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The effect of distance on reaction time in aiming movements

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Running head: Reaction time and target distance

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Abstract

Target distance affects movement duration in aiming tasks but its effect on reaction time is poorly documented. RT is a function of both preparation and initiation. Experiment 1 pre-cued movement (allowing advanced preparation) and found no influence of distance on RT. Thus, target distance does not affect initiation time. Experiment 2 removed pre-cue information and found that preparing a movement of increased distance lengthens RT. Experiment 3 explored movements to targets of cued size at non-cued distances and found size altered peak speed and movement duration but RT was influenced by distance alone. Thus, amplitude influences preparation time (for reasons other than altered duration) but not initiation time. We hypothesise that the RT distance effect might be due to the increased number of possible trajectories associated with further targets: a hypothesis that can be tested in future experiments.

Key Words: Movement, Reaction time, Preparation, Fitts' law, aiming

INTRODUCTION

The relationship between duration, movement amplitude (the length of the movement path) and target size was first described formally by Fitts (1954). Fitts captured the relationship between movement time (MT), amplitude (A) and target size (W) in the following manner:

$$MT = a + b \log_2(2A/W) \qquad (1)$$

where a and b are constants that depend upon the individual and the task. This equation captures well the data from a wide range of experiments and has come to be known as Fitts' law. There are limits to the applicability of Fitts' law; since the law is an empirically derived relationship, it may apply only to data of the type collected in the experiments that support it (see Plamondon & Alimi 1997). Two things about these experiments are always similar. First, the data are obtained from people who are required to perform close to the limits of their ability to be both fast and accurate. Second, the targets to which movements are directed are always stationary. Even for the types of data and experimental context from which the law was originally derived, there is some debate about the form of the relationship (cf Plamondon & Alimi 1997). Other formulations of the speed-accuracy trade off (such as the power law formulation) have been found to provide slightly better descriptions of empirical data sets (Plamondon & Alimi 1997).

Fitts' law was originally applied to repetitive tasks involving one degree of freedom movements but it came to be recognised that it also describes the duration of a number of different movements, such as discrete aiming actions that unfold across three-dimensional space. Fitts' equation can be recast as:

$$MT = a + b \log_2(A) - c \log_2(W) \qquad (2)$$

where a, b and c are constants that depend upon the individual and the task. Equation (2) better describes an individual's data in a discrete aiming task and better captures group performance over a wider range of tasks than equation (1) (see e.g., Kerr 1974, Sheridan 1979, Welford 1968, p. 153, MacKenzie 1989). Thus, the execution of aiming actions takes (on average) a constant period of time that can be predicted for a given individual carrying out a specific task on the basis of target size and target distance.

The observation that the execution of an aiming movement takes a constant time leads to the question of whether the time taken to *prepare* and *initiate* the movement also follows such a lawful relationship. In a movement task, the appropriate action needs to be prepared, initiated (i.e. the feedforward component needs to be triggered) and subsequently guided (i.e. online feedback used to correct any errors). We define preparation as selecting the action and the appropriate effectors (limbs, joints and muscles) and determining how 'working point(s)' need to move over time to achieve the goal under the current conditions. It is not known whether the time taken to prepare and initiate an aiming movement has a lawful relationship with target distance. In order to address this issue, it is necessary to explore reaction time. Reaction time describes the length of time between the appearance of an imperative stimulus and the commencement of movement when the participant has been instructed to respond as quickly as possible. In situations where the goal of the movement is already known, the movement can be prepared in advance so reaction time simply reflects initiation time. It is also possible to measure reaction time where the goal of the movement is not known in advance (i.e. the imperative stimulus also specifies the movement goal) and in this situation the reaction time reflects both the time taken to prepare and initiate the movement.

Henry and Rogers (1960) showed that RT increased when participants needed to make a series of movements rather than complete one single action. The basic finding of longer RT with increased movement complexity has been replicated by a large number of authors (e.g. Christina 1992; Fischman 1984; Klapp & Erwin 1976; Rosenbaum & Patashnik 1980; Sidaway, Sekiya & Fairbrother 1995; Quinn et al 1980; Klapp 1996; Khan et al 2006) although there is some debate over the precise factors that define movement complexity. Sidaway, Sekiya & Fairbrother (1995) and Lajoie & Franks (1997) found that RT increased when the size of a second target decreased in a serial aiming response (where two targets are contacted in a fixed order). Riek et al (2003) reported that unimanual aiming responses showed faster RTs than synchronous bimanual aiming movements to separate but identical targets. Moreover, Riek et al found that synchronous bimanual aiming to separate but identical targets produced faster RTs than asynchronous bimanual movements to targets that differed in distance and/or size.

