Fitts's Law Studies of Directional Mouse Movement

James Boritz[1]
Kellogg S. Booth[2]
William B. Cowan

Computer Graphics Laboratory
University of Waterloo
Waterloo, Ontario, Canada N2L 3G1

Abstract

An experiment was conducted to test the hypothesis that there is a relationship between the direction of motion (angle) and the time required to move the mouse tracker to a target and that this relationship depends on the handedness of the user. This was done by testing the time required for subjects to perform a target acquisition task similar to item selection in a pie-shaped menu. Target size, distance and angular placement were varied, with both right handed and left handed subjects tested. A high correlation was found between the empirical data and the predicted behavior according to the standard formulation of Fitts's Law that involves only target size and distance. Right handed subjects showed interesting variations in Fitts's Law parameters when the target angle was varied. Left handed subjects, contrarily, showed no effect. Possible rules of thumb involving tradeoffs between speed and accuracy are suggested by the results, as are a variety of open questions for future research.

Résumé

Une étude fut conduite pour vérifier l'hypothèse q'uil y aurait une relation entre la direction de mouvement (angle) and le temps nécessaire pour pointer une souris sur une cible, et que cette relation dependrait de la chiralité de l'utilisateur. Dans cette étude, des sujets devaient choisir un item dans un menu circulaire. La grosseur de la cible, sa position et le déplacement angulaire étaient changés et ce, pour des sujets droitiers et gauchers. Une forte corrélation fut établie entre les données empiriques et le comportement prévu suivant la formulation courante de la loi de Fitt basée seulement sur la grosseur de la cible et son éloignement. Les droitiers ont démontré des variations interessantes dans les paramètres de la loi de Fitt lorsque l'angle de la cible était modifié. Les gauchers, au contraire, n'ont pas semblé affectés par ces variations. Les résultats suggèrent des règles empiriques pour un compromis entre la vitesse et la précision. Finalement, plusieurs questions sans réponse sont présentées, sujettes à des recherches ultérieures.

Keywords: Circular Menus, Experiment, Fitts's Law, Handedness, Human Performance, Mouse, Pie-shaped Menu, User Interface.

1. Introduction

The layout and style of menus is an important and often-discussed aspect of user interface design. A number of studies have investigated the relative ease of using pie-shaped (circular) menus in contrast to more traditional linear menus. An informal analysis of data reported in one of those studies [3] suggests that the direction of motion might effect the speed at which menu item selection is performed when pie-shaped menus are employed. A preliminary study to explore that hypothesis was conducted in our laboratory using Fitts's Law as a theoretical model of user performance. It indicated that there might be an angular component to Fitts's Law as it relates target acquisition time to target size and to target location for the menu item selection task using pie-shaped menus. This hypothesis led to a formal experiment to test the possibility that there is a relationship between the direction of motion (angle) and the time required to move the mouse tracker to a target and that this relationship depends on the handedness of the user.

The formal experiment measured the time required for subjects to perform a target acquisition task similar to item selection in a pie-shaped menu. Targets varied in size, in distance from the initial mouse tracker position at the center of the menu, and in angular placement around the center of the menu. Both right handed and left handed subjects were tested. Each subject was tested in two sessions, one using the dominant hand, the other using the non-dominant hand. A high correlation was found between the empirical data and the predicted behavior according to the standard formulation of Fitts's Law that involves only target size and distance. There was no significant effect for left handed subjects, but there was for right handed subjects who showed an effect of angle that varied according to hand use.

[1] Present address: Alias Research Inc., Style! Division, 110 Richmond Street East, Toronto, Ontario, Canada M5C 1P1.

[2] Present address: Department of Computer Science, The University of British Columbia, 6356 Agricultural Road, Vancouver, British Columbia, Canada V6T 1Z2.

This paper reports on the results of the experiment and comments on possible guidelines for the design of menu systems involving speed-accuracy tradeoffs that are suggested by the results of the experiment. Section 2 describes Fitts's Law and reviews previous work related to our research. Section 3 provides an overview of the experiment and the methodology employed. Section 4 discusses the analysis of the data and the results obtained. Section 5 provides concluding remarks and suggestions for future work. The importance of having a flexible system for conducting this type of research, both for formal experiments and informal prototypes, is discussed in the context of the current work. References to more complete descriptions of the experiment system are provided at the end of Section 5.

