The Use of Vision in Controlling Discrete Aiming Movements

Stephen A. Wallace
Department of Physical Education/Recreation
University of Colorado

and

Karl M. Newell
Institute for Child Behavior and Development
University of Illinois at Champaign - Urbana

Technical Report No. 112
Institute of Cognitive Science
University of Colorado
Boulder, Colorado 80309
November, 1981

Abstract

An experiment is reported which investigated the use of vision in controlling discrete rapid arm movements. Subjects were required to move as rapidly as possible to several target size - movement distance combinations but under both visual and non-visual conditions. The movement time (MT) data was supportive of Fitts' Law in that MT was linearly related and highly correlated to the Index of Difficulty (ID). MT was also similar for different target size - distance combinations sharing the same ID value. The error rate analysis, which compared visual to non-visual performance, indicated that vision was only used, and to varying degrees, when MT exceeded 200 msec (3.58 ID level). There was evidence that vision was differentially used within target-size - distance combinations sharing the same ID. These results do not support the discrete correction model of Fitts' Law proposed by Keele (1968).

Introduction

There are many motor tasks which require limb movements to be rapidly directed toward confined target areas such as piano playing, typing and certain assembly line tasks. Under conditions whereby terminal accuracy must be maintained, it is clear today that certain variables will affect the time required to complete a movement to a confined target area. In two classic papers, Fitts (Fitts, 1954; Fitts & Peterson, 1964) studied the relationship between movement time and both target width (W) and movement amplitude (A). Using both reciprocal and discrete uni-directional tapping movements, Fitts showed that total movement time (MT) was proportional to $\log_2$ (2A/W) which Fitts called the index of difficulty (ID). This linear relationship is commonly referred to as Fitts' Law, and is robust across a variety of experimental situations such as underwater (Kerr, 1973), under microscopic conditions (Langolf, Chaffin & Foulke, 1976) as well as with different populations such as mentally-retarded individuals (Wade, Newell & Wallace, 1978), and both pre-school (Wallace, Newell & Wade, 1978) and older children (Sugden, 1980). While some criticisms of Fitts' Law exist (Sheridan, 1979; Welford, 1968), it is still considered to be one of the most stable relationships in the perceptual-motor domain.

Why is MT proportionately related to ID? A commonly accepted explanation is the discrete feedback correction interpretation of Fitts' Law (Crossman & Goodeve, Note 1; Keele, 1968). According to this view, following an initial preprogrammed movement which puts the end of the limb close to the target, several corrective movements are made, each requiring a constant amount of time, until the end of the limb falls within the target boundaries. The corrective movements are assumed to be made as a result of visual comparisons between the end of the limb and the target area. An additional assumption is made that improvement in accuracy is constant following each discrete correction. Keele (1968) showed that this model

could predict the slope of the MT-ID relationship if each visual error correction took 260 msec (after Keele & Posner, 1968) and the proportional accuracy of an uncorrected response is 7 per cent (after Vince, 1948). According to Keele (1968) the discrete corrections feedback model predicts that a disproportionate amount of time is spent near the target since presumably several visual error corrections are needed, each requiring roughly 260 msec. Some studies using kinematic analysis have supported this prediction (Annett, Goldy & Kay, 1958; Craik & Vince, 1963).

Using phase-plane analysis of microscopic and larger movements, Langolf et al., found only mixed support for the discrete correction feedback model of Fitts' Law. Langolf et al. assumed that breakpoints (i.e., a marked reduction of velocity during a movement) probably indicate the presence of visual error corrections and found evidence for this phenomenon in microscopic but not larger movements. They pointed out, however, that even phase-plane analysis does not necessarily provide insight into the presence of visual error corrections because (1) inertial damping of the arm may smooth and perhaps mask any changes in velocity and (2) the correction process may be continuous rather than discrete as hypothesized by Crossman & Goodeve (Note 1) and Keele (1968).