The finding that reaction time is a function of movement complexity is important but does not allow us to draw conclusions regarding the relationship between RT and distance in simple aiming movements. Thus, the empirical question of whether the relationship between reaction time and distance can be captured by a function of the type provided in Equation (2) remains unresolved. There have been some previous attempts to address this issue. In his original study, Fitts reported the reaction times in addition to the movement times recorded in a repetitive tapping task (Fitts 1954; Fitts & Peterson 1964). The results suggested that RT was influenced by the task constraints but the relationship was weak. The problem with interpreting these results is that Fitts did not distinguish between the preparation and initiation of the movement and collapsed the effect of target size and movement amplitude together in a manner indicated by Equation (1). Klapp & Erwin (1976) asked participants to make fixed amplitude movements (10cm) inside defined accuracy limits within four different time windows. Klapp & Erwin (1976) found that RT was influenced by response duration such that an MT of 150, 300 and 600 ms produced RTs of 344, 382 and 442ms respectively, although increasing MT to 1200ms resulted in no further increase in RT (443ms). Rosenbaum & Patashnik (1980) and Quinn et al (1980) replicated the essence of this finding. These findings have led to the hypothesis that there is a fixed relationship between movement duration and reaction time (see Klapp 1996 for a review). Klapp (1975) found that RT decreased as target size increased from 0.3cm to 1.2cm to 4.8cm when participants made aiming movements over 0.2cm and 1.1cm. The relationship between RT and size appeared to disappear at the other two distances tested (7cm and 33.6cm) and there was no clear evidence of a relationship between distance and RT. These previous findings are of interest but it is difficult to relate performance under these task conditions to the performance of normal aiming movements over larger amplitudes. Thus, these earlier experiments do not address directly the issue of whether the RT associated with simple aiming movements is captured in the same manner that movement time is captured by Equation (2) and whether or not reaction times have a fixed and direct relationship with movement duration.

In order to determine whether RT is reliably influenced by distance in aiming movements it is necessary to conduct an experiment where the effect of manipulating amplitude is investigated in a systematic manner. It is also necessary to distinguish between the effect on the time taken to initiate a movement and the effect on the time taken to prepare the movement. The present study set out to achieve these aims.

Methods

All experiments involved kinematic data recording as outlined below. An infrared emitting diode (IRED) was attached to a handheld stylus. The position of the IRED was recorded by an Optotrak optoelectronic movement recording system, factory pre-calibrated to a static positional resolution of better than 0.2mm at 250Hz. Data were collected for 3000ms at 100Hz in Experiment 1 and for 4000ms at 100Hz in Experiments 2 & 3. Data were then stored for subsequent offline analysis and filtered using a dual-pass Butterworth second order filter with a cut-off frequency of 16Hz (equivalent to a fourth order zero phase lag filter of 10Hz). The signals for the three different Cartesian dimensions (x, y, z) were mathematically differentiated to produce velocity profiles. Following this operation the tangential speed of the IRED was computed as the resultant of the three velocity profiles (corresponding to the velocities in x, y, z space). The onset and offset of the movement was estimated using a standard algorithm (threshold for movement onset and offset was 5cm/s) from the resultant speed profile. The offset of the movement was unambiguous in all trials as the stylus was still moving when it hit the target (and thus rapidly decelerated to zero velocity). Custom analysis routines were used to compute the dependent variables of interest in this study.

Design

All experiments were of a within-subjects design. The order of trials was fully randomized across and within participants. The independent variables manipulated in each experiment were the distance of the target and the size of the target. The dependent variables of interest were reaction time (RT), movement time (MT) and peak speed (PS). A micro-switch was used to indicate the point at which the stylus left the starting location. In Experiment 1, RT was measured from the presentation of the imperative stimulus (a short auditory tone) until the movement commenced. In Experiments 2 and 3, the target location appeared on the computer screen and thus served as the imperative stimulus providing an index of the preparation time for the movement. In these experiments, RT was calculated as the period between the target appearing on the computer screen and the onset of movement. In all experiments MT was taken as being from the time the movement started until the stylus stopped on the target. The median RTs and MTs were calculated for each of the different aiming situations for each participant. From these median values, repeated-measures Analysis of Variance (ANOVAs) were performed. Median values were selected as a matter of course as they provide a robust indicator of central tendency (i.e. robust to the effects of outliers). We verified that the mean values gave the same pattern of results.

EXPERIMENT ONE

Participants

Ten volunteers took part in the study in total (3 males, 7 females), aged 21- 40 years. Nine were right handed and one participant was left-handed. The left-handed participant used their preferred hand and we verified that their results followed the same pattern as the right-handed participants. All participants had normal or corrected to normal vision and none had any movement abnormalities or disabilities. All participants provided their informed consent prior to their inclusion in the studies. The study was approved by the University ethics committee and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

The participant sat on a height adjustable seat in front of a table with the start point located 5 cm from the edge of the table. Beyond the start point, the targets (coloured circles) were displayed on a board. The targets lay at different distances beyond the start point: 10 cm, 18 cm, 26 cm, 34 cm and 42 cm. The targets ranged in colour allowing the experimenter to indicate the next target goal in advance of the imperative stimulus to move. Two different boards were used. One board had small targets (0.8 cm in diameter) and an identical yet separate board was presented with large targets (3.8 cm in diameter). There were nine trials per condition. Participants were asked to repeat any trials where the stylus did not end on the target when the stylus first landed. This was less than 1% of all trials. The entire task consisted of 90 trials (45 to the small targets and 45 to the large targets). The experiment was counterbalanced so that half the participants aimed towards the large targets first, followed by the small targets, with the other half aiming towards the small targets first, then the large targets. Two way ANOVAs were conducted on the dependent variables with size and distance as factors.

Results

There were no reliable interactions between distance and size on any measure. Figure 1 (upper) illustrates the finding that there was no effect of distance [F (4,36) = 0.864; $P = 0.495$ NS] or target size [F (1,9)= 0.227; $P = 0.645$ NS] on reaction time. Nevertheless, there was a significant effect of distance [F (4,36) = 135.618; $P< 0.05$] and size [F (1,9) = 9.686; $P < 0.05$ NS] on peak speed (see Figure 1, middle). There was a significant effect of distance [F (4,36) = 67.24; $P< 0.05$] and size [F (1,9) = 18.04; $P< 0.05$] on movement time (Figure 1, lower).