2. Fitts's Law and Previous Work

The Keystroke-Level Model of Card, Moran and Newell [5] is a low-level description of a single task, such as menu item selection, that decomposes the task into the discrete operations performed by an expert user while completing the task. The time to complete the task is expressed as the sum of a number of terms related to the operations or subtasks involved, according to the following formula.

$$T = T_k + T_p + T_h + T_m$$

The various terms are as follows for the task of selecting an item from a menu using a mouse.

- T time required to complete the menu item selection task
- T_k time required for the button pushes (keystrokes) that initiate or terminate a menu item selection
- T_p time required to position the mouse at the desired menu item by hand movement
- T_h time required to home onto the mouse with the hands prior to positioning
- T_m time required to mentally prepare for the actions

The Keystroke-Level Model has been well studied and its appropriateness validated for a number of tasks related to user interfaces, including tasks such as menu item selection [5]. Another low-level description, the Model Human Processor defined by Card [4], breaks human performance into perceptual, cognitive and motor components, each operating at empirically determined fundamental human limits. Using this model, an equation for the positioning time required for menu item selection (T_p) can be derived that has a motor component known as Fitts's Law [7], which is based on a theoretical formulation of the information processing capacity of the human motor system. Fitts's Law predicts that increasing the distance to the target or decreasing the size of the target causes the time necessary to acquire the target to increase.

An often used form of this is the equation

$$T = K_0 + K_1 \log_2 (D/S + 0.5)$$

where T is the motor time, K_0 and K_1 are constants, D is the distance that must be moved, S is the size of the target (in this case the size of a menu item), and the additive term 0.5 within the logarithm is a correction proposed by Welford [10] that is used in many studies. If the constant K_0 is extended to subsume the constants T_k, T_h and T_m, with the remaining logarithmic term being T_p, this equation incorporates all of the terms from the Keystroke-Level Model. This is the form of Fitts's Law used in the remainder of the discussion.

Callahan et al. [3] performed a study comparing the selection times for items in pie-shaped menus with those in linear menus. A pie-shaped menu is one in which items are arranged along the circumference of a circle (Figure 1).

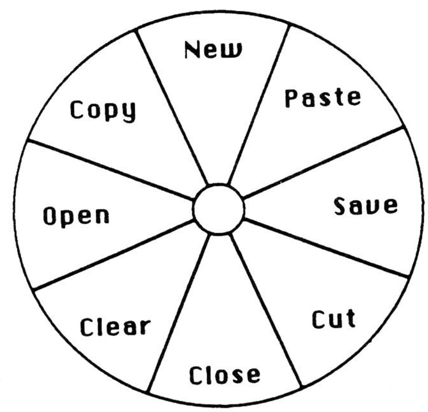

Figure 1. A pie-shaped menu. The inner circle is where the mouse tracker resides when the menu first appears. The pie-shaped wedges between the inner and outer circles represent the activation regions for the (eight) menu items.

In the experiment, as with most implementations of pie-shaped menus, the center of the menu was the starting point for the mouse tracker. Thus all items in the pie-shaped menu were equidistant from the starting point. This contrasts with typical linear menus in which items are arranged in a vertical or horizontal list with the starting point for the mouse tracker being near the topmost or leftmost item in the list (Figure 2).

3. The Experiment

A prototype experiment was conducted based on an informal analysis of the results presented in a conference talk describing the experiment of Callahan et al. in which pie-shaped and linear menus were compared. The prototype involved two of the current authors as subjects, one left handed and one right handed. It was implemented using a flexible environment designed for conducting a variety of cognitive psychology experiments, both formal and informal, with an emphasis on experiments that define quantitative parameters of real-time human performance [1,6].

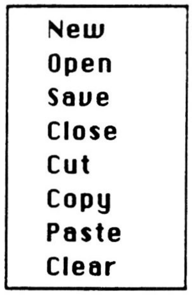

Figure 2. A typical linear menu. The activation region is the rectangular area bounded by the edges of the menu and by the (invisible) boundaries between the menu items. The mouse tracker initially resides at the top of the menu.

