A COMPARISON OF CURSOR CONTROL DEVICES ON TARGET ACQUISITION, TEXT EDITING, AND GRAPHICS TASKS

by

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ABSTRACT

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The current study compared the performance of six commonly used cursor devices (absolute touchpad, mouse, trackball, relative touchpad, force joystick, and displacement joystick) on three types of tasks (target acquisition, text editing, and graphics). Prior to these comparisons, each of the devices was optimized for display/control dynamics in independent experiments.

A total of 30 subjects were used in the five optimization studies. For each device, the optimization experiment compared a range of control dynamics using a target acquisition task (i.e., positioning a cross-hair cursor over square targets of varying sizes and screen distances). An analysis of variance procedure was used to determine the best control dynamics, of the range studied, for each device. Performance was based on a time-to-target (TT) measure.

A comparison of the six optimized devices was then performed on the three task environments. For the target acquisition, text editing, and graphics tasks, a total of

12, seven, and six subjects were required, respectively. For the target acquisition study, the six devices were compared on a task identical to the optimization task; that is, cursor positioning performance for various target sizes and distances. In addition to the TT dependent measure, bipolar scale and subjective rank data were also collected. The text editing task required subjects to perform document correction on the computer using each of the six devices, with cursor keys added as a baseline device. Task completion time (TCT), bipolar scale response, and subjective rank data were collected. For the graphics task, subjects were required to perform basic graphics editing tasks with the six devices. As with the text editing task, TCT, bipolar scale, and rank data were collected.

Results indicated a wide variation in the cursor positioning performance of the devices on the three tasks. Without exception, the mouse and trackball performed the best of the six devices, across all tasks. In addition, these devices were most preferred. In general, the two joysticks performed worse on the target acquisition and graphics tasks than the two touchpads. On the text editing task, however, the rate-controlled joysticks performed better than the touchpads.

An informal comparison of the results across the three tasks indicates that the mouse and trackball are the best overall devices. Although one might expect target acquisition (a generic cursor positioning task) to predict performance on the text and graphics tasks, this is generally not the case. A possible explanation is the interaction of the cursor control device with (1) the use of the keyboard (text editing), (2) function button presses (graphics), and (3) pixel-by-pixel cursor positioning accuracy (graphics). (target size)

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INTRODUCTION

In the past decade, the tremendous increase in the use of interactive computer systems, especially in the "personal computer" industry, has placed emphasis on computer input devices. Special interest has been given to cursor control devices in word processing, process control, and graphics environments. Examples of cursor devices include: (1) indirect devices, such as the cursor key, joystick, trackball, mouse, and touchpad; and (2) direct devices, which include the lightpen and touch screen (Ohlson, 1978).

The body of scientific literature related to cursor devices consists primarily of papers which review the current state of the art and/or discuss the advantages of various devices. A small percentage of this literature has has been research oriented, comparing the performance of two or more cursor devices on target acquisition tasks. The following section reviews the results of 10 studies in which cursor devices were compared for time to complete the task, accuracy, and/or subjective preference.

In general, the results appear to indicate that the direct devices, such as the lightpen and touch screen, perform the best of all devices when time to complete a task is considered. For accuracy, the trackball appears to be the best device. This comparison seems to indicate a speed/accuracy tradeoff for cursor devices. Results from several studies which attempted to evaluate subjective preferences of cursor devices are inconclusive.

In general, it is difficult to extract device design guidelines from the cursor control device comparison literature. In addition, the results from any one study are difficult to interpret due to experimental design inconsistencies. For example, many of the studies did not optimize the control/display gain and/or input button placement of the devices. As a result, performance with certain devices may have been biased. Secondly, most of the studies used artificial target acquisition tasks, which may not be representative of actual text editing, graphics, or process control tasks. That is, the experimental results from an artificial task may not generalize to actual human-computer task requirements. Third, the studies differ widely in the nature of experimental designs, methods, procedures, and analyses. The following section of this dissertation reviews each of the 10 studies in greater depth.

Literature Review

The first notable study aimed at the comparison of cursor devices was performed by English, Engelbart, and Berman (1967). The major portion of the study compared a mechanical mouse, displacement joystick (absolute mode), lightpen, and graphacon. Eight persons with previous experience on both the computer text editing system and the cursor devices served as subjects. The target acquisition task was contained within a simulated word processing environment. That is, the subject used the cursor device to move a cursor within a target area, then press a "select" button. Subjects were given both one-character targets ("X") in a nine-character field ("character mode") and one-word targets ("XXXXX") in a nine-word field ("word mode"). Each subject was allowed two minutes of practice on each device, after which he/she completed 32 trials of character and word targets. The subject completed the 64 trials for each device and then completed all four devices again, but in reverse order. The dependent measures were time to target and error rate. Time to target was based on the time for the subject to move his or her hand from a keyboard space-bar to the device, position the cursor within the target area, and press a select button located on the device. Error rate was the percentage of incorrect targets entered.

The second portion of the experiment was a replication of the first part except that: (1) three inexperienced subjects were used, (2) two additional cursor devices, a displacement joystick (rate mode) and a knee-control device, were evaluated, (3) no practice was given to the subjects, and (4) 80 trials in only the "character mode" were given.

Results for both the experienced and inexperienced subjects were reported as mean values for the time to target and error rate dependent measures. No statistical analysis was performed. For the eight experienced subjects, the mouse had the fastest time to target and lowest error rate of the four devices for both character and word mode. For inexperienced subjects, the knee control was the best device of the six tested devices for time to target, while the mouse had the lowest error rate.

English et al. (1967) point out that their results should not be used to choose among cursor devices. Rather, their main objective in performing the research was to develop an experimental methodology for cursor device comparison. The authors admit the devices were not optimized for control dynamics or input button placement.

For example: (1) the high display/control gain of the joystick (absolute mode) might have resulted in poor positioning in the character mode (fine-positioning), (2) the joystick (rate mode) had a relatively large deadspace around the center position, (3) the lightpen mounting was described as "clumsy", and (4) the select buttons on the Rand tablet and joystick caused incorrect selections due to cursor drift during button actuation.

Mehr and Mehr (1972) compared several joystick and trackball configurations for a simple target acquisition task. The joystick was studied under four configurations: (1) force (rate mode), (2) force (rate mode with thumb operation), (3) displacement (rate mode), and (4) displacement (absolute mode). The trackball was also studied under four conditions (pulses per trackball revolution/grams of drag force): (1) 209/50, (2) 209/35, (3) 409/57, and (4) 409/35. The reasons for choosing these four trackball combinations were not given by the authors.

Twenty-four subjects participated in the study. The methodology, tasks, and procedures used to evaluate the devices were described poorly in the paper. According to the authors, different subjects received various device conditions, but never all conditions. Some subjects dropped out of the study and others were added. Device control dynamics were changed on most of the devices during the study; the number, nature, and time of changes were not reported. The results, reported only in graphical form, showed that the 409/35 trackball configuration and the force (rate mode) joystick were the best devices for time to position, error, and learning curves. Generally, the reporting of data collection procedures, task environment, choice of device dynamics, and subject population was vague. Therefore, the validity of the Mehr and Mehr study results is questionable.

Goodwin (1975) compared a lightpen and a lightgun to keyboard text keys for three simulated word-processing tasks: (1) arbitrary cursor positioning, (2) sequential cursor positioning, and (3) check reading. Six subjects (4 females and 2 males) participated in the study. In all three tasks, the subject was required to acquire 10 character size targets per trial. "Arbitrary cursor positioning" required subjects to position a cursor over each of 10 numbers, in numerical order from 0 to 9, then type over the number with an "X". "Sequential positioning" required the subject to position a cursor over each of 10 "M"s, in order from top to bottom of the screen, then type over the letter with an "X". The "check reading" task required subjects to search the screen for 10 character substitution errors, position the cursor over each error, then replace the letter with an "X". Each subject received 3 devices x 3 tasks x 3 trials x 10 targets, or 270 target acquisitions. The dependent measure was time to complete a 10-target trial. Results showed that the two lightpen devices were significantly faster than keyboard text keys for trial completion time.

The Goodwin (1975) study provides useful results which are based on a sound experimental methodology. Multiple tasks were used to represent the cursor positioning sequences typically encountered in an actual word processing environment. The arbitrary positioning task was similar to menu selection or file editing. The sequential positioning was representative of top-to-bottom document editing and form-filling. The check-reading task was close to actual document editing in that some additional cognitive load was used to identify incorrectly spelled words.

Card, English, and Burr (1978) performed a study which compared a mechanical mouse, force joystick (rate mode), cursor keys, and text keys for a simulated word-processing task. Five subjects with no previous experience on the devices and little experience on computers were tested. The authors state that "one of five subjects was very much slower than the others and was eliminated from the experiment" (Card et al., 1978, p. 602). Thus, only four subjects were used in the data analysis. The devices were "informally" optimized.

The task was simple target acquisition in nature, but differed from the previously discussed studies in several ways. First, both target size and target distance were varied; four target sizes (1, 2, 4, and 10 characters) and five target distances (1, 2, 4, 8, and 16 cm) were used. Second, subjects were required to perform the target task on each device until a learning asymptote had been reached; the authors estimated the asymptote to occur between 1200 and 1800 trials, based on multiple t-tests of 200 trial blocks.

The target which the subject was to acquire was a character or word with inverse lettering. The subject pressed a space bar, moved his hand to the device, used the device to position the cursor over the designated target, and pressed an enter button. For the mouse, the enter button was located on the device. For the other three devices the opposite hand was used to push an enter button. Each subject completed at least 1200 trials for each device, with an average of 600 trials per day.

Dependent measures were time to target acquisition and error rate. (In addition, the authors calculated the learning curves and applied the results of the mouse and joystick to Fitts' Law.) Results show that across all target sizes and distances, the time to target was significantly faster for the mouse and joystick than for the step keys and text keys. Across target size, the mouse had the lowest error rate of the four devices. Although no post-hoc statistical analyses were offered for differences among devices for target distance and target size, the mouse appears to be the fastest of the four devices.

The Card et al. (1978) study was unique at that time in the treatment of target size and target distance as independent factors, which allowed independent assessment of each factor. One limiting factor is that target sizes and shapes were representative of only word-processing environments and might not transfer well to graphics, process control, or other task environments. The authors also showed a very close relationship between the operation of continuous cursor devices and Fitts' Law. Although the study was unique in its experimental approach, the inconsistencies in the optimization of the devices, the use of only four subjects, and the practice of eliminating subject's performance data under the premise of being an "outlier" weaken any conclusive results that the mouse was the optimum device of those tested.

A study performed at the Naval Ocean Systems Center (NOSC) (Gomez, Wolfe, Davenport, and Colder, 1982) compared a trackball and touchpad (absolute mode). Sixteen subjects, eight trained on the system with a trackball and eight with no experience on either the trackball or touchpad, participated in the study. Each subject was given 5 training blocks and 10 test blocks. For each block, subjects performed 48 target acquisition trials. Targets were 0.32-cm in diameter and were displayed in random positions on the CRT screen. For the touchpad, an absolute device, the subject used the touchpad to position the cursor within the target area; then he pressed an enter switch with the opposite hand. In the case of the trackball, the cursor always started in the center of the screen. The subject moved the cursor into the target area, and then pushed an enter button with the same hand. Dependent measures were response time (time to target) and error (distance from target center).

Results indicated no difference between the touchpad and trackball for time to target. The error associated with the trackball was significantly lower than that of the touchpad across both groups. In addition, error results indicated that trained individuals, across both devices, had a significantly lower error rate than did untrained individuals. These results suggest that the experience of a subject with a cursor device might affect his/her approach to a target acquisition task.

Gomez et al. (1982) published the first study to incorporate the use of equal size user groups to distinguish bahavior associated with the use of cursor devices. Although the test results show that the two devices, trackball and touchpad, did not differ significantly in overall performance, the study does show the difference in device choice one might make based on the experience of the user population, that is, the interaction between device type and previous experience. These results may indicate the importance of performing cursor device optimization and comparisons with both experienced and inexperienced users of computer systems.

A comprehensive comparison of devices was performed by Albert (1982) for a simple target acquisition task, with a 3.18-cm square target. Seven devices were used in the comparison: (1) touch screen, (2) lightpen, (3) touchpad (with "puck"), (4) trackball, (5) displacement joystick (rate mode), (6) force joystick (rate mode), and (7) cursor keys. The control/display ratios and velocity factors for the trackball, joysticks, and cursor keys were nonlinear and subjectively optimized for this experimental task.

Each of eight subjects (five males and three females) was tested under each device. (The touch screen and lightpen were also tested in three additional conditions, but these results are not discussed here.) Each subject was tested under 5 blocks of 10 trials each (i.e., 50 data points). Dependent measures were positioning speed (effective pixels/s), positioning accuracy (pixels from target center), and subjective preferences (comfort, learning, fatigue). For the speed and accuracy measures, results were based on an analysis of variance (ANOVA). Although there were significant differences among the devices, no post-hoc analysis results were reported (i.e, Newman-Keuls, simple-F, etc.). Based on means for positioning speed, the order of best to worst cursor device was: touchscreen, lightpen, touchpad, trackball, force joystick, displacement joystick, and cursor keys. For positioning accuracy, the order was trackball, touchpad, force joystick, touchscreen, lightpen, dispacement joystick, and cursor keys. No statistical analyses were performed on the subjective ratings, but an inspection of means indicated that the touchscreen, lightpen, and touchpad were considered the most comfortable, easiest to learn, and least tiring to use.

The Albert (1982) study was perhaps the first cursor device comparison to incorporate a representative group of available devices on an equal test evaluation level. One of the important devices omitted was the mouse. The results support those of previous research: touch entry devices (e.g., touch screens, lightpens) are the fast pointers, but they are inaccurate. The trackball is the most accurate, but not extremely fast.

Thus, there appears to be a speed/accuracy tradeoff associated with most cursor devices. This tradeoff seems to indicate that the touch entry device is only acceptable for tasks with relatively large targets (menus, air traffic control). When the task environment involves the acquisition of relatively small targets, the trackball and touchpad appear to be the best choices.

Albert was the first researcher to attempt to define the utility of a cursor device beyond its speed and accuracy; that is, to address the preferences of users. He evaluated ratings of comfort, ease of use, and fatigue. Because the task used for evaluation was somewhat artificial and short in duration, the subjective responses might have been based on different criteria than those of daily, work-related users.

Following the development of a touchpad for use in the Royal Signals and Radar Establishment (RSRE) for air traffic control tasks, Whitfield, Ball, and Bird (1983) compared the RSRE touchpad with a trackball and a touchscreen. Although three separate and related experiments were conducted, only the third encompassed all three devices and is reported here.

Twelve males participated in the experiments. The factors of interest were device type and the resolution level (i.e., target sizes ranging from 1.5 cm to 12 cm in increments of 1.5 cm). Dependent measures were time-to-target and error rate. The task required the subject to position the cursor on targets of various sizes, and then depress an enter switch. For the touchpad and touchscreen, the subject lifted his finger to confirm a target choice, whereas the trackball required a separate confirmation key. ANOVA results for time to target indicated significant differences among devices. Although no post-hoc analysis was reported, the authors stated that the touchscreen was ranked fastest and the trackball slowest. For percent error (again no post-hoc statistical analysis was performed) the trackball had the lowest rate of errors and the touchscreen had the highest number of errors.

An analysis of error type indicated the trackball was the best performing device if only the overshoot/fall-out error was considered. The authors, however, concluded that only small performance differences existed among the three devices. Again, the speed/accuracy tradeoff is evident for the trackball and, especially, for the touch entry device.

A more recent study by Struckman-Johnson, Swierenga, and Shieh (1984) compared a displacement joystick (absolute mode), trackball, lightpen, and non-repeating keyboard keys for a simulated text-editing task. Forty-eight subjects (24 males, 24 females) participated in the study. All subjects received all devices in a counter-balanced fashion. For each device, subjects received 10 blocks of 10 character replacement trials. For each trial block, subjects were given a screen containing 50 words in which 10 of the words had a repeated letter error. The subject used each device to position the cursor above the incorrect character, then press an enter key located on the device. Trial completion time and errors per trial were recorded.

Results for the trial completion times for males showed the lightpen and trackball as faster devices than either the joystick or keyboard keys. For females, the lightpen was superior to all other devices for trial completion time. Results also showed that males performed better than females when using the cursor keys, joystick, and trackball, but not the lightpen. When considering errors, the keyboard keys and trackball resulted in lower error rates than did the joystick, across all subjects. Subjects prefered the lightpen and trackball to both the joystick and cursor keys.

In essence, Struckman-Johnson et al. (1984) replicated the Goodwin (1975) study with several additional cursor devices. One additional finding was the gender difference for cursor keys, joystick, and trackball. Therefore, it appears to be important to include equal groups of males and females in research which evaluates or compares cursor devices.

Haller, Mutschler, and Voss (1984) compared a lightpen, touchpad (absolute), mouse, trackball, repeating cursor keys, and a speech recognition device on a simulated word processing task. The task required subjects (three males, three females) to correct 18 one-character replacement errors in a prepared one-page document. Six errors were located in each of three areas: top, middle, and bottom. Prior to performing the text-editing task, subjects were allowed to practice with the devices and to choose the control/display gain associated with the touchpad, mouse, and trackball. The test trial began when each subject reached an asymptote in his/her learning curve. Positioning time (time to target) and character replacement time were measured.

Time-to-target results indicated that the lightpen was superior to all other devices and voice input was inferior to all other devices. In addition, the lightpen and cursor keys showed the smallest error rate. Of all devices in the study, the lightpen was most preferred.

The Haller et al. (1984) research was unusual in two respects: (1) the adjustable nature of the control dynamics for the mouse, touchpad, and trackball and (2) the use of voice control as a cursor control device. The use of variable control dynamics (i.e., giving the subjects the option of control dynamics) resulted in a possible lack of standardization across all subjects. As a result, the control dynamics for the devices is a confounded variable which may have affected the results of the study.

Karat, McDonald, and Anderson (1984) compared a touchscreen, an optical mouse, and keyboard keys. Twenty-four males and 24 females participated in the experiment, which consisted of a menu-type target acquisition task imbedded within two applications tasks: (1) a computer-based telephone aid and (2) an appointment calendar. Each subject was given all devices and both applications. The applications portion of the procedure consisted of 10 sub-tasks for each calendar and telephone task. These sub-tasks consisted of menu selection, file management, and some actual text entering. Only the menu selection required the use of the three devices and was the basis for data collection. Total time to complete each sub-task was recorded. Prior to performing each application task, subjects were given 288 practice trials. Each practice trial consisted of positioning a cursor onto a target, for the touchscreen and mouse; or choosing the correct letter associated with a target, for the keyboard. Time to target and error rate were recorded.

Results indicated that, for the target acquisition task, the touchscreen was superior for speed, but that the keyboard was best for accuracy. For the applications tasks, the touchscreen was superior to both the mouse and the keyboard for menu selection. For performance during the applications tasks (menu selection), subjects preferred the touchscreen and keyboard over the mouse, but there were no preferences for the practice tasks.

The Karat et al. (1984) study was unique in that both an artificial target task and a realistic menu selection task were given within the same study. An interesting finding was that the performance of the devices for the two tasks was very similar. This similarity would indicate that an artificial task can be a good predictor for cursor device performance, at least on a menu-selection task.

Summary

The body of cursor device research has provided mixed information concerning the "best" cursor devices. Generally, the 10 studies agree that touch entry devices (e.g., touch screens, lightpens) are best when fast acquisition of relatively large targets is required. That is, touch entry devices are typically fast, but inaccurate. The studies do not agree on the most accurate device, but the majority recommend the trackball or mouse. No generalizable conclusions can be drawn from the subjective data.

The lack of consistency in the general conclusions among the studies is further confounded by three factors. First, the 10 experiments used varied experimental methodologies, procedures, and analyses. Second, the researchers typically used artificial target acquisition tasks to predict device performance on word-processing, graphics, menu selection, air traffic control, or other tasks. The transfer and generalization of cursor device performance from an artificial target task to actual real-world task conditions is questionable. Third, the devices compared in the studies were not optimized or, at best, optimized subjectively (i.e., cursor control transfer functions, control/display gains, and "enter" button placement were not optimized for the application task). These differences may have resulted in biased performance of certain cursor devices. Based on these three factors, generalizing these research results to actual computer systems and work situations may be of limited validity.

Research Objectives

The research contained in this dissertation avoids the deficiencies in previous research by maintaining both objectively optimized cursor devices and realistic tasks for the subjects. The objective of this research is, therefore, twofold.

First, cursor devices representative of devices available for computer systems are individually optimized. The optimization procedure results in an approximation of the best cursor control display/control dynamics for each device. In this way, all devices are treated as objectively as possible for subsequent tasks.

Second, the optimized devices are compared on an artificial target acquisition task and two actual computer-based tasks: text editing and graphics. The results of the research produce a cursor device/task taxonomy for recommending specific cursor devices for certain tasks. Another result of the research is the evaluation of artificial target tasks as predictors of actual performance of cursor devices on non-artificial, typical tasks.

These objectives are met in a series of three types of studies:

(1) Each device is experimentally optimized.

(2) The optimized devices are compared experimentally on an artificial target acquisition task.

(3) The optimized devices are compared experimentally on a text editing and graphics task.

METHOD: CURSOR CONTROL DEVICE OPTIMIZATION

The cursor control device optimization portion of the research consists of a series of five separate experiments. Each experiment was conducted to determine optimized display/control (D:C) dynamics for the cursor devices prior to comparing them on the target acquisition, text editing, and graphics editing tasks. In this way, an unbiased comparison of cursor device performance can be performed.

Subjects

A total of 30 subjects, six for each device experiment, was used for the optimization portion of the research. All subjects were naive users of the computer cursor control devices. Each subject was paid $ 4.00 per hour for participation.

Equipment

The experimental equipment consists of five cursor control devices, a Texas Instruments Professional Computer

(TIPC) with a 33-cm diagonal color monitor, and a Texas Instruments Portable Professional Computer (TIPPC). A schematic of the experimental set-up is shown in Figure 1.

The cursor control devices, representative of commercially available units, included:

(1) Trackball. Measurement Systems Model 621 trackball (4-cm diameter),

(2) Mouse. Mouse Systems Model M-2 optical mouse with a 23 x 20 cm optical pad,

(3) Relative touchpad. Keytronics relative-mode, finger sensitive touchpad (8 x 8 cm),

(4) Displacement joystick. Measurement Systems Model 521 rate-controlled, miniature displacement joystick,

(5) Force joystick. Measurement Systems Model 462 rate-controlled, miniature force joystick.

The TIPC was used to present the target acquisition task, collect performance data, and control the relative touchpad dynamics. The TIPPC was used to control the trackball, mouse, displacement joystick, and force joystick dynamics.

The target selection input button was operated with the subject's opposite hand for the trackball, touchpad, and

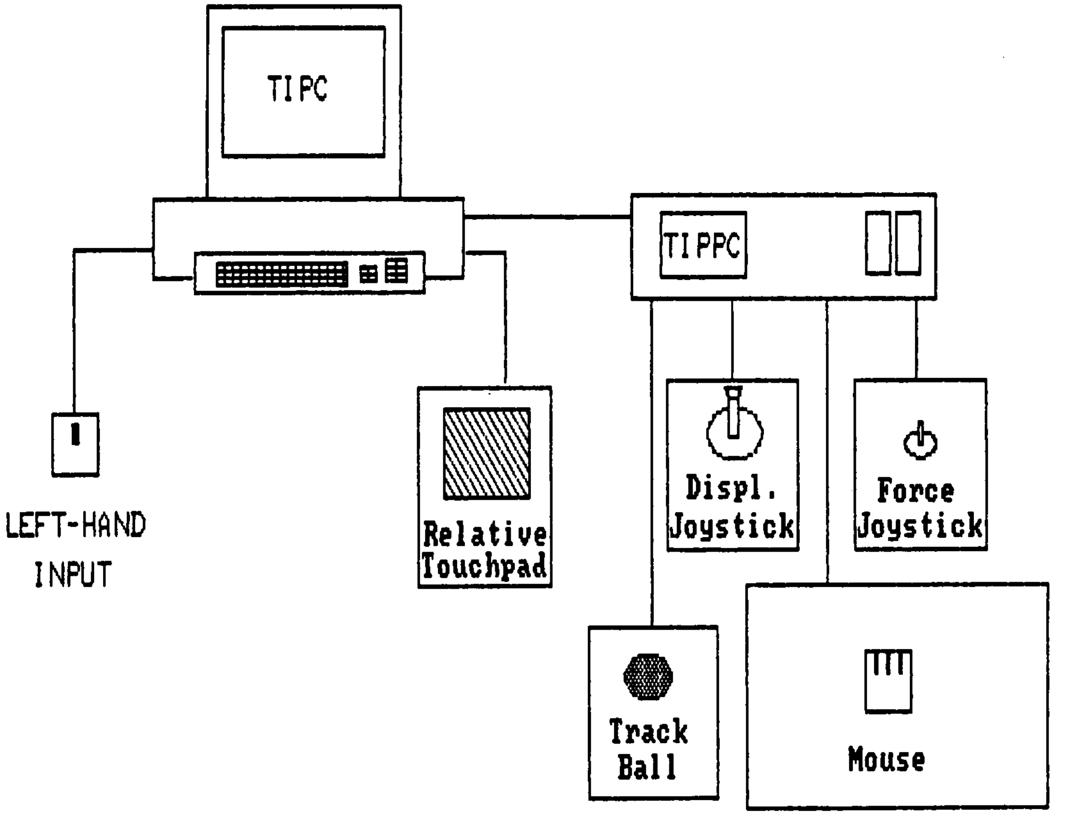

Figure 1. Experimental set-up for the cursor device optimization.

joysticks. For these four devices, the input button was located on a separate mouse placed on the opposite side of the keyboard from the cursor control device. The optical mouse had the input button located on the device.

Experimental Design

For each of the five optimization experiments, a five-way, within-subjects factorial design was used for data collection. Independent variables were target size, target distance, and three velocity scale components. For the five optimization experiments, target size had five levels of target width: 0.13, 0.27, 0.54, 1.07, and 2.14 cm (4, 8, 16, 32, and 64 pixels, measured horizontally). The targets were approximate squares. Due to the pixel resolution of the CRT (720 x 300), the number of vertical pixels differed from the number of horizontal pixels for all target sizes. Target distance had four levels of screen distance: 2, 4, 8, and 16 cm. The three velocity scale components, which differed across the five optimization studies, defined the range of display/control relationships investigated for each device.

The goal of each optimization experiment was to determine the combination of the three velocity scale component levels (i.e., control order) which resulted in the best cursor positioning performance across a range of target sizes and target distances. The levels of each component which were tested in the experiments were determined by prior pilot studies and are intended to bracket useful ranges. The target sizes/distances used in the study were chosen as representative of the range typically encountered in text editing, graphics, and process control task environments.

The dependent measure for all five experiments was time to target (TT), defined as the time required to move the cursor from a start position on the screen to a square target, position the cursor within the target boundaries, and press an input button.

Trackball. The experimental design for the trackball optimization experiment is shown in Figure 2. The three velocity scale components were zero-order, first-order, and second-order scaling. Zero-order velocity scaling had two levels of display/control (D:C) gain: 5 and 10 cm of cursor movement per trackball 360-deg revolution (trackball circumference of 12.5 cm). First-order scaling had three levels: none (NO), low (LO), and high (HI). Second-order scaling had three levels: none (NO), low (LO), and high

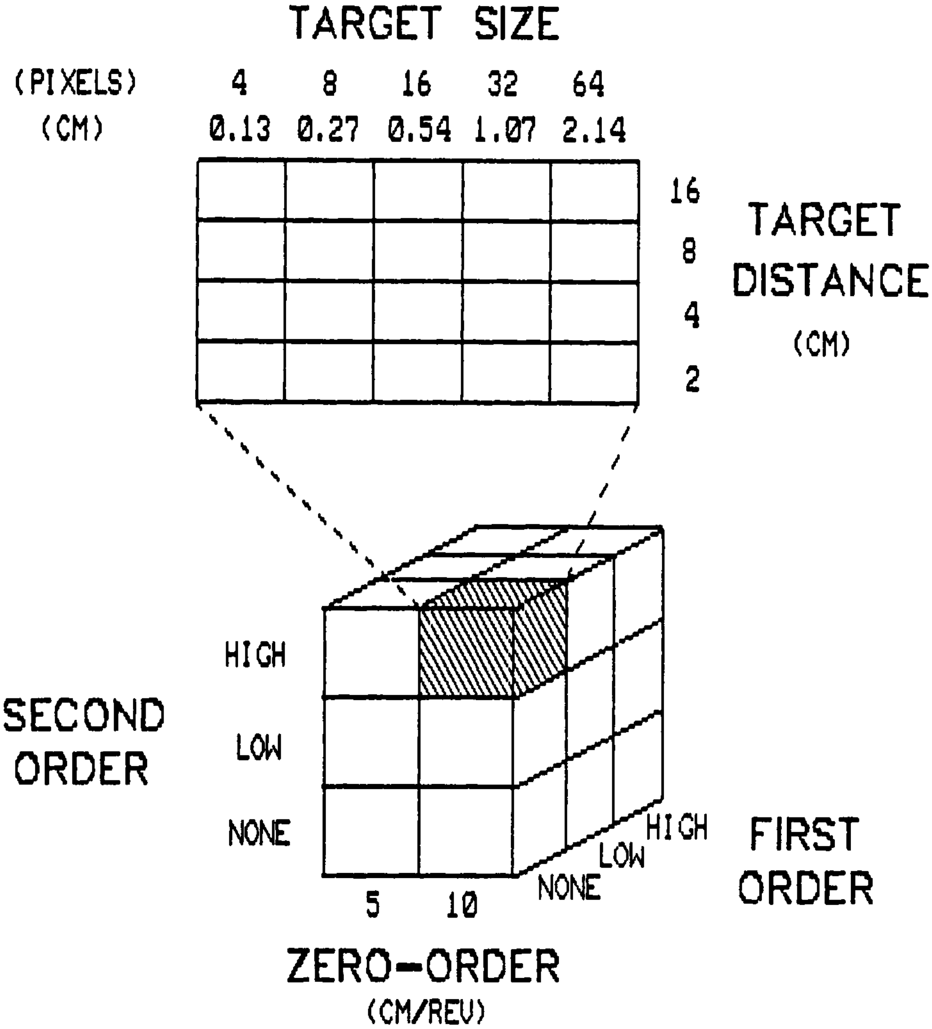

Figure 2. Experimental design: Trackball optimization.

(HI).

Appendix A shows the calibrated curves for the 18 combinations of zero-, first-, and second-order trackball velocity scaling. The trackball velocity curves represent the relationship between trackball rotation speed (rev/s) and D:C gain (cm cursor movement/degrees trackball rotation). Idealized velocity curves for zero-, first-, and second-order components are shown in Figure 3. Velocity scales with only zero-order portions represent a linear D:C gain, or sensitivity. Regardless of the trackball rotation speed, the D:C gain (cursor movement distance on the screen per trackball rotation) remains constant. First-order portions of the velocity scale increase the D:C gain linearly as the speed of trackball rotation increases. Second-order portions of the velocity scale increase the D:C gain in an exponential fashion as the speed of the trackball rotation increases.

Each subject performed five trial blocks (100 trials) with each of the 18 (2 x 3 x 3) velocity scales. Each trial block consisted of 20 target size x target distance combinations (5 x 4 = 20 trials).

<u>Mouse</u>. The experimental design for the mouse optimization experiment is shown in Figure 4. The three

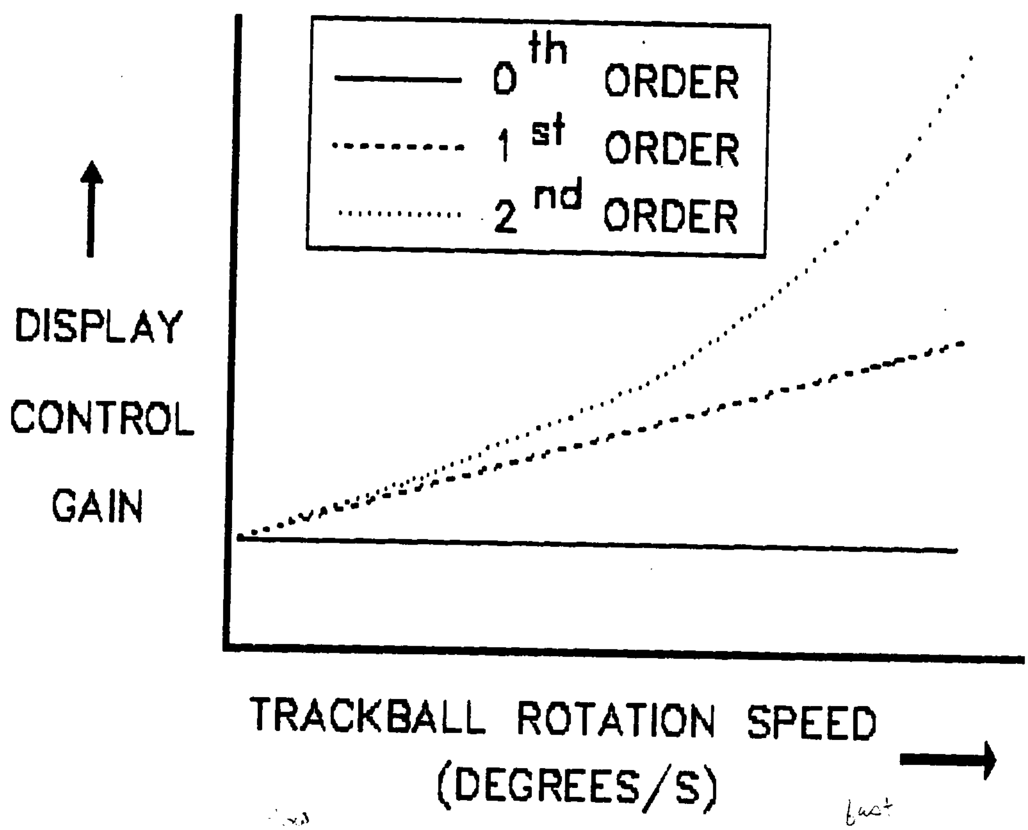

Figure 3. Idealized velocity curves: Trackball.

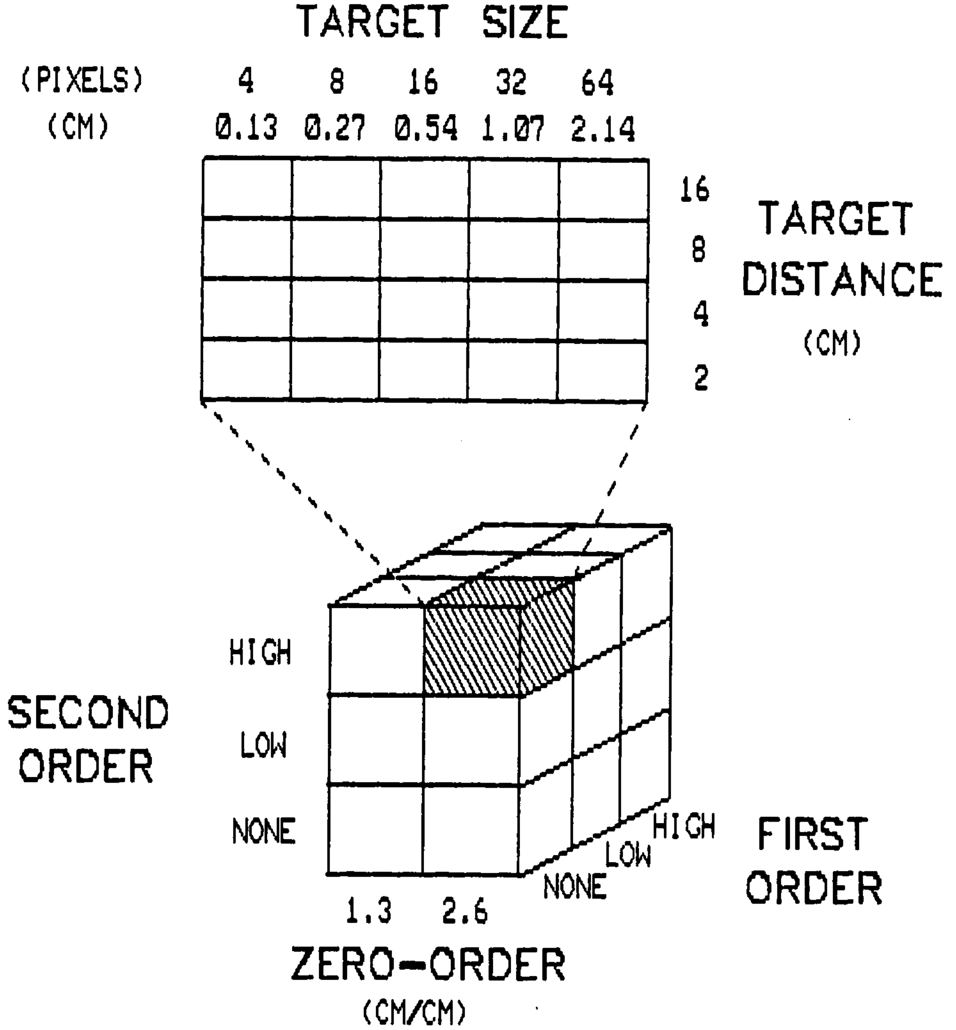

Figure 4. Experimental design: Mouse optimization.

velocity scale components were zero-, first-, and second-order scaling. Zero-order velocity scaling had two levels of D:C gain: 1.3 and 2.6 cm cursor movement per cm of mouse movement. First-order scaling had three levels: none (NO), low (LO), and high (HI). Second-order scaling had three levels: none (NO), low (LO), and high (HI).

Appendix A shows the calibrated curves for the 18 combinations of zero-, first-, and second-order mouse velocity scaling. The mouse velocity curves represent the relationship between mouse movement on the optical pad (cm/s) and D:C gain (cm cursor movement/cm mouse movement). Idealized velocity curves for zero-, first-, and second-order components are shown in Figure 5. Velocity scales with only zero-order portions represent a linear D:C gain, or sensitivity. Regardless of the mouse movement speed, the D:C gain remains constant. First-order portions of the velocity scale increase the D:C gain linearly as the speed of mouse movement increases. Second-order portions of the velocity scale increase the D:C gain in an exponential fashion as the speed of the mouse movement increases.

Each subject performed five trial blocks (100 trials) with each of the 18 (2 x 3 x 3) mouse velocity scales. Each trial block consisted of 20 target size x target

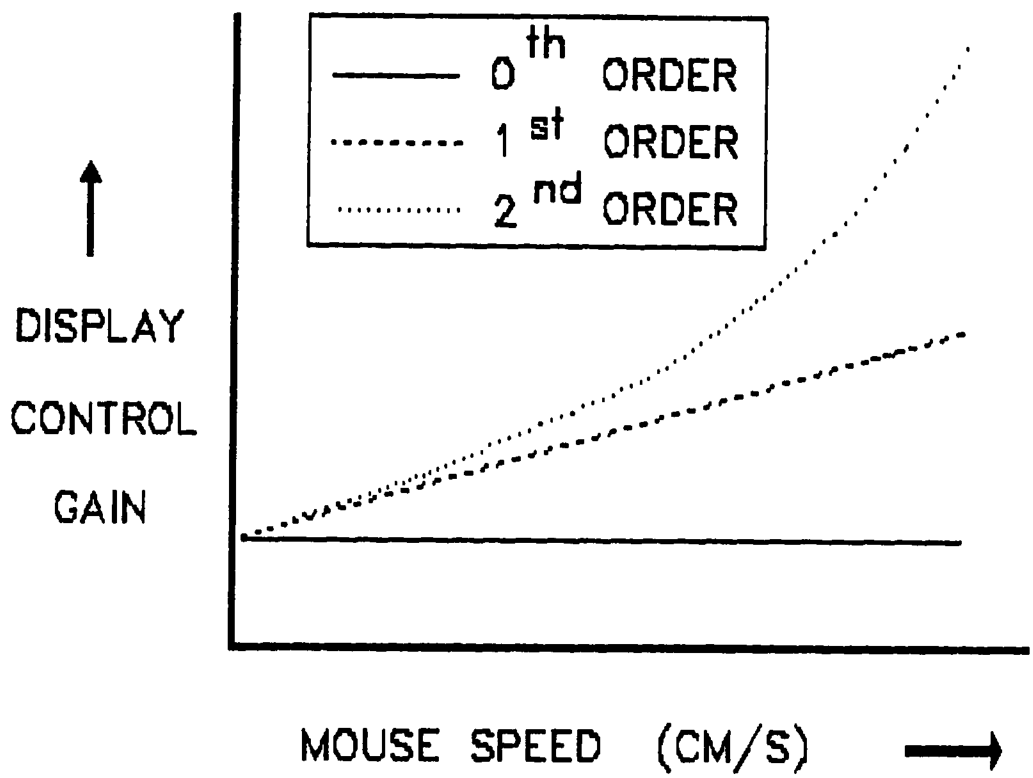

Figure 5. Idealized velocity curves: Mouse.

distance combinations (5 x 4 = 20 trials).

Relative touchpad. The relative touchpad experimental design is shown in Figure 6. The three velocity scale components were zero-, first-, and second-order scaling. Zero-order velocity scaling had three levels of D:C gain: 0.33, 1.0, or 2.0 cm cursor movement per cm finger movement on the touchpad. First-order scaling had three levels: none (NO), low (LO), and high (HI). Second-order scaling had three levels: none (NO), low (LO), and high (HI).

Appendix A shows the calibrated curves for the 27 combinations of zero-, first-, and second-order touchpad velocity scaling. The touchpad velocity curves represent the relationship between finger speed across the touchpad surface (cm/s) and D:C gain (cm cursor movement/cm finger movement). Idealized velocity curves for zero-, first-, and second-order components are shown in Figure 7. Velocity scales with only zero-order portions represent a linear D:C gain, or sensitivity. Regardless of the speed with which the finger is moved across the touchpad, the D:C relationship remains unchanged. First-order portions of the velocity scale increase the D:C gain linearly as finger speed increases. Second-order portions of the velocity curve increase the D:C gain in an exponential fashion as

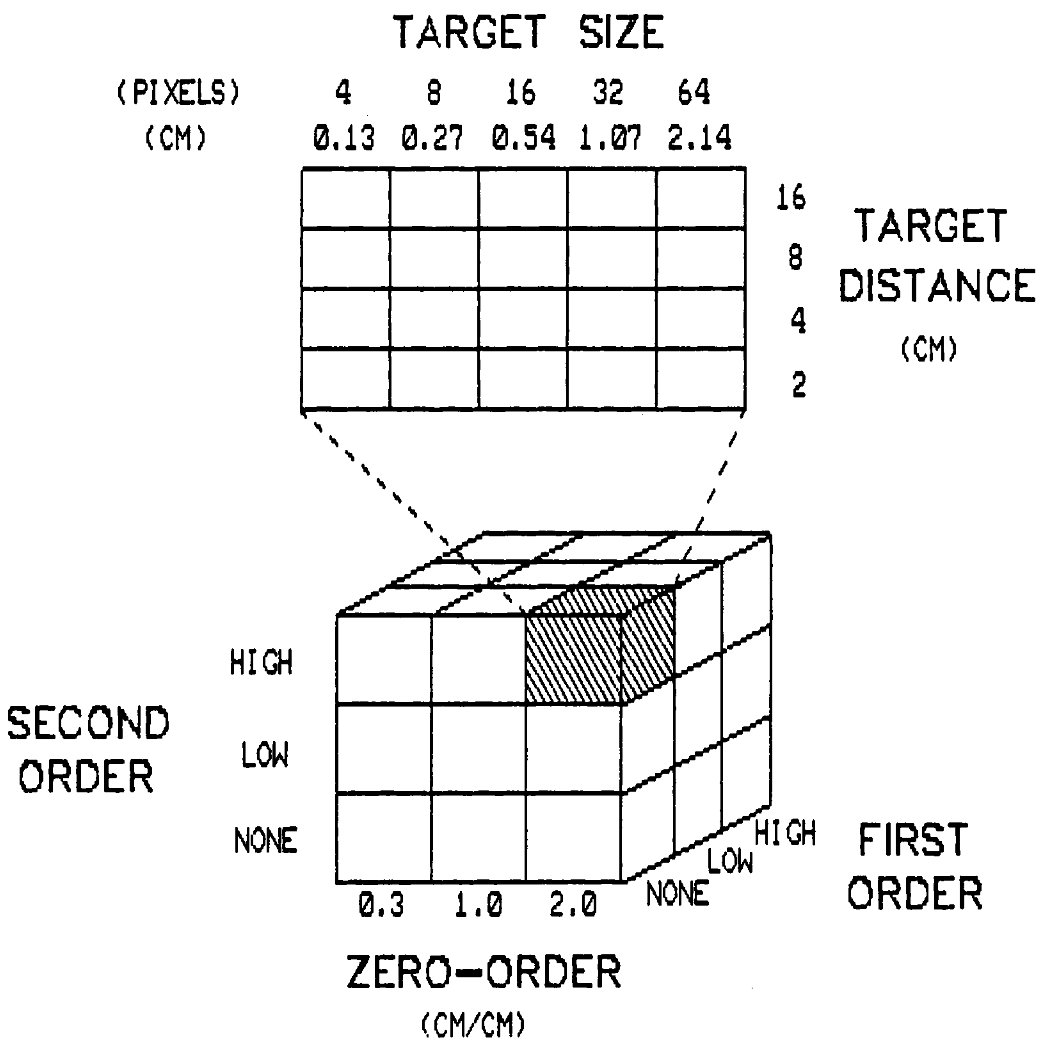

Figure 6. Experimental design: Relative touchpad optimization.