In the present study, we directly manipulated the presence and absence of visual feedback during the production of uni-directional tapping movements thus providing a more direct test of the discrete corrections feedback model of Fitts' Law. The rationale for this approach is that the need for visual feedback to control a movement is indicated by a significantly higher terminal error rate under non-visual compared to visual conditions (Keele & Posner, 1968). Other studies have utilized this technique to study the visual control of movement (Beggs & Howarth, 1970; Keele & Posner, 1968; Klapp, 1975; Vince, 1948; Woodworth, 1899). However, in each study only a small number of target size - distance combinations was used,

and it is quite possible that the need for visual feedback is more influenced by target size than distance moved (Sheridan, 1979). Thus, our experiment required subjects to perform under several target size - distance combinations which yielded ID values from 1.58 to 6.58. Also, because we were primarily interested in testing the discrete corrections feedback model of Fitts' Law, we required subjects, as in the Fitts' paradigm, to move as rapidly as possible but to try and maintain accuracy. Most of the above studies trained subjects to move at designated speeds and thus, their results do not necessarily pertain to the Fitts' paradigm.

If changes in MT as a function of ID are due to the presence of visual error corrections thus reflecting an increasing need for vision, we would predict that changes in MT as a function of ID should be accompanied by concomitant and significant inflated error rates of non-visual compared to visual conditions. In other words, as ID increases, the need for vision should increase. Also, under different target size - distance combinations which yield the same ID (and similar MTs), we might suspect that the need for vision would be the same since a similar number of visual error corrections might be used. In summary, the experiment examined; (1) whether the use of vision would increase as MT increased as a function of ID, and (2) whether different target size - distance combinations within the same ID required the same need for vision.

Method

Subjects

Five female and four male volunteers from the University of Illinois at Champaign-Urbana served as subjects.

Apparatus

The apparatus which rested on a table, consisted of a 16 x 42 cm aluminum plate on which four target holes were located 1.5, 3, 6, and 12 in. (3.81, 7.62, 15.24,

and 30.48 cm) away from the starting point. The starting point, a small copper pin with an indentation on the top where the tip of the stylus could rest, was located to the extreme right of the aluminum plate. The target holes were to the left of the starting point in a straight line at the distances mentioned above. Three circular copper targets could be inserted into these holes and the targets measured .25, .5, and 1 in. (.64, 1.27, and 2.54 cm) in diameter. A red 28 v. incandescent lamp (.9 cm in diameter) was located beside each hole.

Three dependent measures were recorded: reaction time (RT), movement time (MT) and error rate. RT was the time interval between the onset of the stimulus light and the removal of a hand held stylus from the starting point. MT was the time interval between stylus lift-off at the starting point to contact with the target. Error rate was the percentage of misses relative to the total number of trials. These dependent measures were automatically recorded on a Hewlett-Packard printer (Model #5050B) via a digital interface unit which also determined the foreperiods used on each trial. A 28 v. incandescent table lamp was used to illuminate the entire aluminum plate on which the targets were located. This lamp could be programmed to immediately extinguish as the stylus left the starting position. When the lamp turned off at stylus lift-off, the entire testing room remained dark until either the target or the surrounding aluminum plate was touched by the stylus.

Procedures

The subject was comfortably seated facing the apparatus. At the beginning of each trial, the subject, using a pencil-like grip, placed the stylus on the starting point and awaited a warning tone controlled by the experimenter. Following the warning tone, a randomly ordered foreperiod of 1, 2, 3, or 4 sec occurred prior to stimulus light onset. The subject was instructed to immediately lift the stylus in

response to the light and move to the target as rapidly as possible and try to hit the target on every trial.

For each distinct target - distance combination, each subject was given practice trials under visual conditions, non-visual conditions, and conditions where the table lamp was randomly extinguished. Forty experimental trials were then administered at each of the target - distance combinations. On twenty of the trials at each target size - distance combination, the table lamp was extinguished as soon as the stylus left the starting point so that the entire movement was performed without visual guidance. Visual and non-visual trials were randomly distributed over the forty trials of each target - distance combination.

Design

A 2 x 3 x 4 (visual condition x target width x distance) completely within-subject factorial design was used. The three levels of target size and four levels of distance (twelve possible combinations) were presented to each subject in a random order under visual and non-visual conditions. Table 1 indicates the various target size - distance combinations as well as the associated ID values for each combination (Table 1 about here).

Results

Reaction Time

We report the RT results even though they were not the primary focus in this experiment. Only the Distance main effect was significant, $F = 13.98$, $df = 3, 24$, $P < .01$, with RT longer at the greater distances. While this finding has been reported before (Williams, 1971) it is not a consistent effect (Hayes & Marteniuk, 1976). Fitts and Peterson (1964) reported, as in the present study, a significant effect of movement amplitude but not target width (see Quinn, Schmidt, Zelaznik, Hawkins, & McFarquhar, 1980 and also Marteniuk & MacKenzie, 1980 for a recent analysis of the effects of target size and movement amplitude on RT).