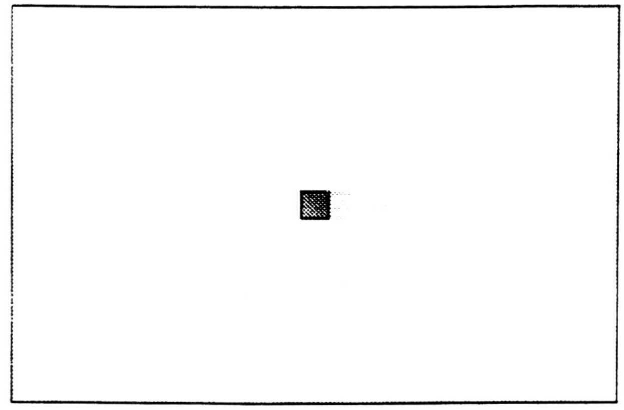

Figure 3. The experiment screen before the subject depresses a mouse button, when only the starting position and the mouse tracker are displayed. Each trial begins when a button is depressed.

The results of the prototype suggested that there might be an effect of angle for menu item selection of small targets close to the starting position and that for some angles there was a mirror-image (left-to-right reversal) of the rank of performance times determined by the handedness of the subject. In the informal experiment subjects used both dominant and non-dominant hands, but no record was kept of the hand used in a given session, so it was not clear how to interpret the results other than to conclude that some effect might exist.

The formal experiment was designed to test the hypothesis that selection times for small targets close to the starting position of the mouse tracker differ based on the angular position of the item to be selected from a pie-shaped menu. The experiment was a 2x2x2x2 factorial design in which each cell is an element of the cross product of hand dominance, hand use, target size and target distance.

Subjects completed a handedness inventory [9] at the beginning of the experiment session to determine the dominant hand. Each subject participated in two sessions, one using the dominant hand, the other using the non-dominant one. The order of sessions was balanced among subjects of each handedness. Two target sizes (11x11 pixels and 17x17 pixels) and two target distances (30 pixels and 60 pixels) from the starting position were used. Subjects performed the experiment for all cells in the experiment matrix corresponding to their hand dominance in accordance with a blocking scheme to counter-balance the order in which conditions were presented.

In each experiment block, the target size and target distance were held constant and the hand used by the subject was held constant. Eight target positions, spaced equally around a circle starting at the far right (0°) and continuing counterclockwise in 45° increments, were used. Each angle was repeated six times within each cell for a total of 48 trials per cell, with the trials randomized within a cell. The 48 trials were preceded by six familiarization trials of the same target size and target distance.

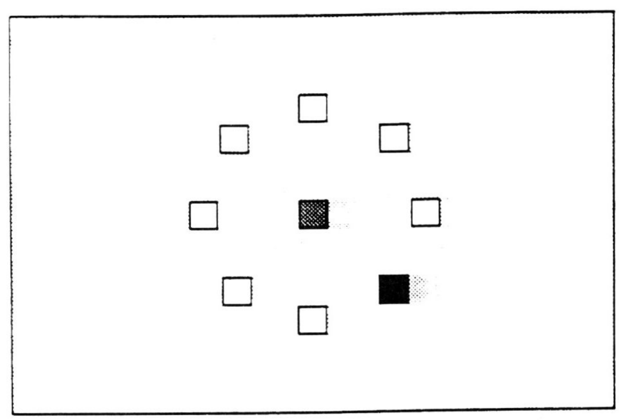

Figure 4. The experiment screen with the targets revealed after the subject has depressed a mouse button. One of the targets is displayed in red to indicate that it is the target to be acquired.

Each trial was initiated by the subject pressing a mouse button. While keeping the mouse button depressed, the subject visually searched for and moved the mouse tracker to the required target. When target size and distance were considered, a high correlation was found between the results and the predictions of Fitts's Law. The exact sequence of events was as follows.

(1) A bright green square, the start object, is displayed in the centre of a black screen with an X representing the mouse tracker displayed over it. The mouse tracker can be moved, but must remain over the start object for the trial to be valid (see Figure 3).