These results confirm the lawful relationship that exists between movement time and both size and distance. Nevertheless, there was no effect of size or distance on RT, suggesting that the initiation time for an aiming movement is not reliably affected by the movement duration (which is a function of target size and movement amplitude). The subsequent experiments set out to explore the effect of target size and movement amplitude on RT when advance information was absent. If we discover that size or amplitude influences RT under these circumstances then it is reasonable to suppose that it is the preparation of the movement that has been affected (as the initiation time is not affected by these factors).

EXPERIMENT TWO

Eight participants took part in this experiment (4 males and 4 females) aged 19 to 23 years. The task requirements were similar to the first in that the participant had to aim towards a target with a stylus in as fast and accurate a manner as possible. However, this task differed with respect to the presentation of the target whereby the target would suddenly appear rather than being on constant display. Participants again sat at a height adjustable seat in front of a table with a flat computer screen lying on top of the tabletop. It was this screen that would eventually display the targets. A starting button (1cm x 1cm) was located 8cm from the table edge closest to the participant. The potential targets appeared one at a time in a vertically straight line, in line with the starting button. The screen was initially black and the target, which was a green dot, appeared against a white background after the participant had indicated they were ready. Two conditions were employed: (a) The circular targets remained constant in size (2.6 cm) and were presented at five different distances beyond the start point: 25, 31, 36, 41 and 45 cm; (b) the targets varied in size (0.8, 1.7, 2.6, 3.5 and 4.3 cm in diameter) but the distance remained constant (in the middle of the screen 36 cm from the starting position). The two conditions were embedded in a randomised fashion within the experiment so that all nine conditions were possible on any given trial.

The task required that the participant held the stylus upright on the start button in such a manner that it was depressed. When the participant indicated they were ready, an experimenter initiated recording and displayed the target. On presentation of the target, the participant's task was to make a swift but accurate movement towards the dot and finish by placing the stylus on the green dot. The time between the target appearing and the release of pressure from the start button represented the RT. The participant was instructed to move as quickly and accurately as possible and to remain in the finish position until told to move back to the start. Participants were asked to repeat any trials where the stylus did not end on the target when the stylus first landed. This was less than 1% of all trials. A period of 4 seconds was allowed to complete the task.

At the start of each testing session participants performed some practice trials in order to familiarise themselves with the task requirements and ensure that they were holding the stylus in a suitable manner. Following this, each testing session involved 81 trials being completed (nine trials for each of the size and distance combinations). It should be noted that the same nine trials were used for both the middle size target and the middle distance target, as these targets were identical. Each new trial did not commence until the participant indicated that they were ready. Two separate ANOVAs (one for distance and one for size) per dependant variable were conducted to explore the effect of distance and size. It was necessary to conduct two separate ANOVAs because the different sizes only appeared at one distance.

Results

In this experiment, distance had a statistically significant effect on reaction time [F (4,28) = 49.742; $P < 0.05$]. In contrast, target size did not have a significant effect on RT [F (4,28) = 0.589; $P = 0.673$ NS] as shown in Figure 2. There was also a significant effect of distance on peak speed [F (4,28) = 28.289; $P < 0.05$]. We found no effect of size on peak speed [F (4,28) = 1.292; $P = 0.297$ NS]. As in Experiment 1, distance [F (4,28) = 26.468; $P < 0.05$] and target size [F (4,28) = 11.455; $P < 0.05$] affected movement time. The left column of Figure 2 shows the effect of target size on RT, PS and MT whilst the effect of distance is shown in the right column.

In order to better understand the fact that target size altered movement time but not peak speed we also computed the time at which maximum speed was reached. We found that distance affected the time taken to reach peak speed [F (4,28) = 9.594; $P<0.05$] but there was no effect of size on the time taken to reach peak speed [F (4,28) = 0.222; $P = 0.924$ NS]. These results strongly suggest that the alterations in movement time as a function of target size are being driven by differences in the deceleration phase (presumably as a result of corrective adjustments). We tested this directly by using ANOVA to explore the relationship between deceleration time (time from peak speed to the end of the movement) and target size. As predicted, there was a reliable effect of target size on the duration of the deceleration phase [F (4,28) = 5.742; $p < 0.05$].

These results demonstrate again that, as expected, the size and distance of a target affect MT. Interestingly, the distance of the target affected RT. In contrast, there was no effect of target size on reaction time. The lack of a relationship between size and RT cannot be interpreted as showing that size does not affect preparation time. The problem is that the normal effect of target size on peak speed (larger targets produce faster peak speeds) was not present. This suggests that the only factor influencing the initial movement preparation was distance. The movement time was reliably altered but the time to peak speed was unaffected by size. This was because the disparities in movement duration to the different sized targets were caused by changes in the deceleration phase of the movement: the phase in which it is widely accepted that visually guided corrections are made (Elliott et al 2001).

The evidence therefore suggests that the participants programmed stereotypical movement patterns that altered only as a function of distance and made more or less on-line adjustments in the latter part of the movement according to the difference in target size from the average. The strategy adopted by the participants meant that we couldn't determine whether reaction time is affected by target size in the same way as it is affected by movement amplitude.

