Journal of Motor Behavior, 1996, Vol. 28, No. 2, 157–163

Cinematographical Analysis of Movement Pathway Constraints in Rapid Target-Striking Tasks

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ABSTRACT. Several features of the actual movement pathway in two rapid target-striking tasks were quantified by using high-speed cinematography, and whether the movement pathway is constrained as a function of the accuracy demands imposed by the size of the subtended angle was determined. Subjects ($N = 16$) first hit an 8-cm-diameter target located 10 cm to the left of a start position and then, depending on the condition, moved another 10 cm to hit either a 6-cm- or 1.5-cm-diameter target. Subtended angles were 17.1 and 4.3° for the large and small second-target conditions, respectively. Fifty trials per condition were performed, the last 3 of which were filmed at 120 Hz. The vertical dimension of movement (peak height along the z-axis) was captured directly from the camera view, whereas the horizontal (y-axis) dimension, that is, the dimension orthogonal to the principal direction of motion, was captured through a mirror positioned above the target board. Reaction times and movement times were significantly longer in the small second-target condition, thus replicating the well-known response complexity effect. Kinematic analyses revealed that when the subtended angle was smaller, there was significantly less horizontal pathway deviation as well as significantly higher peak vertical displacement in the movement. Therefore, the accuracy demands imposed by a smaller subtended angle do constrain the actual movement pathway.

Key words: accuracy constraints, movement pathway, programming time, subtended angle

The quest to understand the response complexity effect in rapid programmed responses (the notion that programming time increases as a function of the complexity of the movement) has been an ongoing research problem since Henry and Rogers (1960) introduced the memory drum theory of neuromotor programming (see Christina, 1992, for a review). Currently, two main hypotheses seek to explain the effect. The first is the "number hypothesis" (e.g., Fischman, 1984), which attributes the effect simply to the number of connected movement parts of the task, without regard to the nature of the parts. The second is the "accuracy hypothesis" (Sidaway, 1991), which proposes that the effect is a result of constraints placed on the movement as a function of the required accuracy. Greater accuracy demands supposedly force the limb to take a more constrained movement pathway in moving to a target, and the planning for such a constrained movement is evidenced in longer programming time.

Henry and Rogers (1960) first suggested that the complexity effect for large-scale motor responses was a function of the number of movement parts. Their idea was supported and furthered by several investigators (Anson, 1982; Christina, Fischman, Lambert, & Moore, 1985; Christina, Fischman, Vercruyssen, & Anson, 1982; Christina & Rose, 1985; Fischman, 1984) whose studies served to rule out alternative explanations for the complexity effect, such as motor reaction time as opposed to premotor reaction time, anatomical unit, distance of movement, changes in movement direction, and stopping or following through with the movement. The effect has also been shown to persist even after fairly extensive amounts of practice (Fischman & Lim, 1991), although unequal distributions of practice may mediate the typical effects of task complexity (e.g., Fischman & Yao, 1994b), and to apply to small-scale movements such as speech and typewriting (Sternberg, Monsell, Knoll, & Wright, 1978).

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Sidaway, Christina, and Shea (1988) recently investigated the relationship between programming time and accuracy demands when they reinterpreted previous research and argued that programming time is predominantly a function of constraints placed on the output of the motor system by the accuracy demand of the responses. In their analysis, accuracy demands were quantified in terms of Fitts' (1954) Index of Difficulty (*ID*). The *ID* is a mathematical expression of the relationship between movement amplitude and target size and is defined as $ID = \log_2 (2A/W)$, where A is the amplitude, or distance, of the movement and W is the width (or, in the case of circular targets, the diameter) of the target. Although the *ID* was originally intended to describe a speed–accuracy tradeoff effect on movement time (MT), later work by Fitts and Peterson (1964) showed a .79 correlation between reaction time (RT) and *ID*, which Sidaway et al. (1988) used to quantify the directional accuracy constraints placed on response initiation. Additionally, because the *ID* for a circular target is a ratio of movement distance to target diameter, Sidaway et al. (1988) demonstrated that this index could also be expressed as the *subtended angle* or the angle subtended at the starting position by the diameter of the target orthogonal to the direction of movement. Targets that subtend smaller angles supposedly place greater directional accuracy constraints on the movement pathway because, it is assumed, subjects keep the stylus within the confines of the subtended angle as they move to the target. Thus, the demand for directional accuracy inherent in the movement response constrains the pathway of the limb, in the sense of producing less movement excursion. The more constrained movement pathway produced by smaller subtended angles also requires more programming time, typically showing up as lengthened RT.