Movement Time

In Figure 1, all the various target size - distance combinations performed under visual and non-visual conditions are arranged in order of their respective ID value and are plotted against MT (Figure 1 about here). Under both visual and non-visual conditions, there was a linear relationship and high correlation between MT and ID. Under visual conditions, the correlation between mean MT and ID was .98 accounting for 96% of the variability. The linear regression equation fitted to this data was MT = 30.08 + 49.67 ID. For non-visual performance, the correlation between MT and ID was .973 accounting for roughly 95% of the variability. The linear regression equation was MT = 23.80 + 49.43 ID for the non-visual data. While the MT - ID slopes for both visual and non-visual performance were quite linear there appeared to be a slight flattening at the lower ID values, a phenomenon which has been reported before (Klapp, 1975; Welford, 1968).

Examination of the constants in the two above equations indicates that the non-visual MT - ID relationship is displaced slightly downward (with respect to the visual function) without a change in slope. This suggests that MT under non-visual conditions was slightly faster overall compared to visual conditions. This was confirmed by a 2 x 3 x 4 (Visual Conditions x Target Size x Distance) ANOVA conducted on the MT data. The vision manipulation had a slight, but significant effect on MT, $F = 19.09$, $df = 1, 8$, $P < .01$. Overall, MT under non-visual conditions was 6 msec faster than under visual conditions, with means of 226 and 232 msec, respectively. As anticipated, both the Target Size and Distance main effects were significant $F = 65.94$, $df = 2, 16$, $P < .01$, respectively. MT increased as target size and as distance increased.

Particularly, within IDs 3.58 to 5.58 there existed trends of MT being greater under target size - distance combinations having the larger distances and these trends

were evident in both visual and non-visual performance. The lack of any significant higher order interactions between visual conditions, target size and distance, prevents us from concluding that any particular target size - distance combination within any given ID value was significantly different from another. Thus, in spite of the trends, we are forced to summarize by saying that the MT data supported Fitts' Law in that it was highly correlated to ID and that MT within 4 of 6 ID conditions (2.58 to 5.58) remained statistically constant despite changes in target size and distance.

Accuracy

In Figure 2A, error rate is plotted as a function of visual condition, target size and distance moved. By inspection we see that under visual conditions, subjects were able to maintain error rate near the 10% level. In contrast, under non-visual conditions error rate systematically increased as distance increased, particularly under the smallest target condition (Figure 2 about here).

All main effects and interactions were significant at or beyond the .001 alpha level with the exception of the Vision x Target Size x Distance interaction which was significant at the $P < .002$ level, $F = 4.09$, $df. = 6, 48$, $P < .002$. This high order interaction supercedes the other main effects and interactions and several simple main effects and Tukeys post hoc tests were done on this interaction which resulted in the following findings. Under visual conditions there was a target size effect but no distance effect on error rate. As target size reduced from 1 in. to .25 in., error rate increased. But, as we pointed out earlier, error rate under visual conditions was low, averaging 6%. Under non-visual conditions, only error rate under the .5 in. and .25 in. target size systematically increased as distance increased with the latter increase more pronounced. Although there was a slight trend in the 1 in. target size condition for error rate to increase as distance increased, it was not significant.

Of particular interest was whether visual feedback was used to a greater extent as ID increased and to determine whether the use of vision was the same for target size - distance combinations within the same ID. For the purposes of visual inspection we re-plotted the error rate data in Figure 2A as a function of target size - distance combinations within the various ID levels and Figure 2B is the result. In general, we can see that error rate increases as ID increases but particularly for the non-visual condition. Post hoc comparisons revealed that there were no significant differences between visual and non-visual conditions at the 1.58, 2.58 and 3.58 ID levels. At the 4.58 ID level, significant differences between visual and non-visual conditions occurred at the 1-2 and 2-3 combinations but not the 3-4 combinations. At the 5.58 ID level, error rate under non-visual conditions was significantly greater than visual for both target size - distance combinations. At the 6.58 ID level, non-visual error rate was significantly greater than visual error rate for the 1-4 combination. Thus, we can conclude that up to the 4.58 ID level, there is no evidence that visual feedback is used. Whereas beyond the 4.58 ID level, visual feedback seems to be used to help control the movements in this experiment.