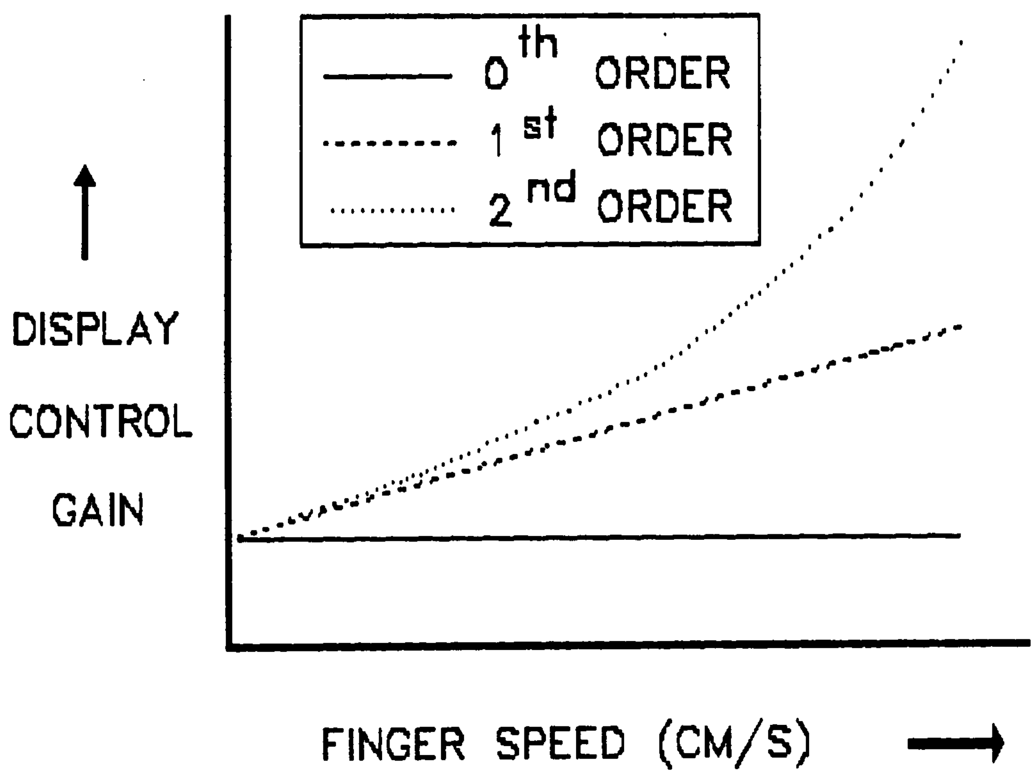

Figure 7. Idealized optimization curves: Relative touchpad.

the finger speed increases.

Each subject performed five trial blocks (100 trials) with each of 27 (3 x 3 x 3) touchpad velocity scales. Each trial block consisted of 20 target size x target distance combinations (5 x 4 = 20 trials).

<u>Displacement joystick</u>. The experimental design for the displacement joystick is shown in Figure 8. The velocity scale components were minimum cursor velocity, first-order, and second-order scaling. Minumum cursor velocity had two levels: 0.24 and 0.45 cm of cursor movement per second. First-order velocity scaling had three levels: low (LO), medium (MD), and high (HI). Second-order scaling had three levels: none (LO), low (LO), and high (HI).

Appendix A shows the calibrated curves for the 18 combinations of minimum cursor velocity, first-order, and second-order displacement joystick velocity scales. The joystick velocity curves represent the relationship between stick displacement (cm) at the tip of the joystick and cursor velocity (cm/s). Idealized velocity curves for the three components are shown in Figure 9. The minimum cursor velocity portion of the velocity curve determines the cursor velocity (cm/s) at the 0.2-cm joystick displacement. First-order portions of the velocity curve

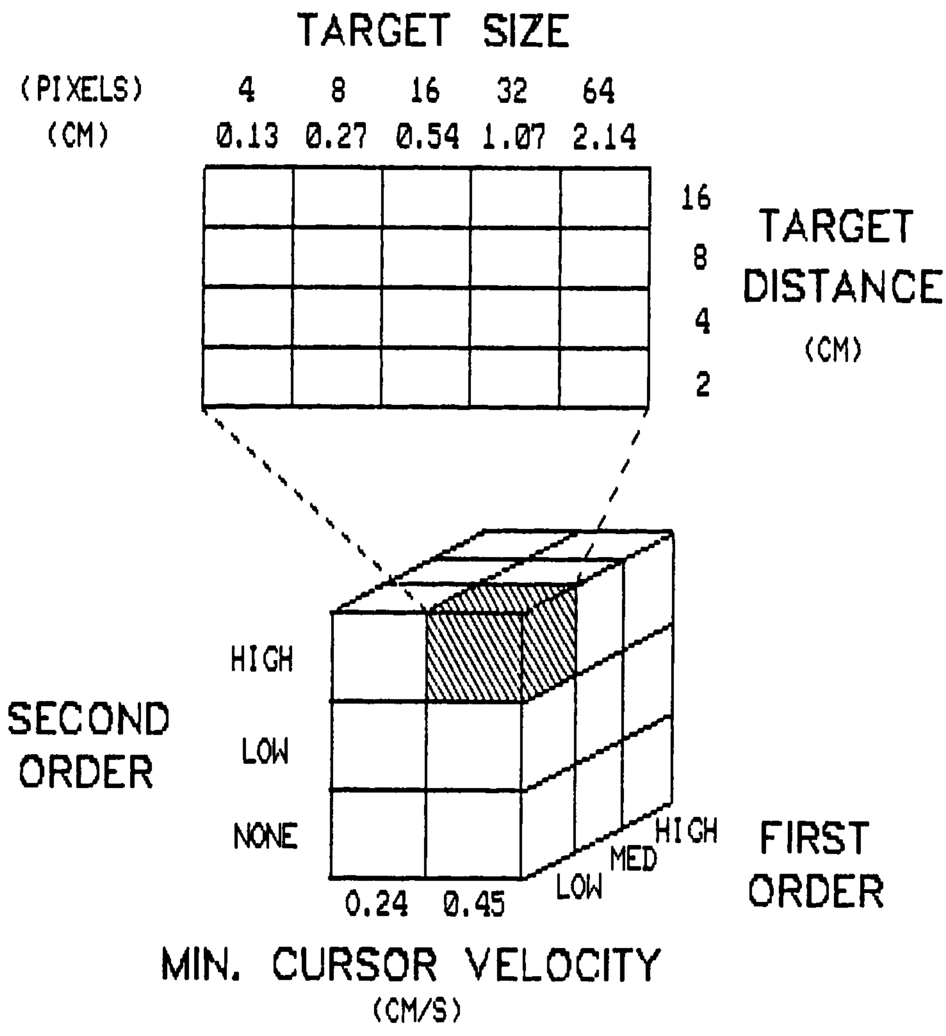

Figure 8. Experimental design: Displacement joystick.

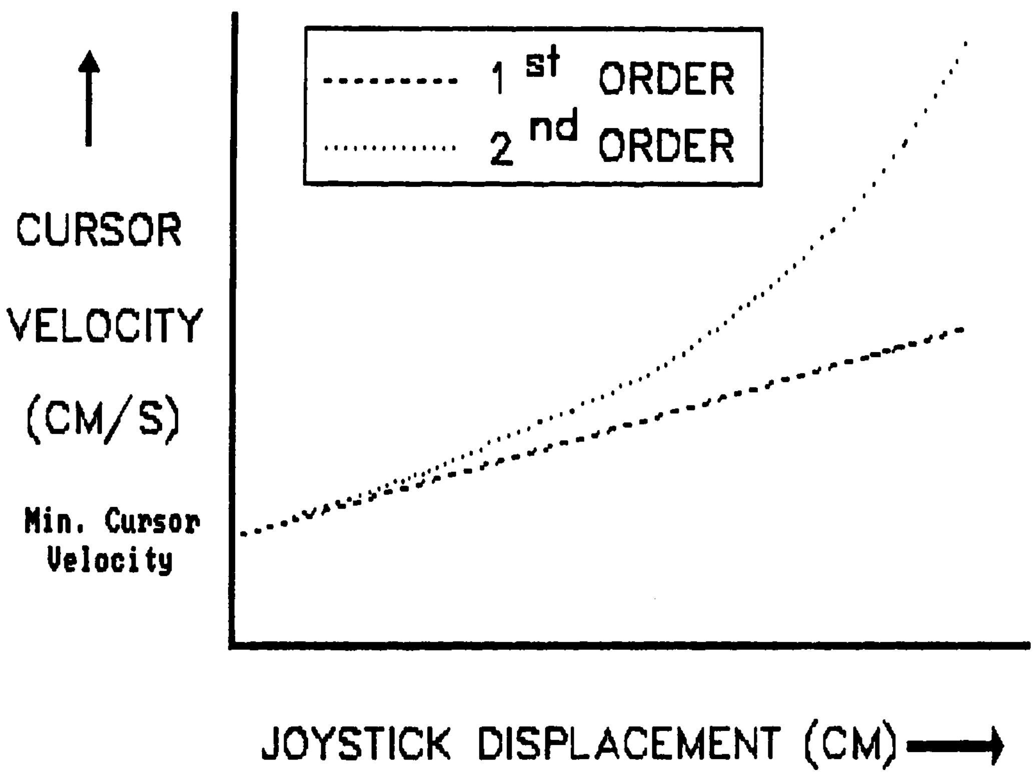

Figure 9. Idealized velocity curves: Displacement joystick.

increase the cursor velocity linearly with joystick displacement. Second-order portions of the velocity curve increase the cursor velocity exponentially with joystick displacement.

Each subject performed five trial blocks (100 trials) with each of 18 (2 x 3 x 3) velocity scale combinations. Each trial block consisted of 20 target size x target distance combinations (5 x 4 = 20 trials).

Force joystick. The force joystick experimental design is shown in Figure 10. The three velocity scale components were minimum joystick force, first-order, and second-order scaling. Minimum joystick force had two levels: 25 and 75 grams. First-order scaling had two levels: low (LO) and high (HI). Second-order scaling had two levels: none (NO) and low (LO).

Appendix A shows the calibrated curves for the eight combinations of minimum force, first-order, and second-order force joystick velocity scales. The joystick velocity curves represent the relationship between force applied to the joystick (grams) and cursor velocity on the screen (cm/s). Idealized velocity curves for minimum force, first-order, and second-order components are shown in Figure 11. The minimum force portion of the velocity

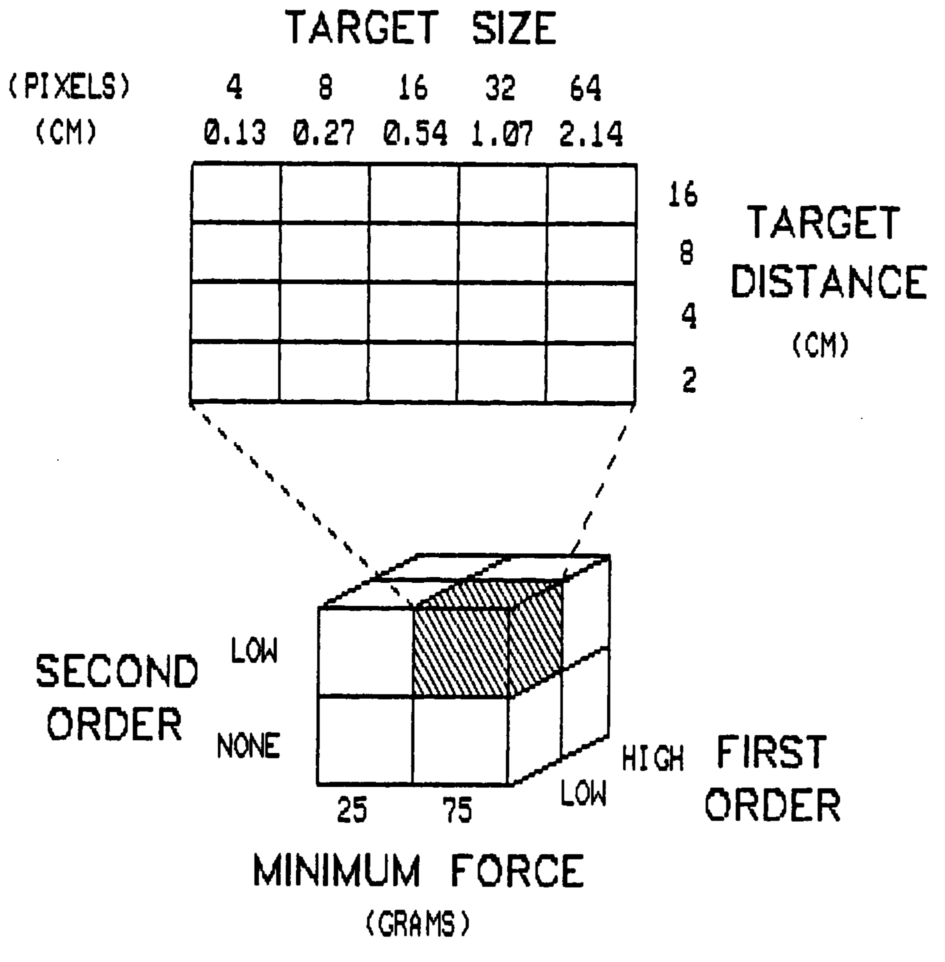

Figure 10. Experimental design: Force joystick.

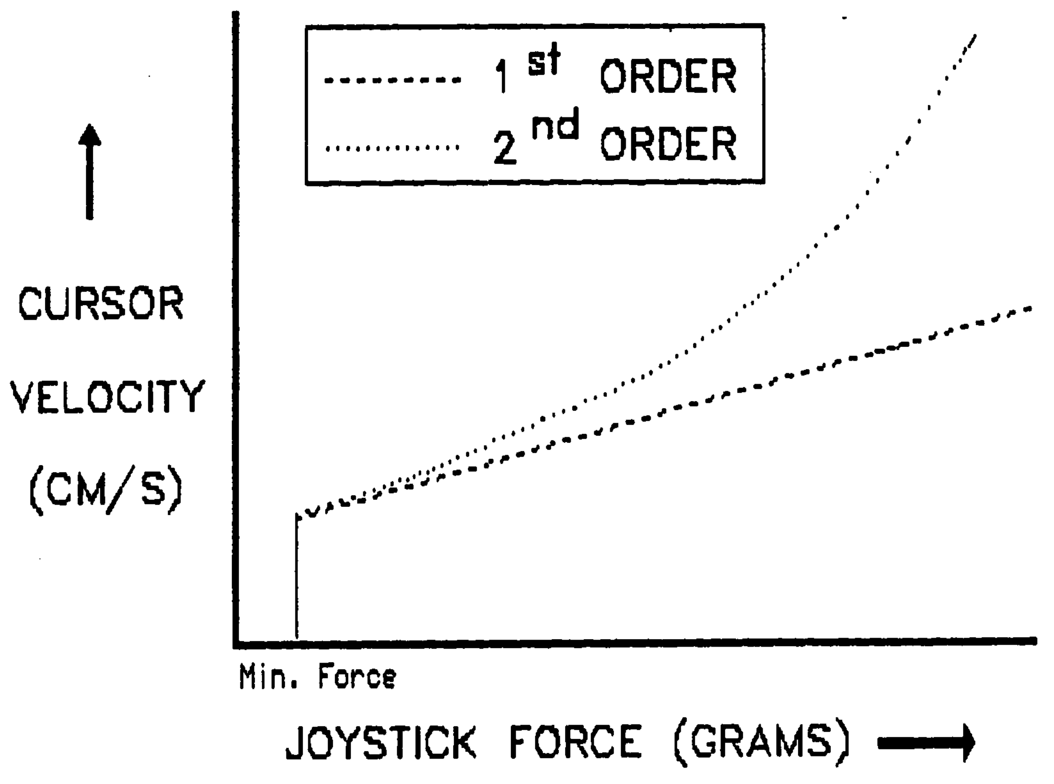

Figure 11. Idealized velocity curves: Force joystick.

curves determines the minimum joystick force, or breakaway force, required to start the cursor in motion. First-order portions of the velocity curve increase cursor velocity linearly with an increase joystick force. Second-order portions of the velocity curve increase the cursor velocity exponentially with an increase joystick force.

Each subject performed 5 trial blocks (100 trials) with each of 8 (2 x 2 x 2) force joystick velocity scale combinations. Each trial block consisted of 20 target size x target distance combinations (5 x 4 = 20 trials).

Target Acquisition Task

For the five optimization experiments, a computer-based target acquisition task was used to compare velocity scale combinations. Each target acquisition trial required the subject to use a cursor control device to (1) move the cross-hair cursor a specific screen distance to a square target, (2) position the cursor within the target boundaries, and (3) press the input button. If the trial was successful, the next target appeared. If the trial was unsuccessful (i.e., the cursor was outside the target boundaries when the input button was pressed), the subject was required to reposition the cursor within the target boundaries and press the input button again.

The direction of cursor movement required to acquire a target was randomized. The starting position of the cursor was the center position of the preceding target. The cross-hair cursor and target boundaries were white on a black screen with a luminance contrast of approximately 8:1. The cross-hair cursor was 1.1 x 1.1 cm and 1-pixel thick. The target boundaries were 1-pixel thick and not part of the active target area.

Experimental Procedures

For all experiments, the first session was approximately 30 minutes in duration. First, each subject was required to read and sign an informed consent form, pass a brief visual acuity test (to a criterion of 25/20), and read instructions for the cursor device (an example of the instructions is shown in Appendix C). Next, each subject performed 200 practice trials of the target acquisition task with the given cursor device. The 200 practice trials were given to reduce learning effects associated with the sequential use of each velocity scale combination. For the five experiments, the number of experimental sessions and procedures differed slightly, as follows.

Force joystick. Subjects returned for a second session the following day in which they performed five trial blocks (100 trials) for each of the eight velocity scale combinations. The velocity scale combinations were randomized among the six subjects.

Trackball, mouse, displacement joystick. The second and third sessions, conducted on the following two days, required subjects to perform five trial blocks (100 trials) for nine first- and second-order velocity scale combinations, at a different zero-order level (i.e., 5 or 10 cm/rev, 1.3 or 2.6 D:C gain, 0.24 or 0.45 cm/s) each day. The order of velocity scale combinations was randomized within each zero-order level for the six subjects. The order of zero-order levels was balanced separately within each of the three experiments.

Relative touchpad. The second, third, and fourth sessions, conducted on the following three days, required subjects to perform five trial blocks (100 trials) for nine first- and second-order velocity scale combinations, at a different zero-order level (i.e., 0.33, 1.0, or 2.0 D:C gain) each day. The order of velocity scale combinations was randomized within each zero-order level for the six subjects. The order of zero-order levels was balanced.

For all sessions and for all devices, subjects were given a brief rest after each 100 trials.

DATA ANALYSIS AND RESULTS: DEVICE OPTIMIZATION

For each of the five optimization experiments, a similar statistical analysis was performed. First, an overall analysis of variance (ANOVA) was performed on the velocity scale x target size x target distance model, based on the time-to-target (TT) dependent measure. The velocity scale independent variable represented the total combinations investigated for each cursor device. The number of levels of velocity scale were 18 for the trackball, mouse, and displacement joystick; 27 for the relative touchpad; and 8 for the force joystick.

A general philosophy was used for the interpretation of the ANOVA results. For each of the five separate cursor control device analyses, as target distance (TD) increases, TT increases, averaged over all other variables. Likewise, as target size (TS) increases, TT decreases, averaged across all other variables. However, the TD and TS main effects and the TD x TS interaction are unimportant when considered alone, as they should logically interact with the various velocity scales (VSs). Accordingly, it is more meaningful to evaluate the interaction of VS with the TD and TS variables. Therefore, the ANOVA results are discussed in terms of significant VS x TS and VS x TD interactions and the VS main effect, when applicable.

For significant interactions and main effects, post-hoc multiple comparisons of TT means over target sizes and target distances were conducted using a Fisher's Least Significant Difference (LSD) Test (alpha = 0.05). Although the LSD test does not protect for experiment-wise alpha error for multiple comparisons, it was chosen for its sensitivity as a "data snooping" technique for isolating the best velocity scales.

Trackball

An ANOVA was performed on the velocity scale (18) x target size (5) x target distance (4) model for the time to target (TT) dependent measure. The results are given in Table 1 (Appendix C). Significant interactions of interest were (1) Velocity Scale x Target Size ($F(68,340) = 3.09$, $p = 0.0001$) and Velocity Scale x Target Distance ($F(51,255) = 4.06$, $p = 0.0001$). Subsequent post-hoc multiple comparisons of these interactions were divided into five velocity scale (VS) groups: (1) zero-order, (2) first-order, (3) pure second-order, (4) low first-order plus second-order, and (5) high first-order plus second-order. Fisher's LSD Test results for the Velocity Scale x Target Size interaction are given in Tables 2, 3, 4, 5, and 6 (Appendix B). Results for the Velocity Scale x Target Distance interaction are given in Tables 7, 8, 9, 10, and 11 (Appendix B).

Zero-order. Velocity scales (VSs) with only a zero-order component (i.e., no first-order or second-order components) represent a trackball with a linear D:C gain. Two zero-order VS gains (5.0 and 10.0 cm/rev) are compared across target sizes and target distances in Figures 12 and 13. The 5.0 gain provides faster target acquisition at the smallest target size, but the 10.0 gain provides better positioning at the 1.07- and 2.14-cm target sizes, as indicated in Figure 12 (Table 2). With respect to target distances, the 10.0 gain provides faster target positioning at the longest screen distance (16 cm), as shown in Figure 13 (Table 7). At other distances, the two gains do not differ significantly. Evidently, the 5.0 gain is good for fine-positioning tasks, whereas the 10.0 gain is best for gross-positioning tasks (i.e., large targets, long screen distances).

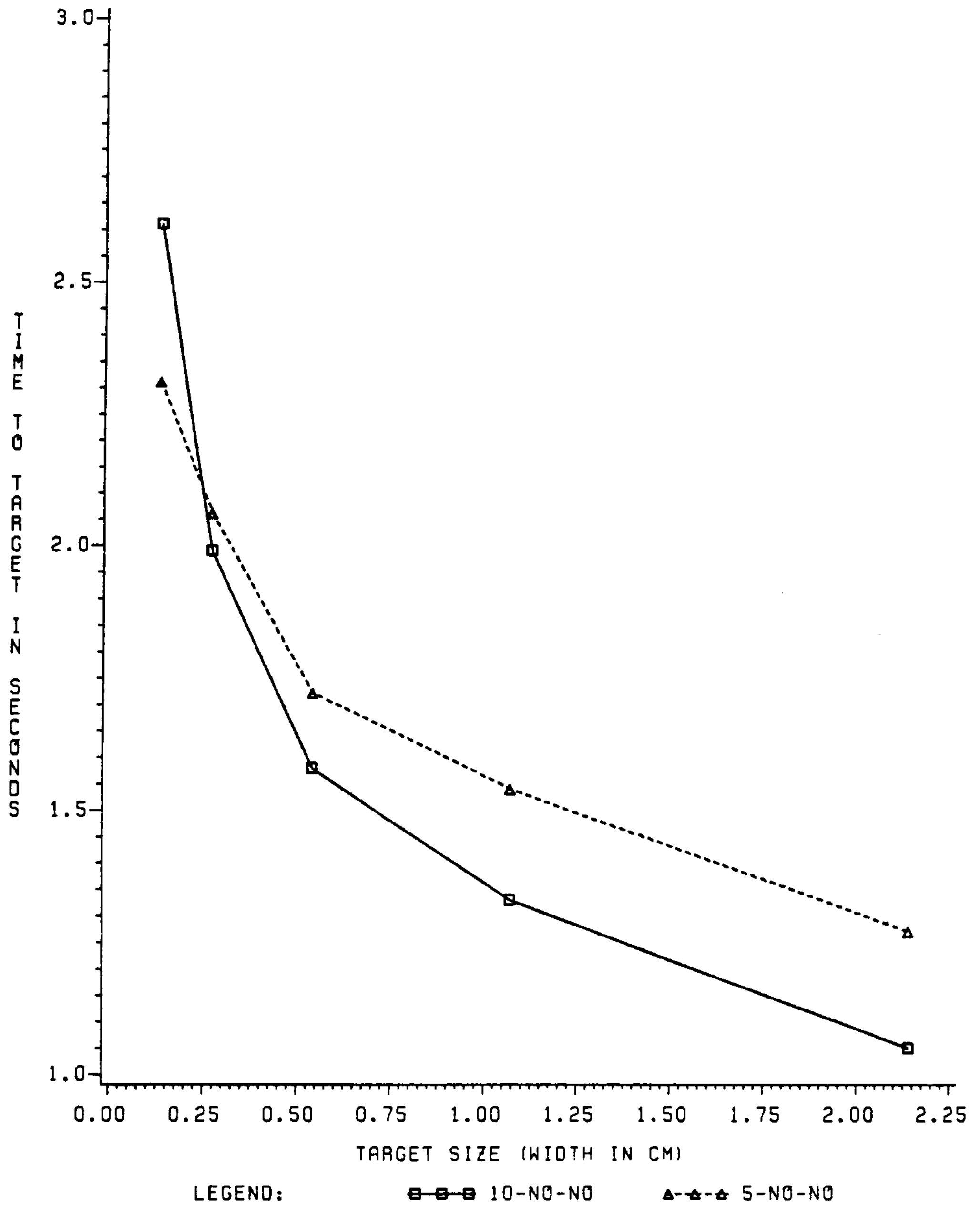

Figure 12. Comparison of the trackball zero-order group across target sizes.

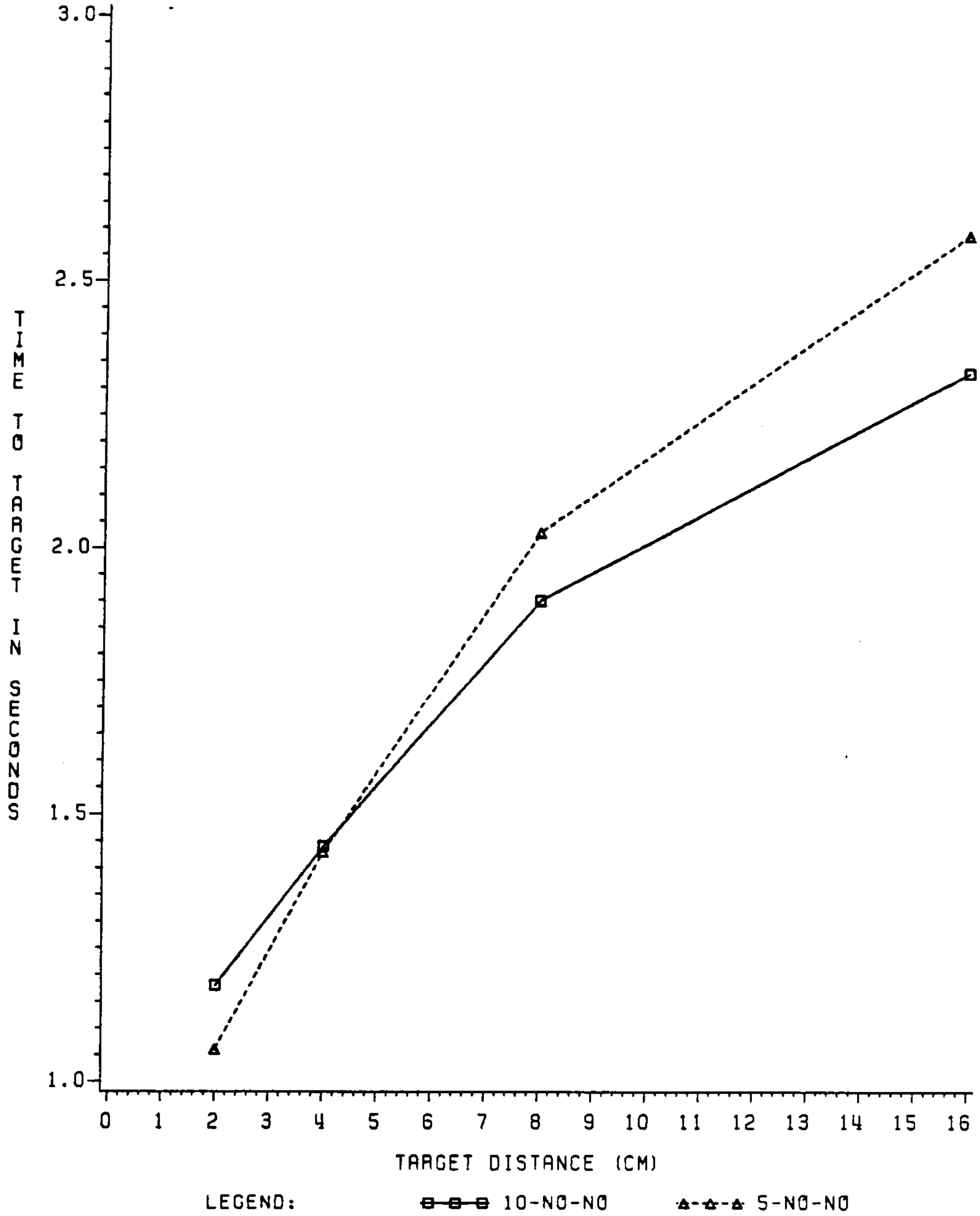

Figure 13. Comparison of the trackball zero-order group across target distances.

First-order. The first-order VS group represents the four combinations of zero-order (5.0 or 10.0) with first-order (LO or HI) components, all having no second-order components. Comparisons of the first-order group across target sizes are shown in Figure 14 (Table 3). For the 0.13-cm target size, the 5.0 gain VSs provide better target acquisition performance than the 10.0 gain VSs, regardless of LO or HI first-order scaling. As target size increases, however, the 5.0 gain in combination with HI or LO first-order scaling provides better performance than does the 10.0 scaling.

A comparison of the first-order group across target distances, shown in Figure 15 (Table 8) indicates that at 8- and 16-cm distances, the 5.0 gain with LO first-order scaling is significantly worse than the remaining VSs. These results indicate the overall superior target positioning performance of a 10.0 zero-order gain in combination with "fast" (i.e., HI) first-order scaling for easier tasks (large targets), and the 5.0 zero-order gain with the HI first-order scaling for difficult tasks (small targets, long screen distances).

Pure second-order. Velocity scales which vary only in zero-order (5.0 or 10.0) and second-order (LO or HI)

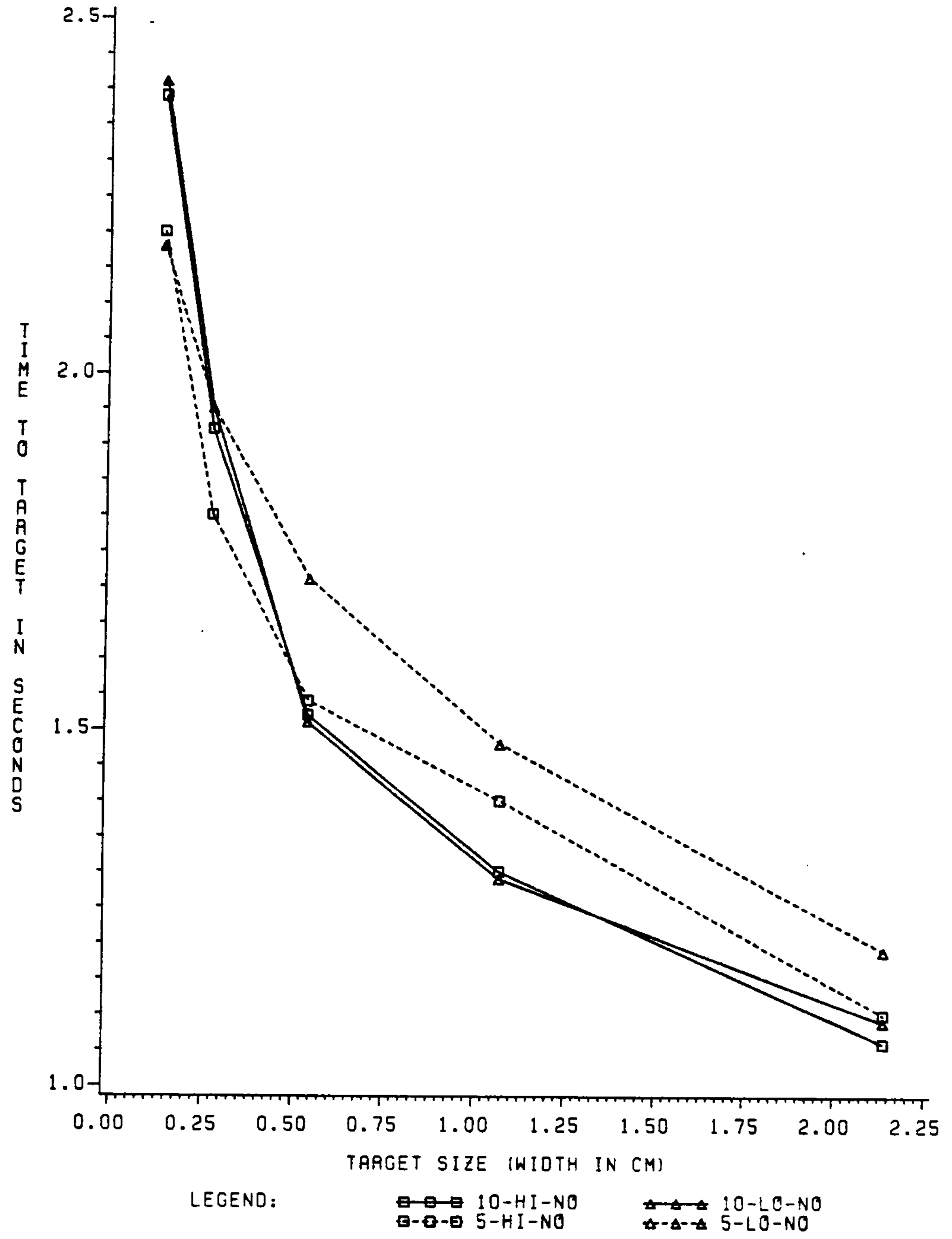

Figure 14. Comparison of the trackball first-order group across target sizes.

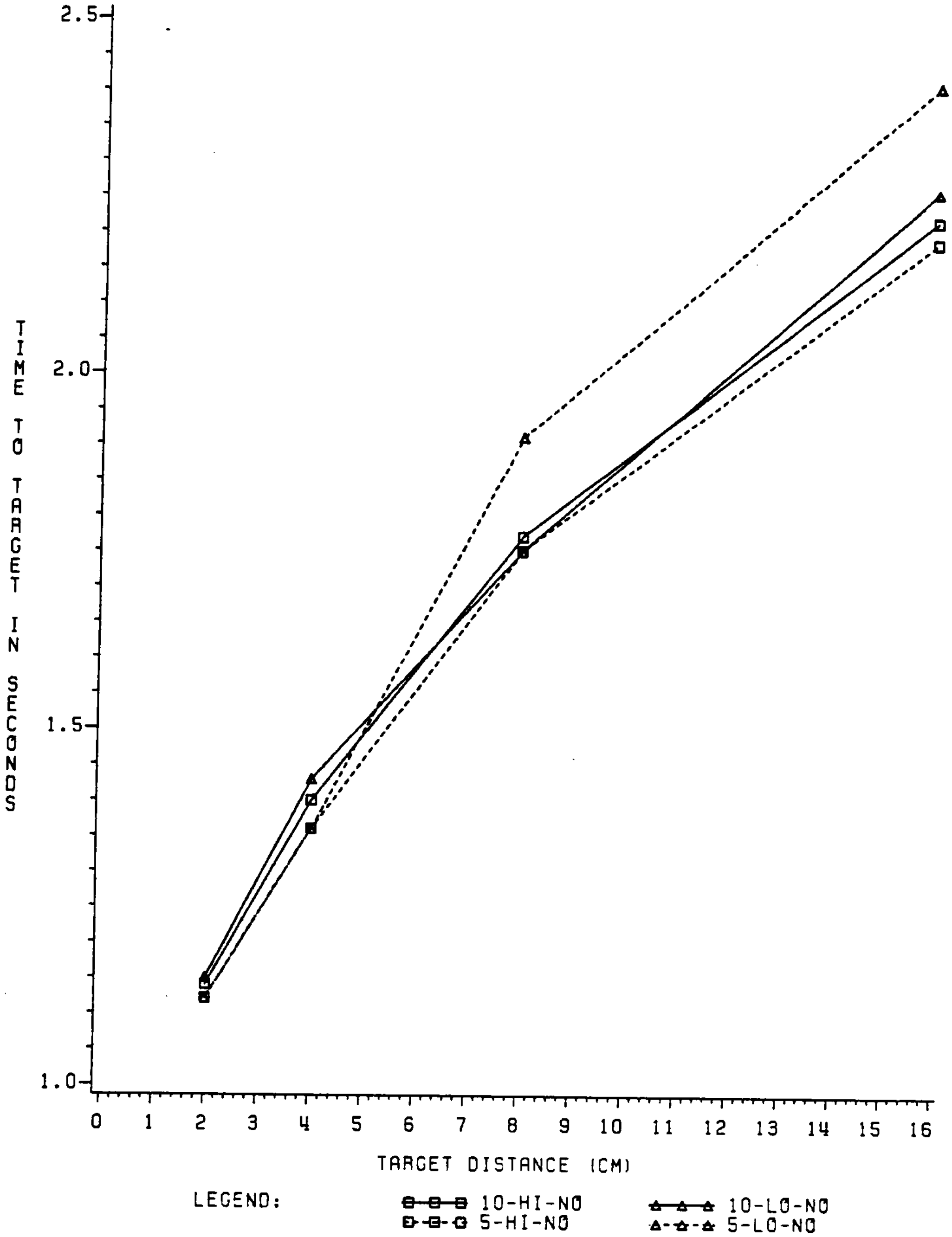

Figure 15. Comparison of the trackball first-order group across target distances.

components are compared across target sizes and target distances in Figure 16 (Table 4) and Figure 17 (Table 9), respectively. At the smallest target size (0.13 cm), results indicate that the 10.0 gain VS with low second-order scaling (10-NO-LO) is slower for target acquisition than the remaining VSs (Figure 16). In addition, 5-NO-LO is slower than 10-NO-HI for the 2.14-cm target. With respect to target distance (Figure 17), the 10.0 gain in combination with a high second-order component (10-NO-HI) is superior to all other VSs at 8- and 16-cm distances, but worse than 5.0 gain with low scaling (5-NO-LO) at the 2-cm distance. This may be the result of over-shoot problems at short target distances for the sensitive 10-NO-HI velocity scale combination.

<u>First-order plus second-order</u>. Velocity scale combinations with low first-order plus second-order components are shown across target sizes and distances in Figure 18 (Table 5) and Figure 19 (Table 10), respectively. At small target sizes (0.13 and 0.27 cm), 5-LO-HI out-performs 10-LO-HI, but differences diminish as target size increases. In addition, no differences between these two VSs exist for target distances in excess of 2 cm (Figure 19). At 2 cm, the 10-LO-HI is inferior to the two

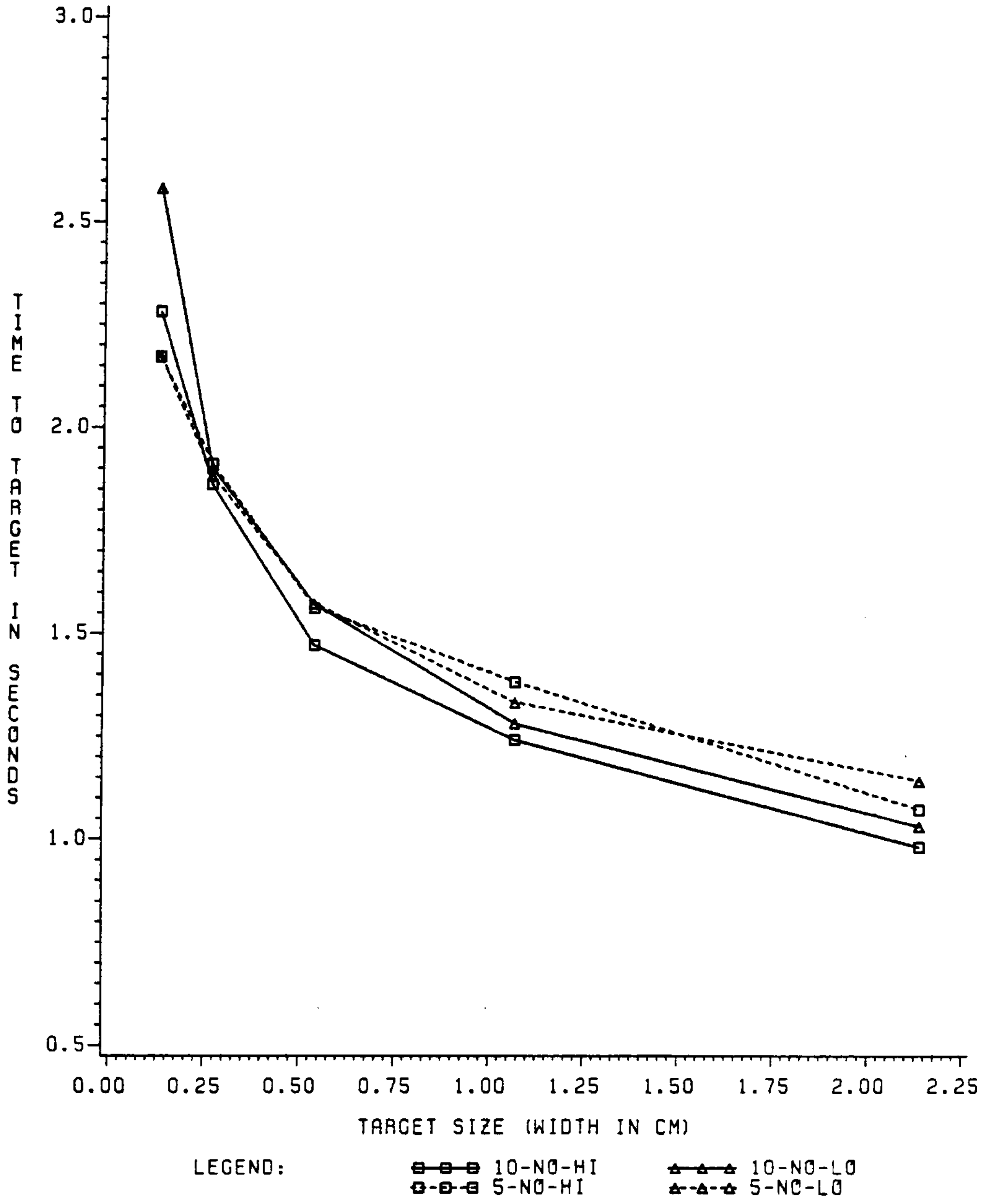

Figure 16. Comparison of the trackball pure second-order group across target sizes.