Fischman and Mucci (1990) extended the research of Sidaway et al. (1988) by including additive indexes of difficulty in target-striking tasks involving changes in direction, and Sidaway, Schoenfelder-Zohdi, and Moore (1990) varied subtended angles, target position, and target size and showed that the size of the accuracy constraint had a significant effect on RT, whereas position of the most constraining target did not.

Sidaway (1991) conducted three experiments in which the number of targets, subtended angle, and movement distance were independently manipulated. His research demonstrated that response programming time was more a function of the subtended angle than any of the other variables. But Fischman and Yao (1994a) recently showed that in a serial aiming response in which subjects initially moved to the farthest target and then reversed direction and came back toward the starting position, RT increased even though the subtended angle was held constant. In this experiment, however, the subtended angle was constant for the first target to be hit but varied for the second target because of the movement reversal.

In the most recent work in this area, Sidaway, Sekiya, and Fairweather (1995) stated that in research conducted thus far on accuracy demands no one has attempted to analyze the movement pathway resulting from experimentally imposed constraints such as target-size differences and movement amplitude differences. They conducted two experiments designed to examine the effect of varying the accuracy demand of a second target on the dispersion and location of contacts on a first target of constant size. Sidaway et al. (1995) claimed that they were recording the orthogonal variability of the movement pathway at a common stage across conditions, the common point being the termination of movement on the first target. They reasoned that if the accuracy demand of the last target constrains the movement pathway of the response, then a smaller last target should result in a smaller dispersion in the contact points on the first target. Their experiments examined the dispersion, or variability, of contact points on the first target in both large and small second-target conditions and found significant changes between the two conditions. When the second target was large, the mean x coordinate (horizontal deviation from the center of the target) of the contact point on the first target shifted only slightly from the center of that target toward the second target. This shift was far greater, however, when the second target was small. The mean x coordinate was much closer to the second target, with much less orthogonal, or y-axis, variability in the individual contact points. On the basis of this evidence, they suggested that the movement pathway itself was in some way constrained.

Sidaway et al. (1995) also found longer RTs in their small second-target condition. They hypothesized that the small second target causes increased programming time because subjects produce a more constrained movement pathway throughout the entire response to achieve contact with the second target. A limitation of their research, however, which they acknowledged, is that they sampled movement pathway dispersion at only one point, the contact on the first target. The assumption that one can "work backward" from contact points (i.e., only one point in the movement) and reconstruct the actual movement pathway is questionable. Simply monitoring the dispersion of contact points on the first target does not provide sufficient information about the limb's trajectory during the first segment of the movement, nor does it provide any information about the limb's trajectory during the second segment of movement. These limitations prompted Sidaway et al. (1995) to call for further research that would provide a more detailed description of the actual movement pathway. This is precisely what the present experiment was designed to do.

Although the accuracy constraint hypothesis, as conceptualized by Sidaway and his colleagues (Sidaway, 1991; Sidaway et al., 1988; Sidaway et al., 1995), predicts a more constrained movement pathway throughout the entire response, it is clear from their writing that the more constrained pathway is in the dimension orthogonal, or at right angles, to the principal direction of motion (see Howarth & Beggs, 1985, for a discussion of aiming errors). Thus, as the stylus moves from right to left (x dimension), for example, there should be less horizontal (y dimension) deviation from a straight-line path between the starting position and the target. What about the vertical (z) dimension of movement, or the height of the stylus above the targets as it moves through the various segments of the response? The accuracy constraint hypothesis does not specifically address this dimension of movement, yet an analysis of this dimension is clearly important to a full description of the actual movement pathway.

If accuracy demands place constraints on the movement pathway, such constraints may be evidenced by differences in the horizontal, vertical, or in both dimensions of the movement's trajectory, although the accuracy constraint hypothesis is directed mainly at the horizontal dimension. In this study, we measured, by means of high-speed cinematography, features of the actual movement pathway in two rapid target-striking responses to determine whether they change as a function of constraints imposed by the size of the subtended angle.

Method

Subjects

Sixteen right-handed male volunteers ranging in age from 20 to 29 years ($M = 23.2$) served as subjects. None had prior experience with the experimental task. Informed consent was obtained before testing began.