Planned comparisons were performed to determine whether there were differences in the extent to which vision was used in target size - distance combinations within the same ID level. For this purpose, difference scores between visual and non-visual error rate were calculated for each subject under the target size - distance combinations of interest. Thus, the planned comparisons tested whether the magnitude of the difference scores between visual and non-visual error rates were statistically greater in one target size - distance combination compared to another within the same ID. We focused our analysis at the 4.58 and 5.58 ID level because, (1) previous analyses indicated that below these ID levels there were no differences between

visual and non-visual error rates and (2) these two levels had two or more target size - distance combinations which could be compared. At the 4.58 ID level, visual - non-visual error rate difference scores in the 1-2 and 2-3 conditions were both significantly greater than the 3-4 condition, both $\underline{t}$s = 2.09, $\underline{df}$ = 24, $\underline{P} < .05$. Also, at the 5.58 ID level the difference scores of the 1-3 condition were significantly greater than the 2-4 condition, $\underline{t}$ = 7.19, $\underline{df}$ = 8, $\underline{P} < .05$. Thus, we might summarize by saying only above the 4.58 ID level is there evidence that vision is used. Additionally, we have found evidence for differences in the extent to which vision is used within target - size combinations of the same ID.

Discussion

As have many studies in the past (e.g., Fitts, 1954; Fitts & Peterson, 1954; Jagacinski, Hartzell, Ward & Bishop, 1978; Langolf et al., 1976; Sugden, 1980; Wade et al. 1978; Wallace et al. 1978), we have found MT linearly related to ID. Also in accordance with Fitts' Law, MT was the same for target size - distance combinations within ID. There were non significant trends for longer MT to be associated with target size - distance combinations having the largest distance (see Figure 1). This trend is just the reverse of the original Fitts data (Fitts, 1954) as a recent re-analysis of this data by Sheridan (1979) has shown. In the Fitts (1954) data, there were trends for longer MT to be associated with target - distance combinations having the smaller target size. Whether these opposing trends were due to different tasks (reciprocal vs. discrete tapping) or different methodologies is unclear but because these were non significant trends we prefer not to speculate at this time.

Several models have been developed in attempts to explain Fitts' Law (see Langolf et al., 1976 for a discussion). In the discrete correction model proposed by Keele (1968), emphasis is placed on the use of vision in controlling movements

within the Fitts tapping task paradigm. According to this model, MT increases as a function of ID because a disproportionate amount of time is spent in the later phases of movement as a result of one or more visual corrections, each requiring 190-260 msec (Keele & Posner, 1968). Presumably each increase in ID requires greater demands for the use of vision. Our experiment provides only partial support for the discrete correction model. Only beyond the 3.58 ID level were there increases in the need for vision as ID increased as evidenced by comparisons of visual and non-visual error rates. Up to and including the 3.58 ID level however, there was no evidence that vision was used in controlling movement. Based on these findings, it would appear that there is no one simple explanation of the MT/ID relationship.

Our data suggest that whatever control processes are responsible for MT/ID relationships below the 4.58 ID level, that these processes do not interact with visual feedback to control movement. Thus, one possibility is that up to the point where vision can be used, changes in MT as a function of ID may be the result of motor programming changes.[1] Since the requirement in our version of Fitts discrete tapping task was for subjects to maintain accuracy across all ID levels, subjects must have increased MT in order to reduce the velocity of what could be considered programmed movements. By reducing the velocity of movement for increases in the distance moved or reductions in target size, the subjects' accuracy around the target could be better maintained. Schmidt et al. (1979) have shown that there is a direct relationship between movement velocity and endpoint variability. Subjects in our experiment were given several practice trials at each target size - distance combination with knowledge of results prior to experimental trials. Thus, it is quite possible that in the practice trials subjects were able to learn the appropriate movement strategy that would optimize accuracy at the fastest possible speed.

Beyond the 3.58 ID, our results show that vision was used at varying degrees. But these results provide us with reasons for questioning the validity of the discrete correction model. If we assume that vision is not used until MT reaches roughly 250 msec (ID of 4.58) and that each visual correction takes approximately 200 msec (Keele & Posner, 1968) then only one visual correction could have been possible up to the 6.58 ID level. Otherwise, MT would have been greater than 350 msec which was observed at the 6.58 ID level. It may be that the 200 msec estimate for visual correction time is overestimated and indeed, it must, to account for a MT/ID slope of approximately 50 msec. Smith and Bowen (1980) have shown minimal visual processing times of less than 100 msec. Also, Carlton (1981a) has shown apparent discrete corrections in the kinematic traces of aiming movements after visual feedback has been available for only 135 msec. These data suggest minimal visual processing times of nearly one-half of that found in the Keele and Posner (1968) study.