In the final experiment, we asked participants to aim at targets at different distances in two different blocks with each block using a different sized target. The results of Experiment 2 suggest that we should find RT is affected by target distance. We were confident that the manipulation would also ensure that participants would programme different movements as a function of target size (as indexed by peak speed and time to peak speed). Nevertheless, this design necessitates the participant knowing the size of the target in advance (although they can't programme the movement in advance as the target location is not known). This means that there are two possible results. We might find that reaction time alters as a function of target size in the same way as it is predicted to alter as a function of amplitude. Alternatively, we might find no effect of size on RT. In this latter case, no conclusions can be drawn regarding whether size affects preparation time or not. Moreover, one would be able to conclude (at a practical level) that even if target size does influence RT it is not possible to measure the effect (given the strategies employed by participants) in experiments of this type.

EXPERIMENT THREE

Ten participants took part (2 males and 8 females) aged 21 to 40 years. The third experiment was similar to the previous experiments in that both the size and distance of the targets were manipulated, although the layout of the experiment was slightly different. Participants had to aim towards a green circular target with a stylus. The targets appeared in one of five different distances (25, 31, 36, 41 and 45 cm). The targets were presented in two different (counter-balanced) blocks. One block used a large sized target (2 cm in diameter) and the other block used a smaller target (1 cm in diameter). Participants were asked to repeat any trials where the stylus did not end on the target when the stylus first landed. This was less than 1% of all trials. There were 90 trials, 45 per block, with target size randomised across and between participants. The experiment was counterbalanced so that half the participants aimed towards the large targets first, followed by the small targets, with the other half aiming towards the small targets first, then the large targets. Two way ANOVAs were conducted on the dependent variables with size and distance as factors.

Results

There were no reliable interactions between distance and size on any measure. Distance had a significant effect on reaction time, [F (4,36)=218.748; $P < 0.05$], but size had no reliable effect on RT, [F (1,9) = 0.051; $P = 0.827$ NS]. There was a significant effect of distance on peak speed, F (4,36) = 77.174; $P < 0.05$ and there was a significant effect of size on peak speed, F (1,9) = 5.881; $P < 0.05$. There was a significant effect of distance [F (4,36) = 23.262; $P < 0.05$] and size [F (1,9) = 5.819; $P < 0.05$] on movement time. These results are displayed in Figure 3. The effect of size on peak speed suggests that the participants were programming different movements on the basis of target size. Thus, the target size manipulation is altering the programmed movement but this did not have any notable impact upon the preparation time (as indexed by reaction time). It is always difficult to interpret a failure to reject the null hypothesis but at a practical level these findings indicate that these reaction time experiments are unable to determine whether any differences in preparation time exist as a function of target size. Note that target size was pre-cued in this experimental design, leaving the possibility that target size might influence RT when no advance information is provided.

GENERAL DISCUSSION

We studied whether altering target distance affects the time taken to prepare and initiate movement in an aiming task, in the same way that distance influences movement duration (Fitts 1954). Our findings suggest that initiation time is not affected by target distance (i.e. if advance preparation is allowed then RT is unaffected by distance). In Experiment 2 where no advance information was provided, we found that distance reliably influenced reaction time (the further the distance, the larger the RT). In a third experiment, participants again produced longer RTs, slower movement times and higher peak speeds with increased distance. Nonetheless, there was no reliable effect of target size on RT, despite size influencing movement duration and peak speed. This result shows unequivocally that there is no simple direct relationship between RT and movement time in aiming movements. This finding refutes a previous hypothesis that there is a direct and fixed relationship between these variables (see Klapp 1996 for a review).

The influence of task difficulty on movement time is well captured by Equation (2). The results of this experiment allow us to describe the relationship between amplitude and RT in experiments of this type in the following manner:

$$RT = a + b \log_2 (A) \qquad (3)$$

where a and b are constants that depend upon the individual and the task. The relationship might arise because of the greater number of possible trajectories associated with larger movements. The larger number of possibilities (higher levels of 'redundancy') might increase the time taken to select the appropriate action, but this notion must remain as a working hypothesis at this stage. Nevertheless, this hypothesis can be readily tested and recent research on Hick's law provides some support for our account. Hick (1952) discovered that a lawful relationship exists between reaction time (RT) and the number of response choices: reaction time increases linearly as a logarithmic function of the number of possible responses (the stimulus-response uncertainty effect). More recently, doubts have been raised as to the generality of Hick's law. For example, Kveraga, Boucher and Hughes (2002) found that human saccades did not operate in accordance with Hick's law: i.e. saccadic latencies were unaffected by stimulus response uncertainty. Kveraga et al suggested that saccades are so well learned that selecting the appropriate motor response (the saccade) is not a time consuming process (because the appropriate gaze orientation response will almost inevitably be produced by the same pattern of extraocular muscle activity). In other words, Kveraga et al. (2002) suggested that Hick's law arises when there is redundancy associated with the actions used to explore the effect. The prediction from Kveraga et al.'s hypothesis is that movements with less redundancy will be more likely to violate Hick's law. In support of the Kveraga et al. (2002) hypothesis, Wright, Marino, Belovsky and Chubb (2007) have reported that short aiming movements can be unaffected by stimulus-response uncertainty. Wright and colleagues asked participants to make short (12.7 to 17cm) movements to eight targets distributed in a semicircle. They found that the latency of the aimed hand movements was independent of uncertainty.