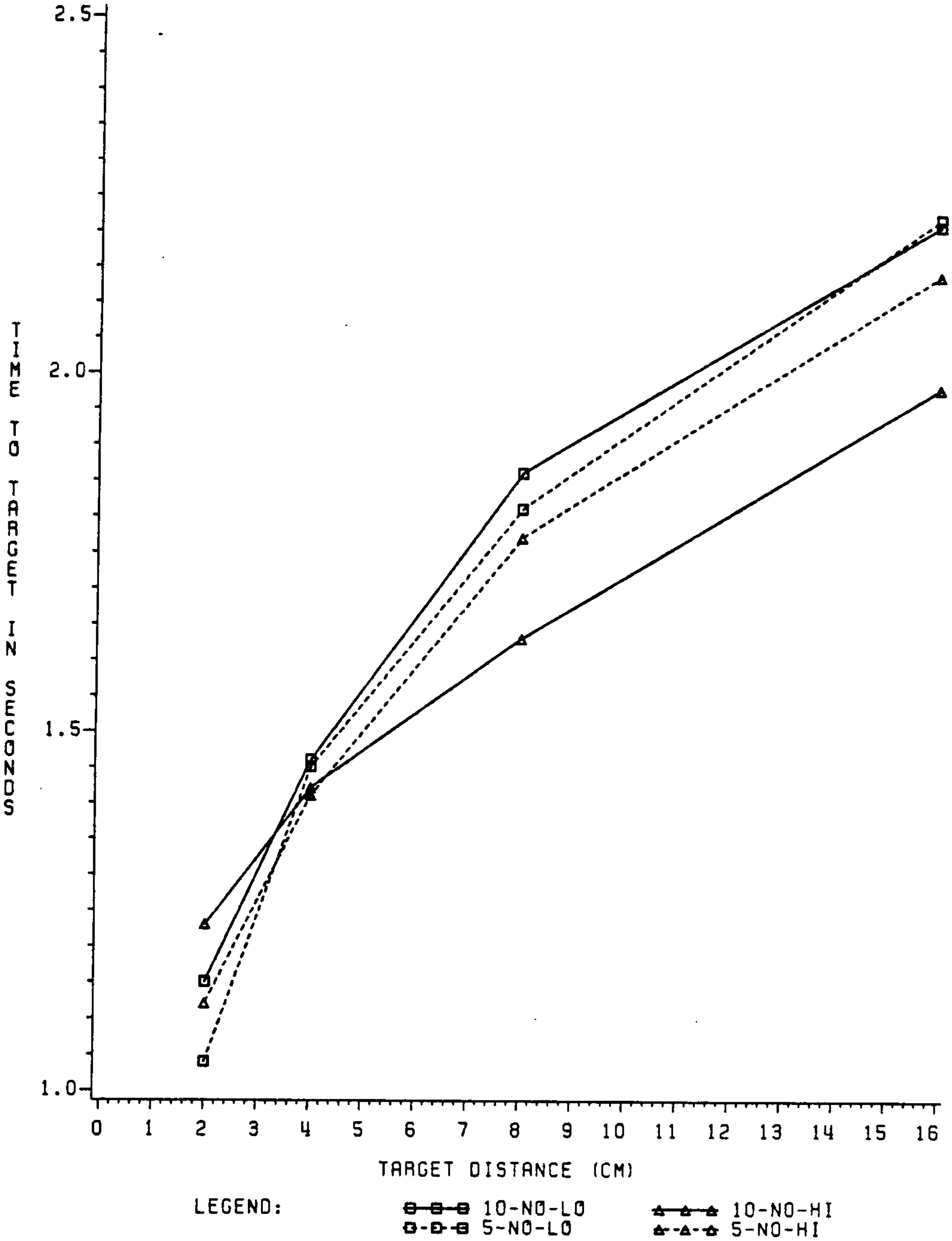

Figure 17. Comparison of the trackball pure second-order group across target distances.

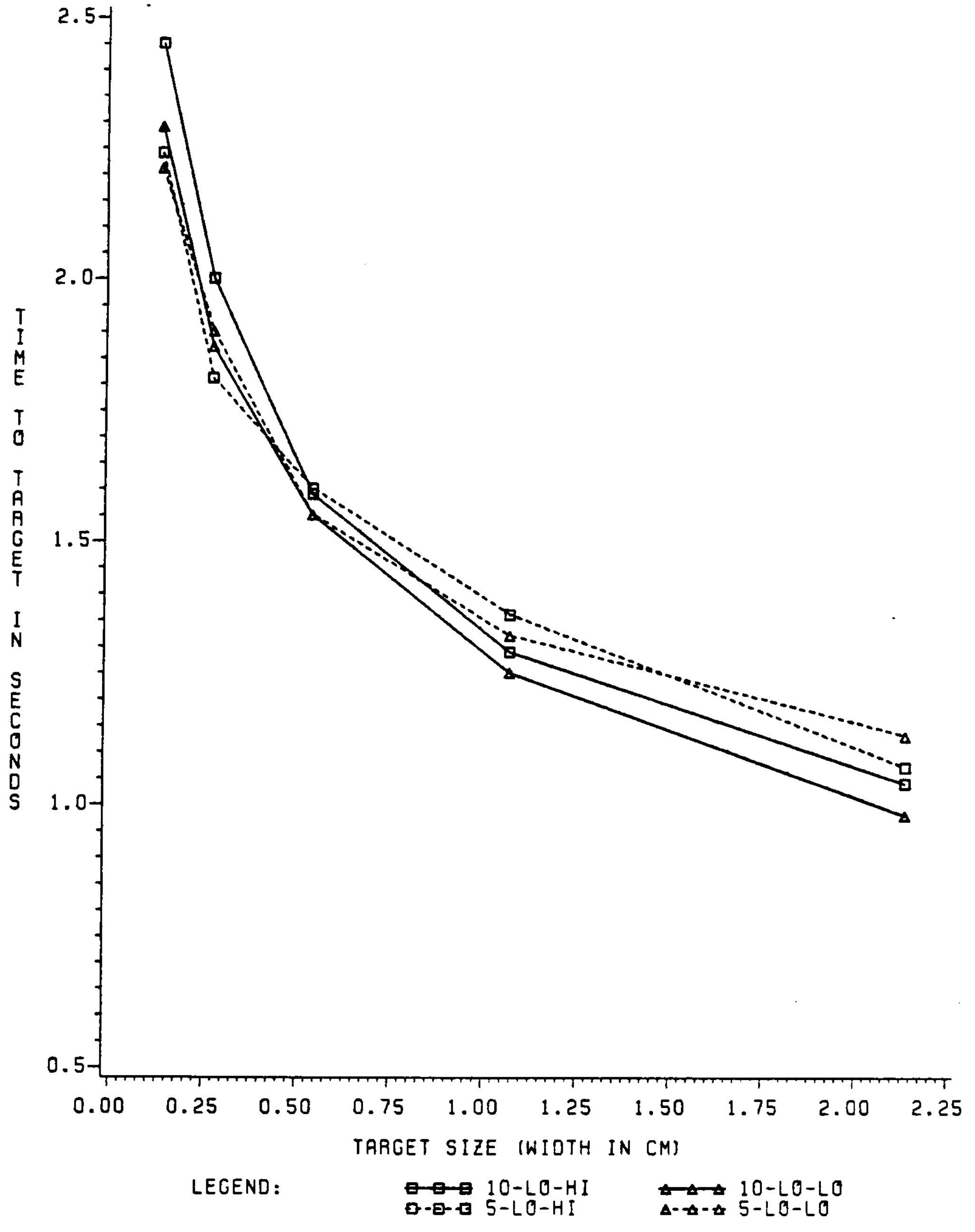

Figure 18. Comparison of the trackball low first-order plus second-order group across target sizes.

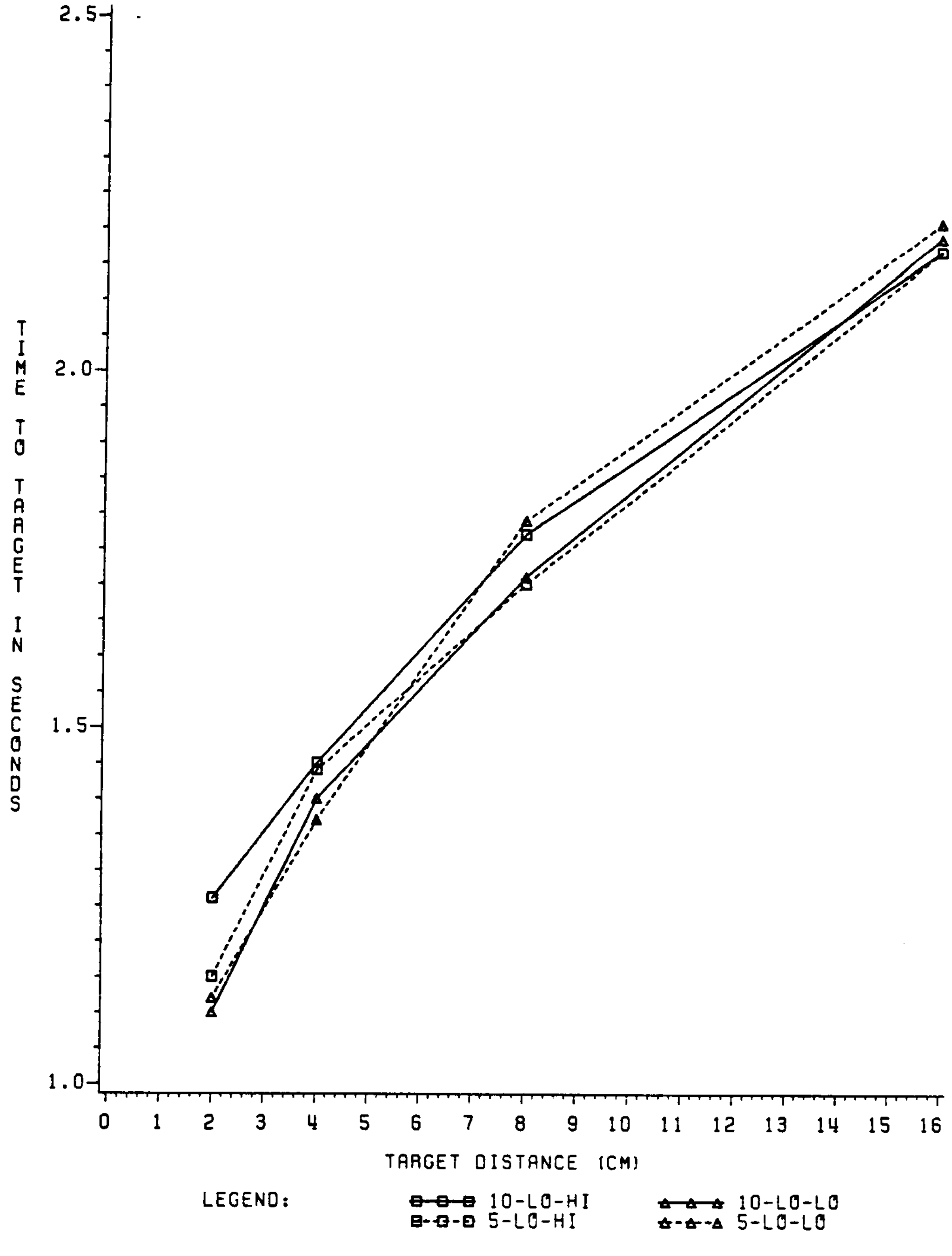

Figure 19. Comparison of the trackball low first-order plus second-order group across target distances.

LO-LO combinations.

A comparison of the velocity scale group with high first-order plus second-order components are shown across target sizes and target distances in Figure 20 (Table 6) and Figure 21 (Table 11). Results indicate that, overall, the 5.0 gain in combination with high first-order and high second-order scaling (i.e., 5-HI-HI) provides the best target positioning performance of this VS group.

<u>The best trackball velocity scale</u>. In general, velocity scale combinations with low zero-order components (i.e., 5.0 gain) provide the fastest target acquisition at small target sizes. Velocity scales with fast first-order and second-order components provide the best performance at long distances. Both of these results were expected. Unfortunately, no one velocity scale combination provides consistently better performance relative to other combinations. In essence, a group of trackball dynamics gave "statistically" similar performance across all target sizes and distances. Therefore, the velocity scale which provided the best overall and most consistent performance across target size and distance was chosen for future study as having the "optimum" trackball dynamics. This velocity scale combines a 5.0 gain with fast first-order and fast

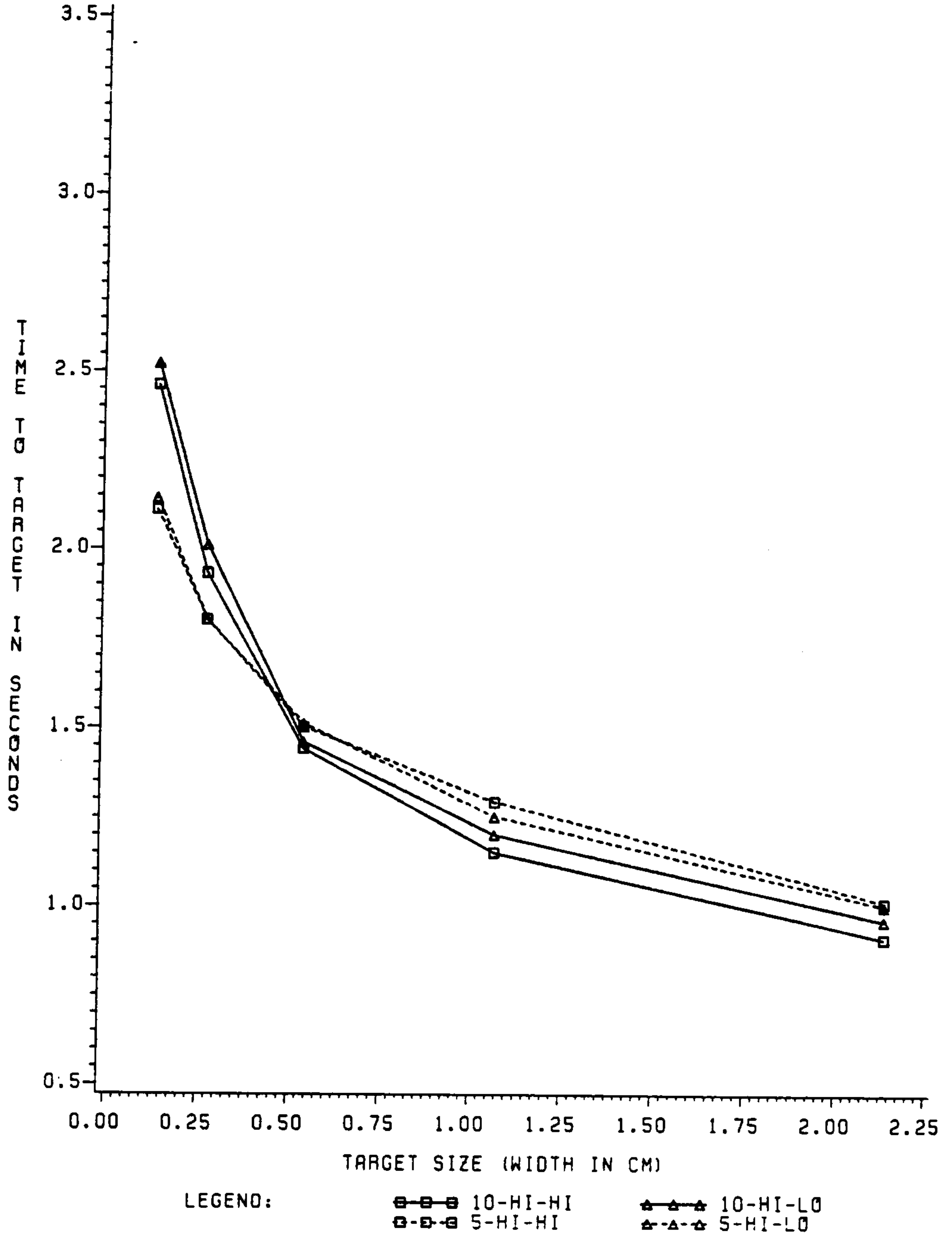

Figure 20. Comparison of the trackball high first-order plus second-order group across target sizes.

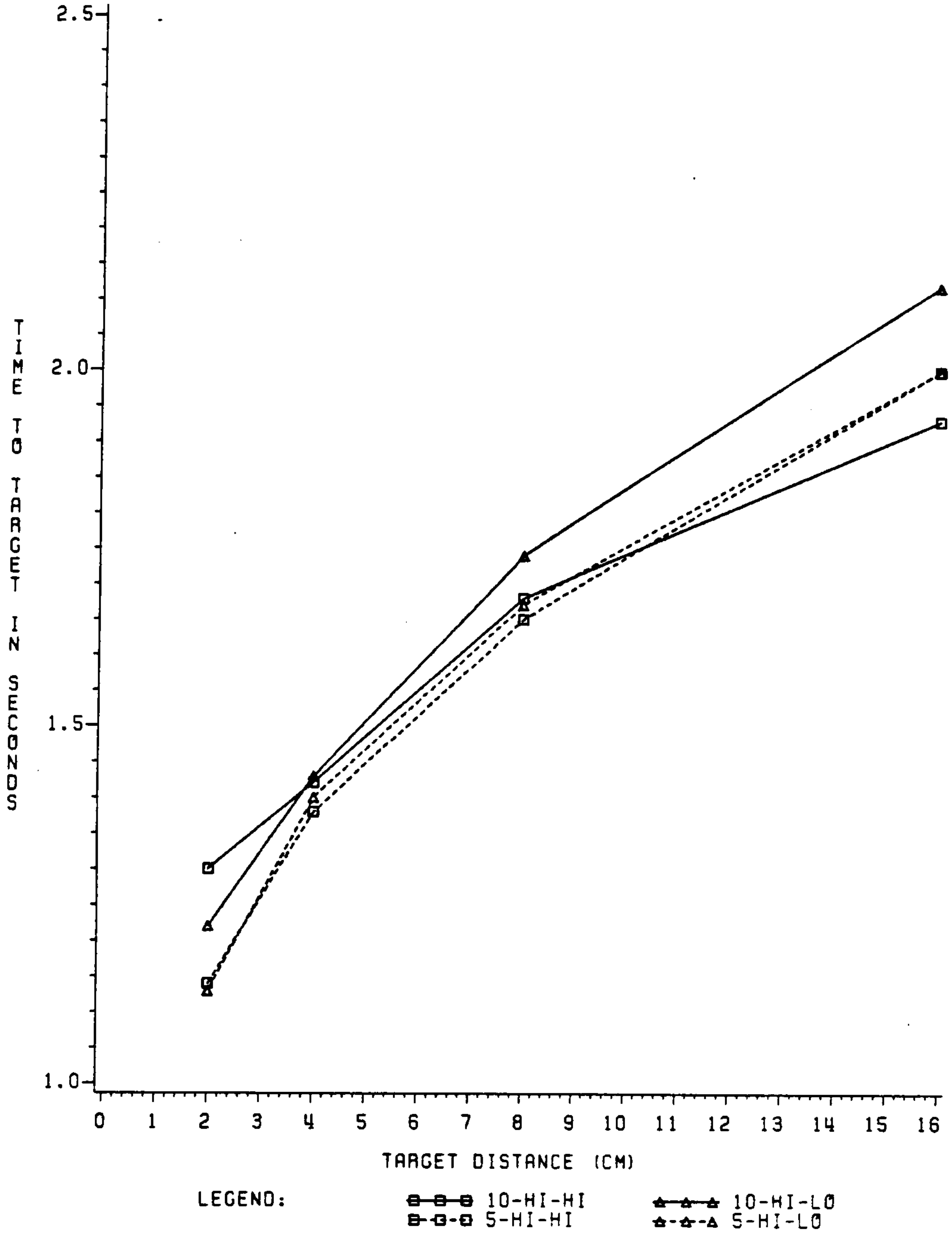

Figure 21. Comparison of the trackball high first-order plus second-order group across target distances.

second-order scaling (i.e., 5-HI-HI).

Mouse

An ANOVA was performed on the velocity scale (18) x target size (5) x target distance (4) model for the time to target (TT) dependent measure. Results are given in Table 12 (Appendix B). Significant interactions of interest are Velocity Scale x Target Size ($F(68,340) = 1.92$, $p = 0.0001$) and Velocity Scale x Target Distance ($F(51,255) = 1.46$, $p = 0.0315$). Subsequent post-hoc multiple comparisons of the interactions were divided into five groups: (1) zero-order, (2) first-order, (3) pure second-order, (4) low first-order plus second-order, and (5) high first-order plus second-order. Results are given for the Velocity Scale x Target Size interaction in Tables 13, 14, 15, 16, and 17 (Appendix B). Results for the Velocity Scale x Target Distance interaction are given in Tables 18, 19, 20, 21, 22 (Appendix B).

Zero-order. Velocity scales with only a zero-order component (i.e., no first-order or second-order components) represent the mouse with a linear D:C gain. Two zero-order VSs (1.3 and 2.6 gain) are compared across target sizes and target distances in Figures 22 and 23. The 1.3 gain provides superior target positioning performance at the 0.13- and 0.27-cm target sizes (Figure 22, Table 13) and at the 2- and 4-cm target distances (Figure 23, Table 18). This result suggests that for graphics and some word processing tasks, which require relatively high positioning accuracy and short cursor moves, the 1.3 gain would be preferred over the 2.6 gain. Under none of the test conditions is the 2.6 gain significantly better than the 1.3 gain.

<u>First-order</u>. The first-order VS group represents four combinations of zero-order (1.3 or 2.6 gain) with first-order (LO or HI) components. Comparisons of the first-order group across target sizes are shown in Figure 24 (Table 14). At the smallest target size (0.13 cm), the combination of a low first-order velocity component with a 1.3 gain (i.e., 1.3-LO-NO) results in better target acquisition performance than the remaining VS combinations. At the 0.27-cm target size, the 1.3-LO-NO is significantly better than 2.6-LO-NO, indicating generally superior performance for the 1.3 gain. These results show a higher fine-positioning sensitivity demonstrated by a 1.3 D:C gain.

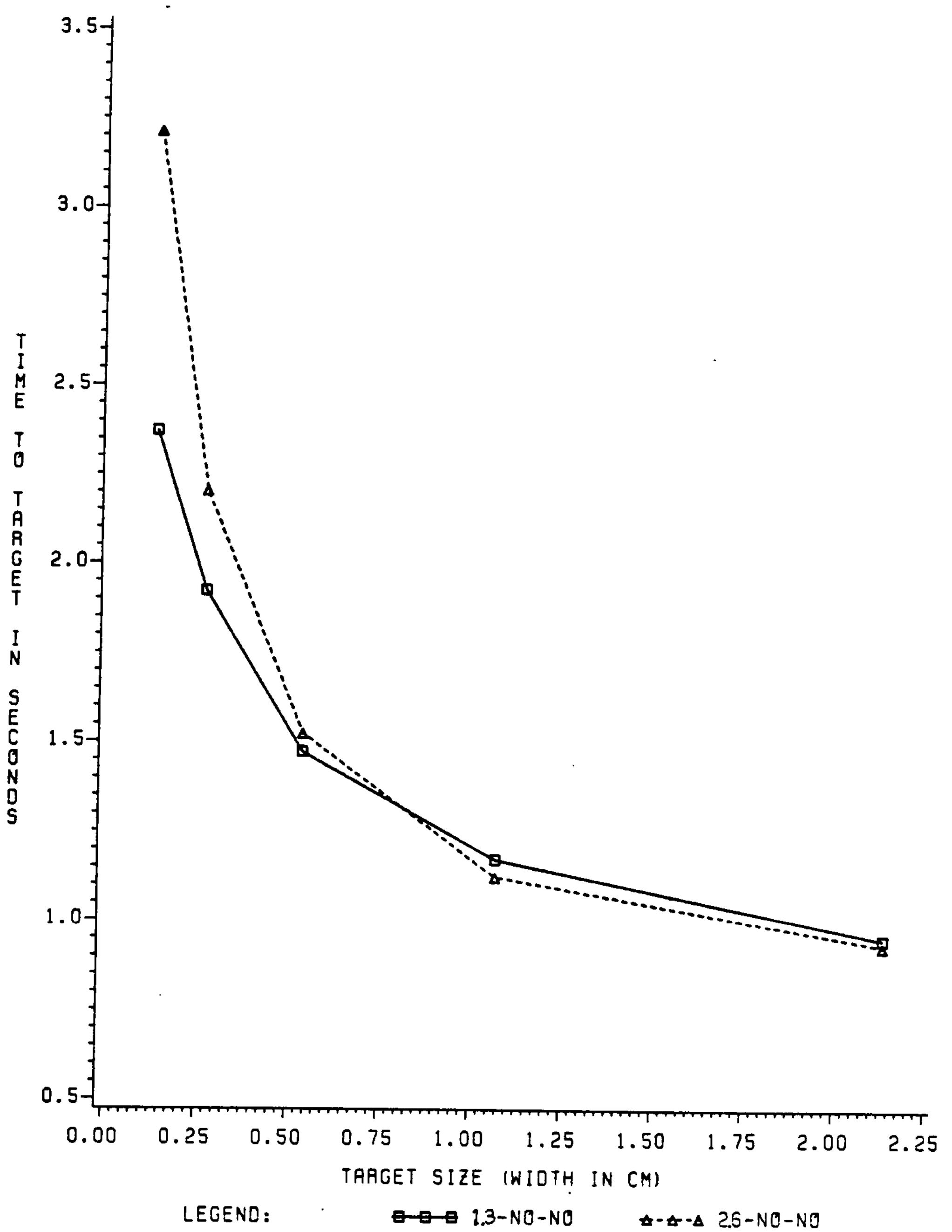

Figure 22. Comparison of the mouse zero-order group across target sizes.

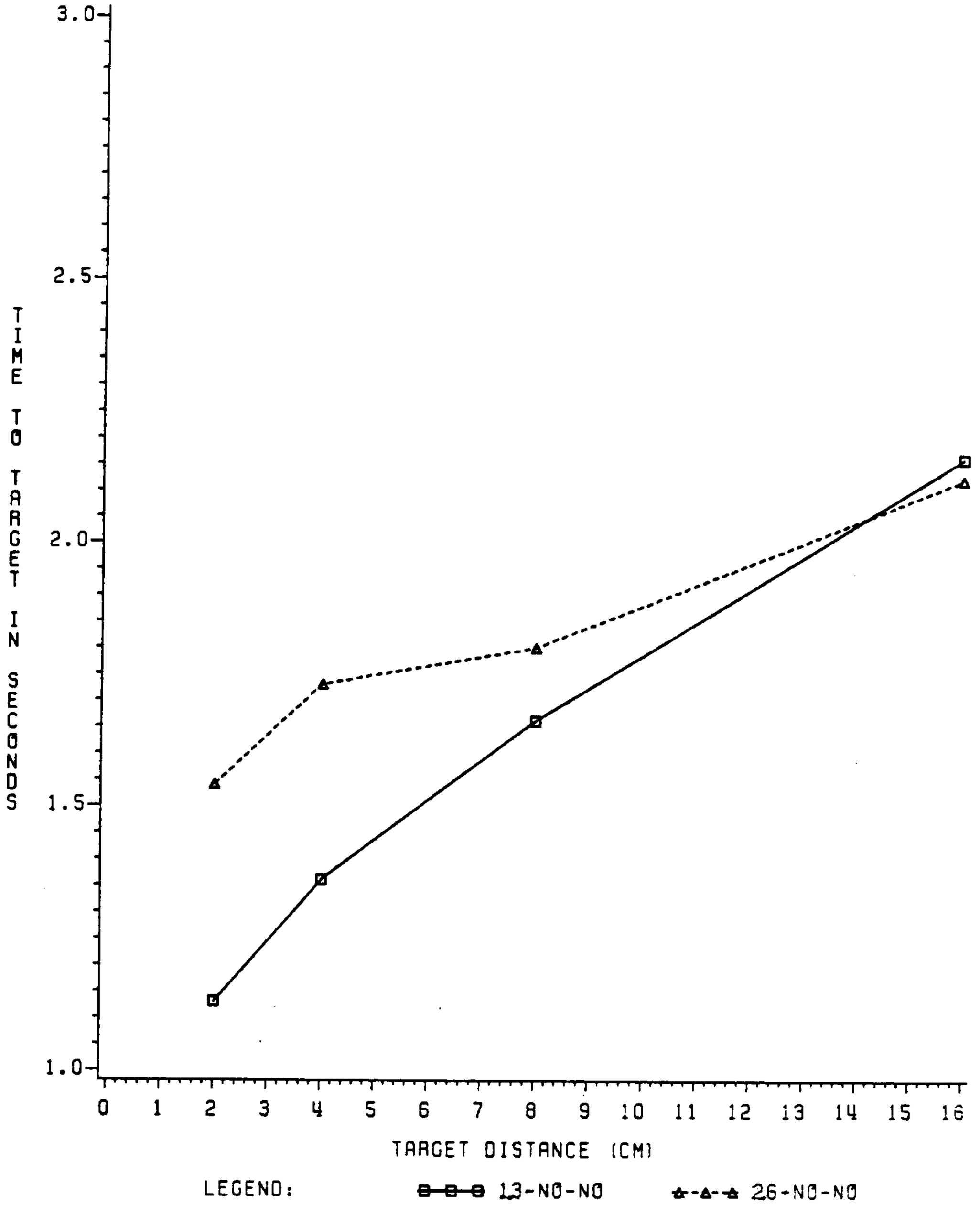

Figure 23. Comparison of the mouse zero-order group across target distances.

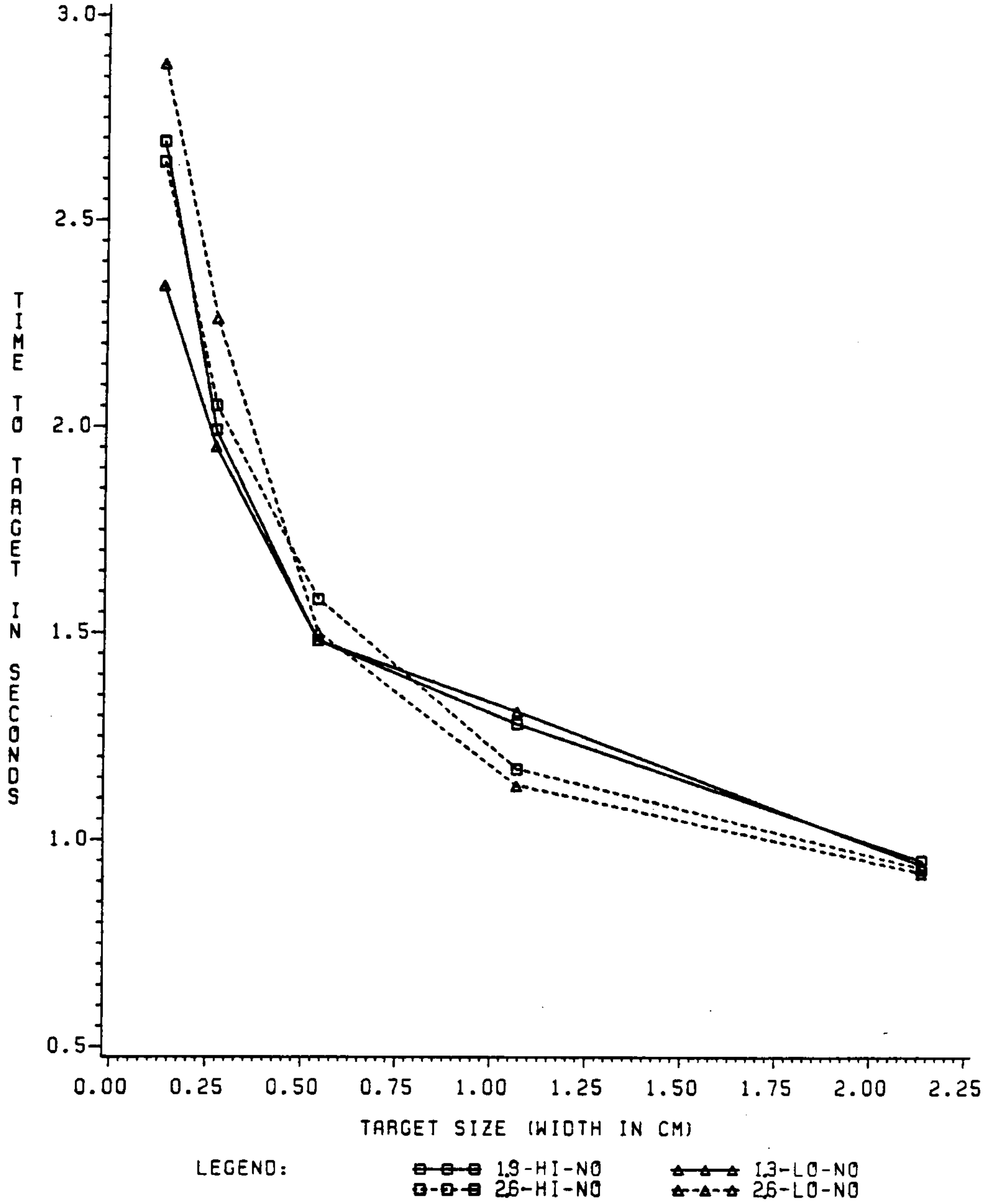

Figure 24. Comparison of the mouse first-order group across target sizes.

Comparison of first-order VSs across target distance indicate better performance for the 1.3 gain VSs at short target distances (2 cm), as shown in Figure 25 (Table 19). A possible explanation for this result may be an over-shoot problem at "short" distances for the 2.6 gain. The poor performance by the 1.3-HI-NO at the 8-cm distance might also be explained by target over-shoot.

Pure second-order. The effects of velocity scales which varied in zero-order (1.3 and 2.6 gain) and second-order (LO and HI) components are shown across target sizes and target distances in Figures 26 and 27 (Tables 15 and 20), respectively. The 1.3 gain VSs are significantly better only at the 0.13-cm target size (Table 15). With respect to target distance, the 1.3 gain in combination with a LO second-order component is superior to the 2.6 gain VSs at 4 cm (Table 20). Again, this may be the result of over-shoot at short target distances.

First-order plus second-order. Second-order velocity scale components with LO first-order components result in better target acquisition performance for small targets and at short distances when a 1.3 zero-order gain is used, as shown in Figures 28 and 29 (Tables 16 and 21). Velocity

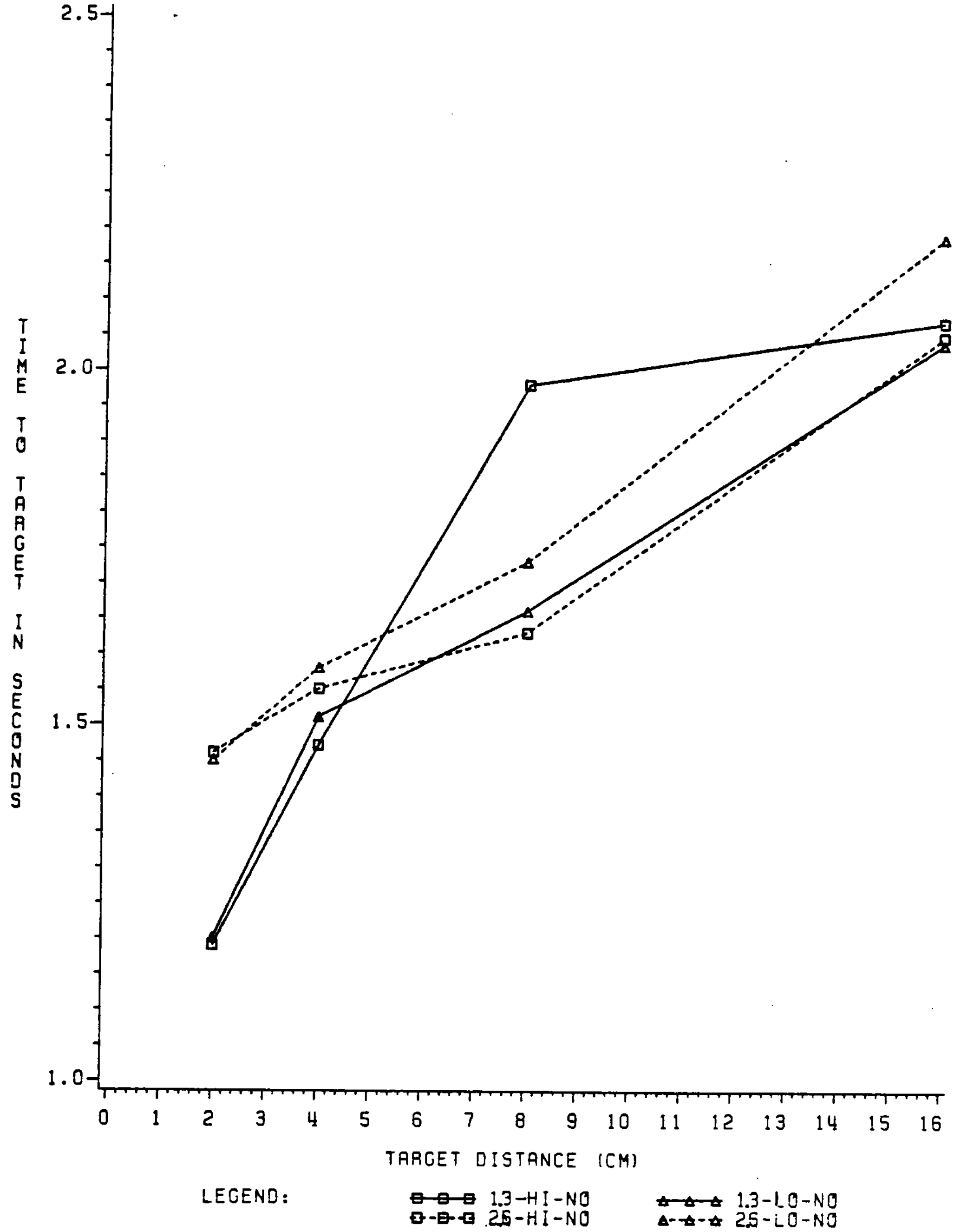

Figure 25. Comparison of the mouse first-order group across target distances.

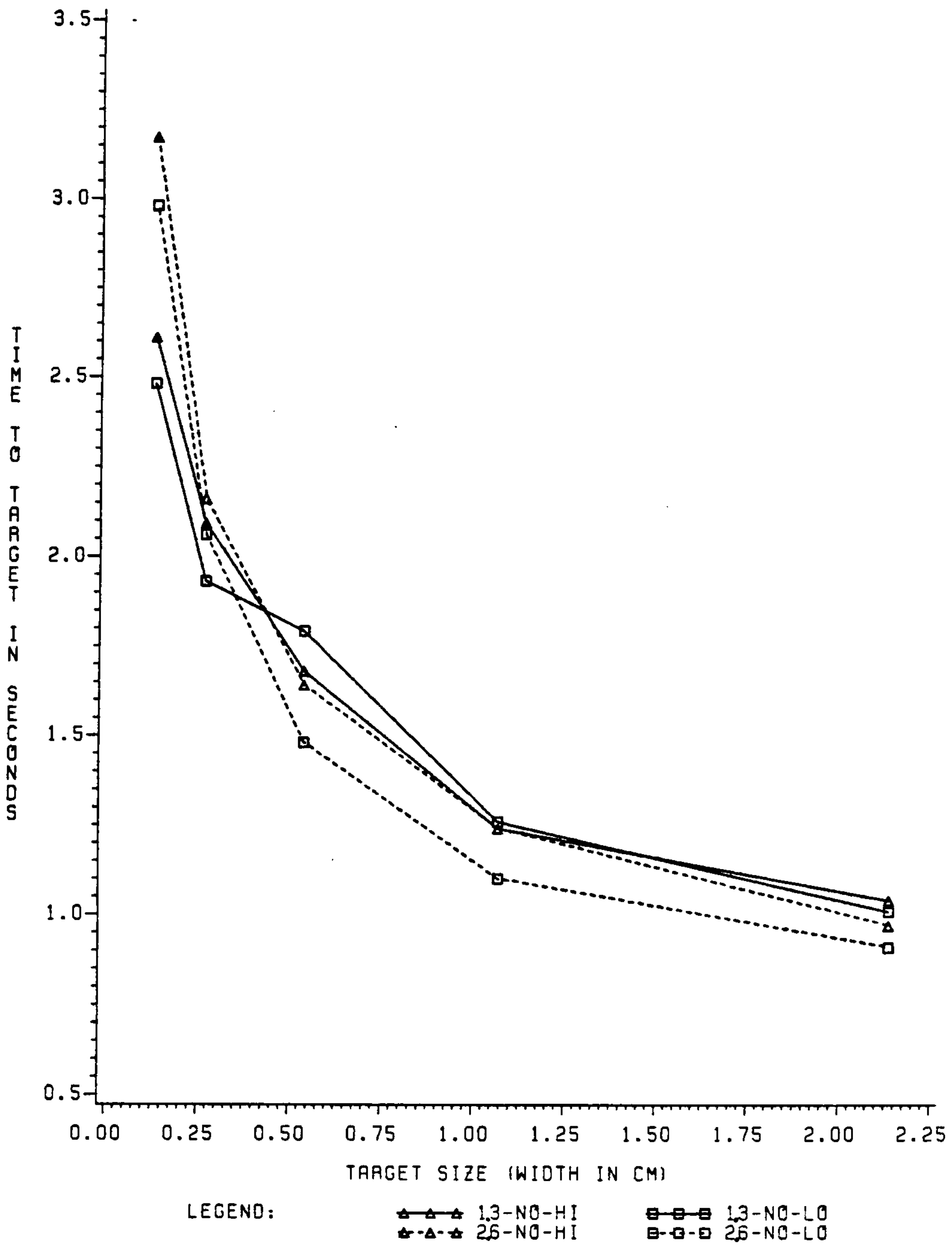

Figure 26. Comparison of the mouse pure second-order group across target sizes.

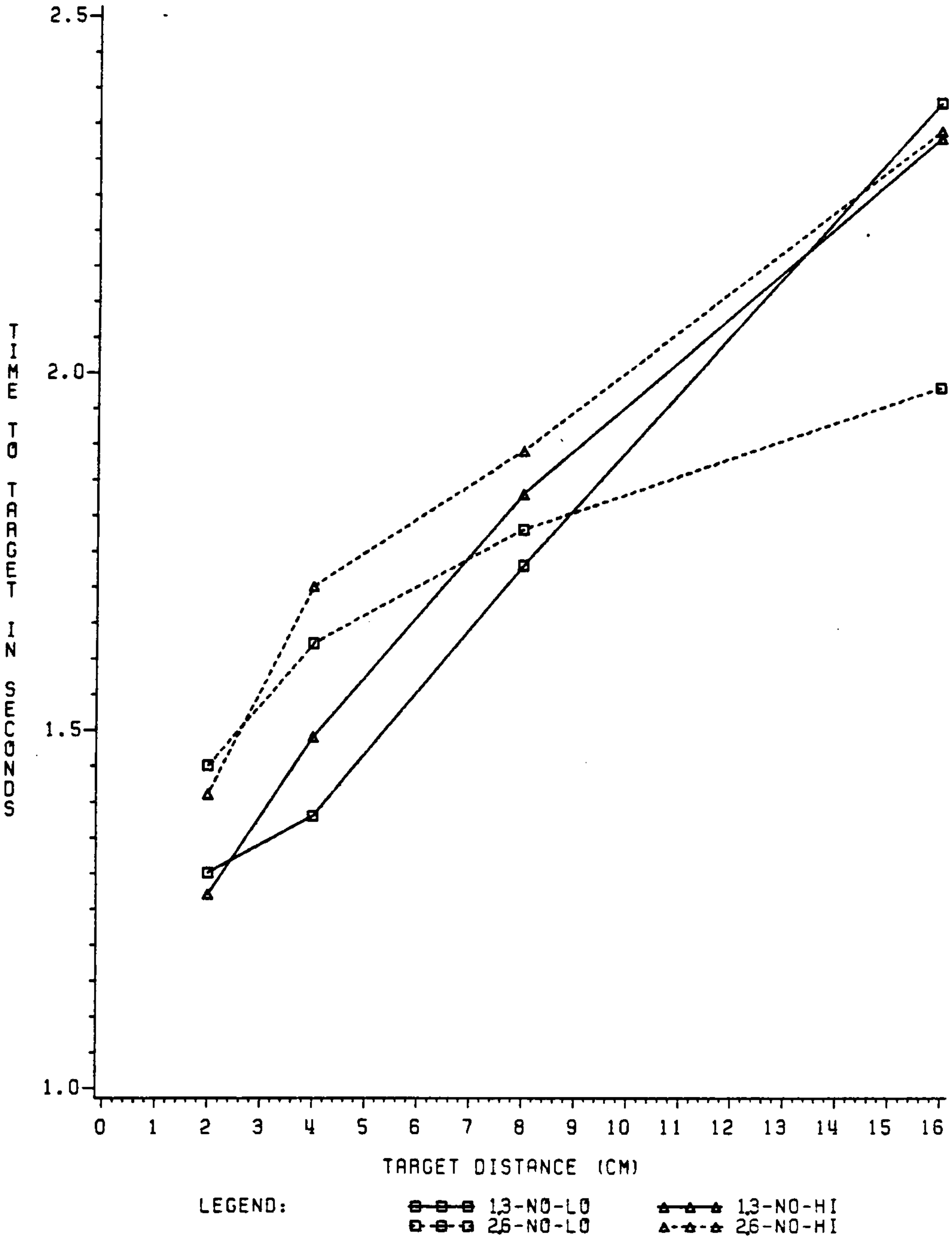

Figure 27. Comparison of the mouse pure second-order group across target distances.