Apparatus and Tasks

The apparatus consisted of an 84 × 43-cm target board (5 cm thick) on which two circular targets and a starting position were mounted. The target board rested on a tabletop (75 cm high) directly in front of the seated subject. The targets and starting position were constructed from steel and were connected to timers that activated when the targets were hit or the starting position released. The first target was 8 cm in diameter and was positioned 10 cm to the left (with respect to the subject) of the starting position. A further 10 cm to the left was the second target, which, depending on the condition, was either 6 cm or 1.5 cm in diameter. These final targets produced subtended angles of 17.1 and 4.3°, respectively (see Figure 1), and were the same as those used by Sidaway et al. (1995, Experiment 1).

Subjects struck the targets with a lightweight (15 g) stylus held in the right hand. The metal starting position was connected to a 400-Hz tone generator/relay that presented the warning signal, controlled the foreperiod, and presented the auditory stimulus signal. Coincident with the onset of the stimulus, three millisecond clocks started recording. Removing the stylus from the start position stopped the RT clock, and contacting the targets anywhere on their surface stopped the corresponding response time clocks. The first-segment movement time (MT1) was the difference between the start position and the first target, and the second-segment movement time (MT2) was the difference between the first target and the second target.

In addition, a motor-driven high-speed camera (Locam, Model 51) with a sampling frequency of 120 Hz was placed 3.5 m in front of the target board at a height of .95 m from the floor. This placement served to negate the effects of angular and linear distortion and provided accurate points to digitize. Considering that the total movement times were expected to be approximately 300–500 ms, on the basis of Sidaway et al. (1995), 36 to 60 frames of motion over a 20-cm distance would be captured. We placed a reference marker in front of the apparatus (with respect to the subject) in line with the camera and the movement to convert the film size to actual life-size. We focused and stabilized the

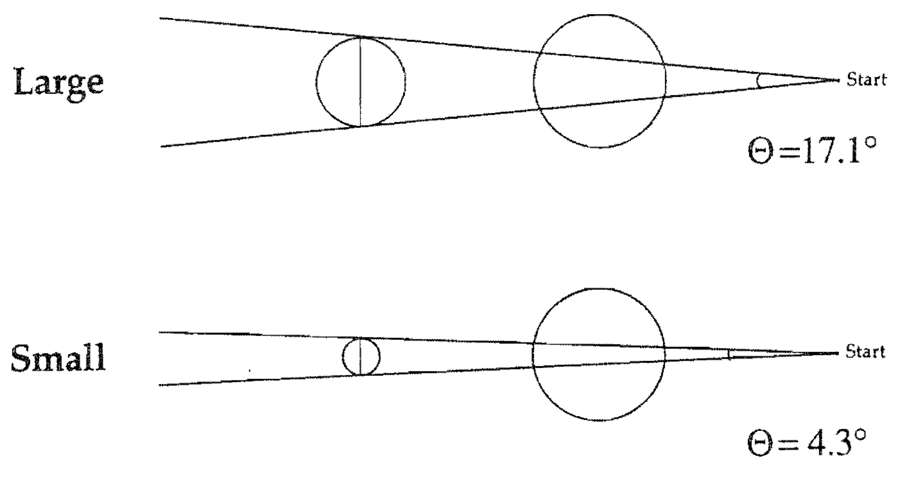

FIGURE 1. Rapid target-striking tasks used in the experimental conditions. Theta (θ) indicates the size of the subtended angle of the second target in each condition. See text for details.

camera and used an f-stop of 2.8 to let in the proper amount of light and avoid blurring. We mounted a 24-in. × 48-in. mirror on a stand above the target board to capture the horizontal displacement during the task. This was done by setting the mirror at a 45° angle to both the camera and the target board, resulting in an overhead view of the target board when looking through the camera.

Procedure

Subjects sat on an adjustable stool, facing the target board, and then read a standardized set of instructions. A demonstration of the movement was given by the experimenter, and then several trials were executed by the subject so that he could become comfortable with the movement. These trials were self-paced, and the auditory stimulus was not presented.

At the start of a trial, the subject gripped the stylus with his right hand and placed the tip on the start position so that it tilted backward at about a 45° angle. Subjects were instructed to maintain this orientation throughout the response. This orientation allowed the tip of the stylus to be digitized from both the camera view and the mirror view without being obscured by the subject's hand. The subject then received two auditory signals from the tone generator. The first was a warning signal, which started a variable foreperiod of 1.0 to 3.0 s (in 0.5-s increments). At the end of the foreperiod, the auditory stimulus was presented. On hearing the stimulus, subjects removed the stylus from the start position and struck the two targets in order as rapidly and accurately as possible and at a rate at which they would commit approximately 10% target-striking errors. Subjects finished the response by maintaining the stylus in contact with the final target for approximately 1 s. After each trial, subjects were told their total response time in milliseconds. Instructions emphasized reducing this response time. The experimenter recorded the data from each clock, then reset the clocks and prepared to initiate the next trial.

