two temporal components is information. The presence of a visual feedback display increased the standard deviations of MT scores in the 800 IMT condition. Therefore, it appears that Klapp was correct in emphasizing the independence of ST and MT scores.

The variables which altered the relationship between the standard deviations of the two temporal components in present studies were IMT, the presence of an auditory warning signal on some trials, and information. In all probability the relationship between the standard deviations of the two temporal components, ST and MT, depends on the conditions under which subjects perform.

References

Adams, J. A. Response feedback and learning. Psychological Bulletin, 1968, 70, 486-504.

Adams, J. A. A closed loop theory of motor learning. Journal of Motor Behavior, 1971, 3, 111-150.

Anokhin, P. K. Cybernetics and the integrative activity of the brain. In M. Cole & I. Maltzman (Eds.), A handbook of contemporary Soviet psychology. New York: Basic Books, 1969.

Brooks, V. B., Kozlowskaya, I. B., Atkin, A., Horvath, F. E., & Uno, M. Effects of cooling denate nucleous on tracking-task performance in monkeys. Journal of Neurophysiology, 1973, 36, 974-995.

Brooks, V. B., Cooke, J. D., & Thomas, J. S. The continuity of movements. In R. B. Stein, K. B. Pearson, R. S. Smith, & J. B. Redford (Eds.), Control of posture and locomotion. New York: Plenum, 1973.

Brooks, V. B. Introductory lecture to session III: Some examples of programmed limb movements. Brain Research, 1974, 71, 299-308.

Chernikoff, R., and Taylor, F. V. Reaction to kinesthetic stimulation resulting from sudden arm displacement. Journal of Experimental Psychology, 1952, 43, 1-8.

Festinger, L. & Canon, L. K. Information about spatial location based on knowledge about efference. Psychological Review, 1965, 72, 373-384.

Fleishman, E. A. & Rich, S. Role of kinesthetic and spatial-visual abilities in perceptual-motor learning. Journal of Experimental Psychology, 1963, 66, 6-11.

Geblewiczowa, M. Influence of the number of warning signals and the intervals between them on simple reaction time. Acta Psychologia, 1963, 21, 40-48.

Granit, R. The basis of motor control. New York: Academic Press, 1970.

Greenwald, A. G. Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. Psychological Review, 1970, 77, 73-99.

Helmholtz, H. von. Treatise on physiological optics. (Ed. & Trans. from 3rd German ed.) by P. C. Southall, New York: Dover, 1962.

Henry, F. M. & Harrison, J. S. Refractoriness of a fast movement. Perceptual and Motor Skills, 1961, 13, 351-354.

Holst, E. von. Relations between the central nervous system and the peripheral organs. British Journal of Animal Behavior, 1954, 2, 89-94.

James, W. Principles of psychology. Vol. 1. New York: Holt, 1890.

James, W. Principles of psychology. Vol. 2. New York: Dover, 1950.

Keele, S. W. Movement control in skilled motor performance. Psychological Bulletin, 1968, 70, 387-403.

Keele, S. W. Attention and human performance. Pacific Palisades. California: Goodyear, 1973.

Keele, S. W. & Posner, M. I. Processing of feedback in rapid movements. Journal of Experimental Psychology, 1968, 77, 353-363.

Konorski, J. Integrative activity of the brain. Chicago: University of Chicago Press, 1967.

Kimble, G. A. & Perlmuter, L. C. The problem of volition. In T. X. Barber, L. V. Dicara, J. Kamiya, N. E. Miller, D. Shapiro, and J. Stoyva (Eds.), Biofeedback and self control. Chicago: Adline, Atherton, 1970.

Klapp, S. F. Feedback versus motor programming in the control of aimed movements. Journal of Experimental Psychology: Human Perception and Performance, 1975, 104, 147-153.

Lansing, R. W., Schwartz, E., and Lindsley, D. B. Reaction time and EEG activation under alerted and nonalerted conditions, Journal of Experimental Psychology, 1954, 58, 1-7.

Lashley, K. S. The accuracy of movement in the absence of excitation from the moving organ. American Journal of Physiology, 1917, 43, 169-194.