From a strict "discrete correction" viewpoint, movements of the same ID also have the same MT because the total number of visual corrections is identical. Yet in spite of the fact the MT was statistically the same within IDs of 4.58 and 5.58, the combination having the smallest target size in both cases had the largest discrepancy between visual and non-visual error rate, and thus demanded vision to a greater degree. Sheridan (1979) had originally speculated that the need for visual feedback is more influenced by target size than distance moved and the above finding would tend to support his contention. But Sheridan (1979) based his arguments on a re-analysis of Fitts (1954) data showing that combinations having the smallest target size tended to have greater MT than other combinations within the same ID. Our results show that target size causes greater demand for vision without the necessity of greater MT within combinations of the same ID.

An alternative explanation of this "within ID" effect focusses on the possible limitation of the error rate analysis utilized in the present study as well as others (Carlton, 1981a; 1981b; Keele & Posner, 1968). The "hit" and "miss" analysis used may not have been sensitive enough to capture the essence of movement endpoint variability and may have masked possible increases in movement variability particularly in the larger target conditions. For example, in two combinations of the same ID, say 5.58, the effect of visual withdrawal might increase movement endpoint variability to the same degree but the larger target would "capture" this variability increase and result in a lower "miss" rate relative to the smaller target of the same ID. Thus, we are forced to interpret our "within ID" effect with caution until future experiments can be done using measurements of actual endpoint variability. Also, our "hit and miss" scoring system, adopted after Keele and Posner (1968), may have reduced the sensitivity of finding differences between visual and non-visual performance between as well as within the various IDs. Perhaps by using some measure of actual endpoint variability we could find differences between visual and non-visual performance at lower IDs (therefore lower MTs). In the present experiment the visual cut-off point was at 4.58 ID level (roughly 200-250 msec MT) which is in fair agreement with Keele and Posner (1968).

In summary, our experiment is supportive of Fitts' Law with MT directly related to ID, and MT within each ID very similar for different target size - distance combinations. Below the 4.58 ID level we find no evidence that vision is used in controlling movement whereas beyond this ID level, vision seems to be used to a greater degree as ID increases. These findings tend to support Welford's (1976, Chap. 5., p. 84) speculation that both programming and feedback control processes are operating in the Fitts task. Movements below the 4.58 ID level are probably under programmed control and can be accurately produced without current visual

control. Beyond the 4.58 ID level, visual feedback seems to be needed and the MT - ID relationship might be partially the result of the delays associated with several visual corrections. Yet, the data do not conform very well with the discrete correction account of Fitts' Law.

Reference Notes

1. Crossman, E. R. F. W., & Goodeve, P. J. Feedback control of hand-movement and Fitts' Law. Proceedings of the Experimental Society, Oxford, 1963.

References

Annett, S., Golby, C. W., & Kay, H. (1958). The measurement of elements in an assembly line task - the information output of the human motor system. Quarterly Journal of Experimental Psychology, 10, 1-11.

Beggs, W. D. A., & Howarth, C. I. (1970). Movement control in a repetitive motor task. Nature, 225, 752-753.

Carlton, L. G. (1981a). Processing visual feedback information for movement control. Journal of Experimental Psychology: Human Perception and Performance, 7, 1019-1030.

Carlton, L. G. (1981b). Visual information: The control of aiming movements. Quarterly Journal of Experimental Psychology, 33A, 87-93.

Craik, K. J. W., & Vince, M. A. (1963). Psychological and physiological aspects of control mechanisms. Ergonomics, 6, 419-440.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67, 103-112.

Hayes, K. C., & Marteniuk, R. G. (1976). Dimensions of motor task complexity. In G. E. Stelmach (Ed.), Motor Control: Issues and Trends. NY: Academic Press.

Jagacinski, R. J., Hartzell, E. J., Ward, S., & Bishop, K. (1978). Fitts' law as a function of system dynamics and target uncertainty. Journal of Motor Behavior, 10, 123-131.

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

Keele, S. W., & Posner, M. I. (1968). Processing visual feedback in rapid movements. Journal of Experimental Psychology, 77, 155-158.