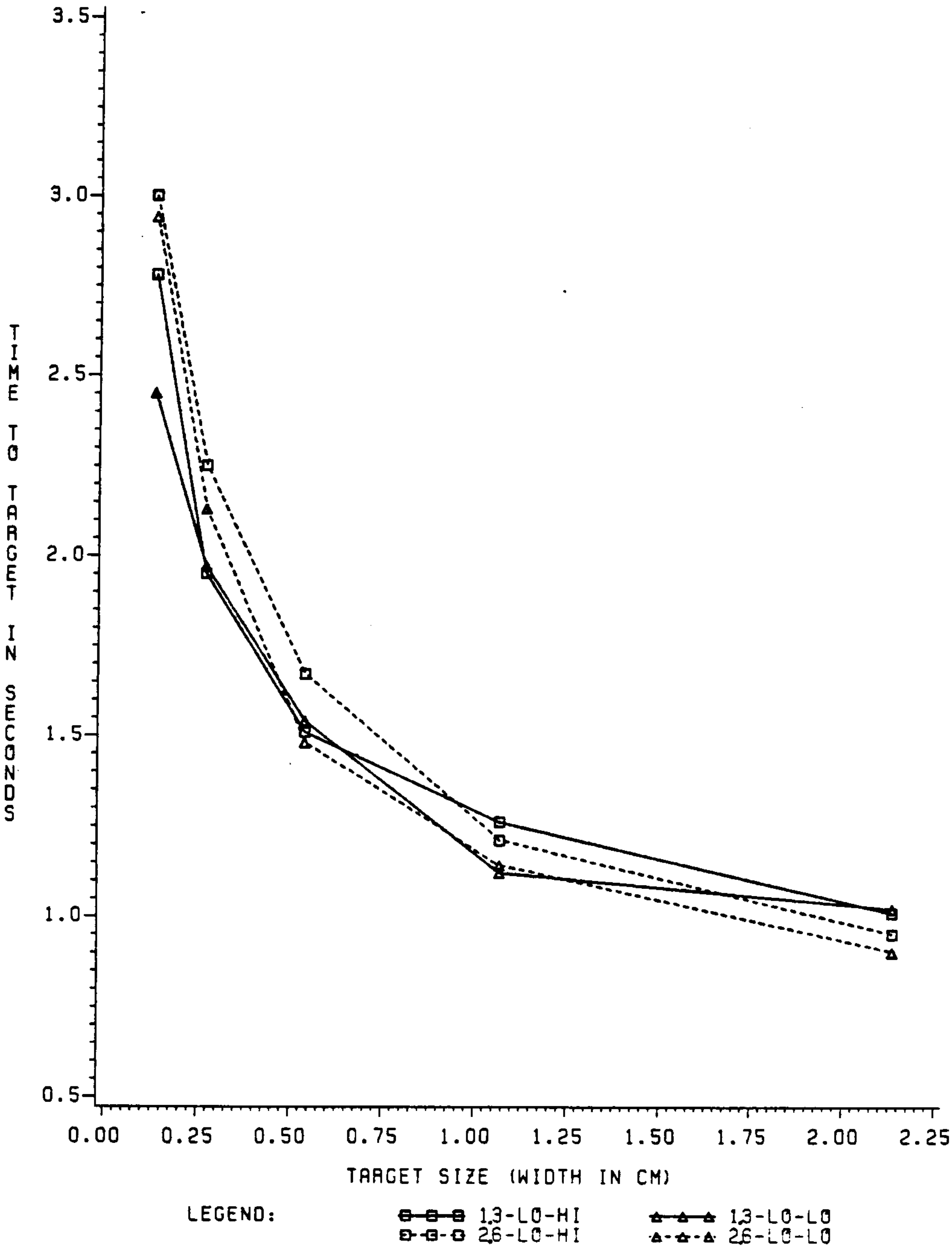

Figure 28. Comparison of the mouse low first-order plus second-order group across target sizes.

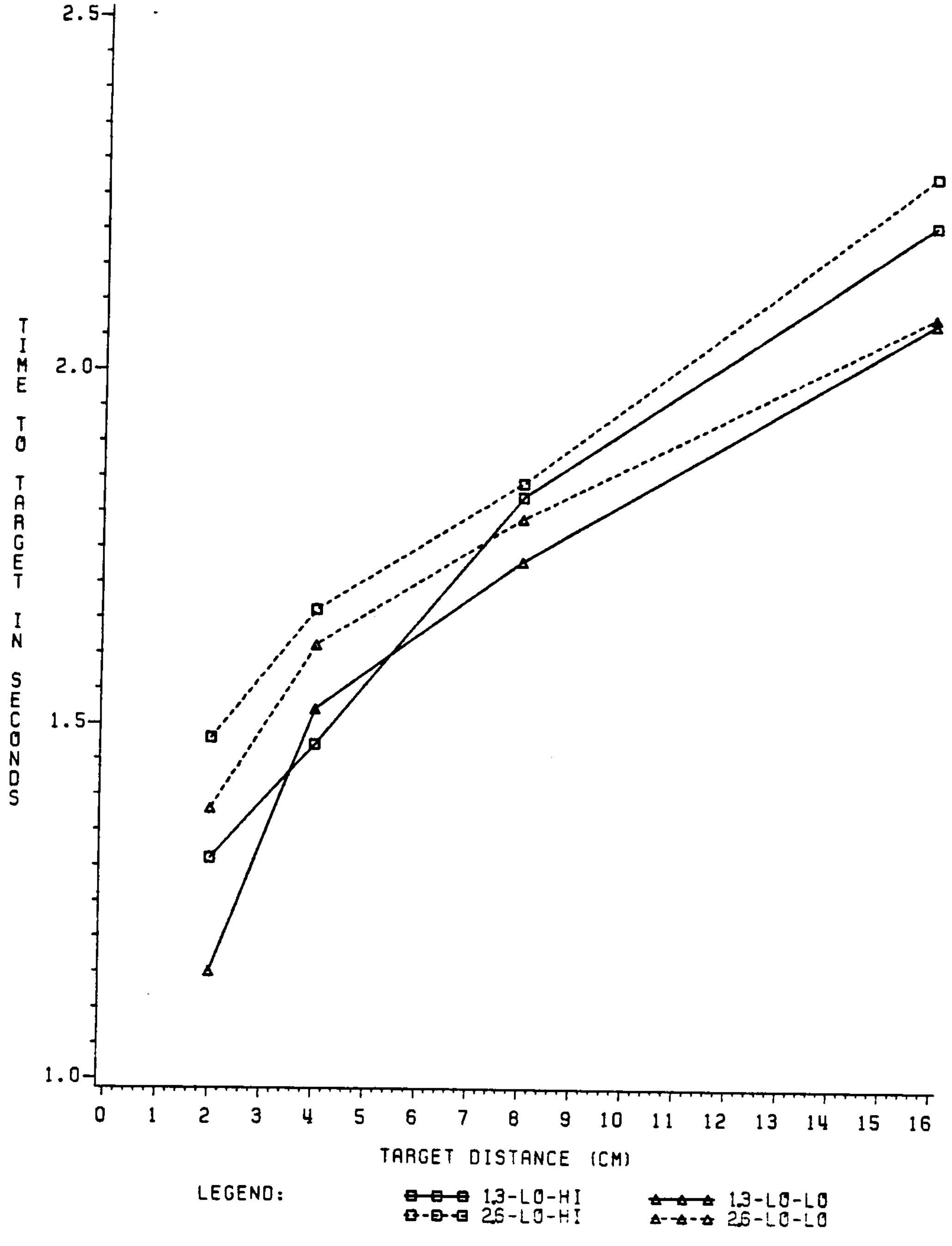

Figure 29. Comparison of the mouse low first-order plus second-order group across target distances.

scales with HI first-order components show similar results across target sizes (Figure 30, Table 17) and target distances (Figure 31, Table 22). These differences are small, however, and not statistically significant in all cases.

The best mouse velocity scale. In general, differences among velocity scale combinations are most notable for small target sizes (0.13 and 0.27 cm) and at short distances (2 and 4 cm). For larger targets and at longer target distances, differences in performance are small and generally nonsignificant. Across velocity scale combinations, performance is best when the zero-order D:C gain is 1.3 rather than 2.6. This is especially true when no first-order or second-order components are used (Figures 22 and 23). When first- and/or second-order components are employed, better performance results when the level of velocity scaling is low. A possible explanation for this result may be target over-shoot problems with higher (i.e., "faster") levels of scaling, due to the more complex control movements required to null the higher-order components to "stop" the cursor over a target.

Comparisons of the best velocity scales from each of the five sub-groups of scale combinations are shown across

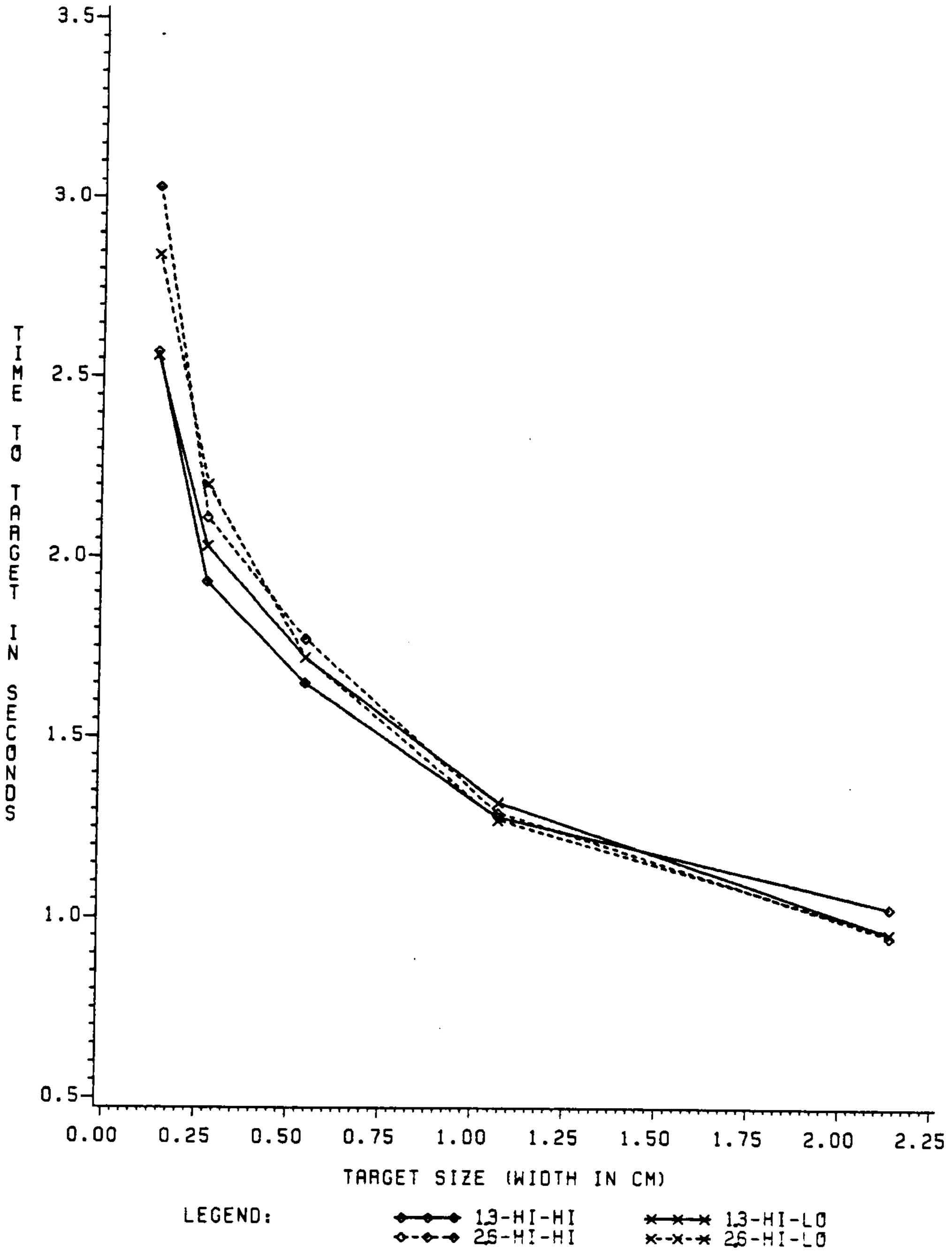

Figure 30. Comparison of the mouse high first-order plus second-order group across target sizes.

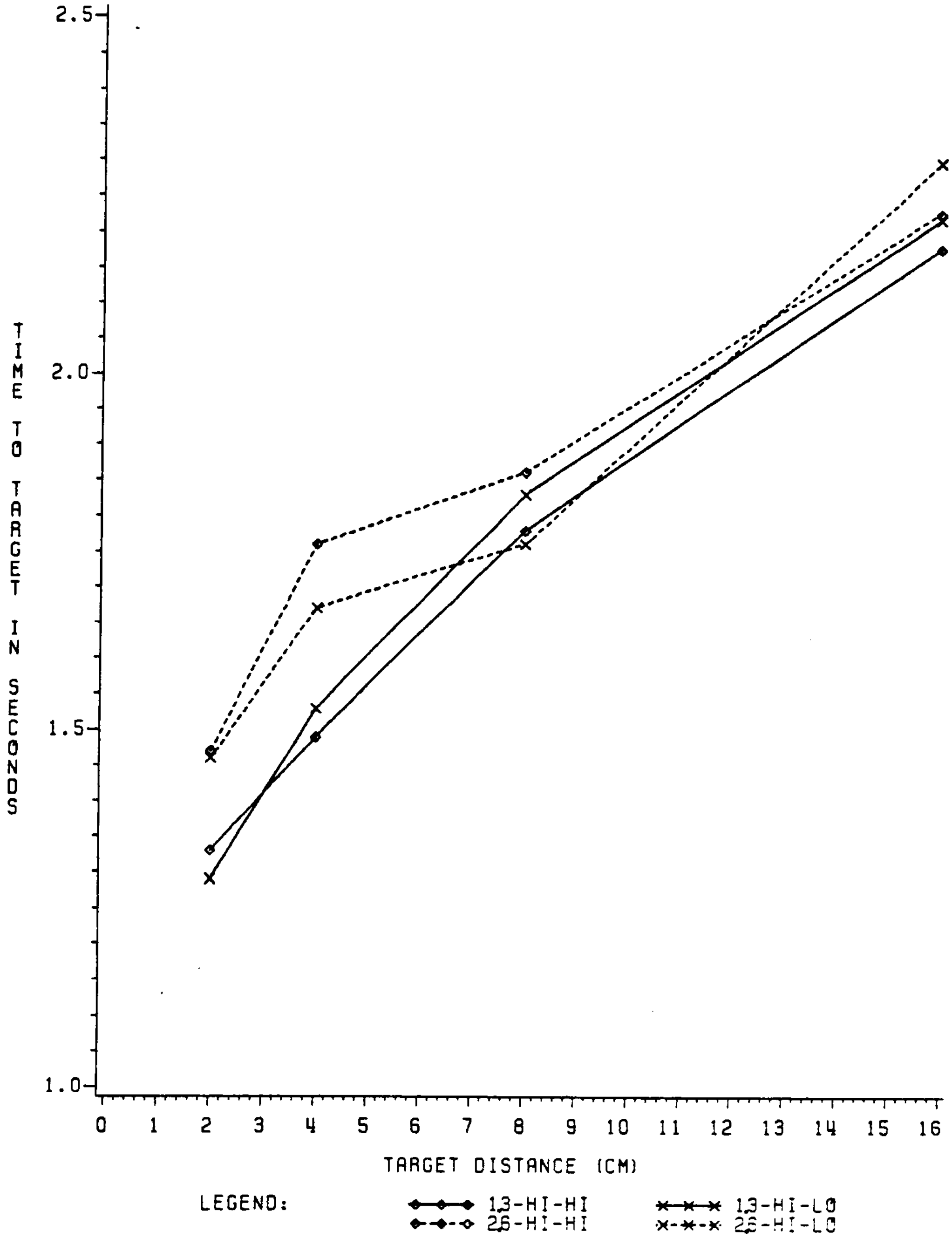

Figure 31. Comparison of the mouse high first-order plus second-order group across target distances.

target sizes and target distances in Figures 32 and 33, respectively. Interestingly, no apparent advantage is gained from the use of first-order or second-order scaling. A simple 1.3:1 display/control relationship between the screen cursor and the mouse results in positioning performance as good as any velocity scale combination.

Relative Touchpad

An ANOVA was performed on the velocity scale (27) x target size (5) x target distance (4) model for the time-to-target (TT) dependent measure. Results are given in Table 23 (Appendix B). The only significant interaction of interest was Velocity Scale x Target Distance ($F(78,390) = 4.36$, $p = 0.0001$). Subsequent post-hoc multiple comparisons of the interaction were divided into five VS groups: (1) zero-order, (2) first-order, (3) pure second-order, (4) low first-order plus second-order, and (5) high first-order plus second-order. Fisher's LSD Test results for the Velocity Scale x Target Distance interaction are given in Tables 24, 25, 26, 27, and 28 (Appendix B).

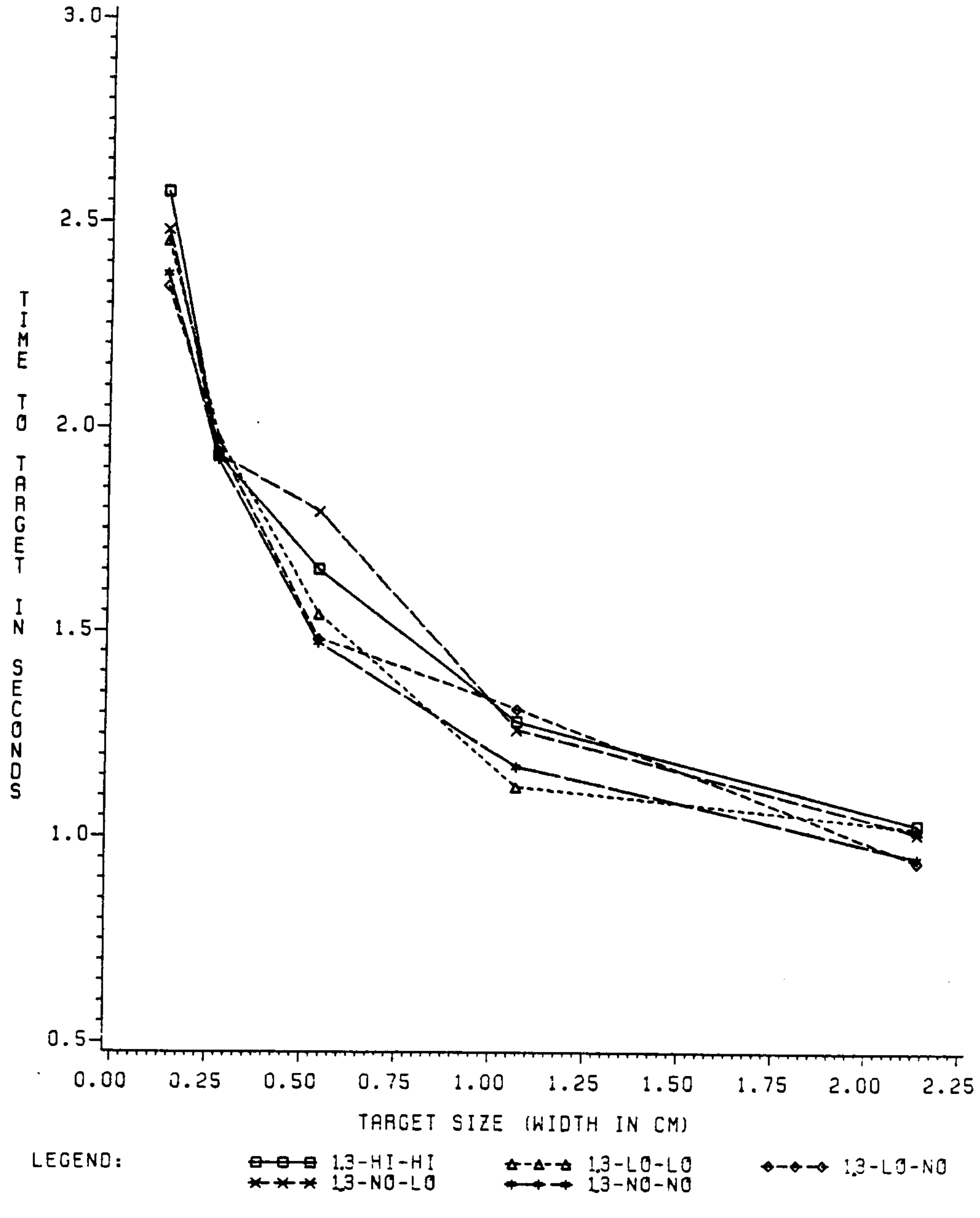

Figure 32. Comparison of the best mouse velocity scales across target sizes.

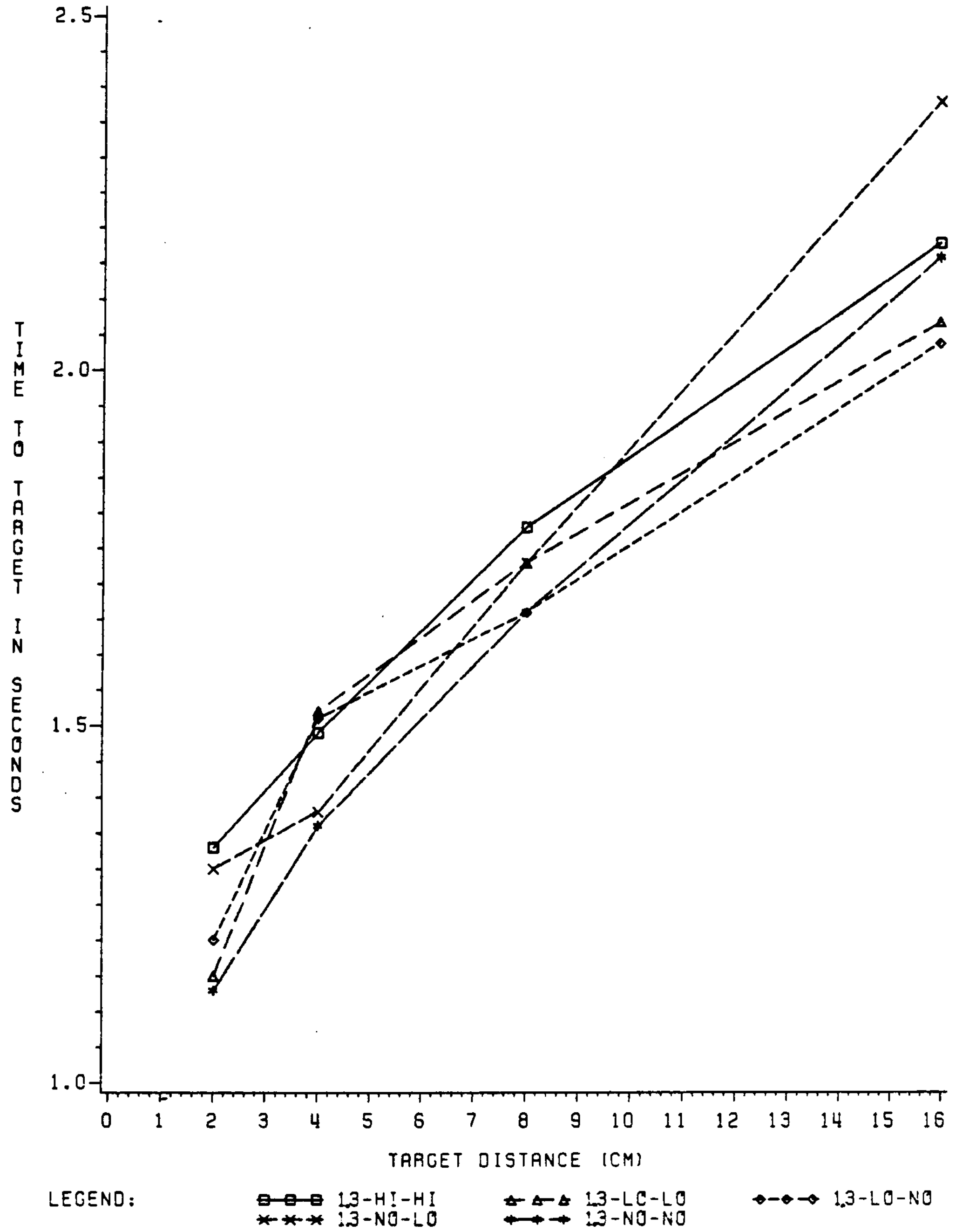

Figure 33. Comparison of the best mouse velocity scales across target distances.

Zero-order. Velocity scales (VSs) with only zero-order components (i.e., no first-order or second order components) represents a touchpad with linear, D:C gain. The three zero-order VSs (0.3, 1.0, and 2.0 D:C gains) are compared in Figure 34 (Table 24). At the 2-cm target distance, the 0.3 and 1.0 gains are superior to the 2.0 gain. At target distances greater than 4 cm, the 1.0 and 2.0 gains are significantly faster for target acquisition than the 0.3 gain. The poor performance of the 0.3 gain at longer target distances is apparently due to the repetitive sliding of the finger across the touchpad required to acquire targets. For example, if the subject slid his/her finger across the pad 6 cm, only 2 cm of cursor movement would result. Therefore, a target at 8 cm required approximately four "swipes" of the subject's finger.

First-order. The first-order VS group represents the six combinations of zero-order (0.3, 1.0, or 2.0) with first-order components (LO or HI). Comparisons of the first-order group are shown in Figure 35 (Table 25). No differences among the first-order group of VSs were found at the 2-cm distance. At 4 cm, the 2-LO-NO combination is worse than the 1-LO-NO, due to possible overshoot problems at the higher zero-order gain. At the medium target

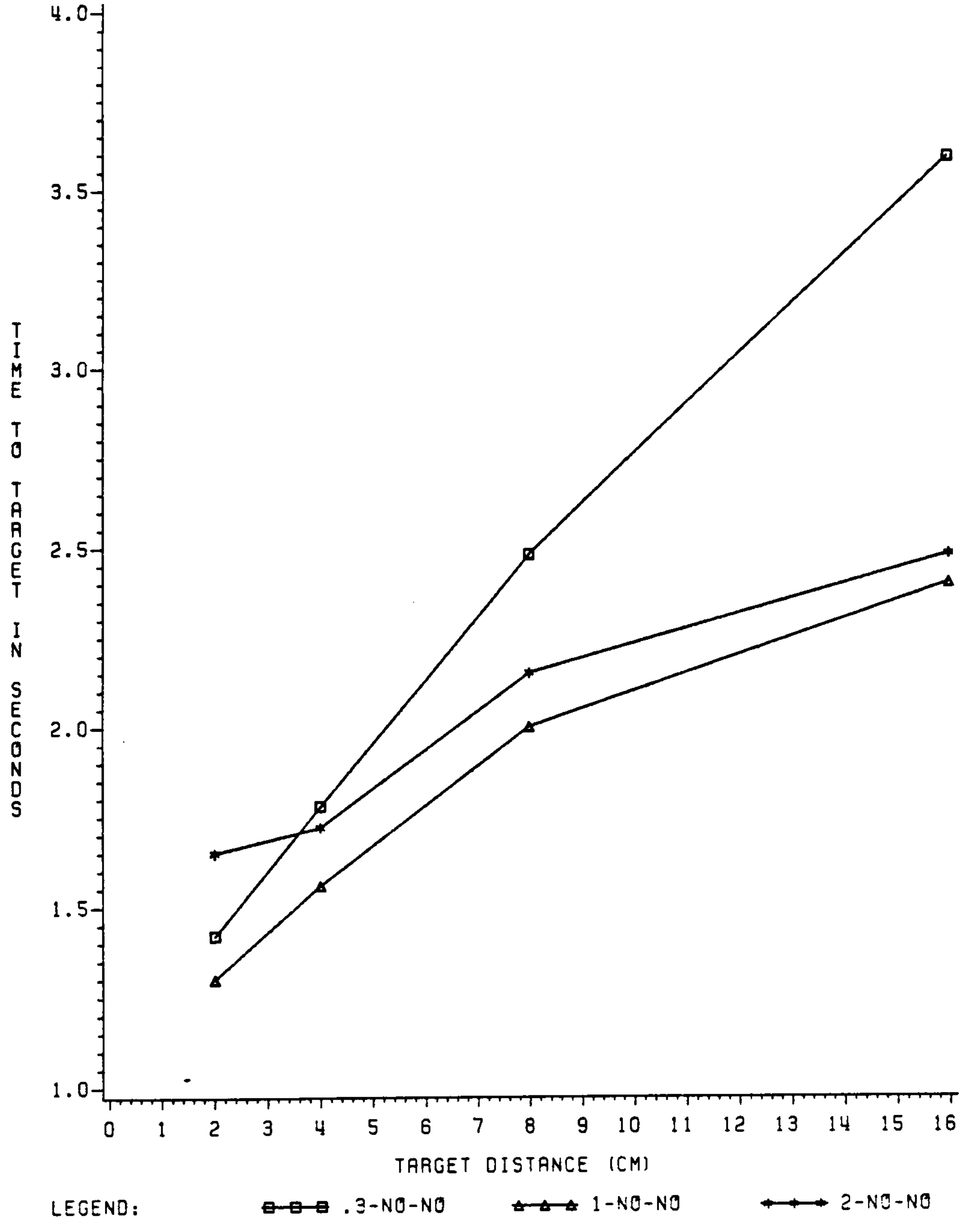

Figure 34. Comparison of the touchpad zero-order group across target distances.

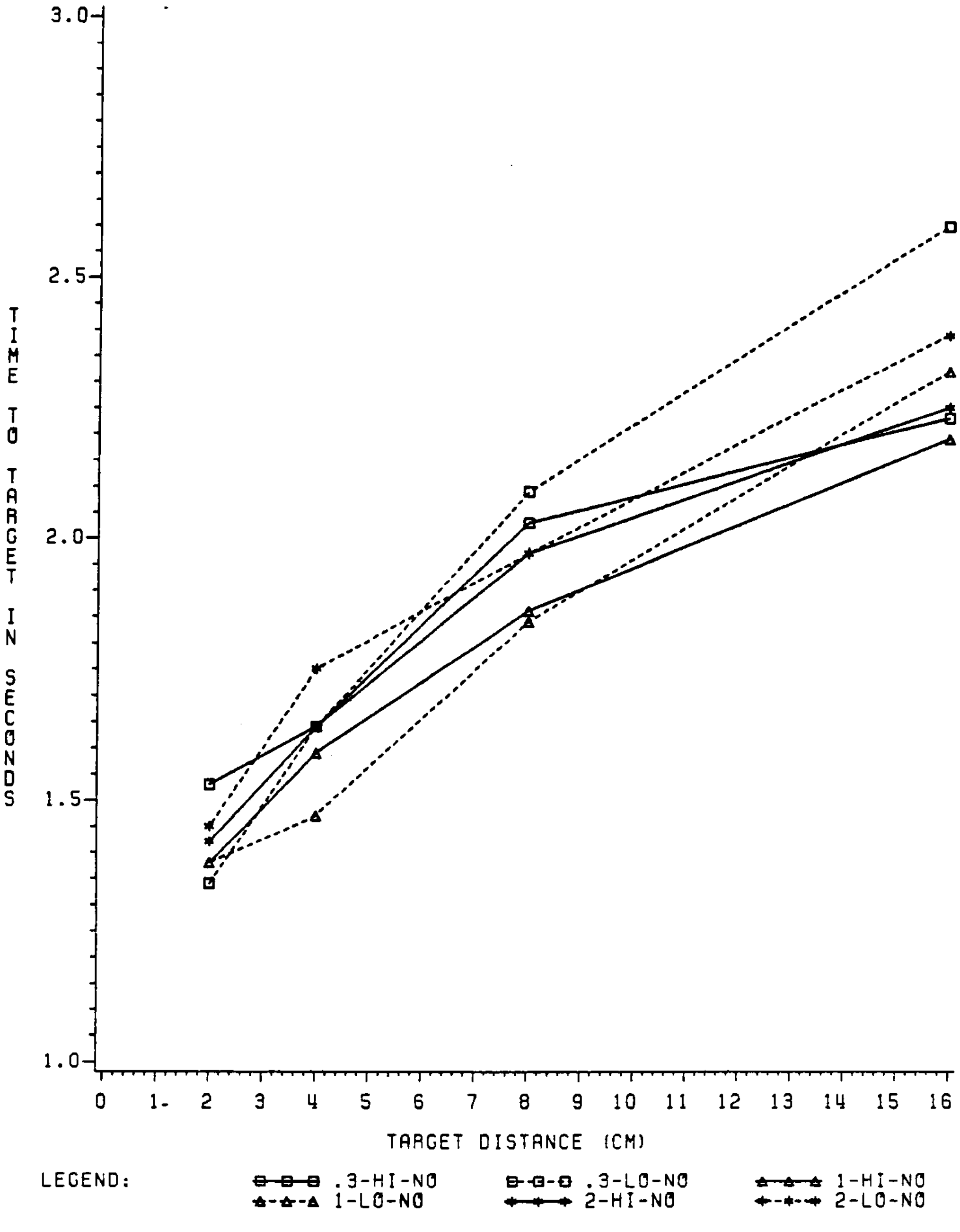

Figure 35. Comparison of the touchpad first-order group across target distances.

distance (8 cm), the 1.0 zero-order VSs provide faster target positioning than the 0.3-LO-NO, regardless of high or low fist-order scaling. At 16 cm, all other VSs are superior to 0.3-LO-NO. Of interest is the relative increase of TT for the 0.3-LO-NO scale compared to the 0.3-HI-NO scale.

Pure second-order. Pure second-order VSs represents the six combinations of the zero-order (0.3, 1.0, or 2.0) plus second-order (LO or HI) components. Figure 36 (Table 26) shows the results for the pure second-order group across target distances. At the 2-cm distance, the 2.0 gain VSs, regardless of high or low second-order scaling, provides significantly slower target acquisition than 1-NO-HI and 0.3-NO-LO. At the longer target distances (8 and 16 cm), the 1.0 and 2.0 gain VSs with high second-order scaling provides the best target acquisition. In general, the 1-NO-HI velocity scale provides the best target acquisition of this group across all distances. A likely explanation for this result is that the 1-NO-HI scale combination provides a 1:1 display/control relationship for short moves, yet enables subjects to "slew" across the screen for long cursor moves.

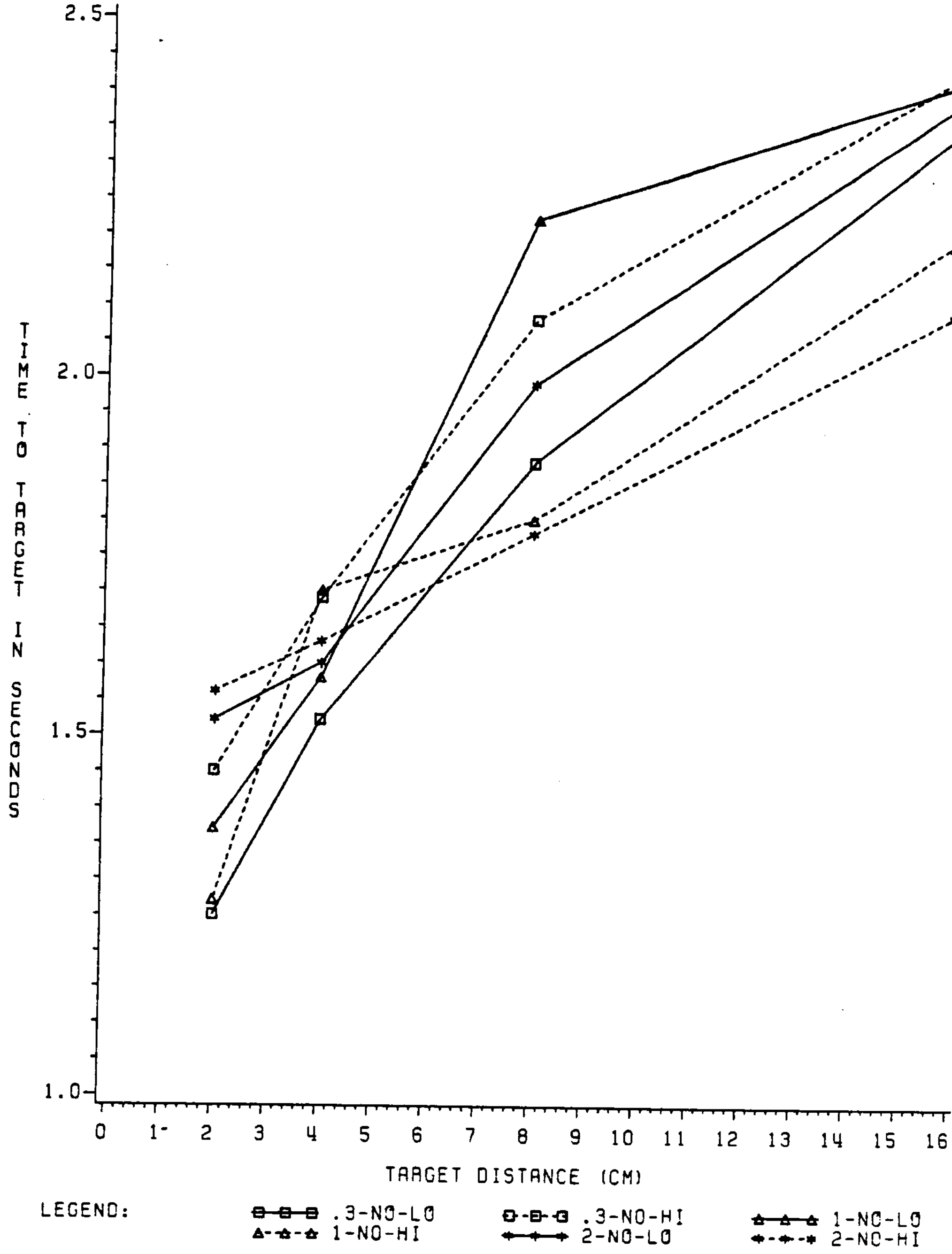

Figure 36. Comparison of the touchpad pure second-order group across target distances.

First-order plus second-order. Velocity scale combinations of low first-order with second-order components are shown in Figure 37 (Table 27). At the 2- and 4-cm distances, the 1.0 gain in combination with low second-order scaling provides better positioning performance than the 0.3 gain in combination with high second-order scaling, due to possible target over-shoot problems associated with high second-order scaling. At the longest target distance, the 1-LO-HI combination is better than 0.3-LO-LO. This may be due, in part, to the multiple finger-sliding required to acquire long distance targets with the 0.3-LO-LO scaling. In general, the 1-LO-HI combination is the best across all target distances.

High first-order plus second-order. Velocity scales with high first-order in combination with second-order components are shown in Figure 38 (Table 28). No differences were found among the VSs at the 2-cm distance. At distances above 2 cm, the 0.3-HI-LO scale provides significantly faster target positioning than 0.3-HI-HI. Apparently, fast higher-order scaling results in control problems, perhaps due to target over-shoot or compensation for the high responsiveness of the touchpad when combined with the low 0.3 zero-order gain.

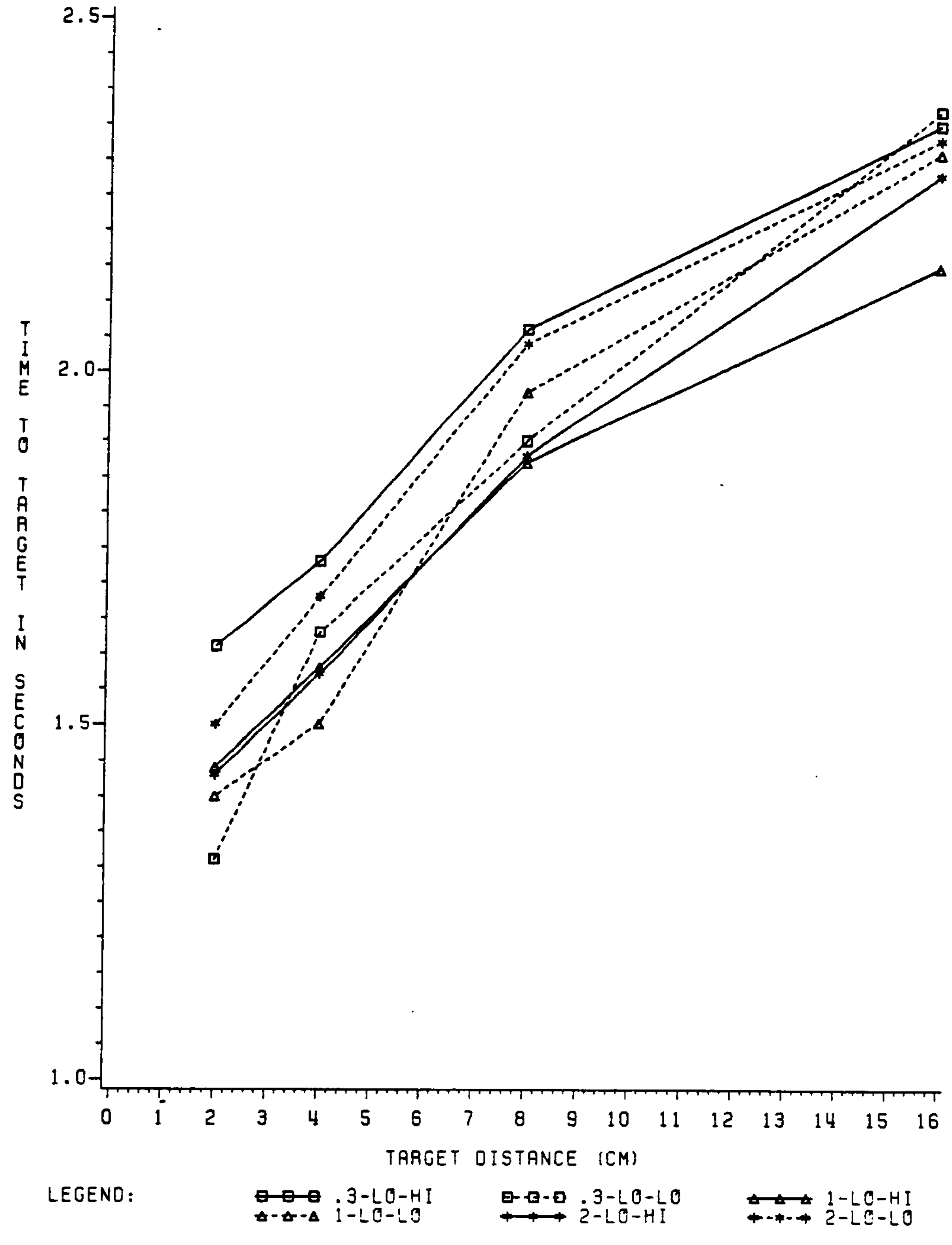

Figure 37. Comparison of the touchpad low first-order plus second-order group across target distances.