(2) The subject starts the trial by depressing any mouse button while the mouse tracker is over the start object. This causes eight potential targets to appear in each of the eight octants equally spaced around the start object.· One of the targets is displayed as dull red, the others are all displayed as white (see Figure 4).

(3) The subject visually searches for the red target.

(4) The subject moves the mouse to position the mouse tracker over the desired target (presumably the red one). As the mouse tracker moves off the start object it becomes a dull green. When the mouse tracker moves over the target it becomes a bright red.

(5) When the target is bright red, the subject releases the mouse button and the trial terminates. All targets are immediately removed from the display and the start object is then removed after about 100 milliseconds. Releasing the mouse button before the correct target has been acquired results in a failed trial.

Steps 3-5 may proceed in parallel if the subject chooses to move the mouse tracker prior to visually acquiring the appropriate target. This in fact was observed to happen in the experiment. The selection time for a trial is considered to be the time from the mouse down event that begins the trial until the mouse up event that terminates the trial. The times for all events within each trial were logged and a record was kept of the mouse trajectories.

Figure 5 provides a schematic representation of the experimental setup showing the location of the subject in front of a display monitor and mouse with the experimenter sitting behind the subject using a Unix workstation and a special-purpose psychology workstation to administer the experiment.

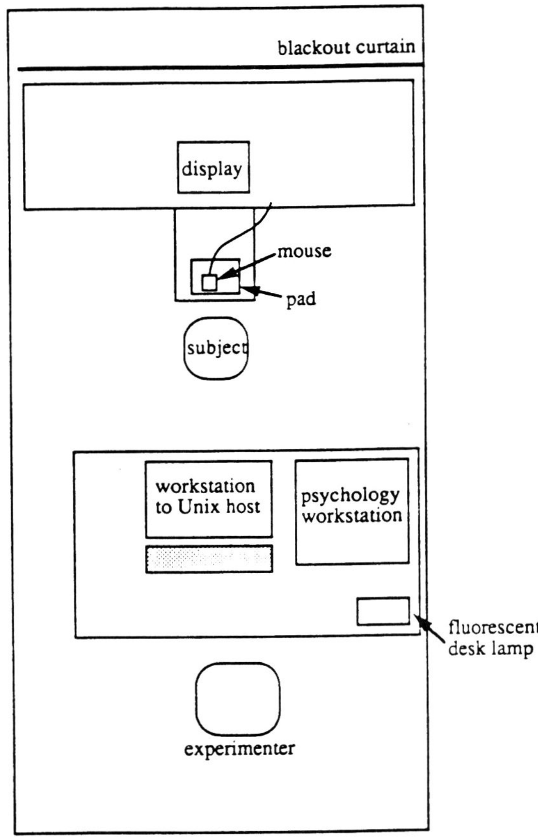

Figure 5. Organization of the experiment room showing the location of the experimenter, the subject, and the major pieces of equipment.

4. Results

There were a total of 9,216 trials over all subjects in the experiment. Failed trials and trials in which target selection required more than 2.5 seconds were excluded from the analysis. There were 8,729 trials used in the analysis, corresponding to an error rate of about 5%. Table 1 shows the mean selection time for each of the sixteen conditions of the experiment.

A multivariate analysis of variance (MANOVA) was performed on the data as a whole. It showed a significant difference for angle $F(7,8675)=4.53$, $p<0.0001$. As expected, target size had a significant effect $F(1,8675)=865.58$, $p<0.0001$ with large targets selected faster than small targets. Distance had a significant effect $F(1,8675)=944.77$, $p<0.0001$ with near targets selected faster than far targets. The dominant/non-dominant hand of the subject had a significant effect $F(1,8675)=30.37$, $p<0.0001$ with subjects being faster with their dominant hand. The hand used by subjects (independent of dominance) was significant $F(1,8675)=337.89$, $p<0.0001$ with subjects performing better with their right hands.

The remainder of the analysis examined the experimental conditions individually to determine if performance differences due to angle actually occurred. A MANOVA for all dominant left handed subjects revealed no significant effect of angle for any of the experimental conditions. For this reason, the remainder of this sections deals only with the experimental conditions for dominant right handed subjects. Table 2 shows the results of the ANOVAs performed for each of the eight cases involving dominant right handed subjects.