Kerr, R. (1973). Movement time in an underwater environment. Journal of Motor Behavior, 5, 175-178.

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

Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. Journal of Motor Behavior, 8, 113-128.

Marteniuk, R. G., & MacKenzie, D. L. (1980). Information processing in movement organization and execution. In R. S. Nickerson (Ed.), Attention and Performance VIII. Hillsdale, NJ: Lawrence Erlbaum Associates.

Quinn, J. T., Jr., Schmidt, R. A., Zelaznik, H. N., Hawkins, B., & McFarquhar, R. (1980). Target-size influences on reaction time with movement time controlled. Journal of Motor Behavior, 12, 239-261.

Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T., Jr. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. Psychological Review, 86, 415-451.

Sheridan, M. R. (1979). A reappraisal of Fitts' law. Journal of Motor Behavior, 11, 179-188.

Smith, W. M., & Bowen, K. F. (1980). The effects of delayed and displaced visual feedback on motor control. Journal of Motor Behavior, 12, 91-101.

Sugden, D. A. (1980). Movement speed in children. Journal of Motor Behavior, 12, 125-132.

Vince, M. A. (1948). Corrective movements in a pursuit task. Quarterly Journal of Experimental Psychology, 1, 85-103.

Wade, M. G., Newell, K. M., & Wallace, S. A. (1978). Decision time and movement time as a function of response complexity in retarded persons. American Journal of Mental Deficiency, 83, 135-144.

Wallace, S. A., Newell, K. M., & Wade, M. G. (1978). Decision and response times as a function of movement difficulty in preschool children. Child Development, 48, 509-512.

Welford, A. T. (1968). Fundamentals of skill. London: Methuen.

Welford, A. T. (1976). Skilled performance: Perceptual and motor skills. Glenview, IL: Scott, Foresman and Company.

Williams, L. R. T. (1971). Refractoriness of an extended movement to directional change. Journal of Motor Behavior, 3, 389-400.

Woodworth, R. S. (1899). The accuracy of voluntary movement. Psychological Review, 3, (2, Whole No. 13).

Footnotes

1. We do not, of course, rule out the possibility that proprioceptive feedback could have been used below or above the visual cut-off point. Thus, our interpretation that the MT/ID relationship below the visual cut-off point is due to motor programming changes must be made with caution.

Table 1

Target Size - Distance Combinations and

Associated Index of Difficulty (ID) Values

Target Size	Distance	$ID=\log_2 2A/W$
2.54 cm (1 in.)	3.81 cm (1.5 in.)	1.58
1.27 cm (.5 in.)	3.81 cm (1.5 in.)	2.58
2.54 cm (1 in.)	7.62 cm (3 in.)	2.58
.64 cm (.25 in.)	3.81 cm (1.5 in.)	3.58
1.27 cm (.5 in.)	7.62 cm (3 in.)	3.58
2.54 cm (1 in.)	15.24 cm (6 in.)	3.58
.64 cm (.25 in.)	7.62 cm (3 in.)	4.58
1.27 cm (.5 in.)	15.24 cm (6 in.)	4.58
2.54 cm (1 in.)	30.48 cm (12 in.)	4.58
.64 cm (.25 in.)	15.24 cm (6 in.)	5.58
1.27 cm (.5 in.)	30.48 cm (12 in.)	5.58
.64 cm (.25 in.)	30.48 cm (12 in.)	6.58

Figure Captions

Figure 1. Movement time as a function of Index of Difficulty under visual and non-visual conditions. First number of target size - distance combinations refers to target size and second number refers to distance. For target size, 1 = .25 in., 2 = .5 in., and 3 = 1 in. For distance, 1 = 1.5 in., 2 = 3 in., 3 = 6 in., and 4 = 12 in.

Figure 2. In A, percent misses as a function of visual condition, target size and distance. In B, percent misses as a function of Index of Difficulty under visual and non-visual conditions. See Figure 1 caption for explanation of target size and distance numbers.