The order in which the two conditions (6-cm or 1.5-cm final target) were presented was counterbalanced across subjects. In each condition, subjects performed two blocks of 25 trials, with an intertrial interval of approximately 5 s. The rest interval between conditions was approximately 5 min. The first 25 trials were considered practice, and the last 25 trials were test trials, over which the dependent measures of RT, MT1, and MT2 were calculated. In addition, the final 3 trials of each condition were filmed for each subject. Filming involved turning the camera on by using a remote switch approximately 1 s before stimulus onset. This time allowed the camera to achieve the required speed before the movement started. The camera was turned off once the response was completed. Any trials in which a target was missed were repeated, and the error was noted for the subsequent digitizing process. Therefore, each subject was assured of having 3 good filmed trials.

The digitizing process consisted of projecting the developed film onto a digitizing screen and using a manual frame advance to allow one frame of movement at a time to be digitized. A graf/pen sonic digitizer system was connected to a Zenith computer with a self-developed film analysis program so that the x, y, and z coordinates of reference points and stylus position could be digitized. For the mirror view, which is the view from above, the principal direction of motion was assigned an x-axis and the orthogonal deviations from this axis were recorded along the y-axis. These x- and y-axis assignments were the same as that used by Sidaway et al. (1995, Experiment 1). For the camera view, the principal direction of motion was still assigned an x-axis, and the height above this axis, or what we refer to as vertical displacement, was assigned the z-axis. These coordinates were then subjected to a moving-average data-smoothing process in which the local polynomial (moving arc) approximation was obtained by fitting a quadratic function to five adjacent data points (Wood, 1982). The digitizing process was completed once for the vertical dimension of movement (camera view) and then a second time for the horizontal dimension (mirror view).

Data Reduction and Analysis

Subjects' RTs, MT1s, and MT2s were calculated by averaging the last 25 trials in each of the two second-target conditions. As in Sidaway et al. (1995), we used a dependent t test to test for differences in RT between the two conditions, and the effect of second-target size on response segment MTs was analyzed by using a 2 × 2 (Target Size × Response Segment) repeated-measures analysis of variance (ANOVA).

For the horizontal dimension, we calculated the mean absolute horizontal deviations from a reference target line drawn from the start position and passing straight through the centers of the two targets. Essentially, this target line bisected the subtended angle in each condition. The total movement was divided into two segments. The first segment began at the start position and ended at the left edge of the first target. The second segment began at this point and ended when the stylus contacted the second target. It is important to note here that the first and second segments for our horizontal dimension analysis were not equivalent to MT1 and MT2, as the first segment did not end until the stylus passed the left edge of the first target. Therefore, this segment included movement of the stylus from the start position until contact with the target as well as a small portion of movement from contact until the stylus passed the target's far edge. We divided our segments in this manner partly for convenience, but more important, because it allowed the initial segment of the task to be defined identically for all subjects. For each segment, the absolute deviation in each frame was calculated. These deviations were then summed, divided by the number of frames, and then averaged over the three filmed trials. To determine the effect of second-target size on the absolute horizontal deviations in each response segment, we calculated a 2 × 2 (Target Size × Response Segment) repeated-measures ANOVA.

The mean peak vertical displacements (peak z coordinates) for the first segment and the second segment of movement were calculated across the three filmed trials for each subject. Then we used a 2 × 2 (Target Size × Response Segment) repeated-measures ANOVA to determine the effect of second-target size on the peak vertical displacements in each response segment.

Results and Discussion

No subjects were replaced for failure to execute the responses as instructed. However, 1 subject's film data were impossible to view from the developed film; therefore, all film analyses were based on 15 subjects, rather than 16. Error rates (missing a target or failing to terminate the response properly) for the test trials were 8.2% and 10.7% for the large and small second-target conditions, respectively; over 99% of the errors were the result of misses of the second target. There were a few occasions in which a target was missed during the filmed trials, and these were repeated.

Reaction Time and Movement Time

We first report the results of analyses on the timing-dependent variables of RT, MT1, and MT2 to show that we have replicated several well-established findings from the sizable literature on response complexity effects and programming time (see Table 1).