One issue we were unable to resolve within the present study was whether RT is affected by target size when no advance information is provided. Experiment 1 showed that initiation time is not affected by size. Nevertheless, our attempt to manipulate target size in the absence of advance information (Experiment 2) was thwarted because the participants programmed the same movement regardless of size (as indexed by peak speed and time to peak speed) and then adjusted the movement in the deceleration phase. In an attempt to determine whether the relationship between RT and distance was mediated by movement duration, we used blocks involving targets of different size in Experiment 3 but this meant that the participants had advance information about size. Thus, the present experiments cannot resolve the issue of the relationship between RT and target size. There is one study (Klapp 1975) that did find a relationship between target size and RT when small amplitude (0.2 and 1.1cm) movements were made and advance information was available. Figure 4 plots the data from Klapp (1975). It can be seen that there is no clear effect of target distance in these data (although the 33.6 cm data have longer RTs than the 7cm data). The finding of a size effect seems likely to relate to the small amplitude movements used by Klapp in comparison to the amplitudes studied in the present experiments (<2cm versus >10cm).

Previous research has shown that it takes longer to react when generating a series of movements than when making a single action (e.g. Christina 1992; Fischman 1984; Klapp & Erwin 1976; Rosenbaum & Patashnik 1980; Quinn et al 1980; Klapp 1996; Khan et al 2006). These data can be interpreted as showing that the selection of more complex actions takes longer (because there are more possible trajectories). This interpretation implies that movement preparation involves selecting specific existing internal model(s) rather than adjusting the parameters of a generic motor programme. Sidaway, Sekiya & Fairbrother (1995) and Lajoie & Franks (1997) have shown that decreasing the size of a second target in a serial aiming task produces an increase in the time taken to generate a movement to the first target (i.e. reaction time increases). These data can be explained by the increased need to select an accurate action sequence in advance. If the second movement has low accuracy demands then there are less constraints and this might speed the initial action selection process. This account suggests that action-selection processes are responsible for the changes in RT: the same mechanism that we have suggested mediates the effect of distance on RT.

In conclusion, it seems the manner in which distance influences RT provides a reliable index of performance against which change can be measured. We would argue that our results have practical benefit as they allow the researcher (or clinician) to use aiming movements to determine how other task factors (or individual differences) impact upon objective quantifiable measures. The results also raise the interesting theoretical issue of why movement preparation time is longer for movements of greater amplitude. We have provided a hypothesis based on action-selection processes to account for this finding and anticipate future studies will address this issue.

REFERENCES

Christina, R.W. (1992). The 1991 C.H. McCloy research lecture: Unravelling the mystery of response complexity in skilled movement. *Research Quarterly for Exercise and Sport* 63, 218-230

Elliott, D., Helsen, W.F., & Chua, R. (2001). A century later: Woodworth's (1899) two-component model of goal-directed aiming. *Psychological Bulletin* 127, 342-357

Fischman, M.G. (1984). Programming time as a function of number of movement parts and changes in movement direction. *Journal of Motor Behavior* 16, 405-423

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of the 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

Henry, F.M., & Rogers, D.E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly* 31, 448-458

Hick, W.E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology* 4, 11-26

Kveraga, K.V., Boucher, L., & Hughes, H.C. (2002). Saccades operate in violation of Hick's Law. *Experimental Brain Research,* **146,** 307-314

Kerr, R. (1978). Diving, adaptation and Fitts' law. *Journal of Motor Behavior,* 10, 255-260

Khan, M.A., Buckolz, E., & Franks, I.M., (2006). Programming strategies for rapid aiming movements under simple and choice reaction time conditions. *Quarterly Journal of Experimental Psychology*. 59, 524-542

Klapp, S. (1975). T Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology: Human Perception and Performance* **1,** 147-153.

Klapp, S.T. (1996). Reaction time analysis of central motor control. In H.N. Zelaznik (Ed.) Advances in motor learning and control (pp 13-35). Champaign, IL: Human Kinetics

Klapp, S.T., & Erwin, C.I. (1976). Relation between programming time and duration of the response being programmed. *Journal of Experimental Psychology: Human Perception and Performance* **2,** 591-598

Lajoie, J.M., & Franks, I.M. (1997). The control of rapid aiming movements: Variations in response accuracy and complexity. *Acta Psychologica,* 97, 289-305

MacKenzie, I. S. (1989). A note on the information-theoretic basis for Fitts' law. *Journal of Motor Behavior*, *21*, 323-330

Plamondon, R., Alimi, A.M. (1997). Speed/Accuracy Trade-Offs in Target-Directed Movements. *Behavioral and Brain Sciences, 20,* 279-349

Riek, S., Tresilian, J.R., Mon-Williams, M., Coppard, V.L., & Carson, R.G. (2003) Bimanual aiming and overt attention: one law for two hands. *Experimental Brain Research,* 153, 59-75

Rosenbaum, D.A., & Patashnik, O. (1980). Time to time in the human motor system. In R.S. Nickerson (Ed.) *Attention and Performance VIII* (pp 93-106) Hillsdale, NJ: Erlbaum.

Schmidt, R. A. & Lee, T. D. (1999). *Motor control and learning: A behavioral emphasis*. Human Kinetics.