Laszlo, J. I. Training of fast tapping with reduction of kinesthetic, tactile, visual, and auditory sensations. Quarterly Journal of Experimental Psychology, 1967, 19, 344-349.

Luria, A. R. Higher cortical functions in man. New York: Basic books, 1966.

Miller, S. A., Galanter, E. & Pribram, K. H. Plans and structure of behavior. New York: Holt, Rinehart, and Winston, 1960.

McLaughlin, S. C. Parametric adjustments in saccadic eye movements. Perception and Psychophysics, 1967, 2, 359-361.

Mittelstaedt, H. Prey capture in mantids. In B. T. Sheer (Ed.), Recent advances in invertebrate physiology- a symposium. Eugene: University of Oregon Publications, 1957.

Paillard, J., & Brouchon, M. Active and passive movements in the calibration of position sense. In S. J. Freedman (Ed.) The neuropsychology of spatially oriented behavior. Homewood, Illinois: Dorsey Press, 1968.

Pew, R. W. Acquisition of hierarchical control over the temporal organization of a skill. Journal of Experimental Psychology, 1966, 71, 764-771.

Pew, R. W. Human perceptual motor performance. In B. H. Kantowitz (Ed.), Human information processing: Tutorials in performance and cognition. New York: Erlbaum, 1974.

Roy, E. A. & Marteniuk, R. G. Mechanics of control in motor performance: Closed-loop versus motor programming control. Journal of Experimental Psychology, 1974, 103, 985-990.

Schmidt, R. A. The index of preprogramming (IP): A statistical method for evaluating the role of feedback in simple movements. Psychonomic Science, 1972, 27, 83-85.

Schmidt, R. A. A schema theory of discrete motor skill learning. Psychological Review, 1975, 82, 225-260.

Schmidt, R. A., & Russell, D. G. Movement velocity and movement time as determiners of the degree of preprogramming in simple movements. Journal of Experimental Psychology, 1972, 96, 315-320.

Skinner, B. F. The behavior of organisms. New York: Appleton Century Crofts, 1938.

Taub, E., Bacon, R., and Berman, A. J. The acquisition of a trace conditioned avoidance response after deafferentation of the responding limb. Journal of Comparative and Physiological Psychology, 1965, 58, 275-279.

Taub, E. & Berman, A. J. Movement and learning in the absence of sensory feedback. In S. J. Freedman (Ed.) The neurophychology of spatially orientated behavior. Homewood, Illinois: Dorsey Press, 1968.

Taub, E., Ellman, S. J. & Berman, A. J. Deafferentation in monkeys: Effect on conditioned grasp response. Science, 1966, 151, 593-594.

Vita

Date of Birth:	March 23, 1951
Place of Birth:	Sanford, Maine
Home Address:	Yates Street Biddeford Pool, Maine 04005 (207) 282-2936
Higher Education:	Bowdoin College 1969-1973, B.A. Government and Psychology
Professional Experience	Teaching Assistant VPI&SU. 1973-1975

Barry C. Noble

DEGREES OF MOTOR PROGRAM CONTROL

by

Barry C. Noble

(ABSTRACT)

The predictions of a movement control model which states that the degree of motor program control decreases as movement duration increases, were tested in three experiments. The findings indicated that the standard deviations of movement times increases as movement duration increased. However, at longer movement durations, the presence of a visual feedback display decreased the standard deviations of movement times. In Experiment III, the rate of movement was manipulated by varying movement distance while holding movement duration constant. Movement distance did not significantly affect the standard deviations of movement times, which suggests that the degree of motor program control is a function of the duration and not the rate of movement.

The effects of movement duration, distance, and the presence of a visual feedback display on the means and standard deviations of start times - the interval from a signal to initiate movement until movement began - were also assessed. Distance did not significantly affect either the means or the standard deviations of start times. However, the shortest movement duration always produced the shortest and least variable start times. Continuous visual feedback increased the standard deviations of start times as compared to a terminal feedback or knowledge of results condition. It was suggested that the

presence of continuous visual feedback "interfered" with the initiation of movements.

The effects of the independent variables on the ratio of the standard deviations of the two temporal components of the response - SD (start time)/ SD (movement time) - were reported.