For RT, the effect for response condition was significant, $t(15) = 3.59$, $p < .005$. As shown in Table 1, mean RT was longer when the second target was small than when it was large. These RT findings are quite similar to those reported by Sidaway et al. (1995, Experiment 1) and provide support for their notion that the accuracy demand of the final target was taken into account when programming the response.

The movement time analysis revealed significant main effects for both target size, $F(1, 15) = 41.23$, $p < .001$, and response segment, $F(1, 15) = 20.15$, $p < .001$. The target-size effect resulted because movements were slower when the second target was small ($M = 172$ ms, $SD = 34$) than when it was large ($M = 135$ ms, $SD = 26$). The response-segment effect indicated that MT1 ($M = 144$ ms, $SD = 33$) was faster than MT2 ($M = 164$ ms, $SD = 36$). This finding was expected because the first target was larger than the second target in both conditions. The interaction between the factors was not significant, $F(1, 15) = 2.16$, $p > .05$. Taken together, the movement time findings are consistent with an accuracy constraint interpretation (Sidaway et al., 1995) and would also be predicted by Fitts' law (Fitts, 1954; Fitts & Peterson, 1964). Similar to the movement time findings of Sidaway et al. (1995), we also found that the size of the last target slowed both segments of the response to a similar degree, and not just the final segment. MT1 increased by 26% and MT2 increased by 30% when the size of the last target was decreased.

Movement Pathway (Horizontal Dimension)

Our primary purpose in this experiment was to determine how the actual movement pathway in a two-segment target-striking task is constrained as a function of the accuracy demand imposed by the size of the subtended angle. Mean absolute deviations for each segment of movement are presented in Table 2. For the horizontal dimension of movement, which is movement in the dimension orthogonal to the movement's primary direction, the main effect of response segment was not significant, $F(1, 14) < 1$. The main effect of target size was significant, $F(1, 14) = 12.92$, $p < .005$, indicating that there was less deviation from a straight-line path between the start position and targets when the second target was small. This effect, however, was overshadowed by a significant interaction between target size and response segment, $F(1, 14) = 6.11$, $p < .05$. As shown in Table 2, during the first segment of movement, the difference in mean absolute deviation in the horizontal dimension was only .15

TABLE 1
Mean Reaction Time and Movement Time Measures as a Function of Second-Target Diameter

	RT	MT1	MT2
	1.5-cm target diameter		
M	223	160	185
SD	30	34	30
	6.0-cm target diameter		
M	203	127	142
SD	27	23	27

Note. All values are in milliseconds.

TABLE 2
Absolute Deviations in the Horizontal Dimension of Movement as a Function of Second-Target Diameter and Movement Segment

	First segment	Second segment
	1.5-cm target diameter	
M	.57	.50
SD	.22	.23
	6.0-cm target diameter	
M	.72	.83
SD	.40	.37

Note. All values are in centimeters.

cm between the small target and large target. During the second segment of movement, however, this difference was .33 cm, and much less horizontal deviation was produced when the final target was small. Taken together, these findings suggest that subjects adopt a much more constrained movement pathway in the horizontal dimension as a result of the accuracy demand of the final target. These findings provide direct support for the accuracy constraint hypothesis (Sidaway, 1991; Sidaway et al., 1995).

Movement Pathway (Vertical Dimension)

Table 3 presents the peak vertical displacements for each segment of movement. We had no clear a priori predictions regarding the vertical dimension of the movement pathway, mainly because the accuracy constraint hypothesis does not address this dimension. Nevertheless, our analyses of peak vertical displacements revealed that there were significant differences between the small and large second-target conditions, $F(1, 14) = 6.40$, $p < .025$. Peak vertical displacement was greater when the second target was small ($M = 3.08$ cm, $SD = .99$) than when it was large ($M = 2.60$ cm, $SD = .93$). There was also a significant effect for response segment, $F(1, 14) = 52.81$, $p < .001$. Peak vertical displacement was nearly 1 cm greater during the first segment ($M = 3.33$ cm, $SD = .93$) than during the second segment ($M = 2.35$ cm, $SD = .78$). This finding was most likely caused by the combined effects of the inertia that had to be overcome by the subjects so that they could lift the stylus to begin the movement and by the substantial horizontal momentum that was generated once the stylus struck the first target and which continued during the second segment. The interaction between the factors was marginally significant, $F(1, 14) = 4.10$, $p < .063$. Table 3 shows that peak vertical displacement during the first segment of movement was 0.31 cm higher for the small second target than for the large second target. However, during the second segment, peak vertical displacement was 0.65 cm higher when the second target was small than when it was large.