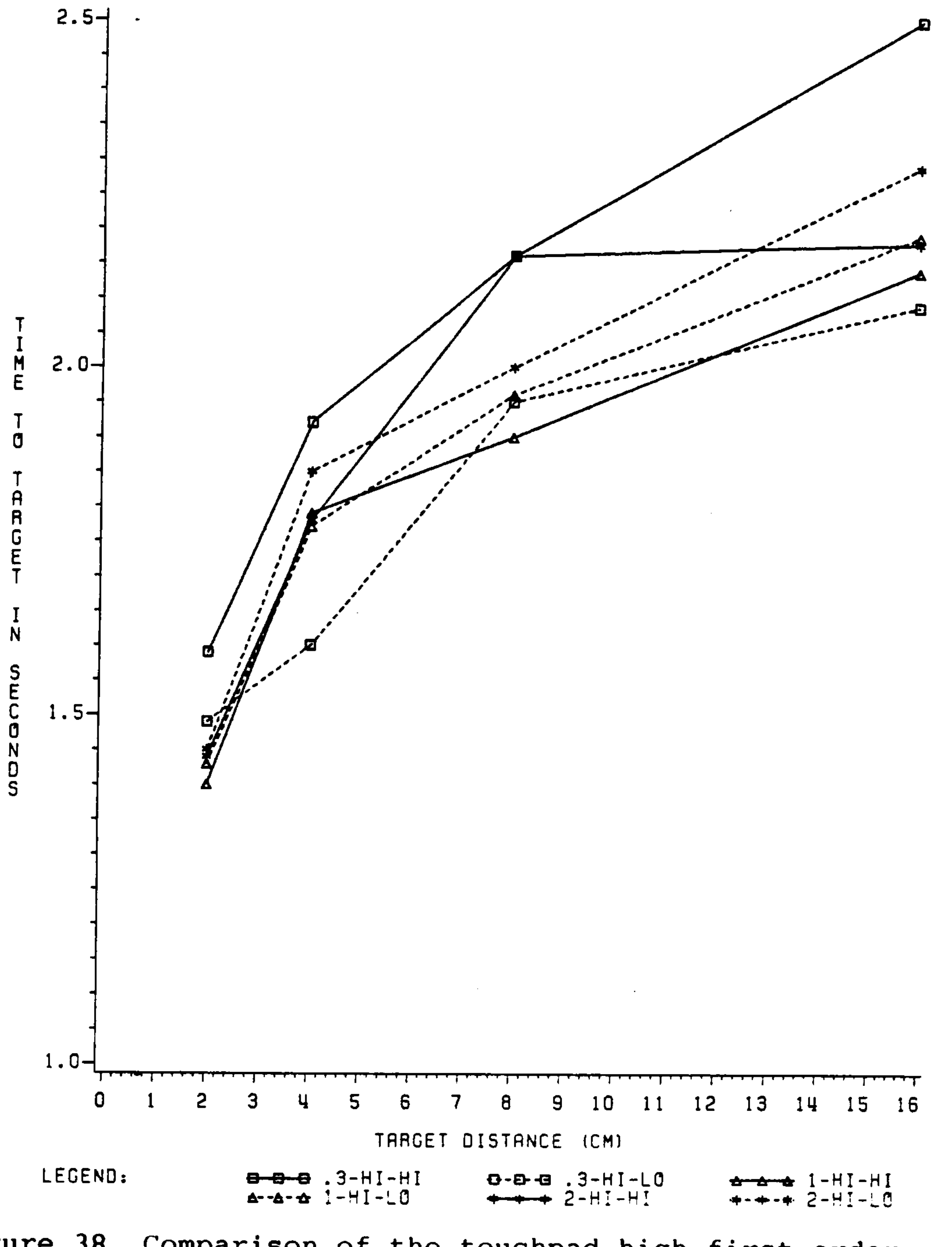

Figure 38. Comparison of the touchpad high first-order plus second-order group across target distances.

The best touchpad velocity scale. In general, two VS combinations appear to provide the best overall and most consistent target acquisition performance: 1-NO-HI and 0.3-NO-LO. Interestingly, both of these VSs are of the pure second-order group. Perhaps these two VSs provide a stable display/control relationship for fine-positioning, yet enable subjects to "slew" the cursor across the screen to acquire targets at long screen distances by taking advantage of the second-order scaling. Based on these results and the slightly better, yet not significant, performance of the 1.0 gain VS, the 1-NO-HI velocity scale is recommended for general applications.

Displacement Joystick

An ANOVA was performed on the velocity scale (18) x target size (5) x target distance (4) model for the time-to-target (TT) dependent measure. The results are given in Table 29 (Appendix B). Significant interactions of interest include Velocity Scale x Target Size ($F(68,340) = 1.56$, $p = 0.0058$) and Velocity Scale x Target Distance ($F(51,255) = 2.28$, $p = 0.0001$). Subsequent post-hoc multiple comparisons of the interactions were divided into three second-order groups: (1) low first-order, (2) medium first-order, and (3) high first-order. Fisher's LSD Test results are given for the Velocity Scale x Target Size interaction in Tables 30, 31, and 32 (Appendix B). Results for the Velocity Scale x Target Distance interaction are given in Tables 33, 34, and 35 (Appendix B).

Low first-order. Comparisons of the low first-order velocity scales across target sizes and target distances are shown in Figure 39 (Table 30) and Figure 40 (Table 33), respectively. At the smallest target sizes (0.13, 0.27, and 0.54 cm), the VS with a low minimum cursor velocity (MCV) and high second-order scaling (0.24-LO-HI) results in significantly better performance than the high MCV (0.45-LO-HI). With respect to target distance, the 0.45-LO-HI scale also performs poorly at all target distances. At 16 cm, the 0.24-LO-HI scale performs better than all other scales, with the exception of 0.24-LO-LO and 0.45-LO-LO. In general, the best overall performance is obtained with the lower MCV and low first- and second-order scaling (0.24-LO-LO). Interestingly, the higher second-order scaling does not, as might be expected, perform best at long target distances. The poor performance of the pure first-order scale (0.24-LO-NO) is evident in the somewhat drastic increase in TT at the 16-cm

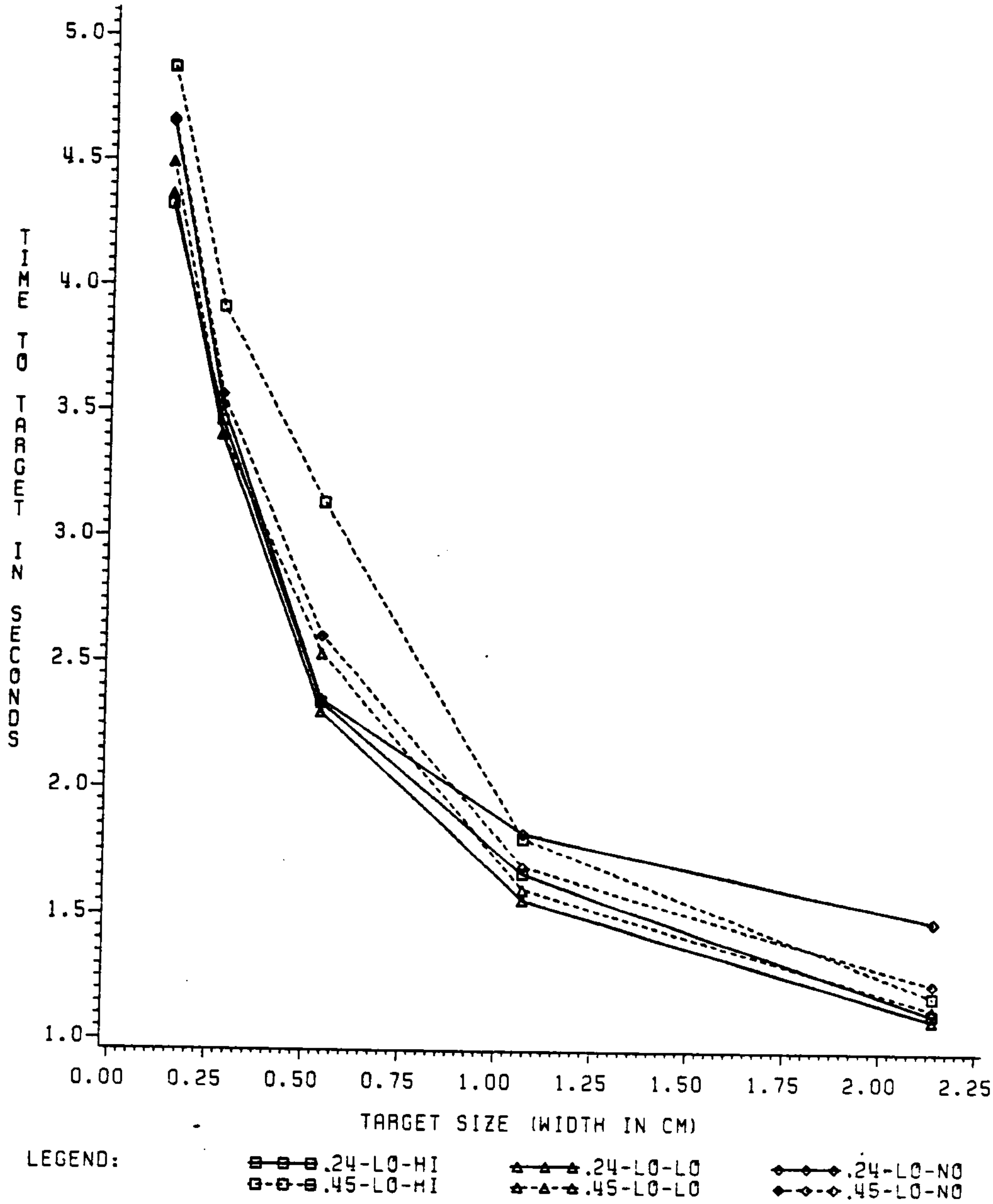

Figure 39. Comparison of the displacement joystick low first-order plus second-order group across target sizes.

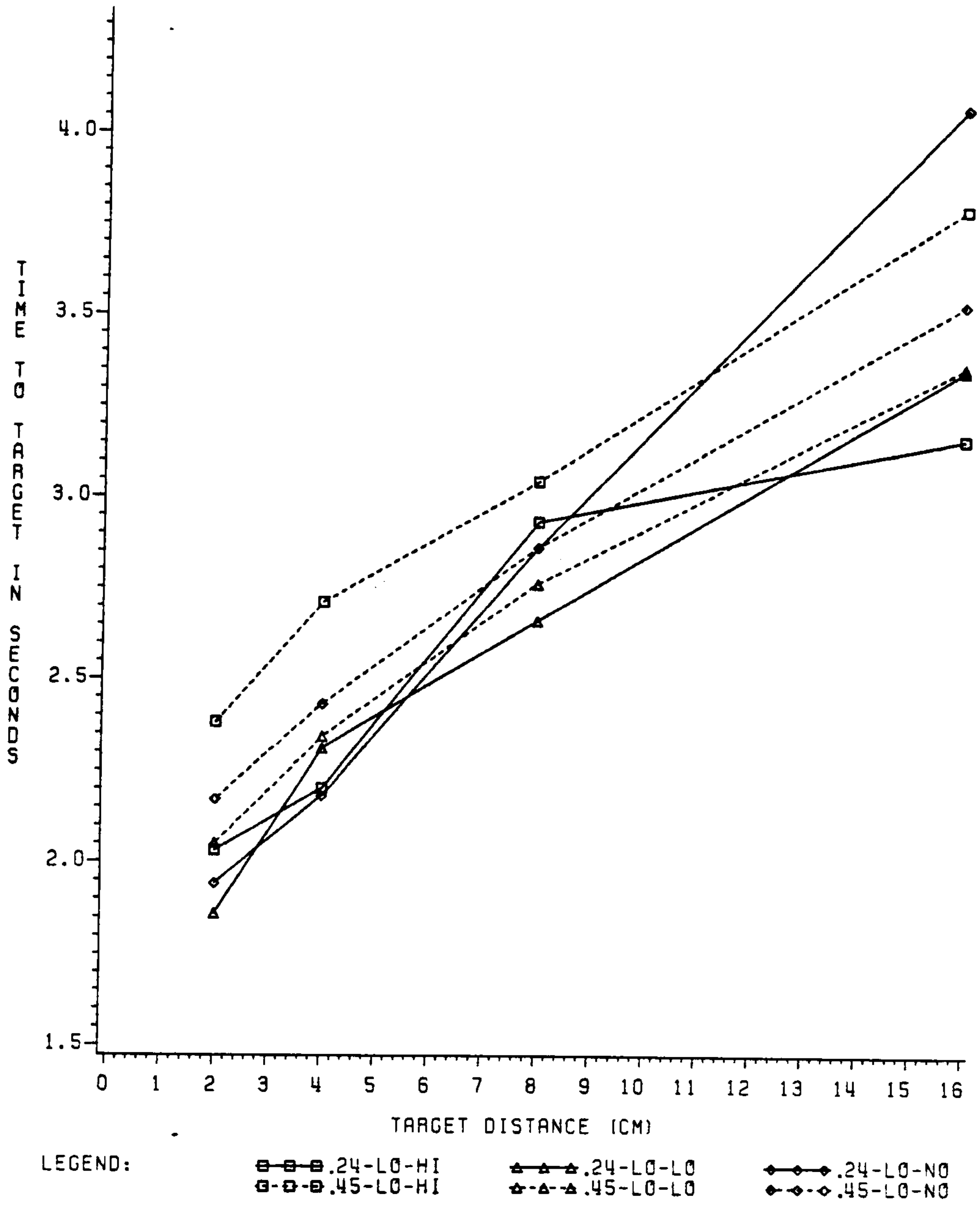

Figure 40. Comparison of the displacement joystick low first-order plus second-order group across target distances.

target distance, although the low second-order scale (0.24-LO-LO) does well at this, and other, distances.

Medium first-order. As shown in Figure 41 (Table 31) and Figure 42 (Table 34), the 0.24-MD-LO scale combination provides the best overall target positioning performance of the six medium first-order scale combinations. This is especially true at the smallest target size and for the shortest target distance. As with the low first-order scales, there is no apparent advantage to the fastest (i.e., HI) second-order scale.

High first-order. The comparisons of the high first-order VSs across target sizes and target distances are shown in Figure 43 (Table 32) and Figure 44 (Table 35), respectively. Once again, the scale combination resulting in the best performance is the lower MCV and low second-order scaling (0.24-HI-LO).

The best displacement joystick velocity scale. In general, joystick velocity scales which include a low minimum cursor velocity and low second-order scaling result in the best target positioning performance. This is true even at the largest target size/longest target distance

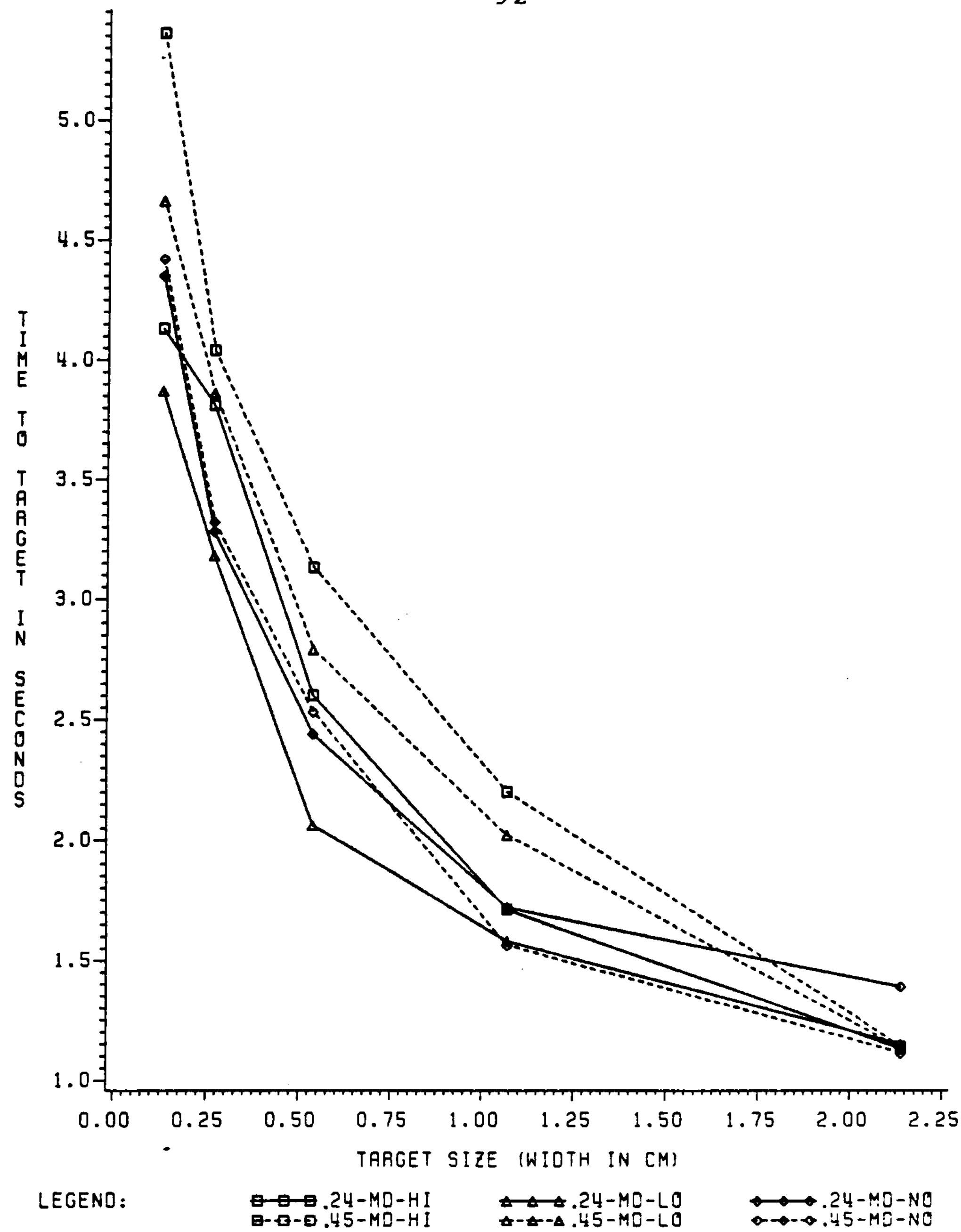

Figure 41. Comparison of the displacement joystick medium first-order plus second-order group across target sizes.

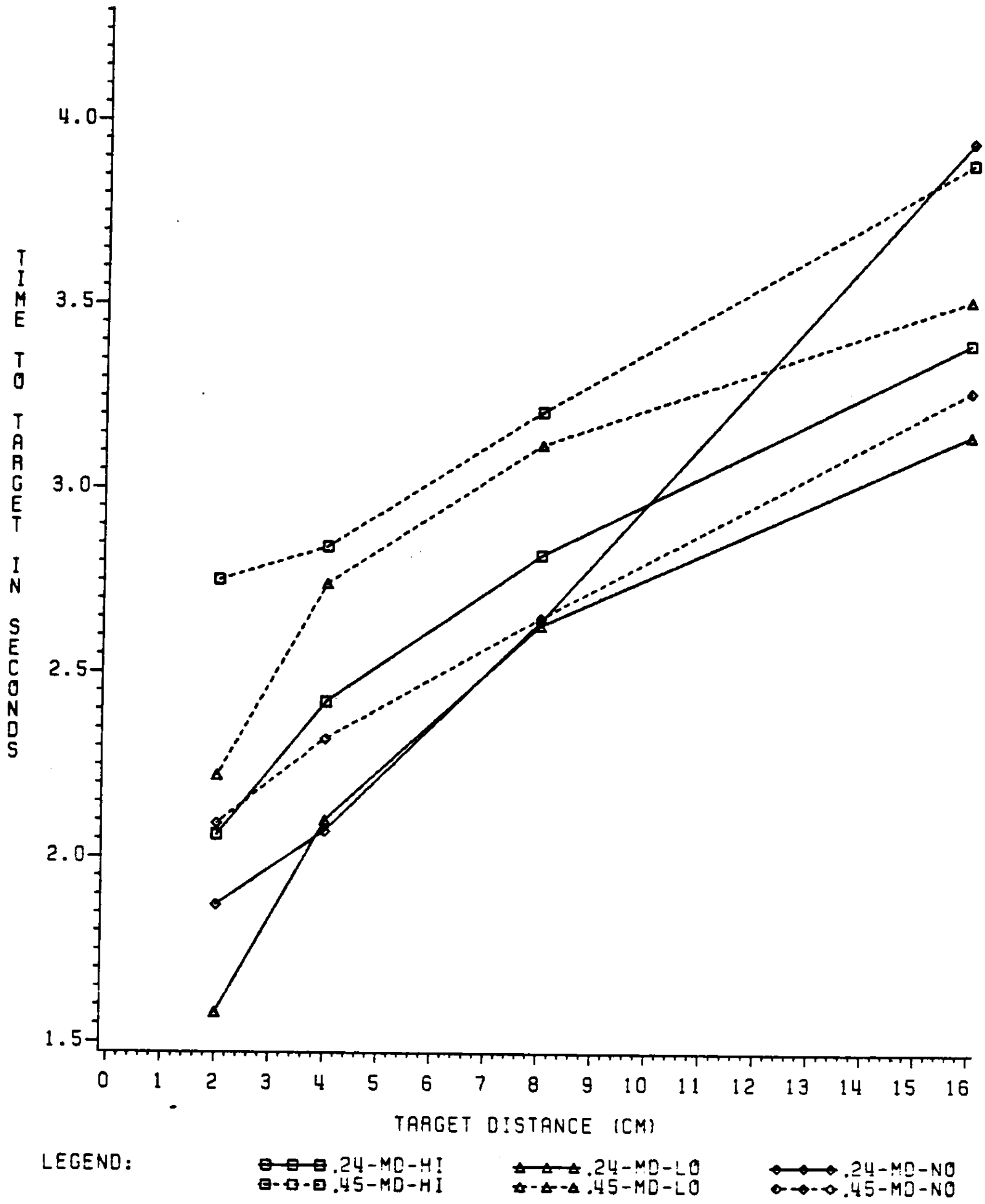

Figure 42. Comparison of the displacement joystick medium first-order plus second-order group across target distances.

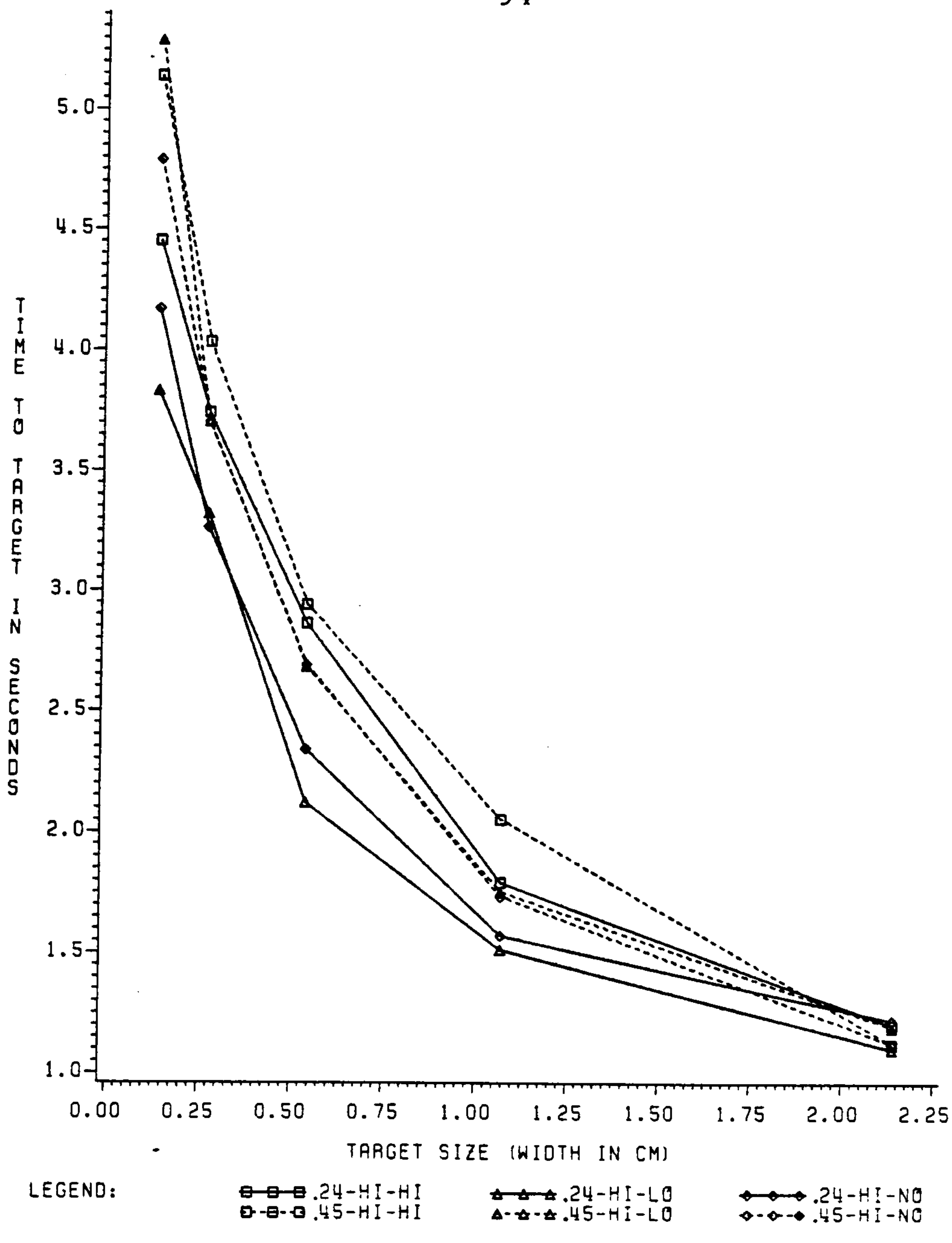

Figure 43. Comparison of the displacement joystick high first-order plus second-order group across target sizes.

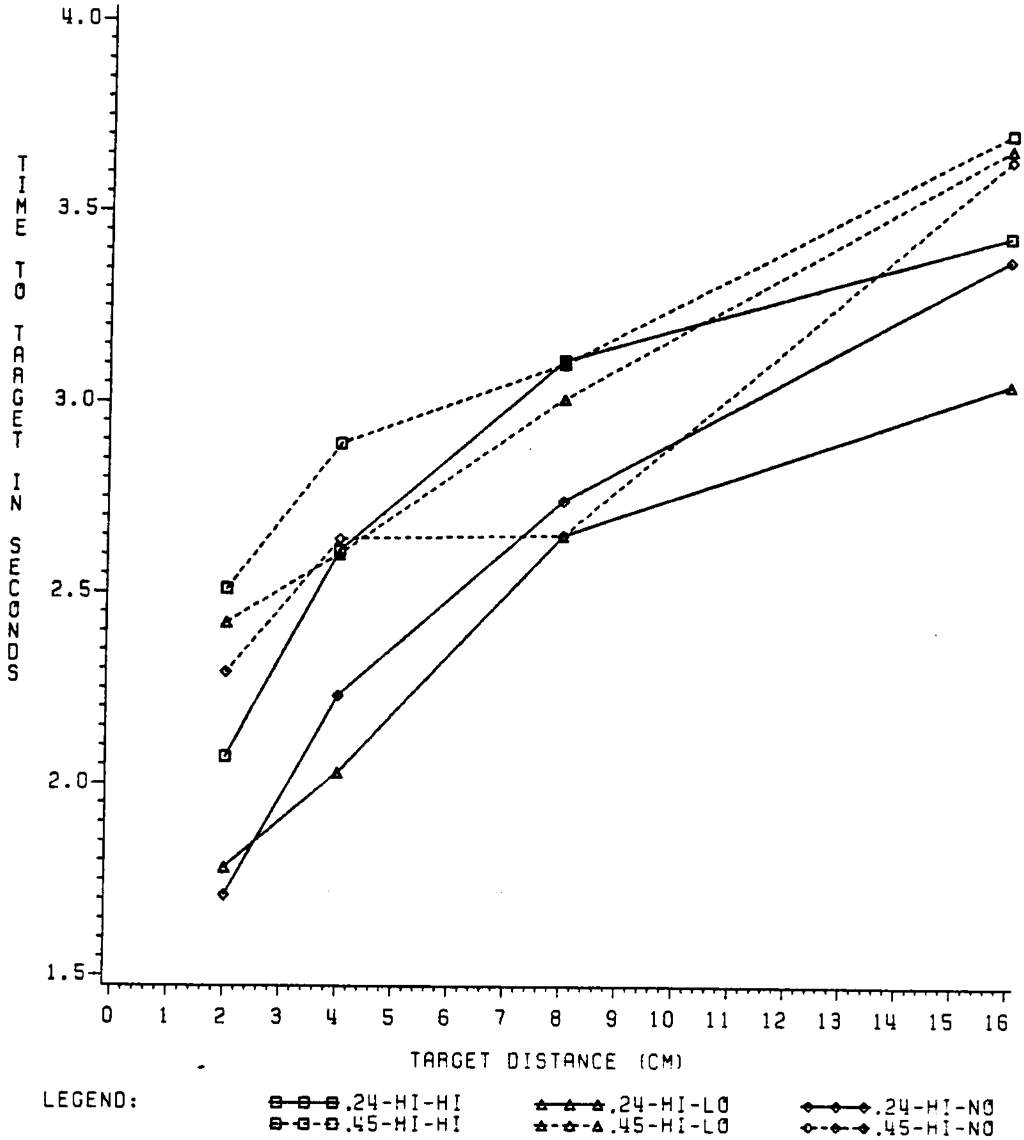

Figure 44. Comparison of the displacement joystick high first-order plus second-order group across target distances.

combinations, in which case one might expect high second-order scales to aid, not degrade, performance.

Comparisons of the best velocity scales from the low, medium, and high first-order groups across target size and target distance indicated that both the 0.24-HI-LO and 0.24-MD-LO velocity scales provide the best target acquisition performance. Although 0.24-MD-LO is better, but not significantly, at short target distances, the 0.24-HI-LO is better at the longest target distance. In general, the 0.24-HI-LO scale is recommended for the wide variety of task conditions.

Force Joystick

An ANOVA was performed on the velocity scale (8) x target size (5) x target distance (4) model for the time to target (TT) dependent measure. The results are shown in Table 36 (Appendix B). The only significant interaction of interest is Velocity Scale x Target Size ($F(28,140) = 2.49$, $p = 0.0003$). In addition, the main effect of Velocity Scale is significant ($F(7,35) = 2.46$, $p = 0.0365$). Subsequent post-hoc, multiple comparisons of the VS x TS interaction were divided into two VS groups: (1) low first-order and (2) high first-order. Results are given for the Velocity Scale x Target Size interaction in Tables 37 and 38 (Appendix B) and results for the Velocity Scale main effect are given in Table 39 (Appendix B).

Low first-order. A comparison of low first-order velocity scales across target sizes is shown in Figure 45 (Table 37). At the smallest target size (0.13 cm), the 25-gram minimum force (MF) VSs provide significantly faster target positioning than do the 75-gram VSs, regardless of none (NO) or low (LO) second-order scaling. Since the intercept of 25-gram VSs is more sensitive (greater display/control gain) than the 75-gram VSs, one might conclude that the higher force sensitivity of the 75-gram scales was overridden by the first- and second-order components for the acquisition of small targets.

High first-order. The comparisons of high first-order VSs across target sizes are shown in Figure 46 (Table 38). At the smallest target size (0.13 cm), the 25-gram VSs are, again, better than the less sensitive 75-gram VSs. In addition, the 25-HI-LO scale combination provides better target positioning than the 75-gram VSs at the 0.27-cm target size. Figures 45 and 46 illustrate that the 25-gram minimum force is advantageous only for the more difficult,

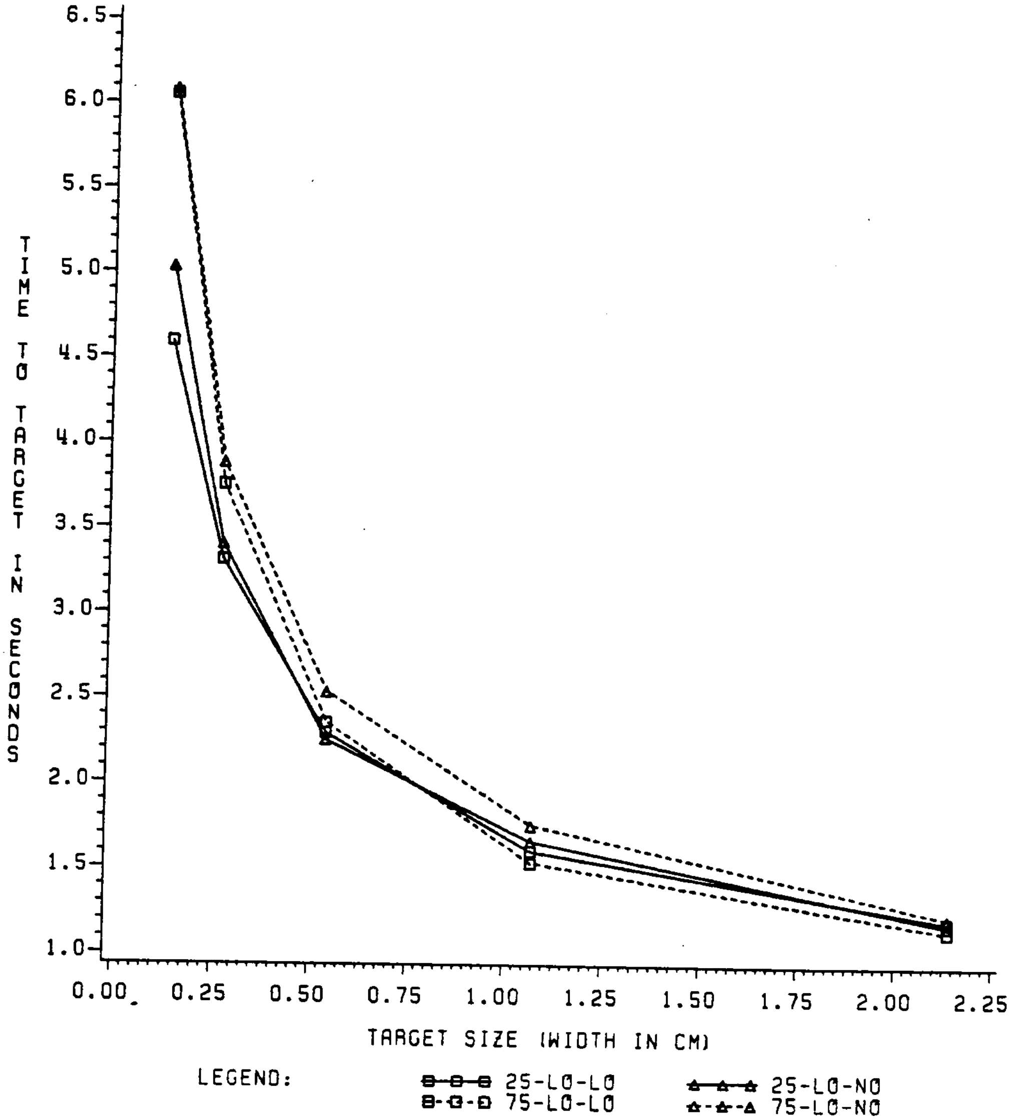

Figure 45. Comparison of the force joystick low first-order plus second-order group across target sizes.

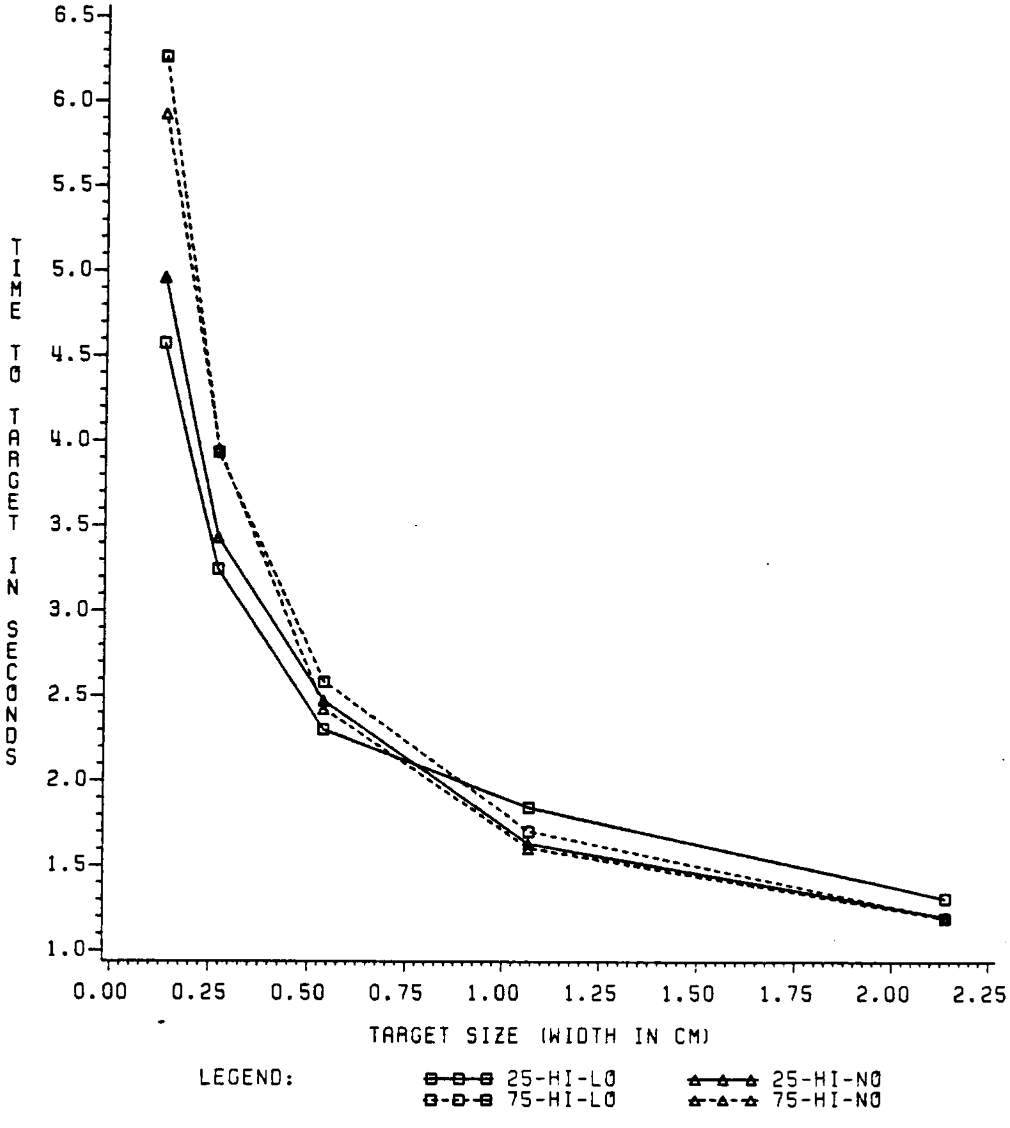

Figure 46. Compariosn of the force joystick first-order plus second-order group across target sizes.

smaller target sizes, irrespective of the first- and second-order component levels.

Velocity scale main effect. A comparison of the target positioning performance of the eight joystick VSs, averaged across all target sizes and distances, is shown in Figure 47 (Table 39). The results indicate the 25-LO-LO scale combination is significantly better than several, though not all, of the remaining VSs. On the average, it is quite clear that the four scales with a 75-gram minimum force are inferior to the four scales with a 25-gram minimum force, regardless of the first- or second-order component.

The best force joystick velocity scale. In general, the 25-gram minimum force provides better target positioning performance than the less sensitive 75-gram force at smallest target sizes. This result is important for computer tasks, such as graphics and word processing, which may require fine-positioning of a cursor. While a force joystick which is too sensitive may result in target over-shoot when the target is small, a joystick that has too small a velocity/force gain will require longer times to position the cursor on a small target, probably due to the relatively greater contribution of the first- and

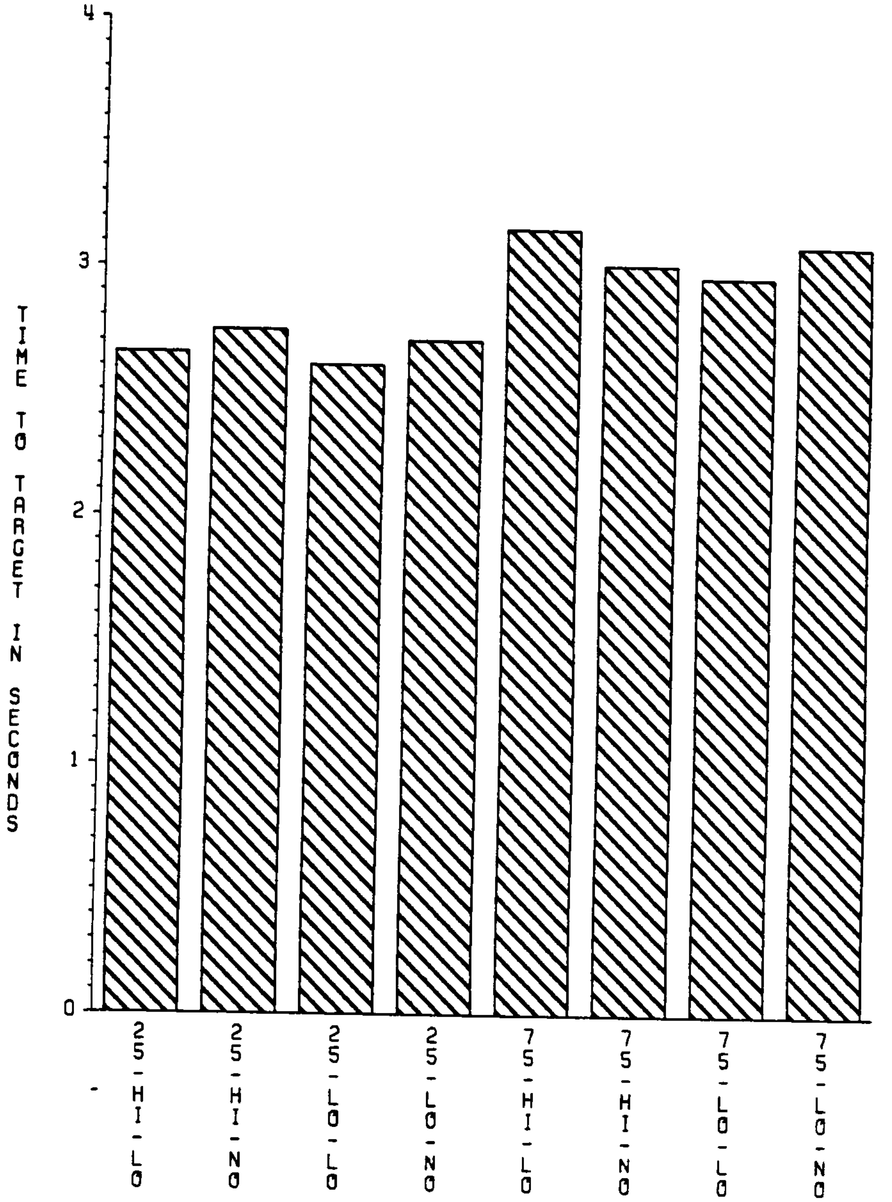

Figure 47. Comparison of the force joystick groups averaged across target sizes and distances.

second-order components, as used in this experiment. Since no differences were found among the various VSs at target sizes above 0.23 cm, the 25-LO-LO velocity scale combination is recommended for general use, as it performs best for small targets and best overall (Figure 47).

METHOD: TARGET ACQUISITION COMPARISON

Subjects

Twelve subjects, six males and six females, drawn from the V.P.I. & S.U community, served as subjects. All subjects were required to read and sign an informed consent form and to have normal vision. To reduce possible experimental bias, subjects were required to be naive users of the cursor control devices compared in the study. Each subject received $ 10.00 for one 2-hr session.

Equipment

The experimental equipment set-up for the target acquisition task, shown in Figure 48, was similar to the device optimization experiment, with the exception that an absolute-mode touchpad was added to the group of five cursor dévices optimized in the previous series of experiments. The TIPC was used to present the target acquisition task, collect performance data, and control the touchpad mode and dynamics. The TIPPC controlled the dynamics for the mouse, trackball, force joystick, and

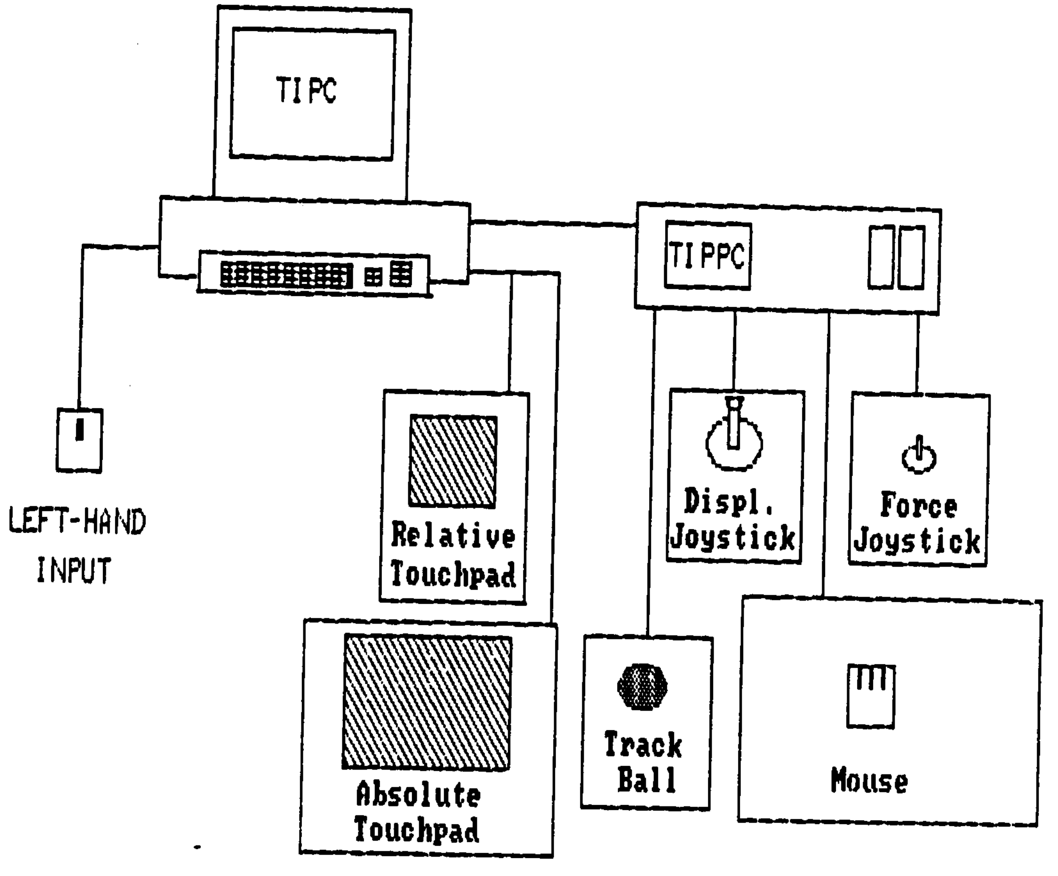

Figure 48. Experimental set-up for the cursor device comparison on the target acquisition task.

displacement joystick.