FIGURE 1

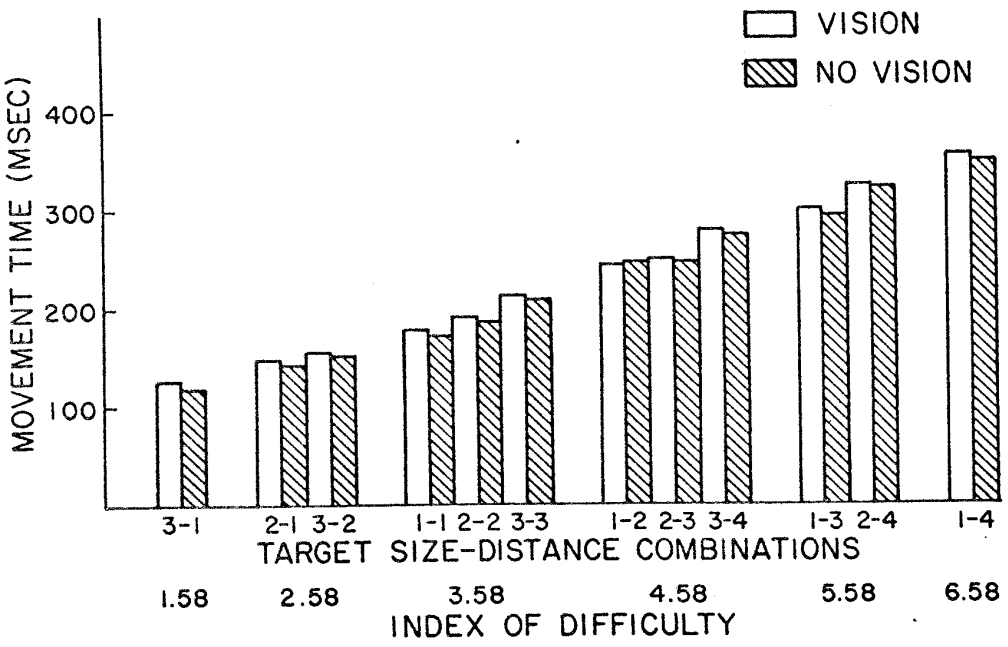
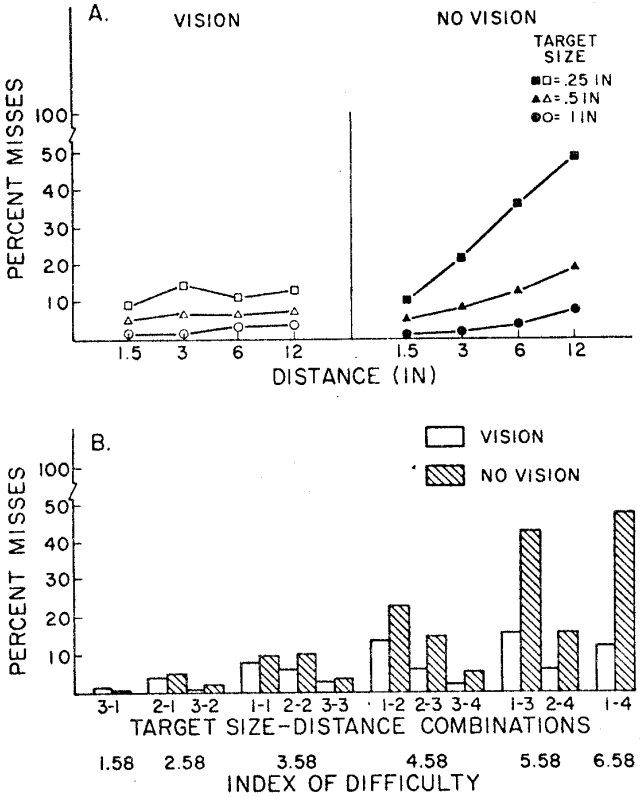

VISION
NO VISION
MOVEMENT TIME (MSEC)
400
300
200
100
3-1
2-1 3-2
1-1 2-2 3-3
1-2 2-3 3-4
1-3 2-4
1-4
TARGET SIZE-DISTANCE COMBINATIONS
1.58
2.58
3.58
4.58
5.58
6.58
INDEX OF DIFFICULTY

FIGURE 2


A.
VISION
NO VISION
TARGET SIZE
■□= .25 IN
▲△= .5 IN
●○= 1 IN
PERCENT MISSES
100
50
40
30
20
10
1.5
3
6
12
DISTANCE (IN)
B.
VISION
NO VISION
PERCENT MISSES
3-1
2-1
3-2
1-1
2-2
3-3
1-2
2-3
3-4
1-3
2-4
1-4
TARGET SIZE-DISTANCE COMBINATIONS
1.58
2.58
3.58
4.58
5.58
6.58
INDEX OF DIFFICULTY