Four of the experimental conditions for dominant right handed subjects showed significant effects of angle at the $p\leq 0.05$ level. These conditions were

(1) subjects using their right hands with small targets near the starting position,

(2) subjects using their right hands with small targets far the starting position,

(3) subjects using their left hands with small targets near the starting position,

(4) subjects using their left hands with large targets near the starting position.

Table 3 shows the mean selection times by angle for the four conditions in which a significant effect of angle exists at the alpha=0.05 level. An examination of the rank ordering of those means in Table 4 shows that for the two conditions in which subjects use their right hands, selection of the target at 0° (straight to the right) is always fastest and selection of the target at 270° (straight down) is always slowest.

In the conditions where subjects use their left hand, selection of the target at 180° (straight to the left) is always fastest followed by the target at 135° (diagonally up and to the left). The target at 270° is slowest for the condition with large targets, and only a few thousandths of a second from being slowest for the condition with small targets.

A Tukey analysis [8, pp. 352-353] was performed to determine which means in the ANOVA were statistically significant. The analysis indicates that there is a statistically significant difference in selection times only between the fastest angle and the slowest angle in each condition. The only exception is the left near case, where there is also a significant difference between the fastest angle and the second slowest angle.

A regression analysis shows a very strong correlation between the experimental data and the prediction of Fitts's Law. The equation of the regression line shown in Figure 6 is

$$T = 1.32 + 0.43 \log_2 (D/S + 0.5) .$$

The equation has a standard error of 0.03 and accounts for 97% of the variance of the means for each target distance and target size combination. The value of 0.43 observed in this study for the constant K_1 is approximately four times greater than the value found by other researchers. The value of 1.32 for K_0 is well within the range established by other researchers.

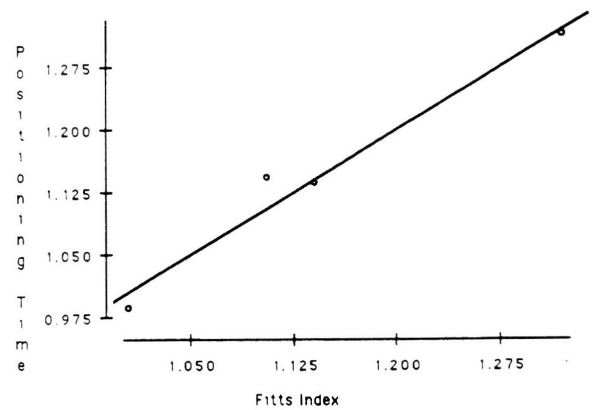

Figure 6. Selection time as a function of the Fitts's Law prediction illustrating the close agreement with the empirical results obtained in the experiment.

5. Conclusions

The experiment supports the hypothesis that there is a performance difference based on angle for small targets close to the starting point of the mouse tracker, and that this performance difference is statistically significant only for the fastest and slowest selection times in each condition. For right handed subjects using their right hands, movement to the right is always fastest. Movement straight down is always slowest. For right handed subjects using their left hands, movement to the left is always fastest. Movement straight down is again always slowest. The lack of any statistical significance due to angle for the dominant left handed subjects is puzzling. It is perhaps explained by an aspect of the subject population that was revealed by the questionaire.

Twenty-four subjects participated in the experiment, all with some previous experience (at least 20-40 hours) using a mouse. According to a modified version of the Edinburgh Inventory [9], eight of these were left handed, the remaining sixteen being right handed. A question added to the inventory asked subjects which hand was normally used to control the mouse. All of the right handed subjects and all but one of the left handed subjects reported using the right hand. This is believed to be the result of all subjects having received their mouse experience in a first-year computer science laboratory in which the mice are permanently attached to the right side of the Macintosh workstations to prevent theft. The anomalous left handed subject owned a personal Macintosh for which the mouse was configured on the left. This unusual pattern of mouse usage probably explains the behaviour of our left handed subjects. Future experiments using a less restricted subject pool are planned in the expectation that they will help us to understand this anomaly.