The six cursor devices, in optimized form, were:

(1) Absolute touchpad. Elographics finger sensitive, absolute-mode touchpad (25 x 19 cm). The finger position on the touchpad was mapped directly to the cursor position on the CRT screen. A 1.0 D:C gain existed between the cursor position on the screen and finger position on the touchpad. The target selection input button was operated with the opposite hand.

(2) Mouse. Mouse Systems "M-2" optical mouse with a 23 x 20 cm optical pad. A 1.3 display/control (D:C) gain existed between cursor movement on the screen and mouse movement. The target selection input button was located on the mouse.

(3) Trackball. Measurement Systems Model 621 low-profile trackball (4-cm diameter). The velocity with which the trackball was rolled determined the distance the cursor moved on the screen (Figure 49). For slow trackball speeds, one full rotation of the trackball (12.57 cm) resulted in 5.0 cm of cursor movement (i.e., 0.4 D:C gain). As the trackball speed was increased, the distance the cursor moved on the screen increased for a given trackball angular rotation. The target selection button was operated with the opposite hand.

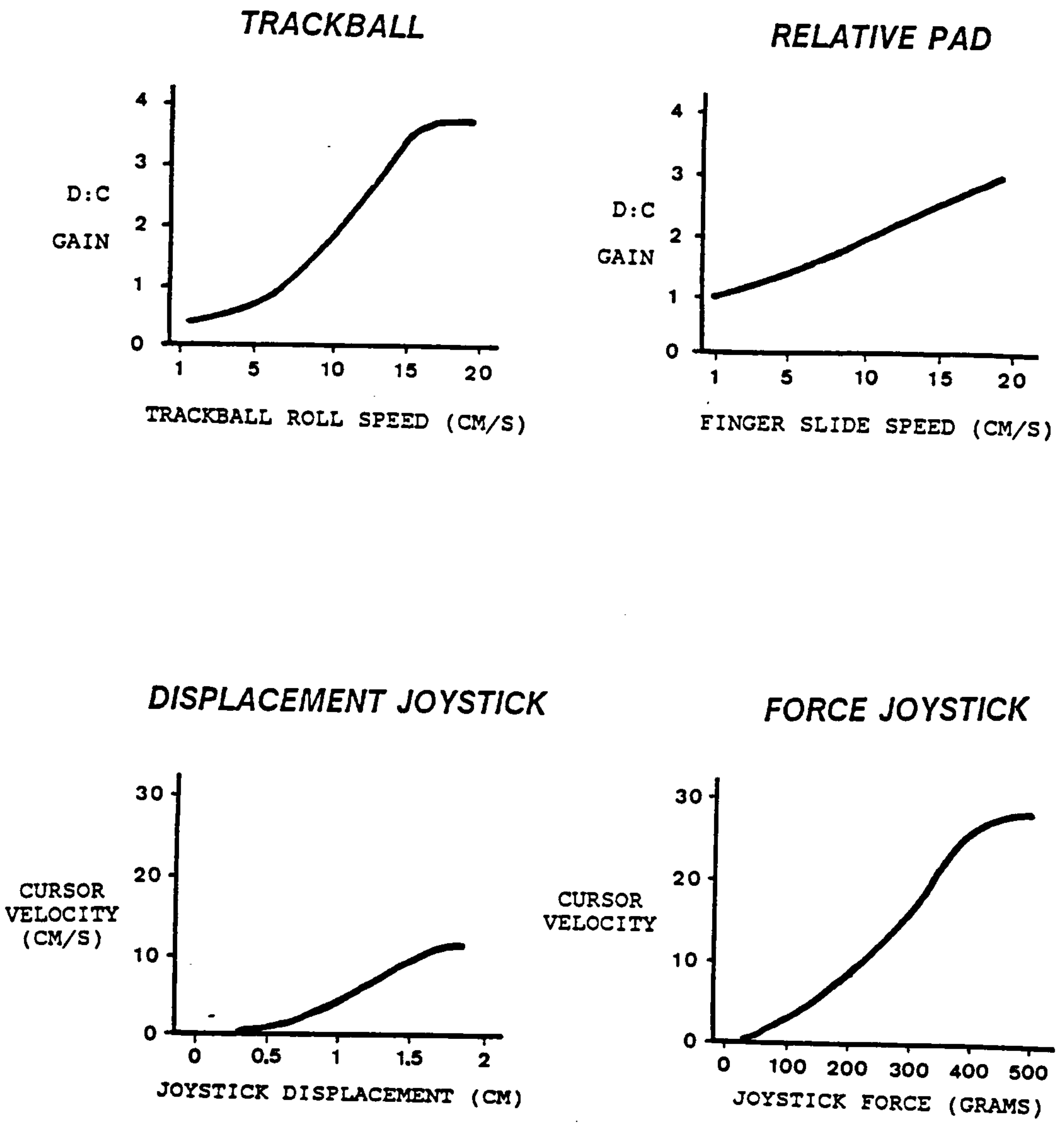

Figure 49. Optimized control dynamics.

(4) Relative touchpad. Keytronics finger sensitive, relative-mode touchpad (8 x 8 cm). The velocity with which the finger was moved across the touchpad determined the distance the cursor moved on the screen (Figure 49). For slow finger speeds, a 1.0 D:C gain existed between the cursor and touchpad. As finger speed was increased, the distance the cursor moved on the screen increased for a given finger movement distance. The target selection input button was operated with the opposite hand.

(5) Displacement joystick. Measurement Systems Model 521 rate-controlled, displacement joystick. The amount of joystick displacement determined the velocity of the cursor on the screen (Figure 49). As the amount of displacement increased, the velocity of the cursor increased. The target selection button was operated with the opposite hand.

(6) Force joystick. Measurement Systems Model 462 rate-controlled, force joystick. The amount of pressure applied to the joystick determined the velocity of the cursor on the screen (Figure 49). As the amount of pressure was increased, the velocity of the cursor increased. The target selection button was operated with the opposite hand.

To reduce possible subjective bias toward any one device, the trackball, force joystick, displacement joystick, relative touchpad, and absolute touchpad were mounted in similar black enclosures.

Experimental Design

The experiment was designed to compare cursor positioning devices on a target acquisition task. The target sizes and target distances chosen for the experiment were representative of graphics, text editing, and process control task environments.

A four-way, within-subjects factorial design was used for data collection and analysis. Independent variables were cursor device, target size, target distance, and trial block, as shown in Figure 50. Cursor device had six levels (types): optical mouse (MOUSE), absolute-mode touchpad (ABSOLUTE), relative-mode touchpad (RELATIVE), trackball (TRACKBAL), displacement joystick (DISPLACE), and force joystick (FORCE). The square targets had five levels of target width: 0.13, 0.27, 0.54, 1.07, and 2.14 cm (4, 8, 16, 32, and 64 pixels measured horizontally). Target distance had four levels of screen distance: 2, 4, 8, and 16 cm. Trial block had five levels, consisting of 40 target trials per block.

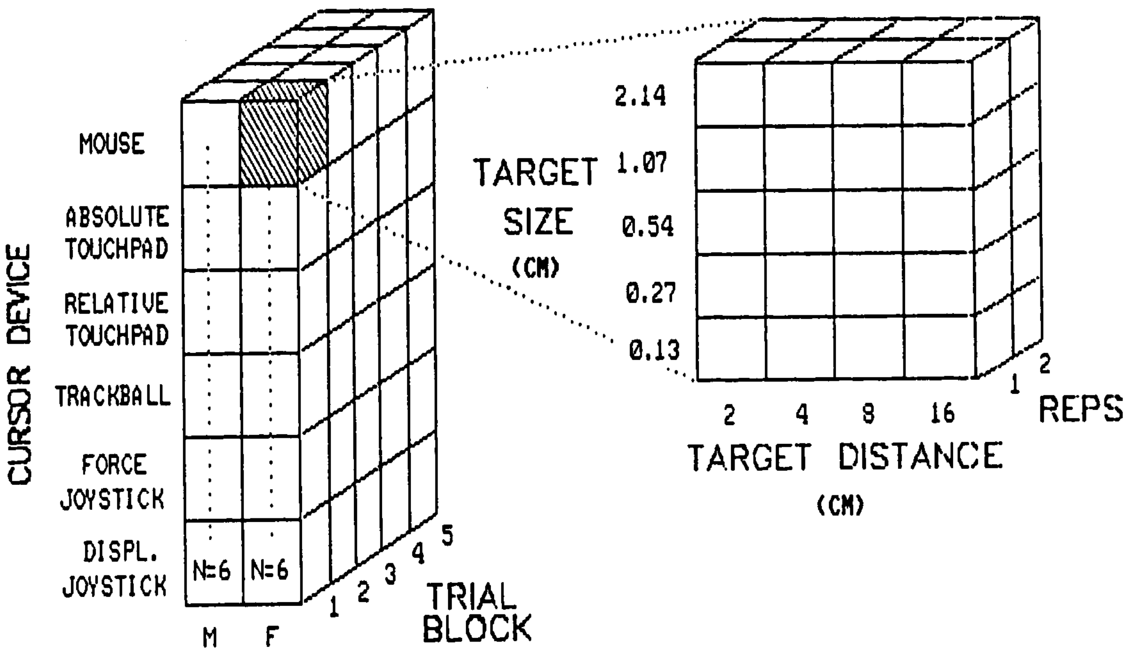

Figure 50. Experimental design: Target acquisition task comparison.

Each subject performed 200 target trials with each of the six cursor control devices. Each trial block (40 target trials) contained two presentations of each of the 20 target size/target distance combinations (2 x 5 x 4 = 40). To reduce possible systematic learning effects associated with the sequential use of the six devices, a Latin-square design was employed for device ordering.

Target Acquisition Task

The target acquisition task used for the comparison of the six cursor devices was identical to the target task described in the device optimization experiments.

Dependent Measures

Performance measure. The performance-based dependent measure, time to target (TT), was defined as the time, in seconds, required to acquire the target. The TT measure provided information on cursor control device performance across target sizes and target distances, an indication of cursor positioning accuracy and speed.

Subjective measures. Subjective measures consisted of bipolar scales and subjective ranks. Bipolar scales were developed to collect user preference data, subsequent to using each device. The 10 bipolar scales are shown in Figure 51. Rank data were collected to augment bipolar scale data and to provide each subject the opportunity to rank the devices after all six had been used. Six ranking criteria were evaluated: (1) preference, (2) positioning accuracy, (3) positioning speed, (4) perceived quality, (5) comfort, and (6) fatigue.

Experimental Procedure

Each subject participated in one 2-hr session, performing 200 target trials with each of the six cursor devices. First, the subject was given an informed consent form to read and sign, followed by a brief visual acuity test to a criterion of 25/20. The subject was then given a written introduction to the experimental task, instructions for completing the bipolar scales (Appendix D), and an example of the scales (Figure 51).

Next, the subject was given written instructions on the operation of the first cursor device (Appendix C). He/she then performed 200 trials with the device, responded to the bipolar scales, and rested for several minutes. The subject repeated the sequence for the remaining five cursor

PLEASE RATE THE CURSOR DEVICE YOU HAVE JUST USED ON THE FOLLOWING DESCRIPTIVE SCALES:

	VERY	QUITE	SLIGHTLY	NEUTRAL	SLIGHTLY	QUITE	VERY	
ACCURATE	____	____	____	____	____	____	____	INACCURATE
SLOW	____	____	____	____	____	____	____	FAST
CONSISTENT	____	____	____	____	____	____	____	INCONSISTENT
UNNATURAL	____	____	____	____	____	____	____	NATURAL
COMFORTABLE	____	____	____	____	____	____	____	UNCOMFORTABLE
FATIGUING	____	____	____	____	____	____	____	RELAXING
UNACCEPTABLE	____	____	____	____	____	____	____	ACCEPTABLE
PLEASING	____	____	____	____	____	____	____	IRRITATING
GOOD	____	____	____	____	____	____	____	BAD
INEXPENSIVE	____	____	____	____	____	____	____	EXPENSIVE

Figure 51. Example of the ten bipolar scales.

devices. When all six devices were completed, the subject was asked to rank the devices on each of six criteria.

METHOD: TEXT EDITING COMPARISON

Subjects

Five females and two males, drawn from the V.P.I. & S.U. community, served as subjects. All subjects were considered computer novices with less than 20 hours experience on text editing tasks. All subjects had performed previous text editing with only cursor keys. The remaining six devices had never been used for computer tasks by any of the subjects; only one subject reported limited experience with a mechanical mouse on computer programming tasks (i.e., not text editing). All subjects were paid $50.00 for their participation, which required approximately eight hours of participation for seven sessions.

Equipment

The experimental set-up, shown in Figure 52, consisted of seven cursor control devices, a TIPC, a TIPPC, a VHS recorder, and a monitor. The seven cursor devices included:

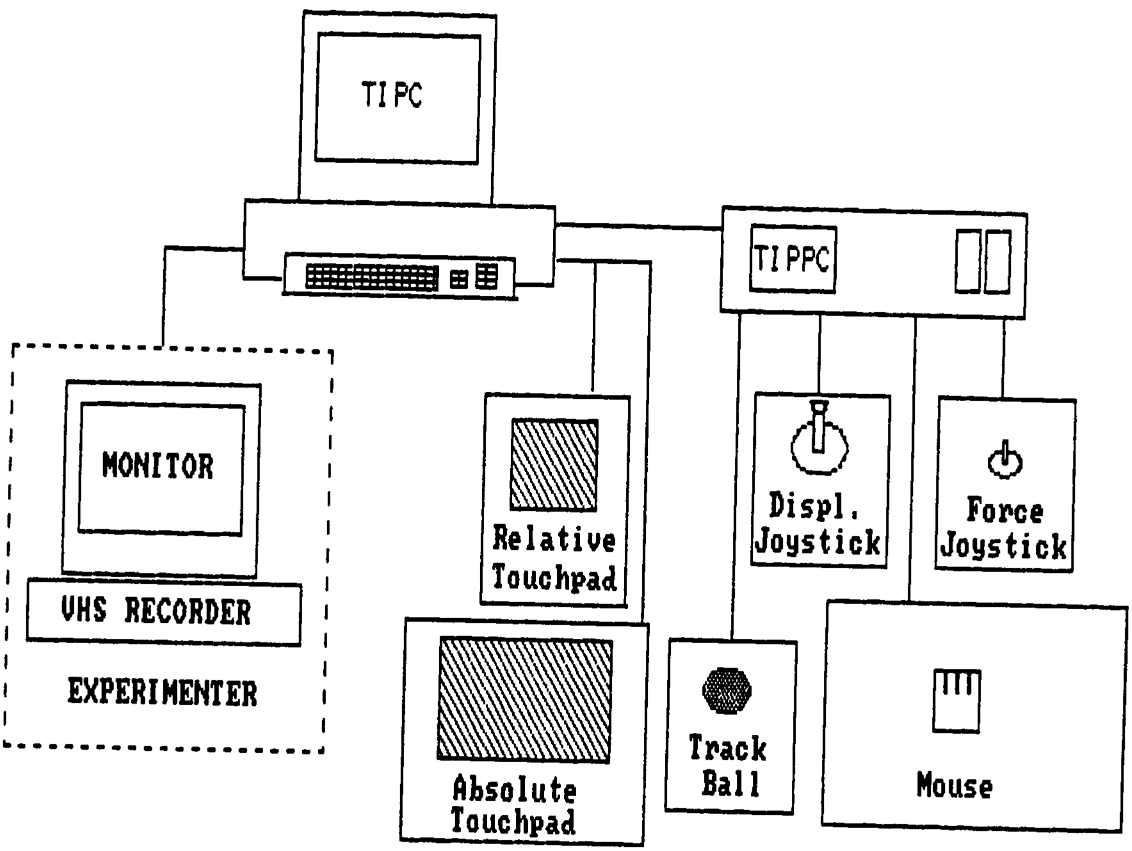

Figure 52. Experimental set-up for the text editing comparison.

(1) Absolute touchpad. Elographics finger-sensitive, absolute-mode touchpad (21 x 14 cm). The finger position on the touchpad was mapped directly to the cursor position on the screen text. A 1.0 D:C gain existed betweeen the screen and the touchpad. Active touchpad areas (15 x 2.5 cm) located above and below the 21 x 14-cm mapped touchpad area were used to scroll through multiple screen files.

(2) Mouse. Mouse Systems Model M-2 optical mouse with a 23 x 20 cm optical pad. A linear 1.3 D:C gain existed between cursor and mouse movements. Scrolling through multiple files was accomplished by sliding the mouse in a forward/backward (away/toward subject) direction on the optical pad.

(3) Trackball. Measurement Systems Model 621 trackball (4-cm diameter). A nonlinear D:C relationship existed between cursor and trackball movements (Figure 49). Scrolling was accomplished by rolling the trackball in a forward/backward direction.

(4) Relative touchpad. Keytronics finger-sensitive, relative-mode touchpad (8 x 8-cm). A nonlinear D:C relationship existed between cursor movement and finger speed (Figure 49). Scrolling was accomplished by sliding the finger forward/backward on the touchpad.

(5) Displacement joystick. Measurement Systems Model

521 rate-controlled displacement joystick. A nonlinear relationship existed between cursor velocity and joystick displacement (Figure 49). Scrolling was accomplished by displacing the joystick in a forward/backward direction.

(6) Force joystick. Measurement Systems Model 462 rate-controlled, force joystick. A nonlinear relationship existed between cursor velocity and joystick force (Figure 49). Scrolling was accomplished by exerting force on the joystick in a forward/backward direction.

(7) Cursor keys. The five-key cursor array, located on the TIPC keyboard, consisted of four directional (up, down, left, and right; the spatial arrangement is two-dimensionally mapped by movement direction) and one "home" key. A key press of a directional key for a short duration (approximately 250 milliseconds) moved the cursor one character. If the key was held down, the cursor moved across the screen at approximately 4.5 cm/s. The home key moved the cursor to the top left portion of the screen. Scrolling was accomplished by holding down the "up" or "down" directional key.

The TIPC was used to present the text editing task to subjects, to control device dynamics and modes for the absolute/relative touchpads, and to estimate task completion times. The TIPPC was used to control the device dynamics for the trackball, mouse, displacement joystick, and force joystick. The VHS video recorder was used to tape all sessions. The monitor enabled the experimenter to watch each session and record task completion time and error data.

Experimental Design

A three-way, within-subjects factorial design was used for data collection and analysis. Independent variables were cursor device, text file, and trial block, as shown in Figure 53. Cursor device had seven levels (types): absolute touchpad, optical mouse, trackball, relative touchpad, force joystick, displacement joystick, and cursor keys. Text file had four levels (types): single screen/character delete, multiple screen/character delete, single screen/text edit, and multiple screen/text edit. Trial block had three levels.

Each subject performed three blocks of text editing for each of the four types of text files with each cursor control device. That is, each subject performed text editing on 12 files for each device. To reduce possible systematic learning effects associated with the sequential

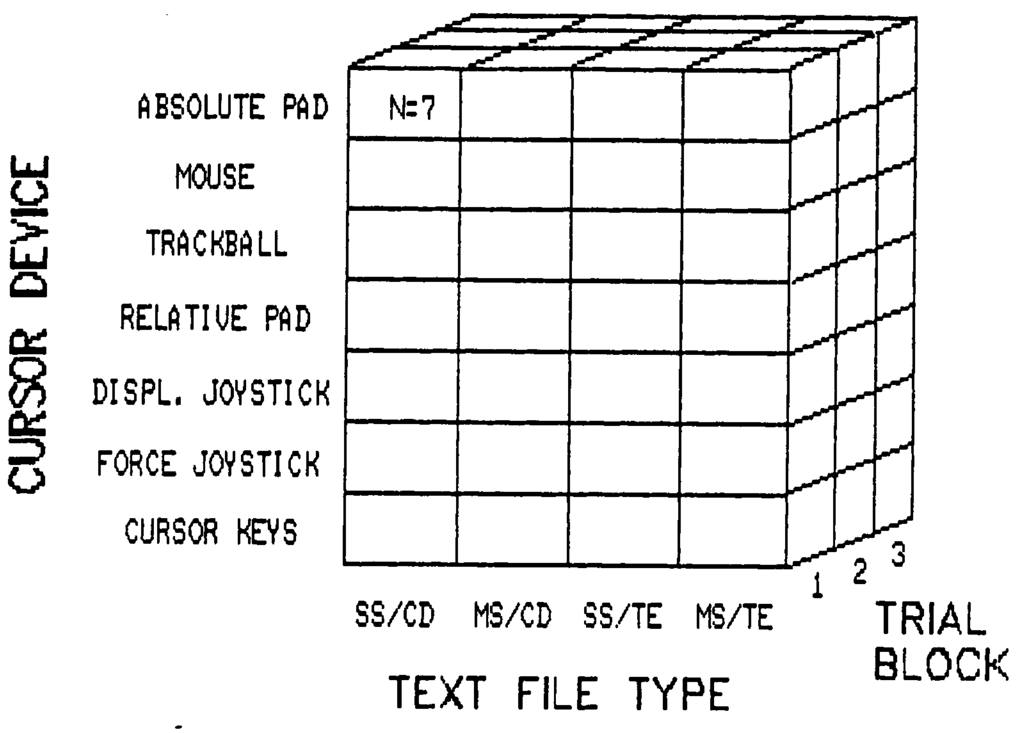

Figure 53. Experimental design: Text editing comparison.

use of seven devices, the order of device presentation was randomized for each subject.

Text Editing Task

PFM editior. The computer-based editor used for the text editing task was the Professional File Management (PFM) editor developed by Texas Instruments. PFM is a 22-line by 75-character, full-screen editor. The top and bottom two lines of text on the screen were "scroll areas." That is, if the cursor was moved into the top two lines of text, the screen document would scroll down. If the cursor was moved into the bottom two lines of text, the screen document would scroll up.

Six function keys were used to perform editing tasks: PAGE UP, PAGE DOWN, DELETE CHARACTER, DELETE WORD, INSERT, and UNDO. Instructions for the use of these function keys, which were given to subjects, are shown in Appendix E. Also shown are the six editing tasks performed by the subjects: delete character, insert character, replace character, delete word, insert word, and replace word. The PAGE UP and PAGE DOWN keys could be used as an alternative to the two-line scroll areas on the screen.

<u>Text file types</u>. Four types of text files were used to compare the seven cursor devices: single screen/character delete (SS/CD), multiple screen/character delete (MS/CD), single screen/text edit (SS/TE), and multiple screen/text edit (MS/TE). Examples of each of these files are shown in Appendix F. Descriptions of the tasks associated with the four files are as follows:

(1) Single screen/character delete (SS/CD). The SS/CD file consisted of six randomly placed symbols (i.e., inverted triangles) imbedded within a full screen (18 lines) of text. Subjects were required to scan the screen for the six symbols, then sequentially position the cursor over each symbol and press the CHARACTER DELETE function key. No paging or page-scrolling was required to edit the SS/CD files.

(2) Multiple screen/character delete (MS/CD). The MS/CD file consisted of 18 symbols imbedded within multiple screens (81-181 lines) of text. The position of each symbol was based on the distribution of text editing changes typically found in documents (Appendix G; adapted from Roberts, 1981). The task was similar to the SS/CD files, except the subject was required to scroll through the multiple screen document using the cursor device or the page keys.

(3) Single screen/text edit (SS/TE). The SS/TE files consisted of six randomly placed text editing changes (character delete, character insert, character replacement, word delete, word insert, and word replacement) imbedded in a full screen (18 lines) of text. Subjects were required to use a hard copy document to perform the editing changes on the screen. For each editing change, the subject positioned the cursor over the first character of the word or over the character to be edited, then performed key presses and text typing as required. No paging or scrolling was required to edit the SS/TE files.

(4) Multiple screen/text edit (MS/TE). The MS/TE files consisted of 18 text editing changes (three occurrences of character delete, character insert, character replacement, word delete, word insert, and word replacement) imbedded within multiple screens (81-181 lines) of text. The position of the editing changes as based on the same distribution used with the SS/CD files. The task was similar to the SS/TE files, except the subject was required to scroll through the multiple screens using the cursor device or page keys.

Three blocks of files were performed by each subject for all seven devices. Each block contained one occurrence of each type of text file in order (SS/CD, MS/CD, SS/TE, MS/TE).Twenty-one files for each of four text files were developed. Subjects never performed second editing changes on the same file.

Dependent Measures

Dependent measures were task completion time, bipolar scales, and subjective ranks. Task completion time was the time, in seconds, to complete an editing change; that is, the total time to complete each file divided by the number of editing changes attempted (seconds per edit). Bipolar scales and ranks were identical to those used in the prior target acquisition experiment (Figure 51).

Experimental Procedure

The experiment was divided into seven sessions, one session on each of seven successive days, for each subject. The first session consisted of a brief introductión to the experiment, training on the PFM text editor, and data collection for the first cursor control device. The six subsequent sessions, conducted on successive days, consisted of data collection for the remaining six devices.

Introduction. First, subjects were given an informed consent to read and sign. Then, each subject was given brief instructions for the experimental session, instructions on the operation of the first device, and instructions on responding to the bipolar scales.

Training session. Each subject was then trained on the text editor using a different device. The training session consisted of editing three blocks of SS/CD, MS/CD, SS/TE, and MS/TE files. The first and second blocks were used to train the subjects on the editing tasks; that is, interrupt the session if the subject ommited editing changes or performed them incorrectly. The third block was used to test each subject to ensure that the tasks were being performed correctly. No subject made more than one editing error on any of the four files in the third block. It was therefore assumed that all subjects had an adequate understanding of the editor and its functions. The training session was of 45 to 60 minutes in duration.

Data collection sessions. The seven data collection sessions consisted of three blocks of each of the four text files. The experimenter did not interrupt these sessions, nor did he answer any editing-related questions posed by the subjects.

Following successful completion of the 12 text files (three blocks of each of the four types of files) with the cursor device, subjects were given the series of 10 bipolar scales. At the end of the seventh session, subjects were asked to rank the seven devices on each of the six criteria.

The experimenter then debriefed the subjects and asked each subject to offer any additonal opinions on what they liked, disliked, or would change about each device. The subjects were then paid and any additonal questions were answered by the experimenter.

METHOD: GRAPHICS EDITING COMPARISON

Subjects

Three females and three males, drawn from the V.P.I. & S.U. community, served as subjects. All subjects were naive users of computer-based graphics editors and of the six cursor control devices used in the study. Each subject was paid $50.00 for participation, which required approximately eight hours over six sessions.

Equipment

The experimental equipment consisted of six cursor control devices, a TIPC, a TIPPC, a VHS video recorder, and a monitor, as shown in Figure 54. The six cursor devices were identical to those compared on the target acquisition task, except that two input buttons were required to perform the graphics tasks. The TIPC was used to present the graphics tasks to subjects. The TIPPC was used to control the dynamics and modes of all six devices. Cursor device output from the TIPPC to the TIPC was in Mouse Systems device protocol for the mouse, trackball, force joystick, and displacement joystick. A

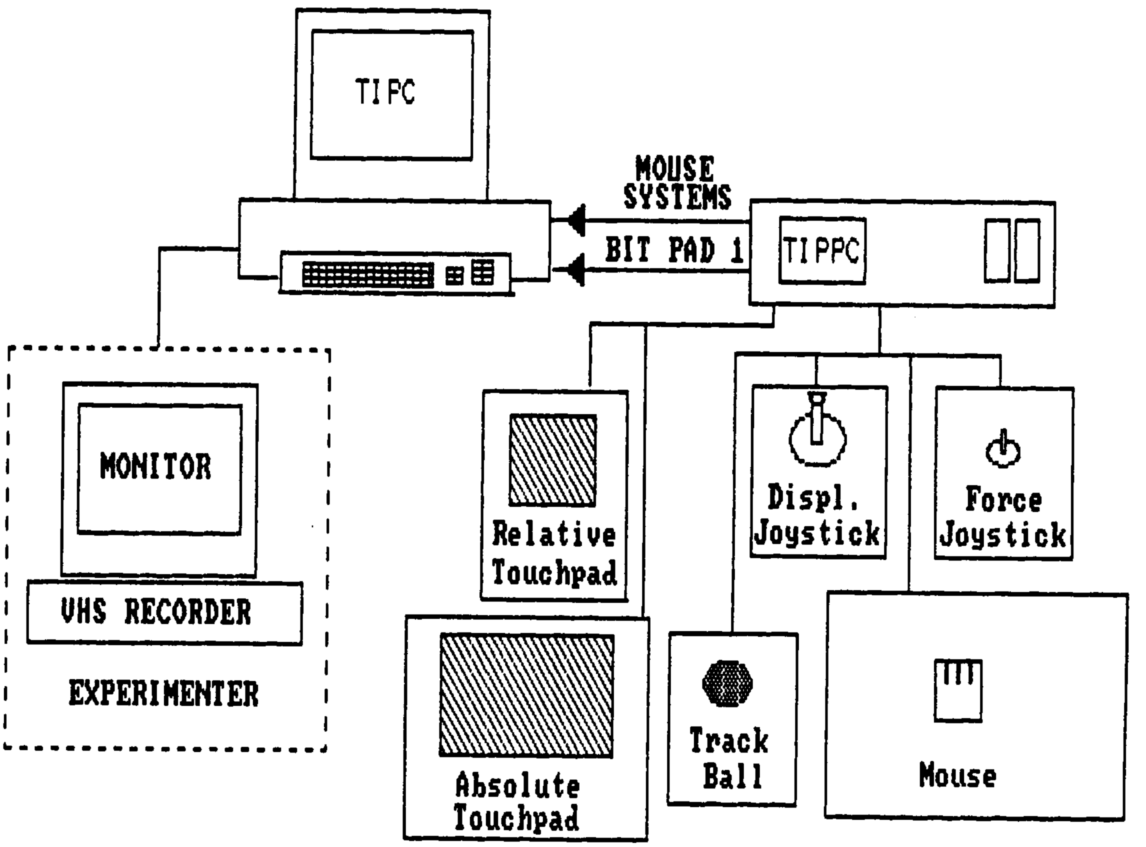

Figure 54. Experimental set-up for the graphics editing comparison.

Bit Pad One device protocol was used for the absolute and relative touchpads. The monitor and VHS video recorder were used by the experimenter to observe sessions, collect task completion data, and obtain error data.

Experimental Design

A three-way, within-subjects factorial design was used for data collection. Independent variables were cursor device, graphics task, and trial block, as shown in Figure 55. Cursor device had six levels (types): absolute touchpad, mouse, trackball, relative touchpad, displacement joystick, and force joystick. Graphics task had seven levels (types): rectangles (RT), horizontal grids (HG), vertical grids (VG), angular grids (AG), fat bits (FB), horizontal lines (HL), and vertical lines (VL). Trial block had three levels.

Each subject performed three blocks of graphics editing for each of the seven types of graphics tasks with each cursor control device, or a total of 21 tasks with each device. To reduce possible systematic learning effects associated with the sequential use of six devices, a Latin-square design was employed for device ordering.

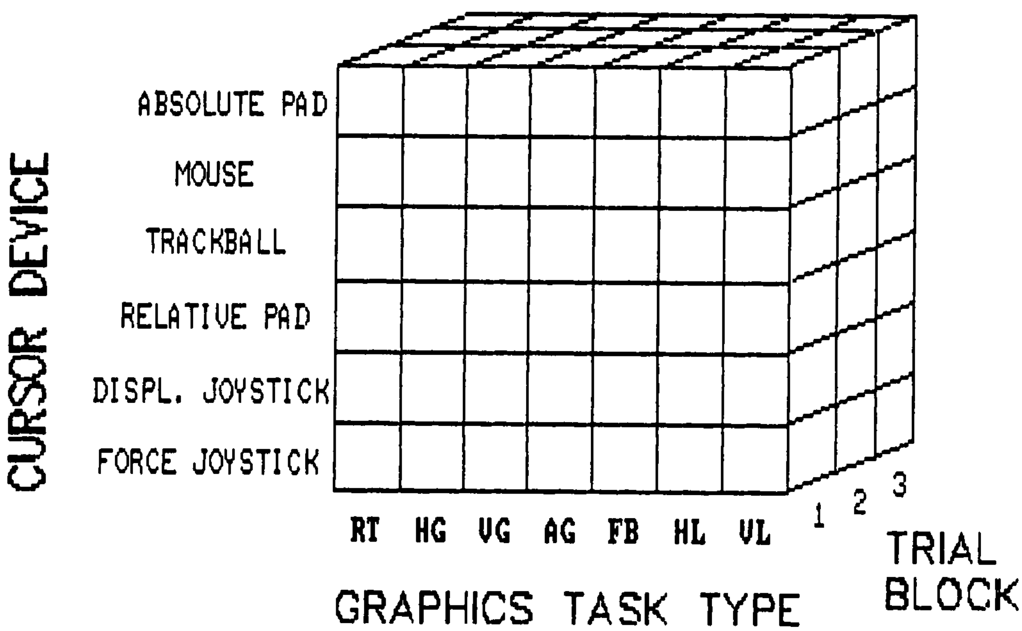

Figure 55. Experimental design: Graphics editing comparison.

Graphics Editing Tasks

Dr. Halo editor. Dr. Halo is an icon-based, direct manipulation interface (DMI) graphics editor. An example of the screen layout is shown in Appendix H. Graphics editing functions are located on the left portion of the screen and paint functions are located along the bottom. Graphics functions are chosen by moving the cross hair cursor within the boundaries of an icon and pressing the input button.

Graphics functions. Three types of graphics functions were used in the experiment to perform editing changes on the seven types of tasks, including (1) draw rectangles, (2) draw lines, and (3) "fat bits". The draw rectangles function enables the user to draw rectangles of various sizes. The draw lines function allows users to draw horizontal, vertical, and oblique lines. The fat bits function allows the user to "zoom-in" on a section of the screen and add or delete "pixels."

Graphics task types. Seven types of graphics tasks, contained on four different graphics files (RECTANGLES, GRIDS, FATBITS, LINES), were used to compare the six cursor control devices. Examples of the four files are shown in Appendix H. Descriptions of the seven associated graphics tasks (rectangles (RT), horizontal grids (HG), vertical grids (VG), angular grids (AG), fat bits (FB), horizontal lines (HL), and vertical lines (VL)) are as follows:

(1) Rectangles (RT). The RT task was performed on the RECTANGLES file. Subjects used the cursor device to adjust the shape of a rectangular-shaped cursor so that it fit within the boundaries of each of the 16 rectangular pairs (Appendix H). The subject adjusted the size and aspect ratio of the rectangular cursor (white) by depressing the middle input button and moving the cursor device simultaneously. Once the rectangular cursor had been adjusted for size and positioned within the target boundaries (yellow), the subject pressed the left button to place the rectangle. The rectangular targets were completed in a top-to-bottom and left-to-right sequence. Four different rectangles, ordered using a Latin-square design, were used. This procedure ensured that subjects would be required to adjust the rectangle in both X and Y screen directions when moving from one rectanguler target to the next.

(2) Horizontal grids (HG). The HG task was one of three tasks performed on the GRIDS file. (VG and AG were the other two tasks.) Subjects used the cursor device to

adjust the length of a horizontal line cursor (white) so that it bridged the grid (yellow), using the draw line function. The horizontal line length was adjusted by depressing the middle input button and moving the cursor device simultaneously. Once the length of the line cursor had been adjusted, the subject was required to position the line cursor to form a continuous line that bridged the grid for the top-most position. Feedback was given to the subject for correct cursor positioning by having the cursor/grid overlap turn blue. Once the horizontal line was correctly positioned, the subject pressed the left input button and proceeded to the next grid position. When the first grid (five lines) was completed, the subject re-adjusted the cursor line length and completed the second grid (five lines). Since the grids and cursor line were 1-pixel wide, line positioning in the vertical axis required approximately 17 pixels/cm positioning accuracy. The order of short and long grids was randomized across trials blocks.

(3) Vertical grids (VG). The VG task was similar to the HG task, except cursor line length adjustment was done in the vertical axis and line positioning was performed in the horizontal axis, requiring approximately 30 pixels/cm positioning accuracy. The order of short and long grids

was randomized across trial blocks.

(4) Angular grids (AG). The AG task was similar to the HG and VG tasks, except the cursor line could be adjusted for both line length and direction (i.e., angle). Therefore, positioning accuracy was a function of both Y (17 pixels/cm) and X (30 pixels/cm) screen resolution. The order of left and right angle grids was randomized across trial blocks.

(5) Fat bits (FB). The FB task, the only task on the FATBITS file, consisted of two sets of 20 target acquisitions performed with the fat bits function. Subjects used the cursor device to position a cross-hair cursor over green, rectangular targets (4 x 4 pixels) and press the left input button. If the cursor was located within the boundaries of the solid rectangular target when the left button was pressed, the color of the "pixel" changed from green to white. If the cursor was outside of the target boundaries when the left button was pushed, an adjacent blank "pixel" turned white, requiring subjects to re-position the cursor over the green target and press the left button again. If the button was held down as the cursor moved outside of the boundaries of the target an adjacent blank "pixel" also turned white. The position of the green targets was randomized across target trials and

cursor devices.

(6) Horizontal line (HL). The HL task was one of two tasks performed on the LINES file (the other was vertical lines, VL). Subjects used the cursor device to connect eight line segments with a sequence of "pixels," using the fat bits function. Each HL task required subjects to join eight line segments. Two replications of segment length (4 and 8) and line-draw direction (left and right) were given. Each of eight line segments contained four red and four green pixel segments, separated by four or eight (pixel) spaces. The subjects were required to join the green/red segments by pressing the left input button and moving the device to draw the required number of "pixels." If the cursor deviated from the segment, an adjacent blank "pixel" turned white and the subject was required to position the cursor over the erroneous "pixel" and delete it using the middle input button.

(7) Vertical line (VL). The VL task was similar to the HL task except subjects were required to draw "pixel" segments in the vertical direction.

Three blocks of graphics files were performed by each subject for all seven devices. Each block contained one occurrence of each type of graphics files in order (i.e., SQ, HG, VG, AG, FB, HL, VL).

Dependent Measures

Dependent measures were task completion time, bipolar scales, and subjective ranks. Task completion time was the time, in seconds, to complete a graphics task; that is, the total time to complete each file divided by the number of graphics editing tasks attempted (seconds per edit). Bipolar scales and subjective ranks were identical to those used in the target acquisition and text editing tasks.

Experimental Procedure

The experimental procedures for the graphics editing task was similar to that of the text editing. The experiment was divided into six sessions on successive days. The first session consisted of a brief introduction to the experiment, training on the graphics editor, and data collection for the first cursor control device. The five subsequent sessions consisted of data collection for the remaining five devices.

Introduction. First subjects were given an informed consent to read and sign. Then, each subject was given brief instructions for the experimental session, instructions on the operation of the first device, and instructions on responding to the bipolar scales.

Training session. Each subject was then trained on the graphics editor; each subject was trained with a different device. The training session consisted of editing three blocks of the SQ, HG, VG, AG, FB, HL, and VL tasks. The first and second blocks were used to train subjects on the graphics tasks. Training concentrated on the graphics functions and the correct use of the two input buttons. No help was given to the subjects in the operation of the cursor device other than the written instructions. The experimenter interrupted the session if the subject ommitted editing changes or performed changes incorrectly. The third block was used to test each subject to ensure that the tasks were performed correctly. Besides device-related positioning errors, only one button press error was made in all six test sessions. It was therefore assumed that all subjects had an adequate understanding of the graphics editor and its functions. The training session was of 45 to 75 minutes in duration.

Data collection sessions. The six data collection sessions consisted of three blocks of the seven graphics tasks, performed with a different device each session.

Prior to beginning each session, the subject was given instructions for the operation of the device to be used that day. The experimenter did not interrupt these sessions, nor did he answer any editing or device related questions posed by the subject.

Following successful completion of the 21 graphics tasks with the cursor device, subjects were given a series of 10 bipolar scales.

At the end of the sixth session, subjects were asked to rank the six devices on each of the six criteria. The experimenter then asked each subject to offer any additional opinions on what he or she liked, disliked, or would change about each device. The subject was then paid and any additional questions were answered by the experimenter.

DATA ANALYSIS AND RESULTS: TARGET ACQUISITION TASK

Separate analyses were performed on the three dependent measures: (1) time to target (TT), (2) ranks, and (3) bipolar scales.

Time to Target

Data analysis. Prior to the comparison of cursor control devices across target size and distance, the target acquisition performance was analyzed across trial blocks to determine the learning effects associated with each device. In this way, the devices could be compared under asymptotic performance. An analysis of variance (ANOVA) was performed on the cursor control device (6) by trial block (5) model for the time-to-target acquisition (TT) dependent measure. Results showed that the Device x Trial block interaction ($F(20,220) = 2.47$, $p = 0.0007$) and Trial Block main effect ($F(4,44) = 46.17$, $p = 0.0001$) were significant (Table 40, Appendix B). A post-hoc comparison, using the Bonferroni-T test, was performed on the interaction means to determine the trial block at which asymptotic performance was attained for each device (Table

41, Appendix B). A comparison was also performed on the Trial Block main effect means, which represented the trial block means averaged across the six devices (Table 42, Appendix B).

The two analyses indicated that the target positioning performance was asymptotic after Block One, as shown in Figure 56. Therefore, subsequent comparisons of the cursor control devices across target size and distance were performed using TT data from Blocks Two through Five.

Following the trial block analysis, an analysis of variance (ANOVA) was performed on the cursor device (6) x target size (5) x target distance (4) model for the time-to-target (TT) dependent measure. A summary of the ANOVA results for TT is shown in Table 43 (Appendix B).

In general, as target size (TS) increases, TT decreases, averaged across all other variables. As target distance (TD) increases, TT increases, averaged across all other variables. However, the TS and TD main effects and the TS x TD interaction are unimportant when considered alone, as they should, and do, logically interact with the various cursor control devices. Accordingly, it is more meaningful to evaluate the interaction of cursor devices with TS and TD.