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

Sidaway, B., Sekiya, H., & Fairweather, M. (1995). Movement variability as a function of accuracy demand in programmed serial aiming responses. *Journal of Motor Behavior,* 27, 67-76

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

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

Wright, C.E., Marino, V.F., Belovsky, S.A. and Chubb, C. (2007) Visually guided, aimed movements can be unaffected by stimulus-response uncertainty. *Experimental Brain Research*, **179,** 475-96

FIGURE CAPTIONS

Figure 1. Reaction time (upper), peak speed (middle) and movement time (lower) in ms plotted as a function of logarithmic target distance. The symbols indicate different size targets, ● represents a big target (3.8 cm) and ○ a small target (0.8 cm). The line shows the least-square quadratic regression across each condition. Results showed no effect of size or distance on reaction time, whilst a significant increase was observed for peak speed and movement time as the distance increased. Varying the target size showed a significant increase in peak speed for big targets and a significant increase in movement time for the small targets.

Figure 2. Reaction time, peak speed and movement time in ms plotted as a function of logarithmic target distance (left column) and logarithmic target size (right column). In the left column graphs target size remained constant (2.6 cm) and distance varied (25, 31, 36, 41 & 45 cm), whilst the right hand column graphs show distance remaining constant (36 cm) and size varying (0.8, 1.7, 2.6, 3.5 & 4.3 cm). The lines show the least-square quadratic regression across each condition. Results showed a significant effect of distance on reaction time and peak speed but size had no effect. With movement time there were significant effects of both distance and size.

Figure 3. Reaction time (upper), peak speed (middle) and movement time (lower) in ms plotted as a function of logarithmic target distance. The symbols indicate different size targets, ● represents a big target (2 cm) and ○ a small target (1 cm). The line shows the least-square quadratic regression across each condition. Results showed a significant effect of

distance on reaction time but size had no effect. There were also significant effects of distance and size on peak speed and movement time.

Figure 4. The reaction time data from Klapp (1975) plotted against the average target size (Klapp's small, medium and large categories). The different symbols show the results for the different distances tested. It can be seen that Klapp found a relationship between target size and RT when small amplitude (0.2 and 1.1cm) movements were made and advance information was available. It can be seen that there is no clear effect of target distance in these data (although the 33.6 cm data have longer RTs than the 7cm data).

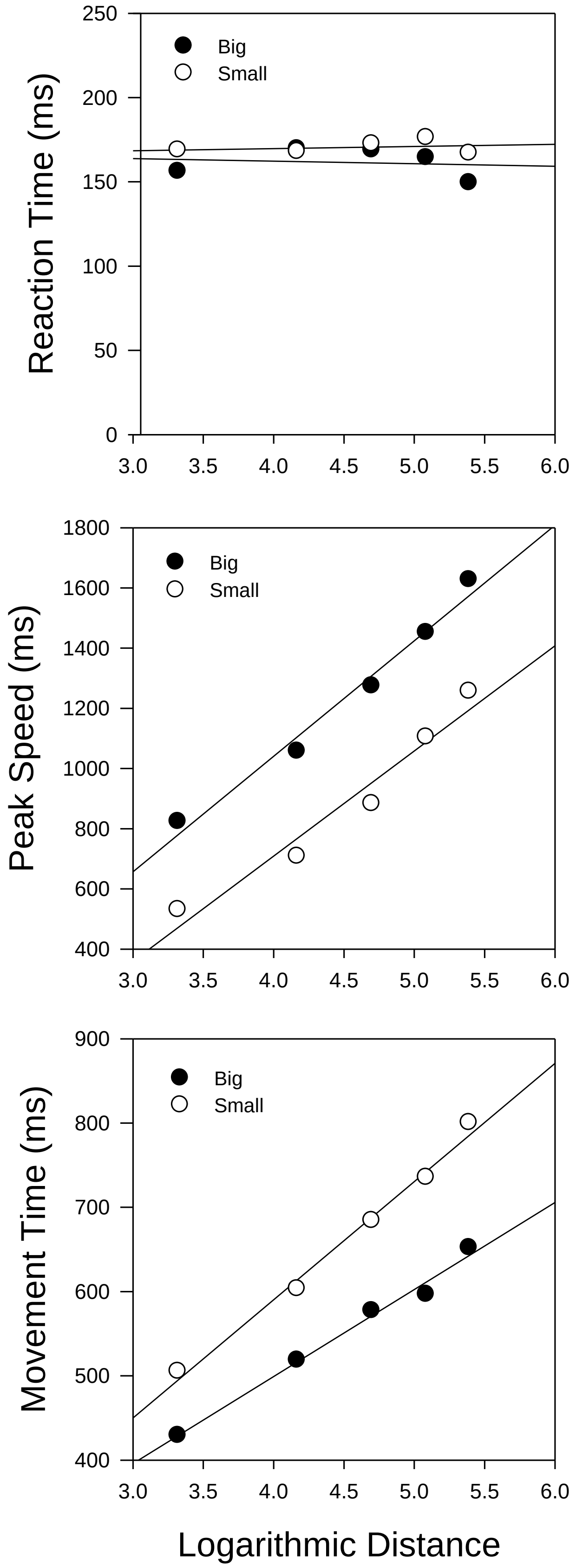
Reaction Time (ms)
Big
Small
0
50
100
150
200
250
Peak Speed (ms)
400
600
800
1000
1200
1400
1600
1800
Movement Time (ms)
400
500
600
700
800
900
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Logarithmic Distance