The data is consistent with a stronger hypothesis, which should be tested in a subsequent experiment, that subjects are faster with their preferred hand. One explanation for this is that users learn strategies with their preferred hand, of which the directional preferences measured in our experiment for right handers are an example. The left handed subjects in our study (with one exception) have not had a chance to learn these strategies, so they do not show the effect. If this stronger hypothesis is supported by experimental evidence, then one recommendation that follows is that it is very important to give left handed users encouragement for using their left hand. Otherwise they will always be at a disadvantage because they are not able to acquire these strategies as well with their non-preferred hand.

The experimental results suggest that target size may play a more important role in pie-shaped menus than distance to the target. Three out of four of the experimental conditions using small targets show a significant effect of angle at the $p \leq 0.05$ level with a fourth condition significant at the $p \leq 0.062$ level. Only a single condition for large targets showed a significant effect at the $p \leq 0.05$ level.

Although further experiments are required to determine the importance of these effects in real applications, this experiment does suggest that angular effects do exist for the short distances and small targets characteristic of pie-shaped menus and that the angular effects play a role in the effectiveness of menu layout. The differences in selection times are not large (well less than a factor of two) and thus are not likely to have a major influence on the time required to complete an application because the total time spent making menu item selections even in interaction-intensive applications is still a relatively small percentage of the total effort. But the correlation of response time with error rate indicates that errors, which are very costly, can be reduced by proper use of our results.

The implications for menu layout are speculative at this point, but the experiment suggests that there are definite differences in performance between menu items placed at different angular positions and that these differences may change with the handedness of the user. One result of this could be a speed-accuracy tradeoff that would dictate the placement of "dangerous" menu items in positions known to have long selection times (the bottom-most position) because they provide the best opportunity for a user to intercept a possibly erroneous selection. Similarly, "safe" menu items should be placed on the right side of the menu, at least for right handed users, with the reverse possibly the case for left handed users.

A subsequent analysis of the number of errors made in each of the sixteen different conditions tested in the experiment reveals some definite patterns.

(1) Using the dominant hand produces fast inaccurate responses; using the non-dominant hand produces slow accurate responses.

(2) Dominant right hand and dominant left hand are about equally hard. Dominant right exhibits a lot more variability, some very slow with high error rates, some very fast with low error rates. Dominant left is a lot more clustered.

(3) Far targets are a little harder than near targets. Near targets tend to generate fast response times with high error rates; far targets the reverse.

(4) Small targets are hard; large targets are easy.

(5) Two anomalous conditions have fast inaccurate responses: dominant right using the right hand for near targets, either large or small.

(6) The hardest condition is right handers using their left hands for small, far targets.

The overall conclusion we might draw is that right handed users, who are known to exhibit more handedness in the general population, work more confidently (fast/inaccurate) with their right hand and the opposite with their left. Left handers, who exhibit less handedness in the general population, do not. This conclusion is consistent with the assumption that the right handers in our experiment learned how to use the mouse automatically but left handers did not.

The formal experiment and the informal prototype that led to the formulation of the hypothesis tested in the formal experiment were both conducted using hardware and software developed in the Computer Graphics Laboratory at the University of Waterloo. Details of the system and examples of its use are reported in a number of earlier papers [1,6,11]. The environment provided by the system is specially tailored to permit fast exploration of working hypotheses, such as occurred in the prototype study, while still maintaining the strict real-time performance required in formal experiments involving user interaction techniques where event timing and trajectory logging can be important.

A more detailed discussion of the work reported here is given in the master's thesis of the first author, which is available as a technical report [2].

Acknowledgements

This research was partially supported by grants from the Natural Sciences and Engineering Research Council of Canada and from the Information Technology Research Centre, a centre of excellence supported by the Province of Ontario, and by equipment donations from Digital Equipment of Canada.

References

[1] Bartram, L.R., Configurable Multi-tasking: A Method of Experiment Prototyping in a Multiprocessor Environment, Master's Thesis, Computer Graphics Laboratory, Department of Computer Science, University of Waterloo, 1989.

[2] Boritz, J., Of Mice and Menus, Master's Thesis, Computer Graphics Laboratory, Department of Computer Science, University of Waterloo, 1990.