Significant interactions of interest, therefore,

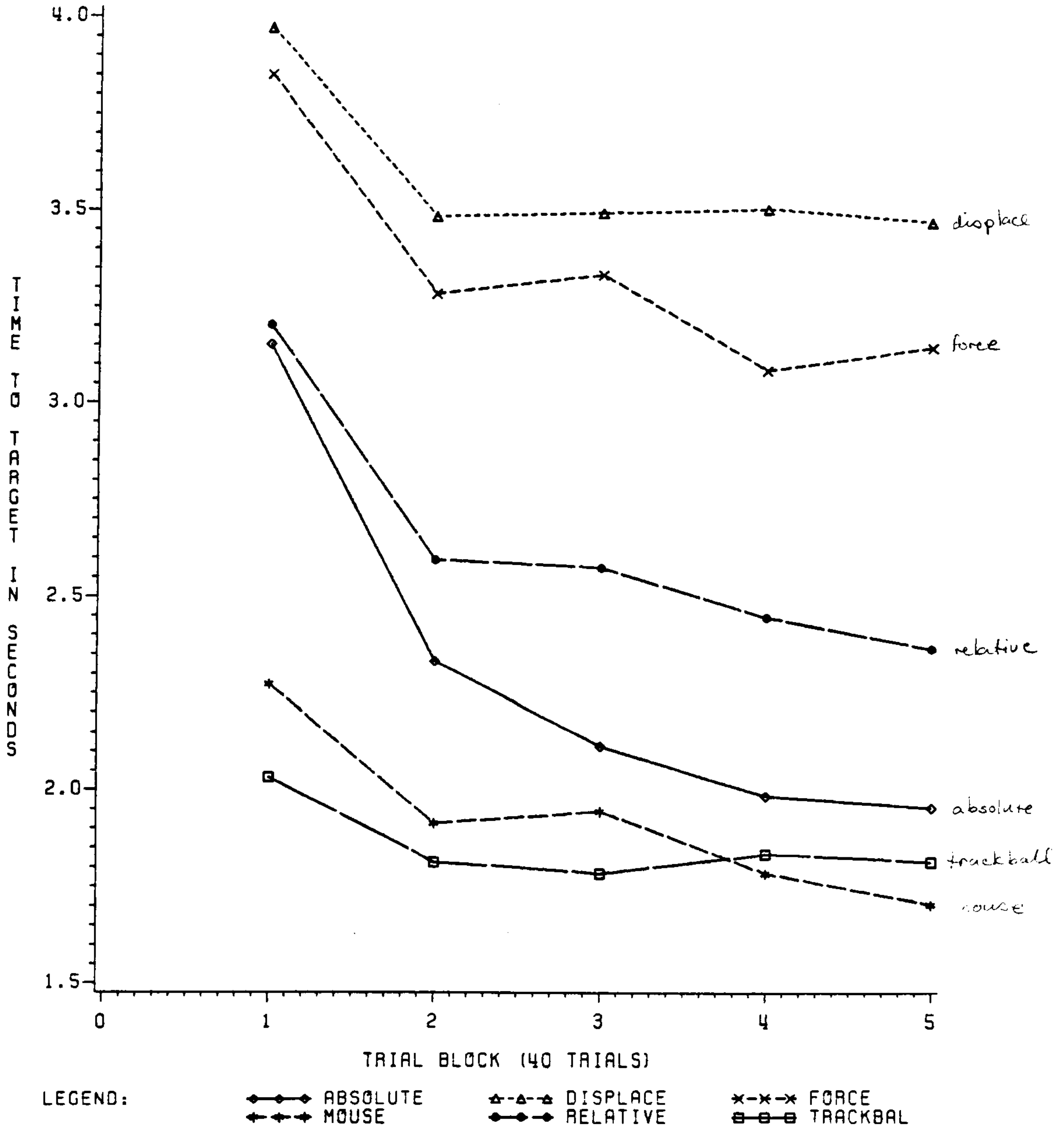

Figure 56. Comparison of cursor devices across trial blocks.

included Device x Target size ($F(20,220) = 25.25$, $p = 0.0001$) and Cursor Device x Target Distance ($F(15,165) = 5.95$, $p = 0.0001$). The main effect of Cursor Device was also significant ($F(5,55) = 32.92$, $p = 0.0001$). Subsequent post-hoc comparisons were performed on the two interactions to determine which devices performed best at various target sizes and target distances. A comparison was also performed on the device main effect to determine the best device, averaged across target size and distance. Bonferroni-T Test results for the two interactions and the main effect are shown in Tables 44, 45, and 46 (Appendix B).

The Bonferroni-T was chosen for post-hoc statistical tests of interactions and main effects, since it provides a relatively conservative test for comparison of means. Specifically, the Bonferroni-T (Dunn) Test protects against Type I error for all comparisons. In general, the Bonferroni-T is more conservative (i.e., it is more difficult to find significant differences among means) than the LSD, Newman-Kuels, and Tukey tests, but less conservative than the Scheffe.

Results. Results for cursor control device performance across target sizes are shown in Figure 57 (Table 44). As target size decreases, performance differences among

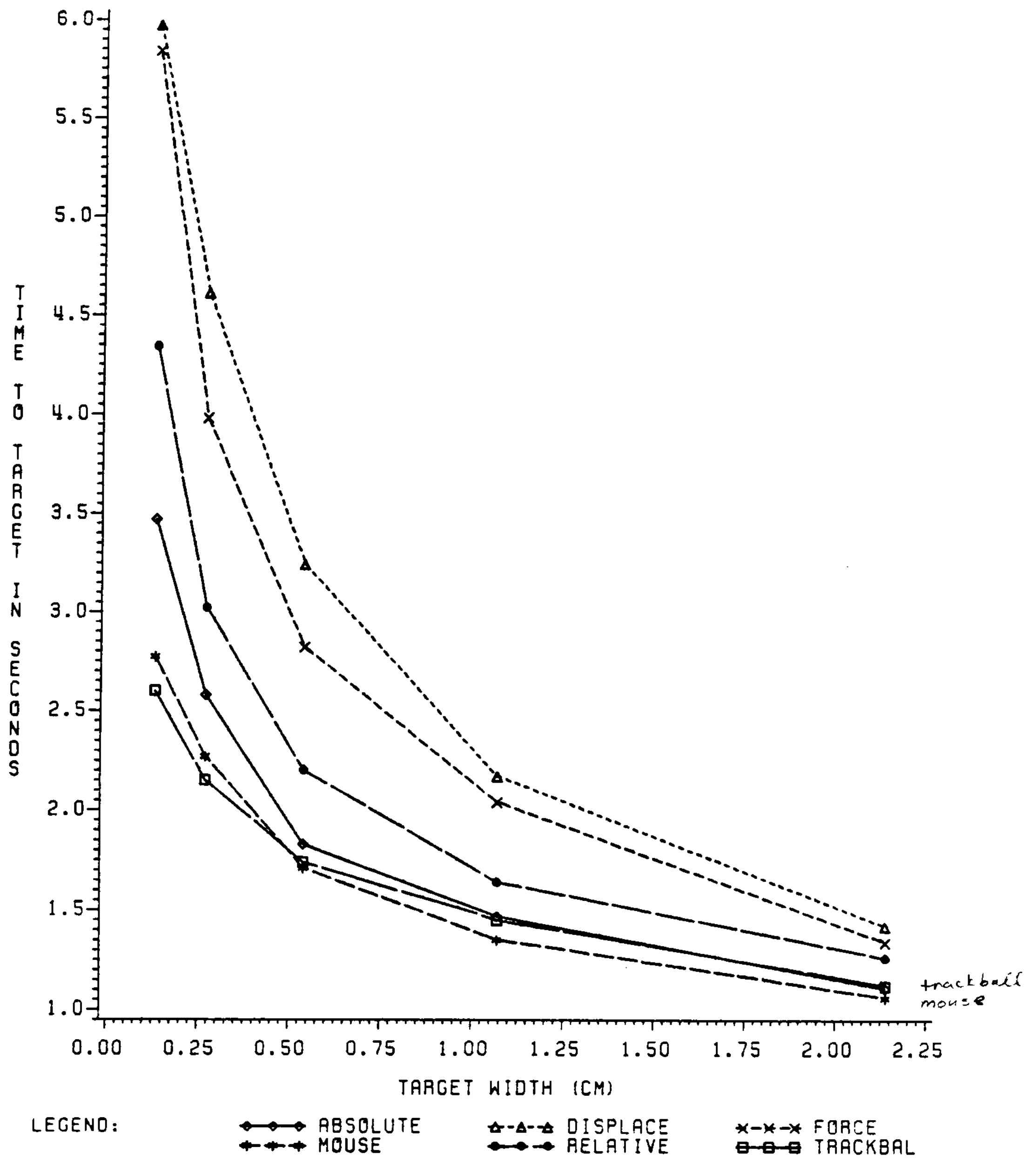

Figure 57. Comparison of cursor devices across target sizes.

devices become more pronounced, indicating large differences among devices for cursor positioning accuracy. For the smallest target size (0.13 cm), the mouse and trackball perform better than the remaining four devices, indicating a high level of device accuracy. In addition, the absolute touchpad performs significantly better than the relative touchpad. The rate-controlled cursor control devices (force and displacement joysticks) perform worse than all other cursor devices. At the 0.27-cm target size, the mouse and trackball are superior to the relative touchpad and, again, the joysticks are worse than the other devices. For medium target sizes (0.54 and 1.07 cm), there are no substantial differences among the mouse, trackball, and touchpads, but these devices are better than both joysticks. At the largest target size (2.14 cm), no statistical differences exist among the six devices.

When considering cursor control devices performance across target distance, the rate-controlled joysticks perform the worst across all distances, as shown in Figure 58 (Table 45). At the shortest screen distance (2 cm), the trackball and mouse perform better than the two touchpads. At 4 cm, the mouse is better for target acquisition than are both touchpads. At distances of 4 cm and greater, the mouse, trackball, and absolute touchpad perform better than

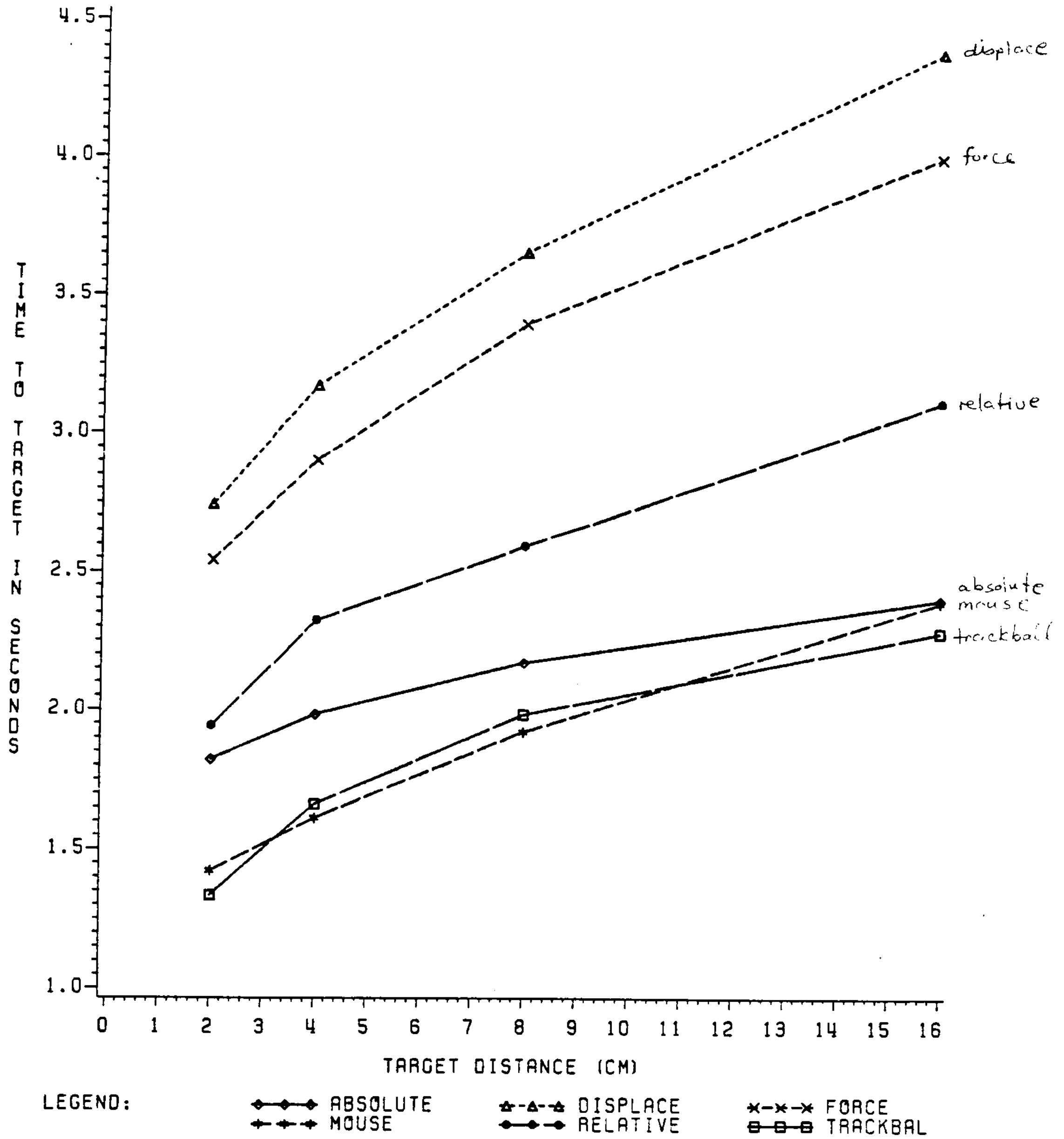

Figure 58. Comparison of cursor devices across target distances.

the relative touchpad. Interestingly, the mouse target acquisition time at the largest target distance increases relative to the absolute touchpad and trackball. This result may be due to the mouse "running off" the optical pad on long moves. As is the case for all target sizes, the TTs are approximately twice as large for the "poor" devices compared to the "best" devices across all target distances.

The results for the main effect of <u>cursor device</u>, a comparison of cursor control device performance collapsed across target sizes, target distances, and trial blocks, are shown in Figure 59 (Table 46). No differences exist among the trackball, mouse, and absolute touchpad. The mouse and trackball perform better than the relative touchpad. The rate-controlled joysticks are significantly worse than all of the remaining devices.

Ranks

<u>Data analysis</u>. The six cursor control devices were ranked by each subject on six criteria: (1) preference, (2) positioning accuracy, (3) positioning speed, (4) perceived quality, (5) comfort, and (6) fatigue. Each criterion was analyzed separately using a nonparametric, two-way Friedman

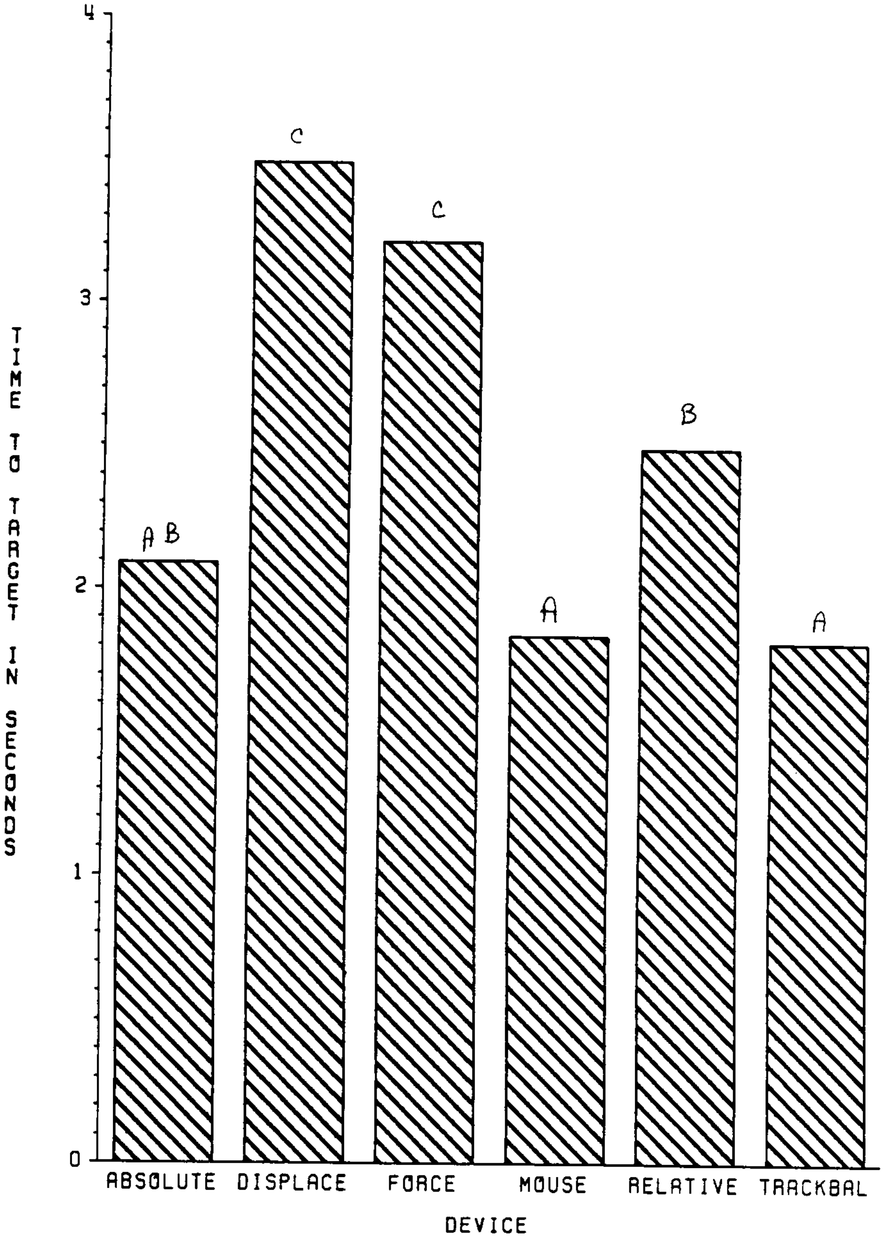

Figure 59. Comparison of cursor devices averaged across target sizes and distances.

Rank Sum test. Cursor device (6) was the factor of interest and subject (12) the blocking factor. The results of the analysis indicated differences among the cursor control devices for all six criteria. Subsequent multiple comparisons (experimentwise alpha = 0.05) were performed on the rank sums to determine differences among cursor devices. Statistical results for the criteria, given in Tables 47 through 52 (Appendix B), indicated a critical rank sum difference of 26.1.

Results. Results for the six criteria are shown in Figure 60. In general, the mouse and trackball are ranked best (i.e., lowest) on the six criteria. Individual criterion results are as follows:

(1) Preference ($S' = 39.53$, $p < 0.001$). The mouse is preferred over the touchpads and joysticks. Both the mouse and the trackball are ranked higher than is the displacement joystick.

(2) Quality ($S' = 24.42$, $p < 0.001$). The mouse is considered to be a higher quality cursor control device than are the touchpads and joysticks.

(3) Positioning speed ($S' = 25.14$, $p < 0.001$). Subjects ranked the trackball and mouse as providing better positioning speed than either of the joysticks.

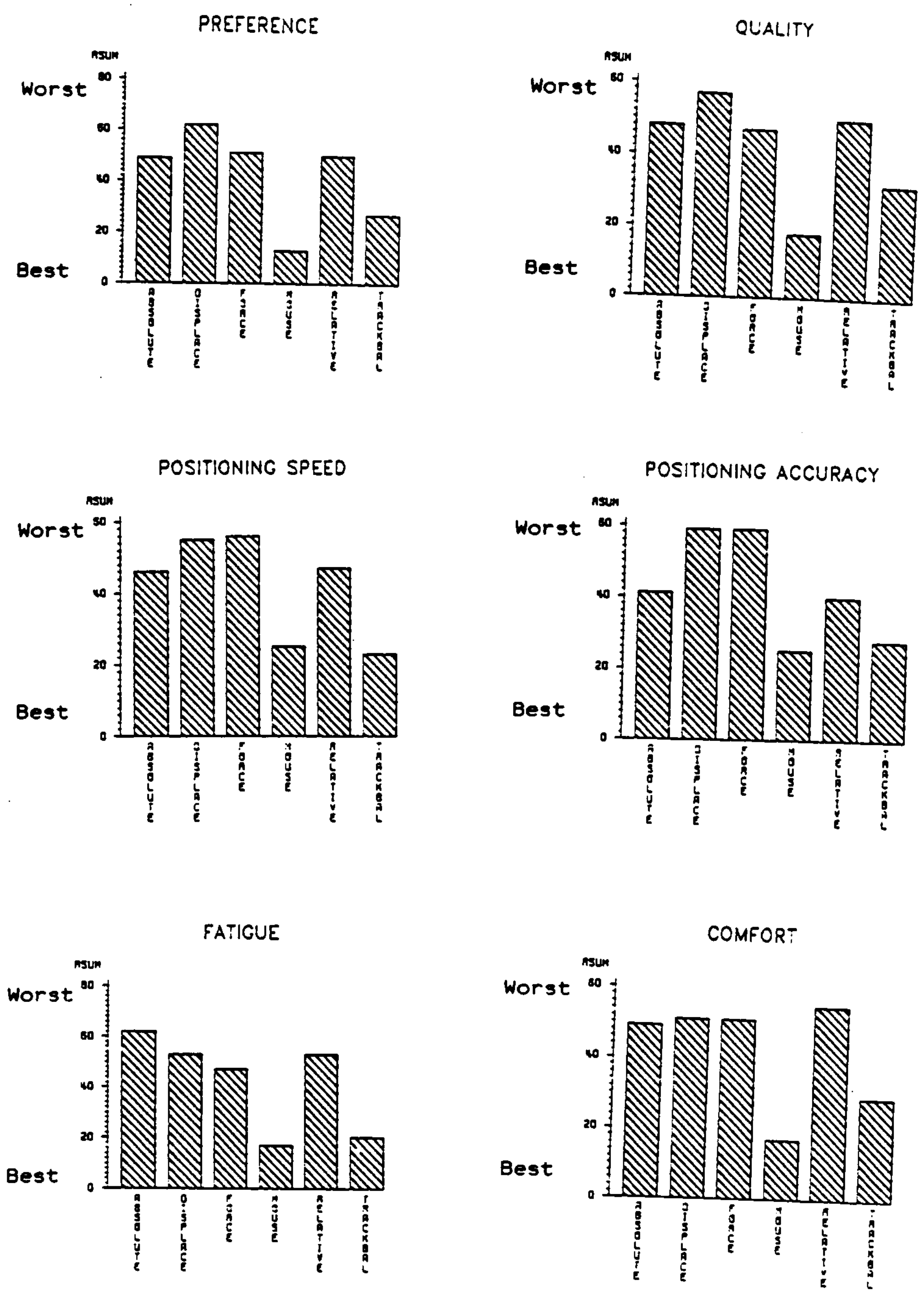

Figure 60. Comparison of cursor devices ranked on six criteria.

(4) Positioning accuracy ($S' = 25.43$, $p < 0.001$). The rank results for positioning accuracy and positioning speed are similar. The mouse and trackball are considered better for positioning accuracy than are the two joysticks.

(5) Fatigue ($S' = 42.49$, $p < 0.001$). Subjects ranked the mouse as causing less fatigue than the touchpads and joysticks. The trackball causes less perceived fatigue than do the touchpads and displacement joystick.

(6) Comfort ($S' = 27.95$, $p < 0.001$). Subjects, again, ranked the mouse as being more comfortable to use than are the touchpads and joysticks. The trackball is considered more comfortable than the relative touchpad.

Bipolar Scales

Data analysis. Two separate analyses were performed on the subject response data associated with the 10 bipolar scales. First, a multivariate analysis of variance (MANOVA) was performed on the one-way, within-subjects model, where cursor control device (6) was the factor of interest and the 10 bipolar scales were the dependent measures. The overall MANOVA indicated significant differences among the cursor devices for the 10 scales ($F[approx](50,213) = 1.52$, $p = 0.0230$). Therefore, separate ANOVAs were performed on each of the scales. A summary of the MANOVA results, subsequent ANOVAs, and Bonferroni-T Tests are shown in Tables 53 through 63, Appendix B.

Second, a single-number Preference Index (PI) was developed by linearly combining responses from the 10 scales. An ANOVA was performed on the one-way, within-subjects model, with cursor device as the factor of interest and the PI the dependent measure. Results indicated significant differences among the six devices ($F(5,55) = 7.74$, $p = 0.0001$). A summary of the ANOVA and the subsequent Bonferroni-T Test are given in Table 64 (Appendix B).

Results. Results for comparisons of the six cursor control devices on each of the bipolar scales are shown in Figure 61. In general, the mouse and trackball are rated best by subjects across all 10 bipolar scales. Individual scale results are as follows:

(1) Accurate (Inaccurate) ($F(5,55) = 4.78$, $p = 0.0011$). The mouse is rated more accurate than the absolute touchpad and the joysticks.

(2) Fast (Slow) ($F(5,55) = 4.39$, $p = 0.0020$). The mouse is rated faster than the relative touchpad and the

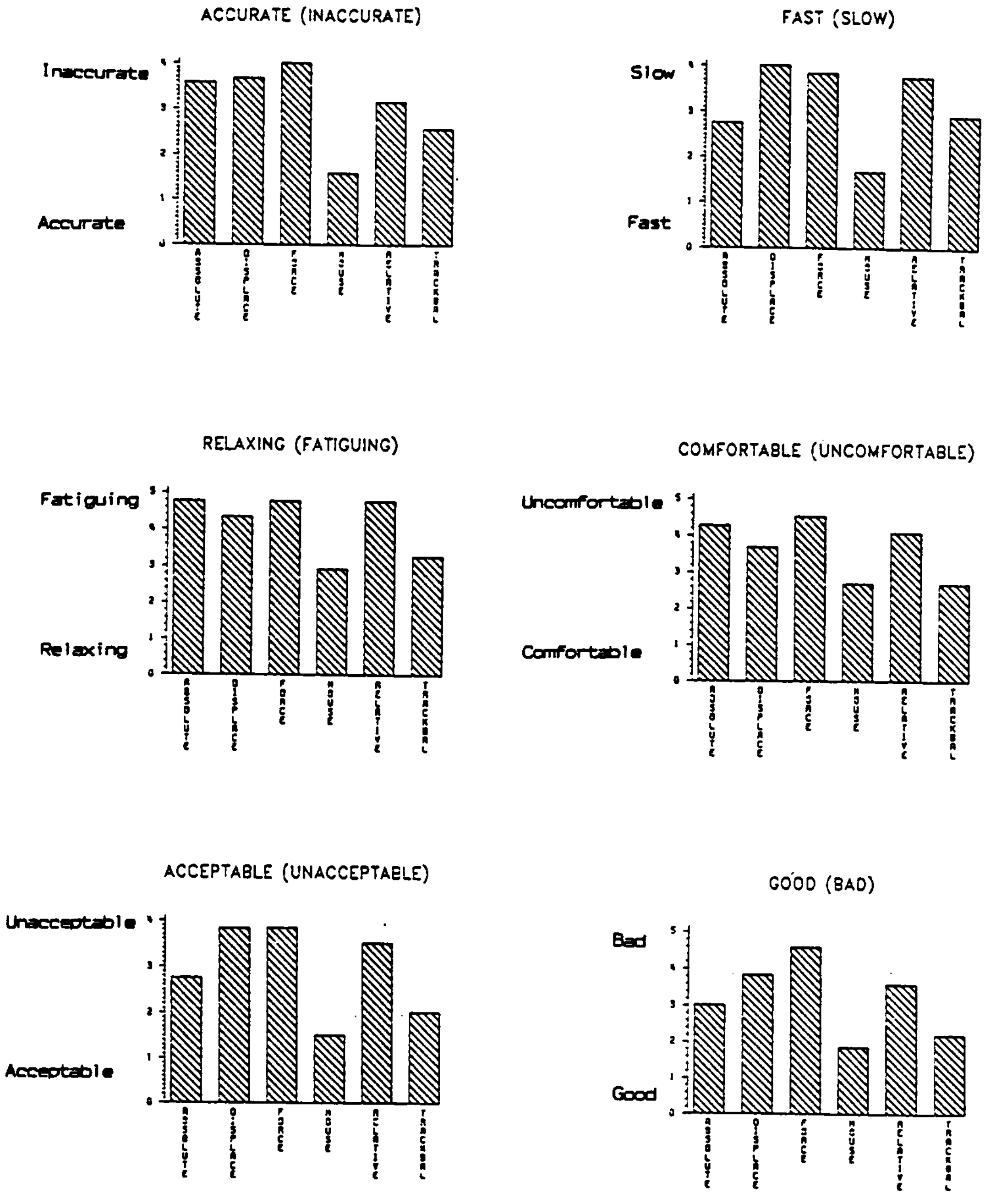

Figure 61. Comparison of cursor devices on the bipolar scales.

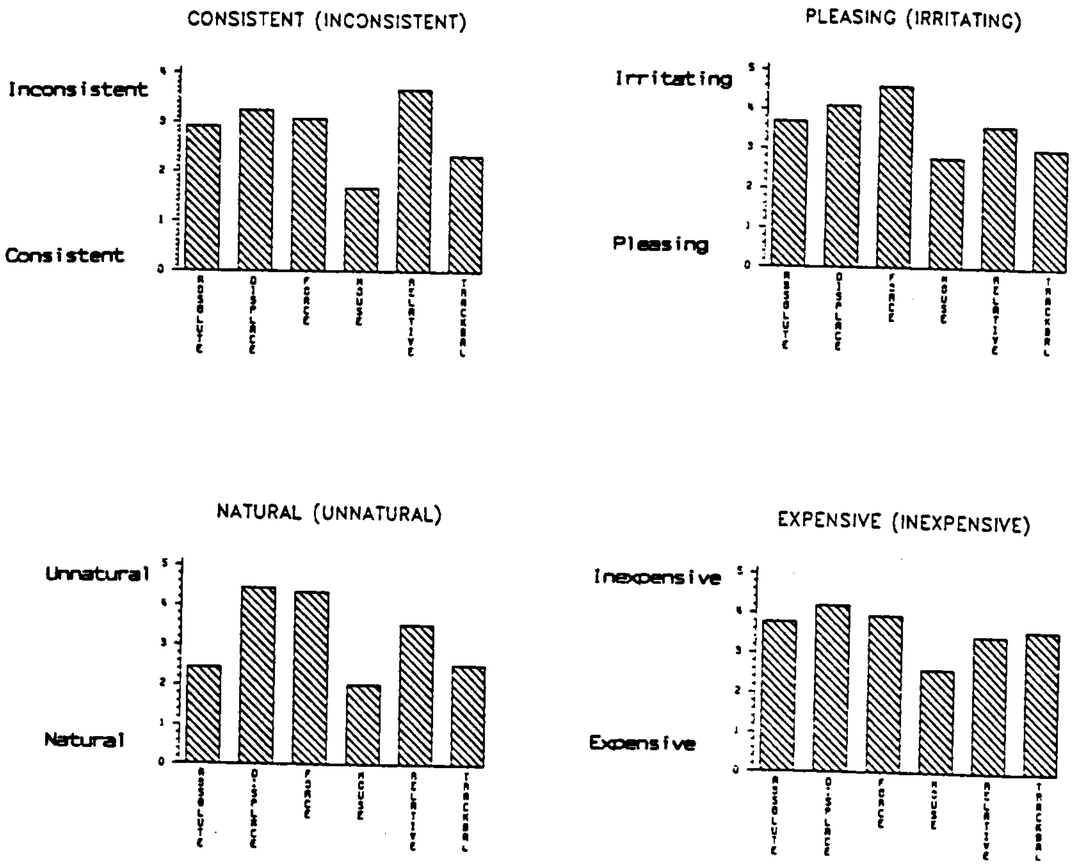

Figure 61. (continued).

joysticks.

(3) Relaxing (Fatiguing) ($F(5,55) = 6.35$, $p = 0.0001$). The mouse and trackball are rated as causing less fatigue than the touchpads and force joystick.

(4) Comfortable (Uncomfortable) ($F(5,55) = 3.09$, $p = 0.0158$). No differences were found among the six devices.

(5) Acceptable (Unacceptable) ($F(5,55) = 5.28$, $p = 0.0005$). Subjects rated the mouse more acceptable than the relative touchpad and joysticks.

(6) Good (Bad) ($F(5,55) = 5.19$, $p = 0.0006$). The mouse is rated better than the joysticks. The trackball is rated better than the force joystick.

(7) Consistent (Inconsistent) ($F(5,55) = 3.41$, $p = 0.0094$). The mouse is rated as more consistent than the relative touchpad.

(8) Pleasing (Irritating) ($F(5,55) = 2.62$, $p = 0.0341$). No differences were found among the six devices.

(9) Natural (Unnatural) (($F(5,55) = 6.99$, $p = 0.0001$). The mouse, absolute touchpad, and trackball are considered more natural to use than the joysticks.

(10) Expensive (Inexpensive) ($F(5,55) = 3.22$, $p = 0.0128$). Subjects perceived the mouse as more expensive than the two joysticks.

To determine the best device based on the 10 bipolar scales, the ratings for responses to the scales were combined linearly into a Preference Index (PI). The analysis indicated significant differences among cursor devices ($F(5,55) = 7.74$), $p = 0.0001$). Results shown in Figure 62 (Table 64) indicate that the mouse is preferred over all other devices except the trackball. In addition, the trackball is preferred over the joysticks.

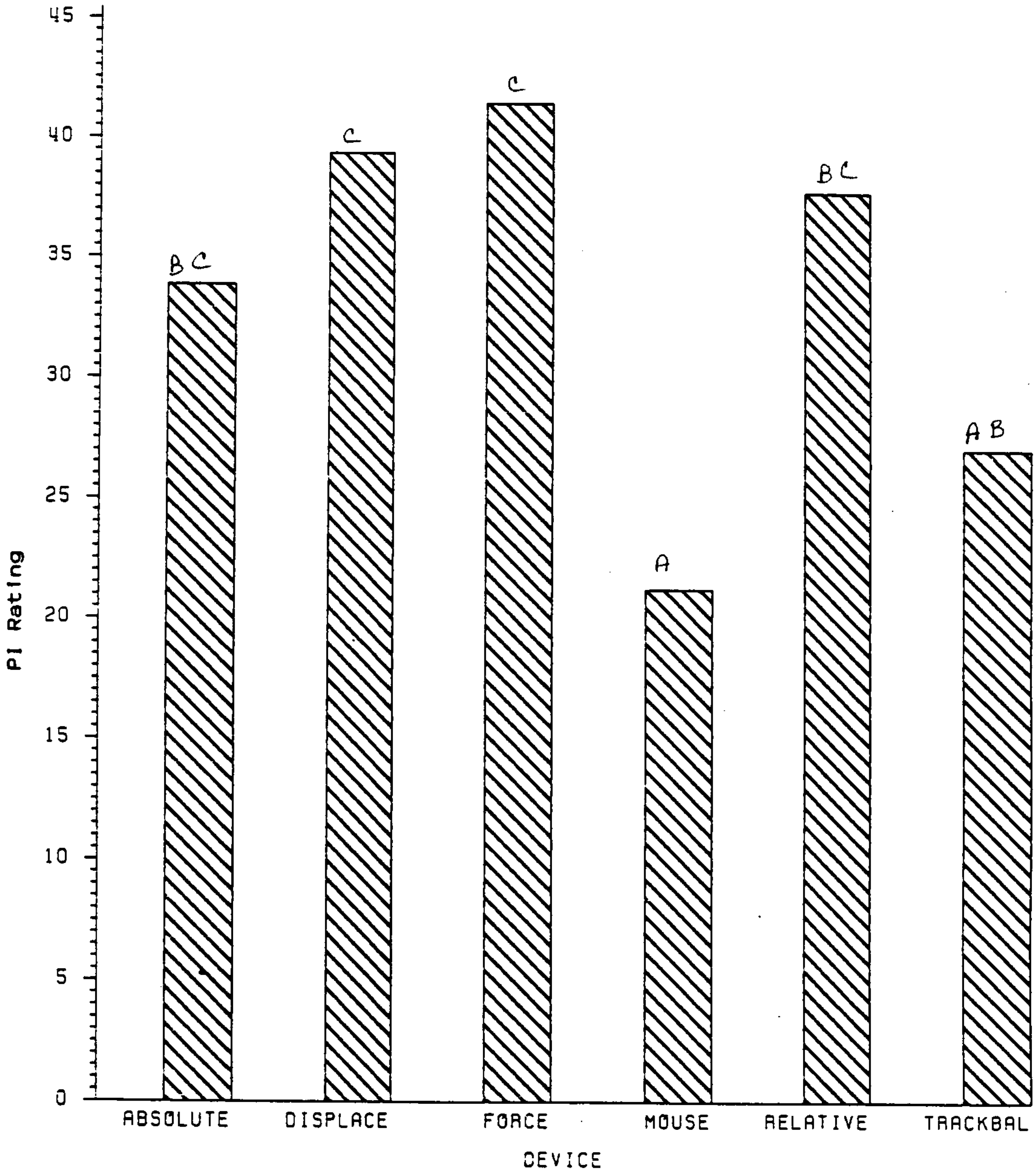

Figure 62. Comparison of cursor devices on the Preference Index (PI).

DATA ANALYSIS AND RESULTS: TEXT EDITING

Three separate analyses were performed on the data collected from the text editing tasks: (1) task completion time, (2) subjective ranks, and (3) bipolar scales.

Task Completion Time

For each of the four types of text files, a separate analysis of variance (ANOVA) was performed on the cursor device (7) by trial block (3) model. The dependent measure, based on task completion time, was the average time to complete editing tasks for each file. Specifically, task time was the total time to complete a text file divided by the total number of editing changes attempted (edits/second).

Single screen/character delete (SS/CD). The ANOVA results for the SS/CD files are given in Table 65 (Appendix B). The SS/CD files required subjects to delete six symbols in a single screen of text using the delete character function key. The Cursor Device x Trial Block interaction ($F(12,72) = 3.16$, $p = 0.0012$), Cursor Device main effect ($F(6,36) = 11.92$, $p = 0.0001$), and Trial Block main effect ($F(2,12) = 21077$, $p = 0.0001$) were significant. For the interaction 0nd main effects, a post-hoc multiple comparison, using the Bonferroni-T Test, was performed on the task completion time means.

The Cursor Device by trial block interaction is shown in Figure 63 (Table 66). For the first trial block, the absolute touchpad performs worse than the remaining six devices. Only the mouse and trackball perform better than the absolute touchpad for the second trial block. No statistical differences among the cursor devices were found for the third block. In general, the most pronounced learning effects can be seen with the absolute touchpad and, to a lesser extent, the optical mouse. For the absolute touchpad, a possible explanation may be the initial problems subjects experienced with finger position/pressure and the bit-mapped aspects of the device.

For the Cursor Device main effect, shown in Figure 64a (Table 67), the absolute touchpad provides slower character deletion performance than the remaining six devices, although the main effect may be driven by the poor performance of the touchpad in the first trial block. The asymptotic performance of the cursor devices (i.e., averaged across trial blocks two and three) is shown in Figure 64b. The main effect of Trial Block, shown in Table

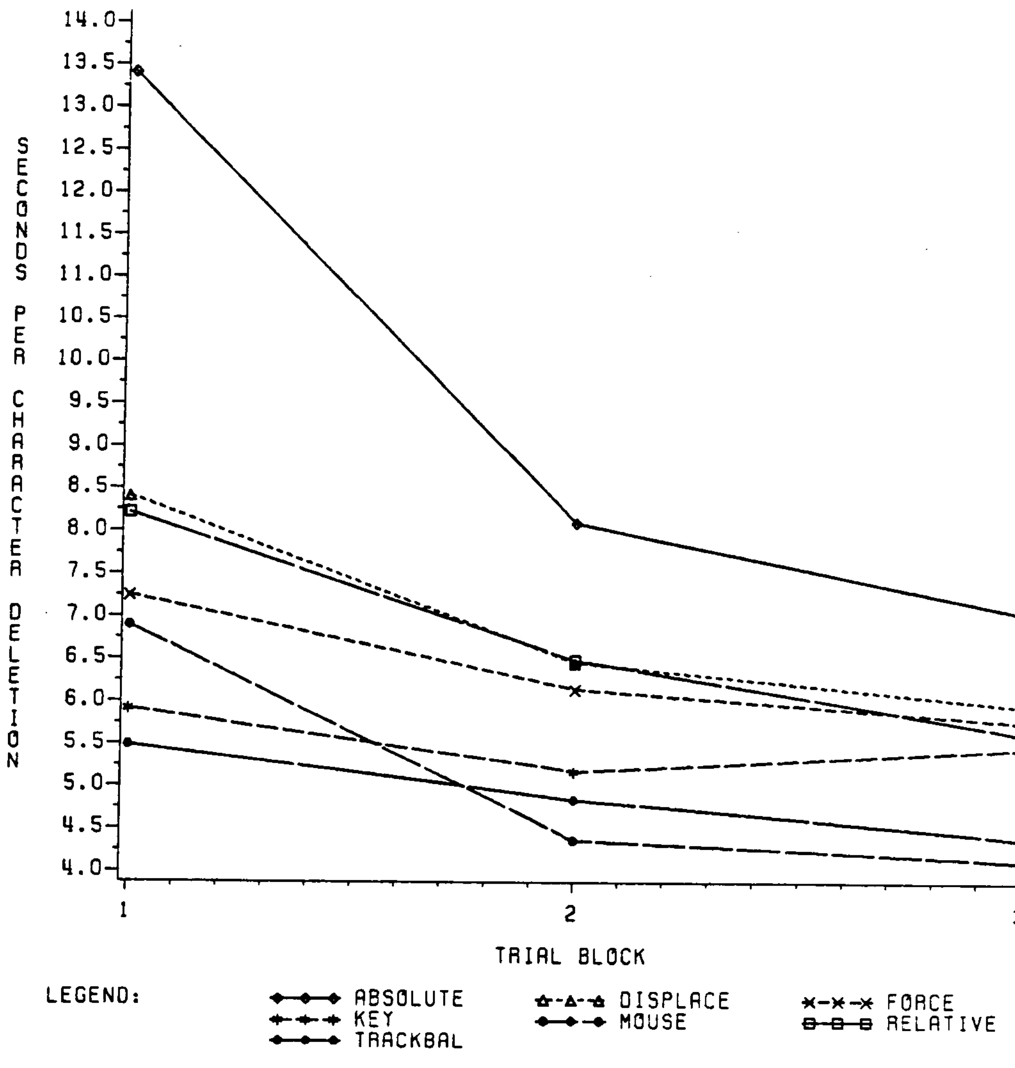

Figure 63. Comparison of devices across trial block for the SS/CD files.

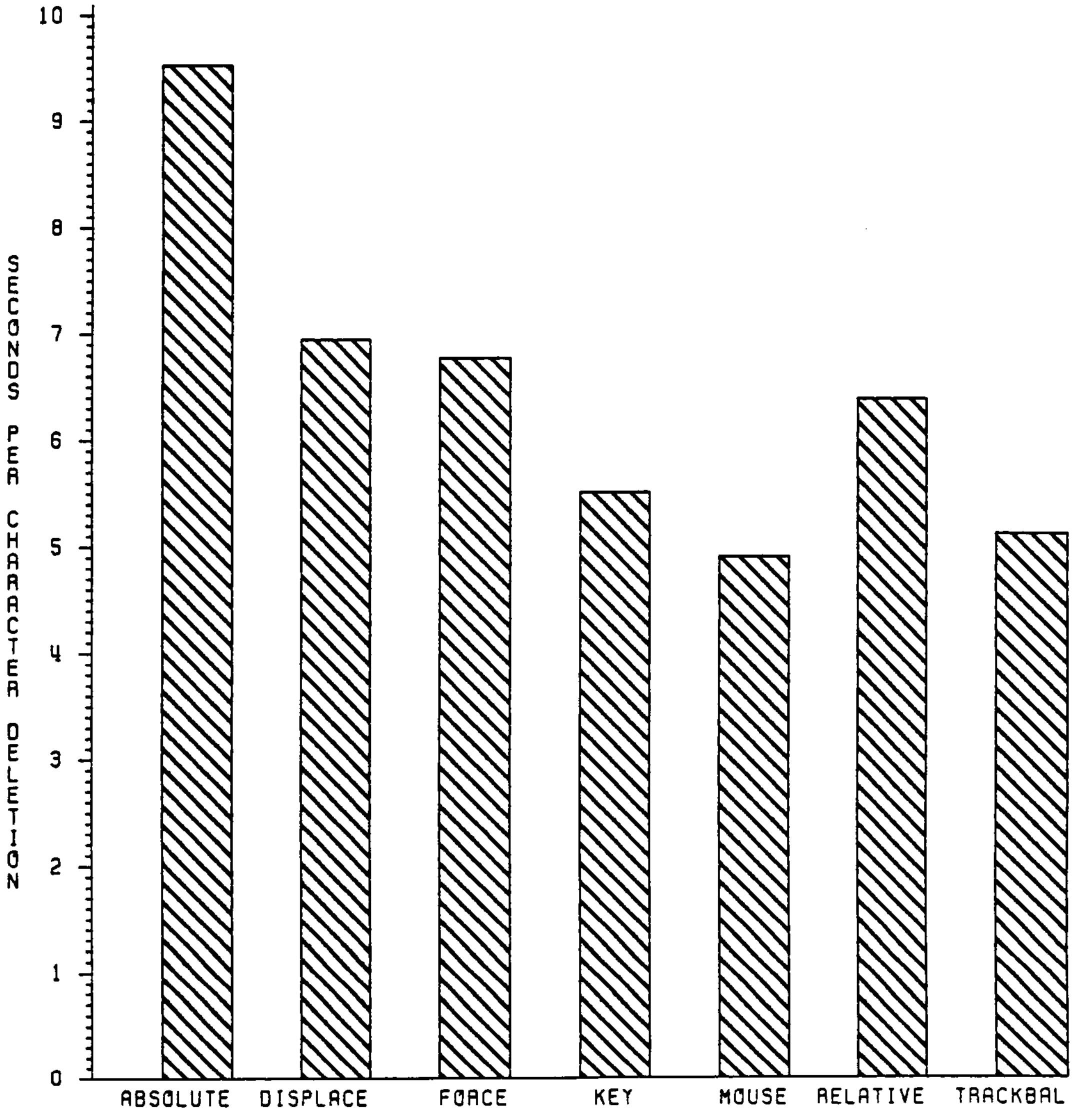

Figure 64a. Comparison of devices for the SS/CD files.