Figure 1

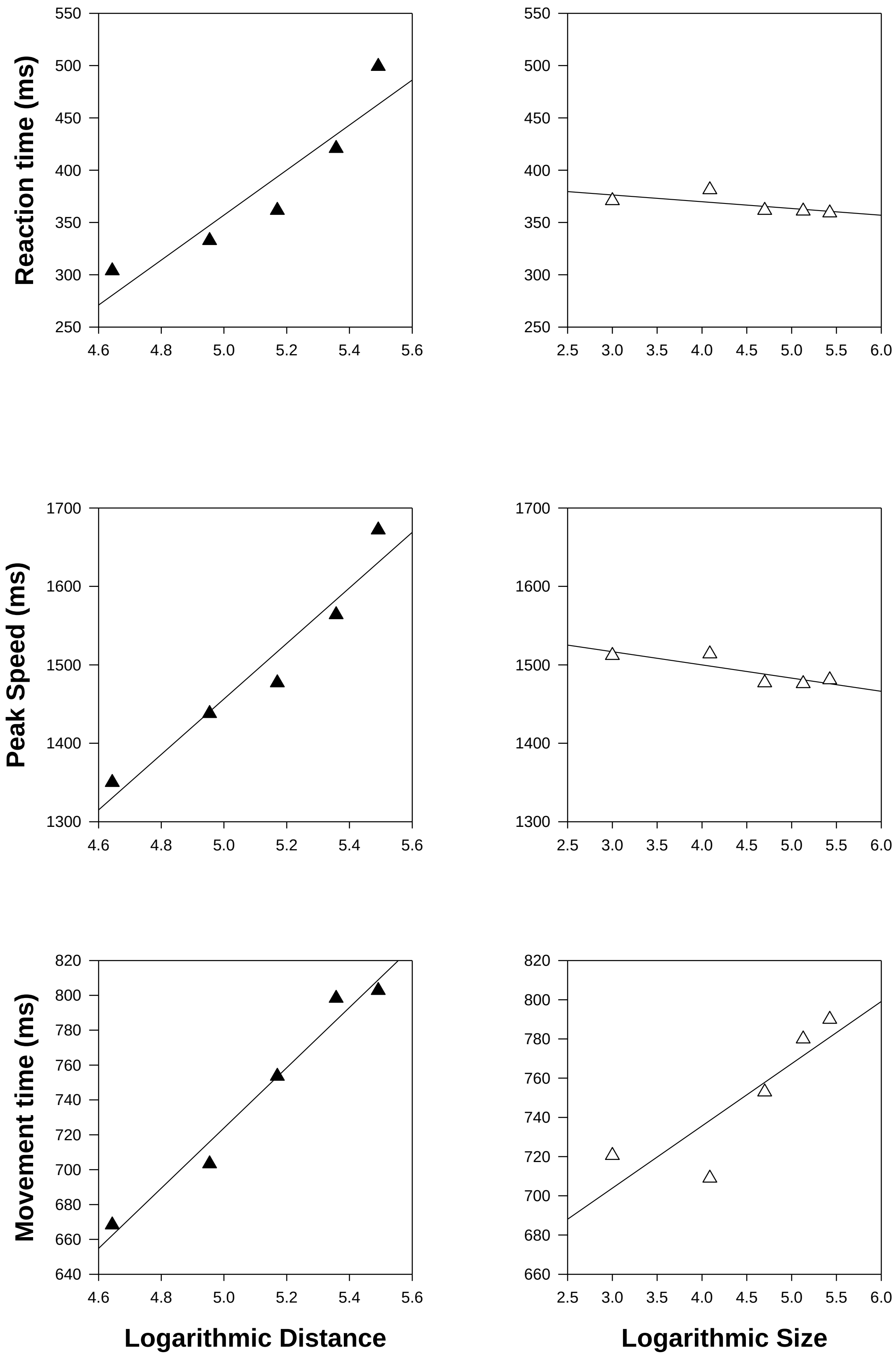
Reaction time (ms)
Peak Speed (ms)
Movement time (ms)
Logarithmic Distance
Logarithmic Size
550
500
450
400
350
300
250
1700
1600
1500
1400
1300
820
800
780
760
740
720
700
680
660
640
4.6
4.8
5.0
5.2
5.4
5.6
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Figure 2