[3] Callahan, J., Hopkins, D., Weiser, M., and Shneiderman, B., "An Empirical Comparison of Pie vs. Linear Menus," In Human Factors in Computing Systems, CHI '88 Conference Proceedings, ACM, New York, 1988, pp. 95- 100.

[4] Card, S.K., "Human Limits and the VDT Computer Interface," Excerpted in Readings in Human-Computer Interaction: A Multidisciplinary Approach, Morgan Kaufmann, Los Altos, CA, 1987, pp. 180-191.

[5] Card, S.K., Moran, T.P., and Newell, A., "The Keystroke-Level Model for User Performance Time with Interactive Systems," Communications of the ACM, Vol. 23 (1980), No. 7, pp. 396-410.

[6] Chionh, E.W., Booth, K.S., Cowan, W.B., Tanner, P.P., "Multiprocessing, Multitasking, Realtime Graphics Workstations for Psychology Experimentation," unpublished manuscript, Computer Graphics Laboratory, Department of Computer Science, University of Waterloo.

[7] Fitts, P.M., "The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement," Journal of Experimental Psychology, Vol. 47

(1954), No. 6, pp. 381-391.

[8] Howell, D.C., Statistical Methods for Psychology, Second Edition, Duxbury Press, Boston, 1987.

[9] Oldfield, R.C., "The Assessment and Analysis of Handedness: The Edinburgh Inventory," Neuropsychologia, Vol. 9 (1971), pp. 97-113.

[10] Welford. A.T., Fundamentals of Skill, Methuen, London, 1968.

[11] Waterhouse, J.F., Developing an Experiment on the Psychology Experiment Machine, Work-Term Report, Computer Graphics Laboratory, Department of Computer Science, University of Waterloo, 1989.

Appendix – Tables

dominant hand		left hand		right hand	
		small target	*large target*	*small target*	*large target*
left	*near*	1.141	0.968	1.138	1.041
	far	1.356	1.161	1.312	1.120
right	*near*	1.210	1.050	1.056	0.900
	far	1.397	1.195	1.207	1.053

Table 1. Mean selection times (seconds) for each experiment condition.

		Source	*df*	*Sum of Squares*	*Mean Square*	*F-ratio*	*Prob*
left near	small	*Angle*	7	1.718	0.245	3.15	0.0028 *
		Error	710	55.316	0.078		
		Total	717	57.034			
	large	*Angle*	7	0.724	0.103	2.11	0.0407 *
		Error	718	35.241	0.049		
		Total	725	35.965			
left far	small	*Angle*	7	1.211	0.173	1.93	0.0619
		Error	687	61.503	0.090		
		Total	694	62.715			
	large	*Angle*	7	0.838	0.120	1.72	0.1018
		Error	722	50.359	0.070		
		Total	729	51.197			
right near	small	*Angle*	7	0.651	0.093	2.03	0.0489 *
		Error	697	31.910	0.046		
		Total	704	32.561			
	large	*Angle*	7	0.220	0.031	1.04	0.4021
		Error	715	21.625	0.030		
		Total	722	21.845			
right far	small	*Angle*	7	0.872	0.125	2.14	0.0376 *
		Error	712	41.431	0.058		
		Total	719	42.303			
	large	*Angle*	7	0.391	0.056	1.28	0.2576
		Error	739	32.296	0.044		
		Total	746	32.688			

Table 2. Analysis of variance for all dominant right handed conditions. Asterisks in the final column denote the four conditions in which statistically significant effects exist.

	left near small	left near large	right near small	right far small
0	1.229	1.044	0.990	1.157
45	1.280	1.074	1.053	1.170
90	1.188	1.060	1.073	1.226
135	1.156	1.017	1.047	1.245
180	1.138	0.984	1.052	1.226
225	1.181	1.063	1.063	1.166
270	1.271	1.082	1.108	1.252
315	1.234	1.076	1.059	1.212

Table 3. Means of selection time by angle.

	left near small	left near large	right near small	right far small
1	180	180	0	0
2	135	135	135	225
3	225	0	180	45
4	90	90	45	315
5	0	225	315	180
6	315	45	225	90
7	270	315	90	135
8	45	270	270	270

Table 4. Rank ordering of angles by mean selection times.