TABLE 3
Peak Vertical Displacement as a Function of Second-Target Diameter and Movement Segment

	Movement segment	
	First segment	Second segment
	1.5-cm target diameter	
M	3.48	2.68
SD	1.07	.74
	6.0-cm target diameter	
M	3.17	2.03
SD	.78	.70

Note. All values are in centimeters.

Results from the vertical dimension analysis showed that, in general, subjects raised the stylus higher during the entire movement when the second target was small. This result was unexpected because it indicates a less constrained rather than a more constrained pathway and thus is counter to the accuracy constraint hypothesis. However, an alternative interpretation of this finding suggests that subjects may have lifted the stylus higher when the second target was small to increase the approach angle to that target, which would have afforded a greater surface area for landing on the target. A strategy such as this could, in fact, be interpreted as a way of dealing with the accuracy constraint imposed by the small second-target condition. This strategy may also account for some of the increase in movement time in the present study, in that subjects used a longer pathway to reach the targets because of the extra movement in the vertical dimension. The important point here is that the accuracy demands of the second target did produce a change in peak vertical displacement, which is an important feature of the actual movement pathway. Further research is needed to determine the full extent of the influence of the vertical dimension of movement on the control of target-striking responses such as these.

Anson (1982, Experiment 2), reported similar findings in rapid arm-pointing movements when he discovered that when the target required greater accuracy, the index finger moved upward and aimed at the target before the shoulder and elbow moved. This strategy produced longer MTs in Anson's small-target condition.

One limitation of the present work is that we were able to film only three trials in each response condition. Therefore, it is possible that subjects' performance on the filmed trials was not representative of their performance on the nonfilmed trials. To check this possibility we calculated mean RT, MT1, and MT2 for the filmed trials and compared these values with those of the nonfilmed trials. Mean RT was 227 and 249 ms for the large and small second-target conditions, respectively. This difference is similar in magnitude to the RT differences we reported earlier in this article, although the RTs were somewhat longer. The reason for the longer RTs on the filmed trials may be that the noise of the camera made it slightly more difficult for subjects to hear the auditory stimulus. More important, however, were the MT1 and MT2 findings, which were quite similar for both the filmed and nonfilmed trials. Mean MT1s for the filmed trials were 120 and 156 ms for the large and small second-target conditions, respectively, whereas mean MT2s were 141 and 174 ms for the corresponding conditions. We are therefore reasonably confident that the features of the movement pathway measured during the filmed trials are representative of performance during the nonfilmed trials.

Summary and Conclusions

In a recent review article on the mystery of the response complexity effect in skilled movements, Christina (1992) stated that "it seems reasonable to conclude that the crucial element of the response complexity effect is the demand for directional accuracy inherent in the movement response" (p. 227). And later he remarked, "the demand for directional accuracy . . . confines the movement trajectories of the arm responses used" (p. 228). Until now, such a position, although reasonable, has been founded on the basis of a body of correlational and indirect evidence (Gordon & Christina, 1990; Sidaway, 1991; Sidaway et al., 1988; Sidaway et al., 1990; Sidaway et al., 1995). Taken together, the findings of the present study are the first to provide objective kinematic evidence to support the position that accuracy demands (specifically, the size of the subtended angle) cause the actual movement pathway to become more constrained, at least in the horizontal dimension, in rapid target-striking responses. In the vertical dimension, our results can also be interpreted as indicating a sensitivity to the accuracy demands of the movement. Thus, the present study adds to our knowledge of the planning and control processes involved in a class of skillful human movement.

ACKNOWLEDGMENT

This study was conducted by the first author as part of the requirements for a master of science degree at Auburn University. We thank Robert Eklund and T. Gilmour Reeve for serving as thesis committee members. We also appreciate the helpful suggestions made by Digby Elliott and Ben Sidaway on a previous version of the manuscript. Martin W. Short is presently a doctoral student in the Department of Exercise and Sport Sciences at the University of Florida, Gainesville. Portions of this research were presented at the 1994 meeting of the North American Society for the Psychology of Sport and Physical Activity, Clearwater Beach, FL

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Submitted July 5, 1994
Revised October 12, 1994
Second revision January 17, 1995