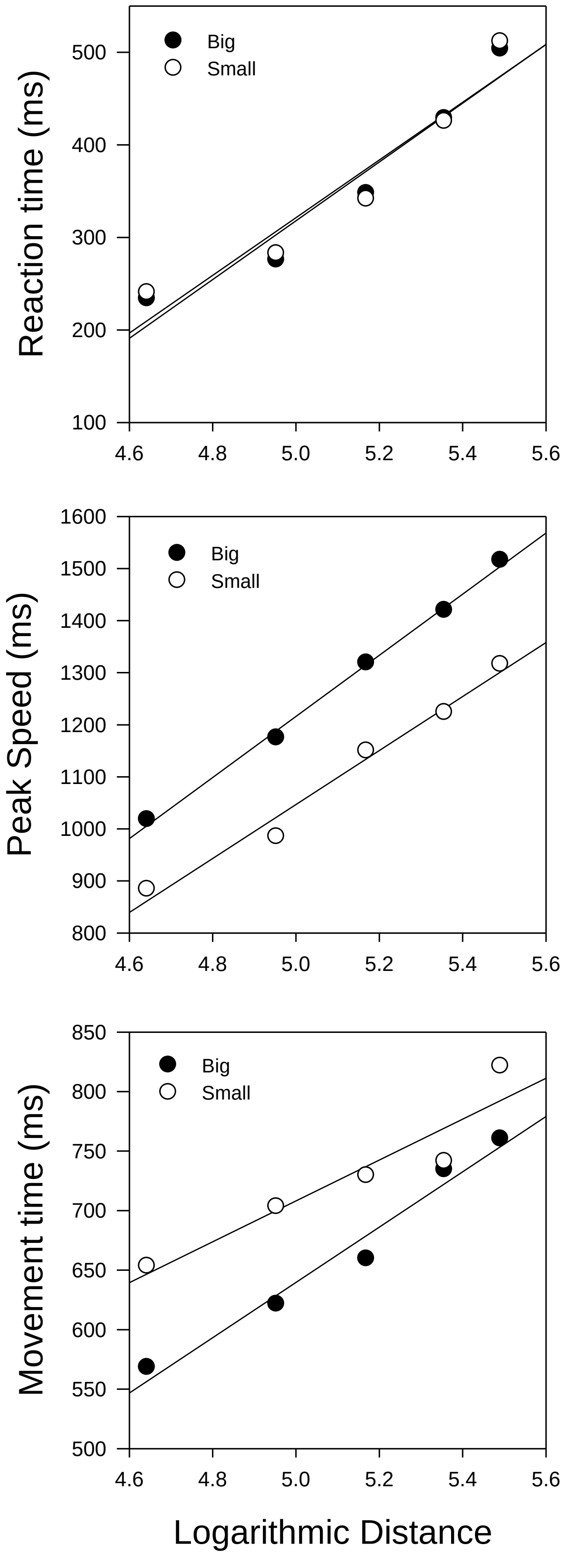
Big
Small
Reaction time (ms)
500
400
300
200
100
4.6
4.8
5.0
5.2
5.4
5.6
Big
Small
Peak Speed (ms)
1600
1500
1400
1300
1200
1100
1000
900
800
4.6
4.8
5.0
5.2
5.4
5.6
Big
Small
Movement time (ms)
850
800
750
700
650
600
550
500
4.6
4.8
5.0
5.2
5.4
5.6
Logarithmic Distance

Figure 3

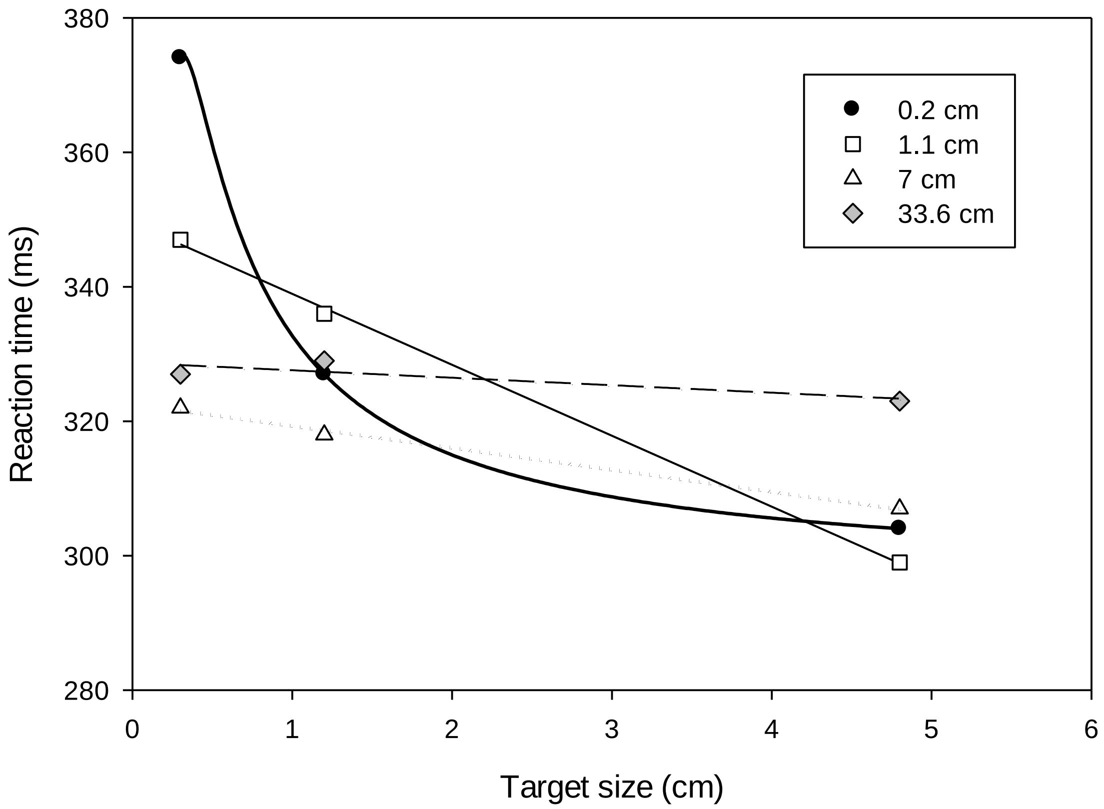
380
360
340
320
300
280
Reaction time (ms)
0
1
2
3
4
5
6
Target size (cm)
0.2 cm
1.1 cm
7 cm
33.6 cm

Figure 4