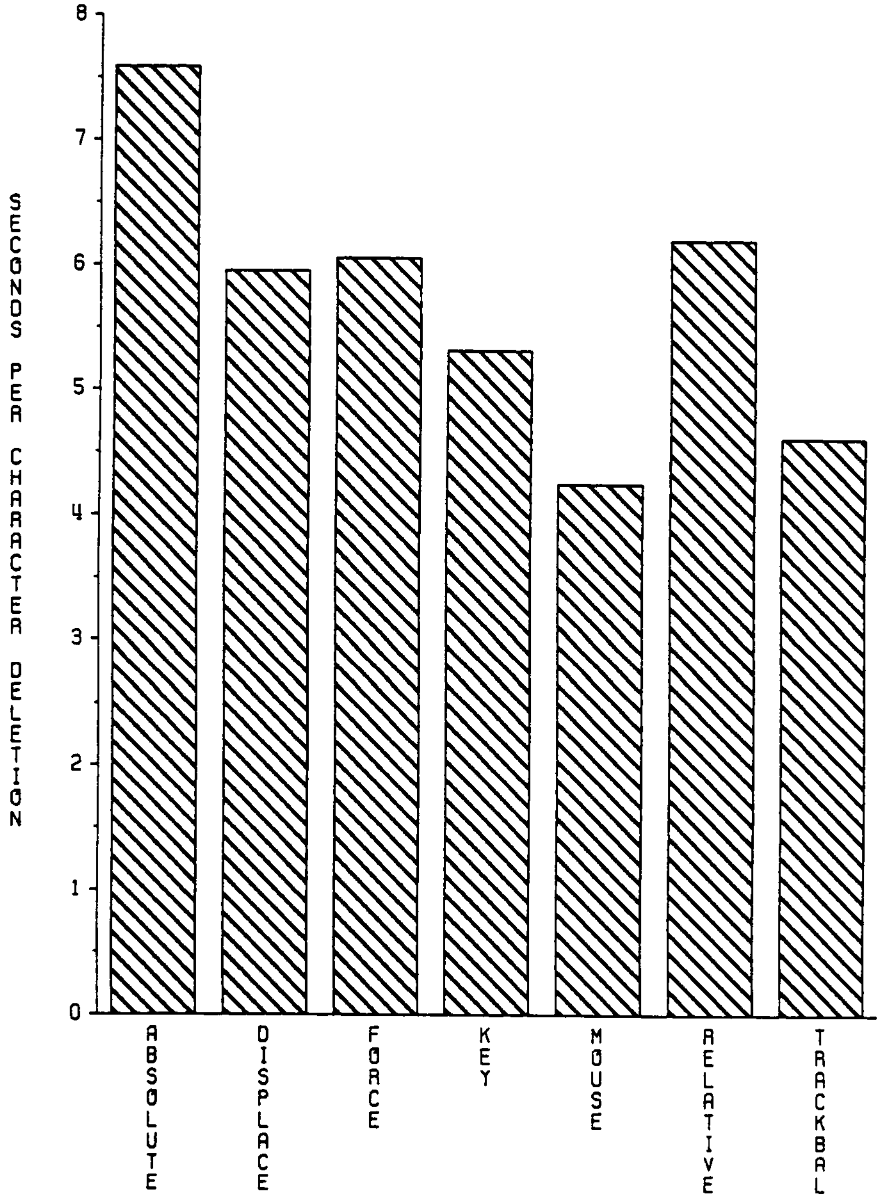

Figure 64b. Comparison of devices for the SS/CD files for asymptotic performance.

68, indicates asymptotic performance is reached by the second trial, averaged across all cursor devices.

Multiple screen/character delete (MS/CD). The ANOVA results for the MS/CD files are given in Table 69 (Appendix B). The MS/CD files required subjects to delete 18 symbols imbedded within multiple screens by scrolling through the file. The Cursor Device x Trial Block interaction ($F(12,72) = 2.48$, $p = 0.0088$), Cursor Device main effect ($F(6,36) = 18.27$, $p = 0.0001$), and Trial Block main effect ($F(2,12) = 46.58$, $p = 0.0001$) were significant. For the interaction and main effects, a Bonferroni-T Test was performed on the task completion time means.

The Cursor Device by Trial Block interaction for the MS/CD files is shown in Figure 65 (Table 70). Differences among devices are more pronounced when scrolling was required than during single screen editing (i.e., SS/CD). For the first trial block, the mouse, trackball, and cursor keys, as a group, provide faster character deletion performance than do the relative joystick and the touchpads. In addition, the absolute touchpad is significantly the worst device. For the second trial block, the absolute touchpad, again, performs worse than all other devices. The mouse performs better than both joysticks and relative touchpad. The trackball is better

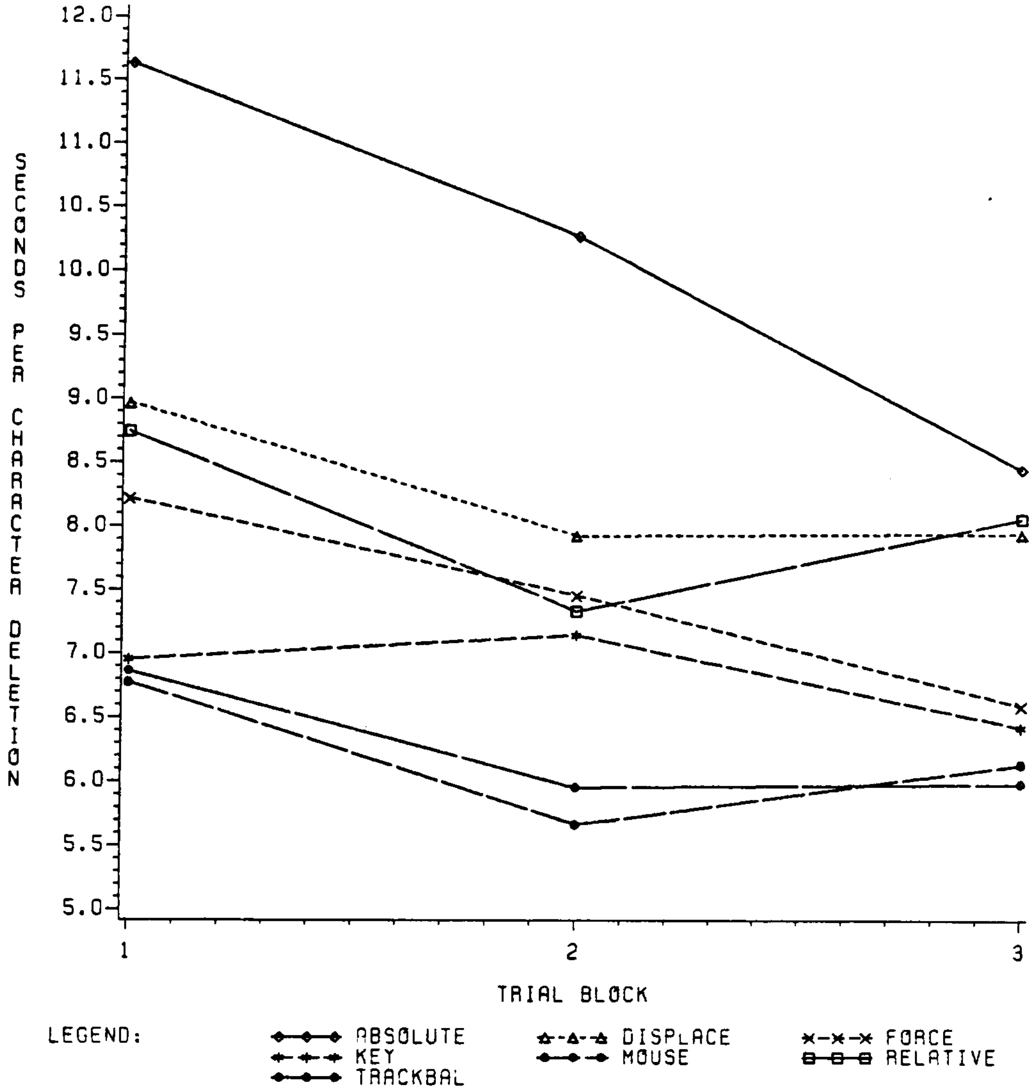

Figure 65. Comparison of devices across trial block for the MS/CD files.

than the displacement joystick. For the third trial block, indicative of asymptotic performance, the mouse and trackball are better than all other devices but the cursor keys and force joystick. In addition, the cursor keys and force joystick provide better performance than the absolute touchpad. Again, the absolute touchpad shows the greatest learning effect of the seven devices.

For the main effect of Cursor Device, shown in Figure 66a (Table 71), all devices provide better character deletion performance than the absolute touchpad. Also, the trackball and mouse are superior to the displacement joystick and the relative touchpad (Table 71). The asymptotic performance of the cursor devices (i.e., averaged across trial blocks two and three) is shown in Figure 66b. The Trial Block main effect analysis indicated that asymptotic performance was reached by the second trial block, shown in Table 72.

Single screen/text edit (SS/TE). The ANOVA results for the SS/TE files are given in Table 73 (Appendix B). The SS/TE files required subjects to perform six types of editing changes within a single screen file. The Cursor Device x Trial Block interaction ($F(12,72) = 2.75$, $p = 0.0040$), Cursor Device main effect ($F(6,36) = 4.17$, $p = 0.0028$), and Trial Block main effect ($F(2,12) = 8.59$, $p =$

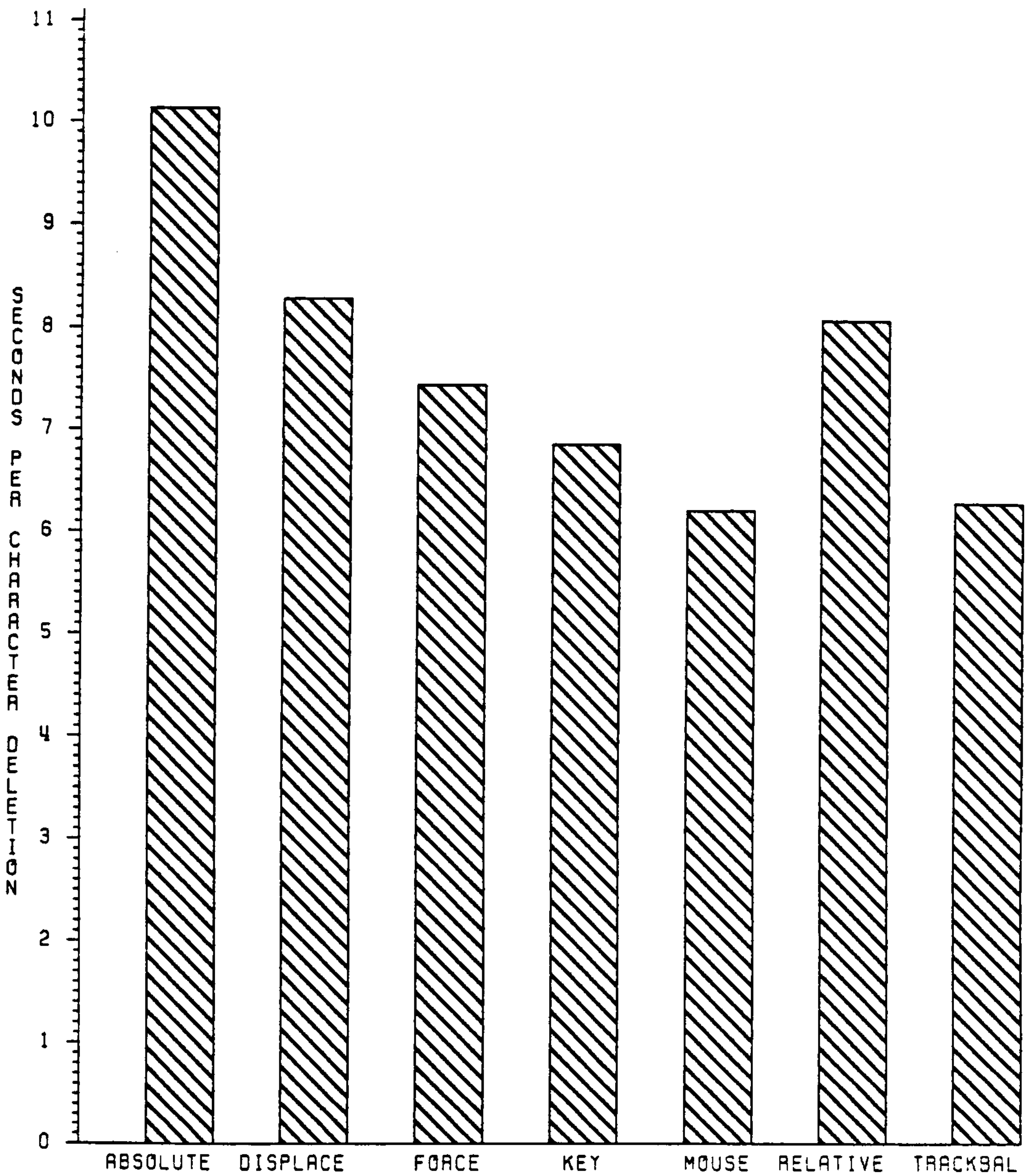

Figure 66a. Comparison of devices for the MS/CD files.

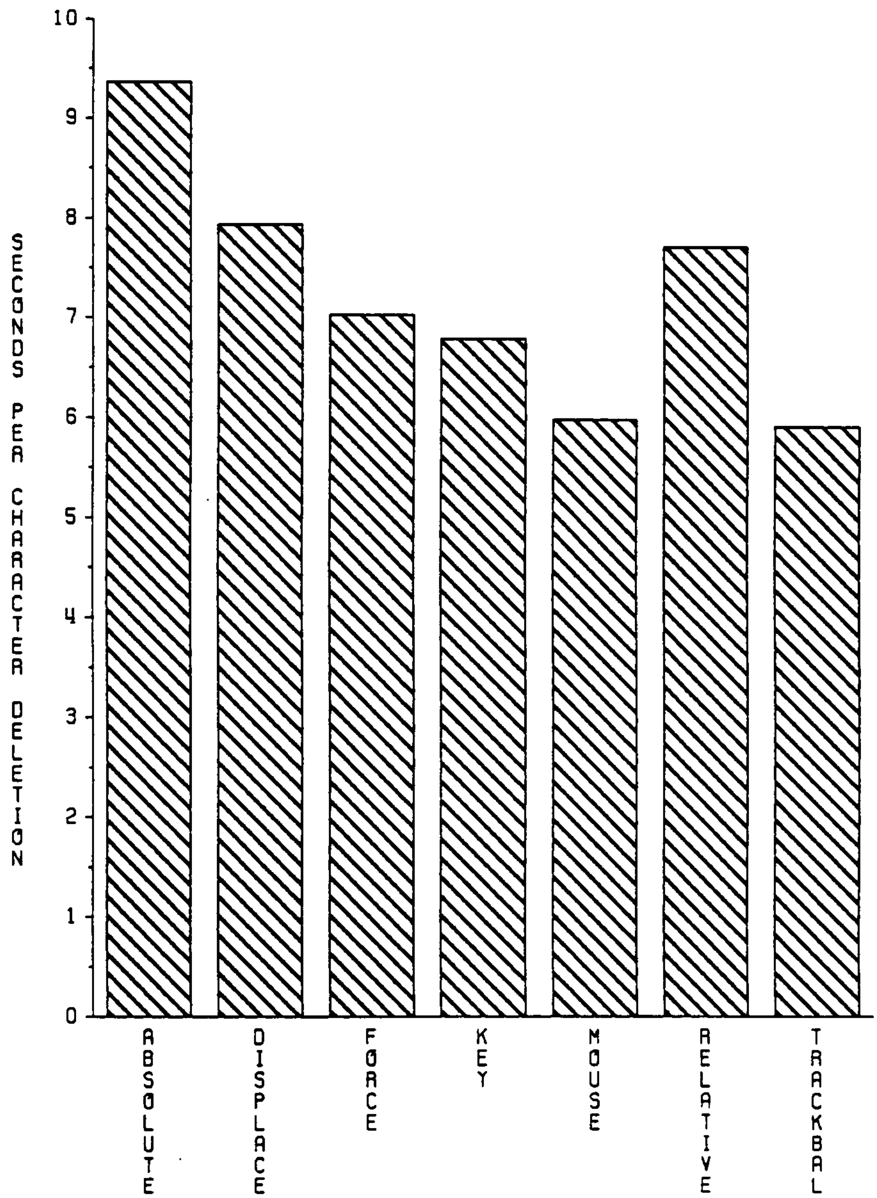

Figure 66b. Comparison of devices for the MS/CD files for asymptotic performance.

0.0048) were significant. For the interaction and main effects, a Bonferroni-T Test was performed on the task completion time means.

The Cursor Device by Trial Block interaction for the SS/TE file is shown in Figure 67 (Table 74). For the first trial block, the absolute touchpad, again, performs worse than the other six devices. For the second trial block, the mouse performs the editing tasks faster than either the displacement joystick or the absolute touchpad. For the third block, which indicates asymptotic performance, editing task performance is faster with the mouse and trackball than the displacement joystick and absolute touchpad. These results may indicate that operation of the trackball was learned faster than other devices. In addition, learning effects similar to the SS/CD are found for the mouse and absolute touchpad.

The Cursor Device main effect (Figure 68a, Table 75) shows that, in general, the trackball, mouse, and TIPC cursor keys provide better text editing perfomance than does the absolute touchpad. The asymptotic performance of the cursor devices (i.e., averaged across trial blocks two and three) is shown in Figure 68b. Again, the Cursor Device main effect should be considered with respect to the interaction results. Results from the Trial Block main

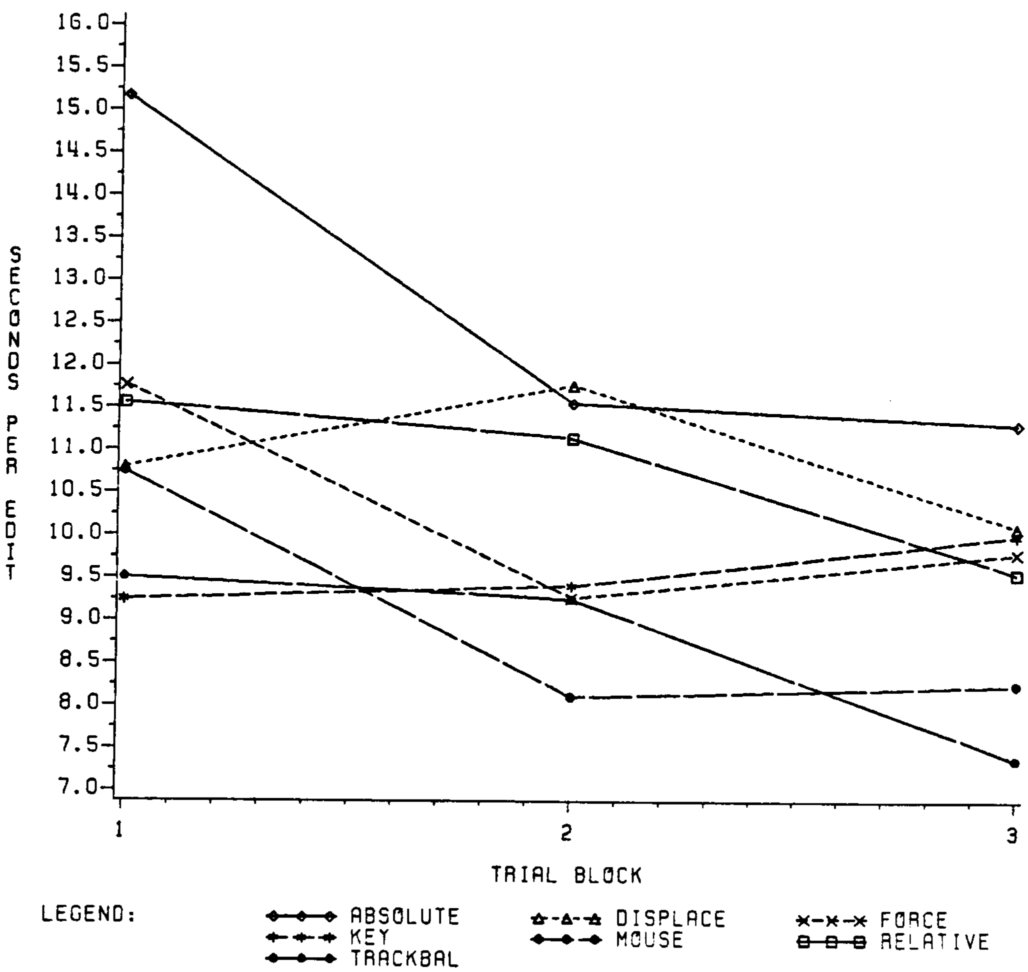

Figure 67. Comparison of devices across trial block for the SS/TE files.

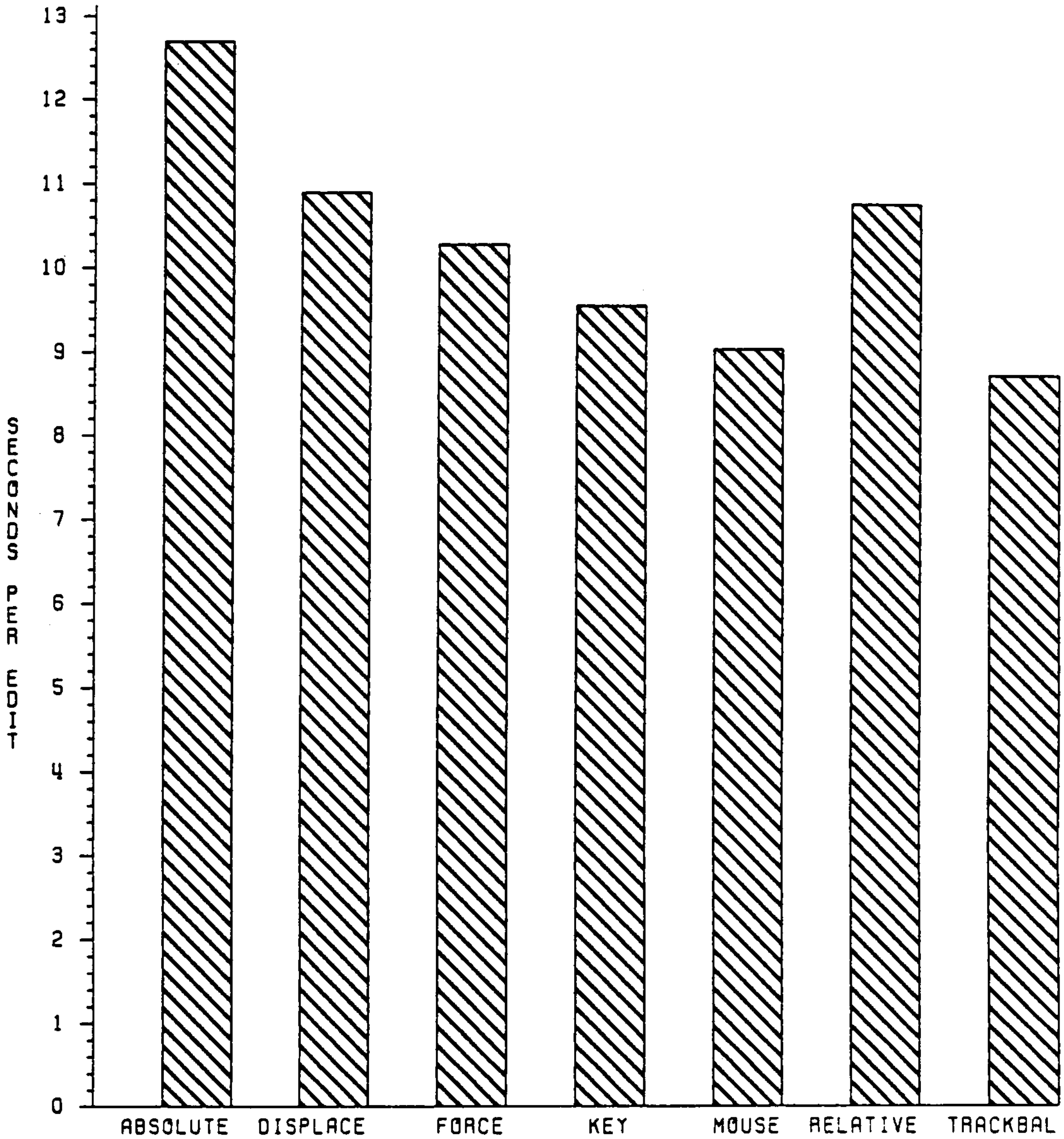

Figure 68a. Comparison of devices for the SS/TE files.

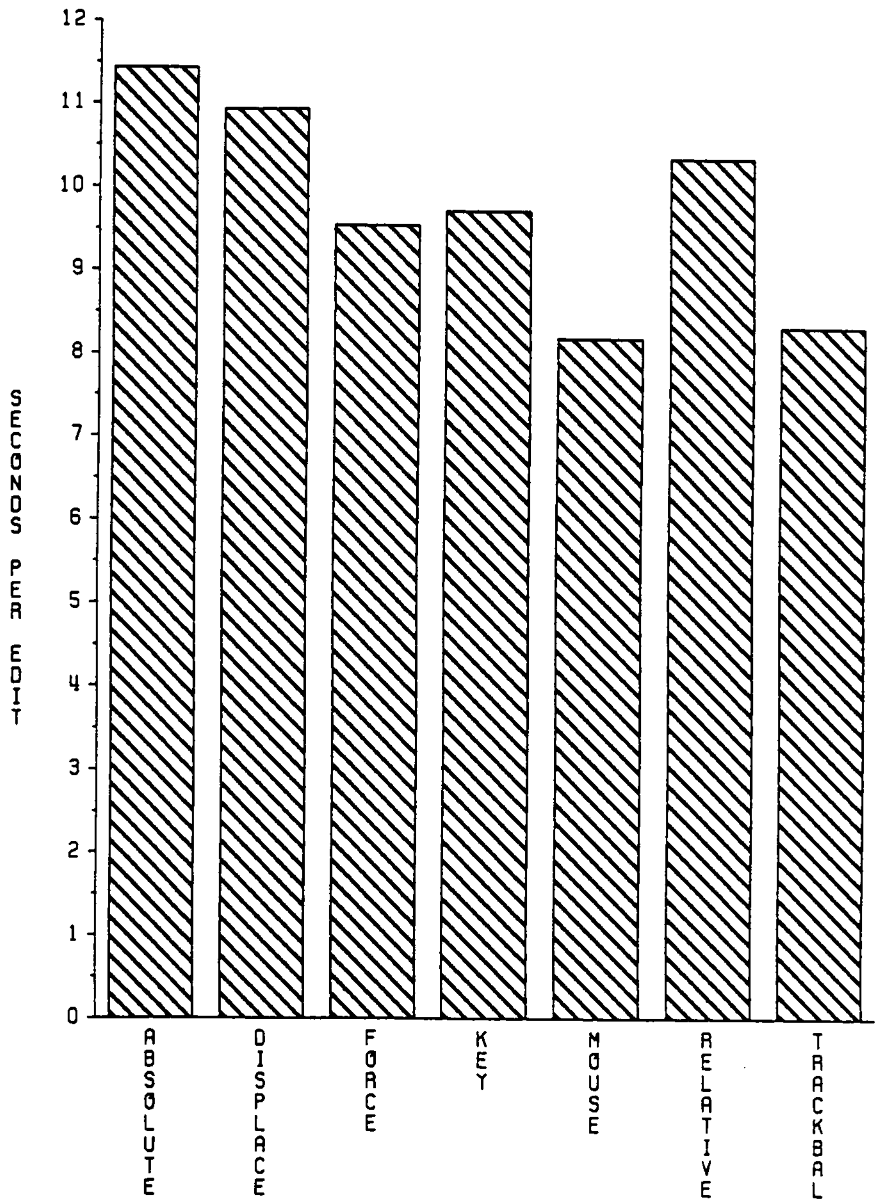

Figure 68b. Comparison of devices for the SS/TE files for asymptotic performance.

effect (Table 76) indicate similar results to the previous analyses, in that asymptotic performance is reached by the second trial block.

Multiple screen/text edit (MS/TE). The ANOVA results for the MS/TE file are given in Table 77 (Appendix B). The MS/TE files required subjects to perform three replications of the six editing changes in a multiple screen file; scrolling was required. The Cursor Device by Trial Block interaction was not significant for the multiple screen/text files ($F(12,72) = 1.39$, $p = 0.1905$). However, the main effect of Cursor Device ($F(6,36) = 5.84$, $p = 0.0003$) and the Trial Block main effect ($F(2,12) = 9.46$, $p = 0.0034$) were significant. For each of the main effects, a post-hoc comparison was performed using the Bonferroni-T Test.

Results for the Cursor Device main effect, shown in Figure 69 (Table 78), indicate that the absolute touchpad is worse than the mouse, trackball, cursor keys, and force joystick for editing multiple screen files. These results are in keeping with those of the analyses of the three other text file types. The Trial Block main effect results are also similar to the three previous analyses in that asymptotic editing performance was reached by the second trial block (Table 79).

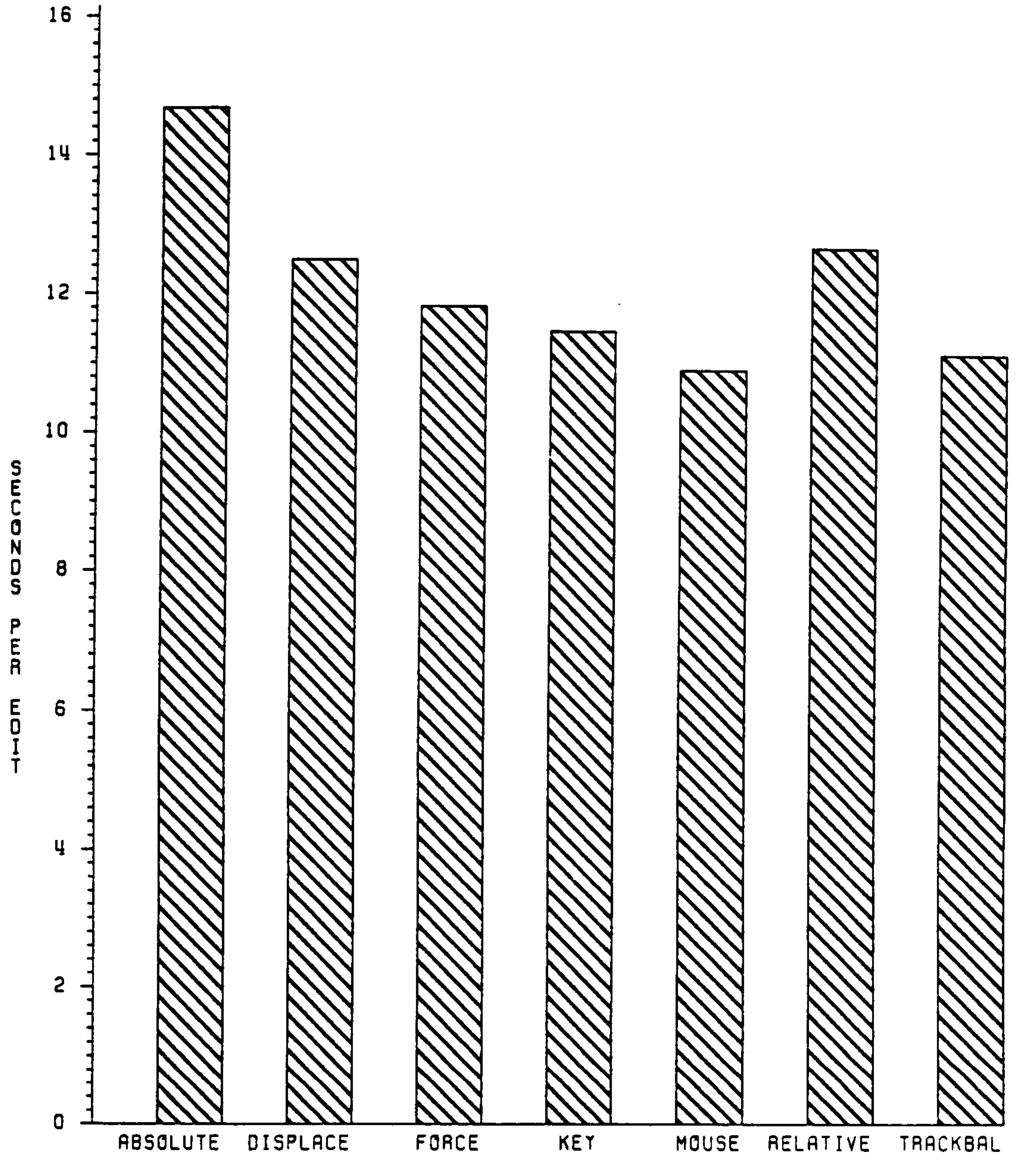

Figure 69. Comparison of devices for the MS/TE files.

Ranks

Data analysis. The seven cursor devices were ranked by each subject on the same six criteria used for the target acquisition task. Each criterion was analyzed separately using the Friedman's Rank Sum Test. The results of the analyses indicate differences among the cursor devices for all six criteria. Statistical results for the rank criteria, given in Tables 80 through 86 (Appendix B), indicate a critical rank sum of 24.0.

Results. Results for the six criteria are shown in Figure 70. Individual results are as follows:

(1) Preference ($S' = 21.18$, $p = 0.002$). The mouse is preferred over the relative and absolute touchpads. The cursor keys are ranked better than the relative touchpad.

(2) Quality ($S' = 17.69$, $p = 0.008$). The subjects considered the mouse and cursor keys to be of higher quality than the relative touchpad.

(3) Positioning speed ($S' = 13.71$, $p = 0.04$). The trackball is considered faster for cursor positioning than the cursor keys.

(4) Positioning accuracy ($S' = 25.53$, $p = 0.001$). Subjects ranked the cursor keys as providing better cursor positioning accuracy than the absolute and relative

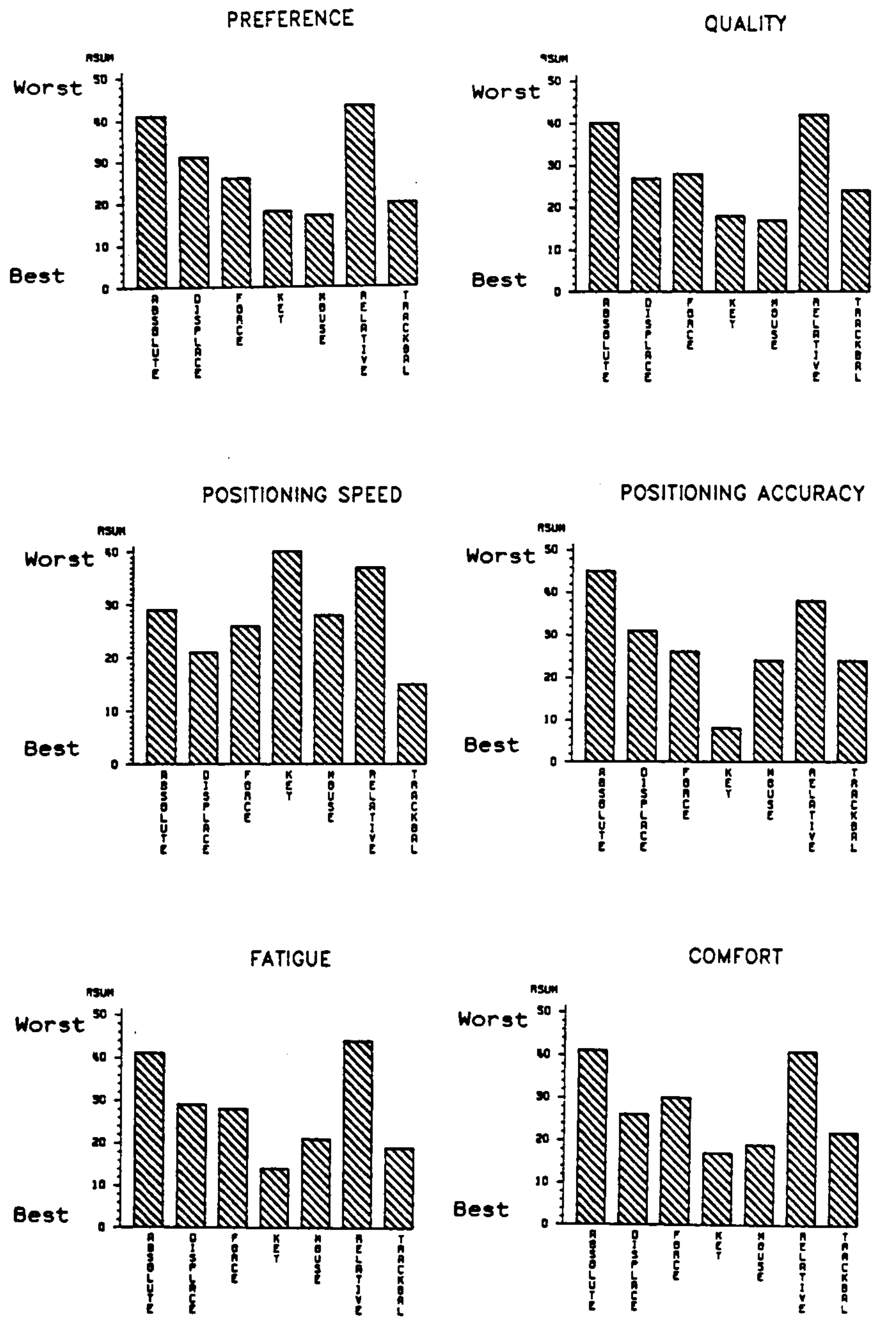

Figure 70. Comparison of devices ranked on the six criteria.

touchpads.

(5) Fatigue (S′ = 23.02, p = 0.001). Subjects ranked the touchpads as causing more fatigue than the cursor keys. In addition, the trackball causes less perceived fatigue than the relative touchpad.

(6) Comfort (S′ = 17.88, p = 0.006). Results for the comfort rank are similar to the fatigue criterion. The cursor keys are ranked more comfortable than the touchpads.

In general, the mouse, trackball, or cursor keys are ranked best on all criteria. Interestingly, the subjective results appear to agree with the performance results.

Bipolar Scales

Data analysis. As with the target acquisition analysis, the bipolar scale data were analyzed two different ways. First, a MANOVA was performed on the cursor device model, with the 10 scales the dependent measures. MANOVA results indicated significant differences among the scales (F[apprx](60,146) = 1.90, p = 0.0010). Therefore, separate ANOVAs were performed on each of the scales. A summary of the MANOVA results, subsequent ANOVAs, and Bonferroni-T Tests are shown in Tables 86 through 96 (Appendix B).

Second, an ANOVA was performed on the Preference Index (PI) data. Results indicated significant differences among the seven devices ($F(6,36) = 4.25$, $p = 0.0025$). An ANOVA summary and subsequent post-hoc comparisons are given in Table 97 (Appendix B).

Results. Figure 71 shows results from the six (of 10) scales which indicated significant differences among cursor control devices. Individual scale results are as follows:

(1) Accurate (Inaccurate) ($F(6,36) = 12.40$, $p = 0.0001$). The mouse and cursor keys are considered more accurate than the touchpads and the displacement joystick.

(2) Fast (Slow) ($F(6,36) = 5.42$, $p = 0.0004$). The trackball and mouse are considered faster for editing than the absolute touchpad and cursor keys.

(3) Acceptable (Unacceptable) ($F(6,36) = 3.02$, $p = 0.0171$). The mouse is considered more acceptable than the absolute touchpad.

(4) Good (Bad) ($F(6,36) = 3.49$, $p = 0.0081$). The mouse is rated better than the absolute touchpad.

(5) Consistent (Inconsistent) ($F(6,36) = 7.28$, $p = 0.0001$). The consistent/inconsistent scale was the more sensitive than all other scales to differences among devices. The cursor keys are rated better than the touchpads and displacement joystick. The mouse is

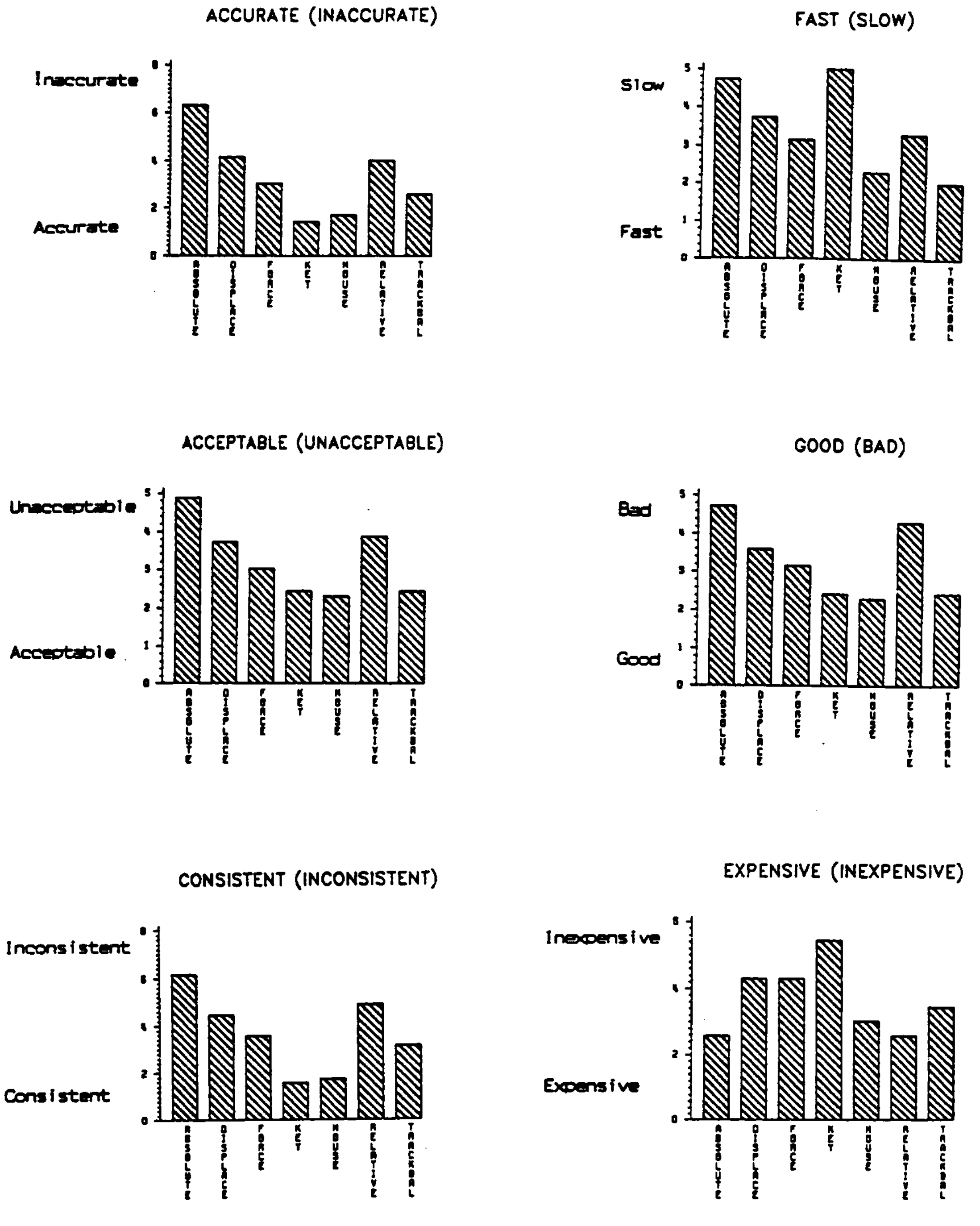

Figure 71. Comparison of devices on six bipolar scales.

perceived as a more consistent device than the touchpads. Finally, the trackball is rated better than the absolute touchpad.

(6) Expensive (Inexpensive) ($F(6,36) = 5.32$, $p = 0.0085$). The relative touchpad, absolute touchpad, and mouse are considered more expensive than the cursor keys.

The mouse, cursor keys and trackball are, again, generally rated as the best devices. The exceptions are the Fast (Slow) scale, in which the cursor was rated worst, and the Expensive (Inexpensive) scale, in which subjects perceived the touchpads as expensive devices, although they rated them poorly for task-related scales.

The PI analysis results, shown in Figure 72, indicate that subjects rate overall the mouse, trackball, and cursor keys better than the absolute touchpad.

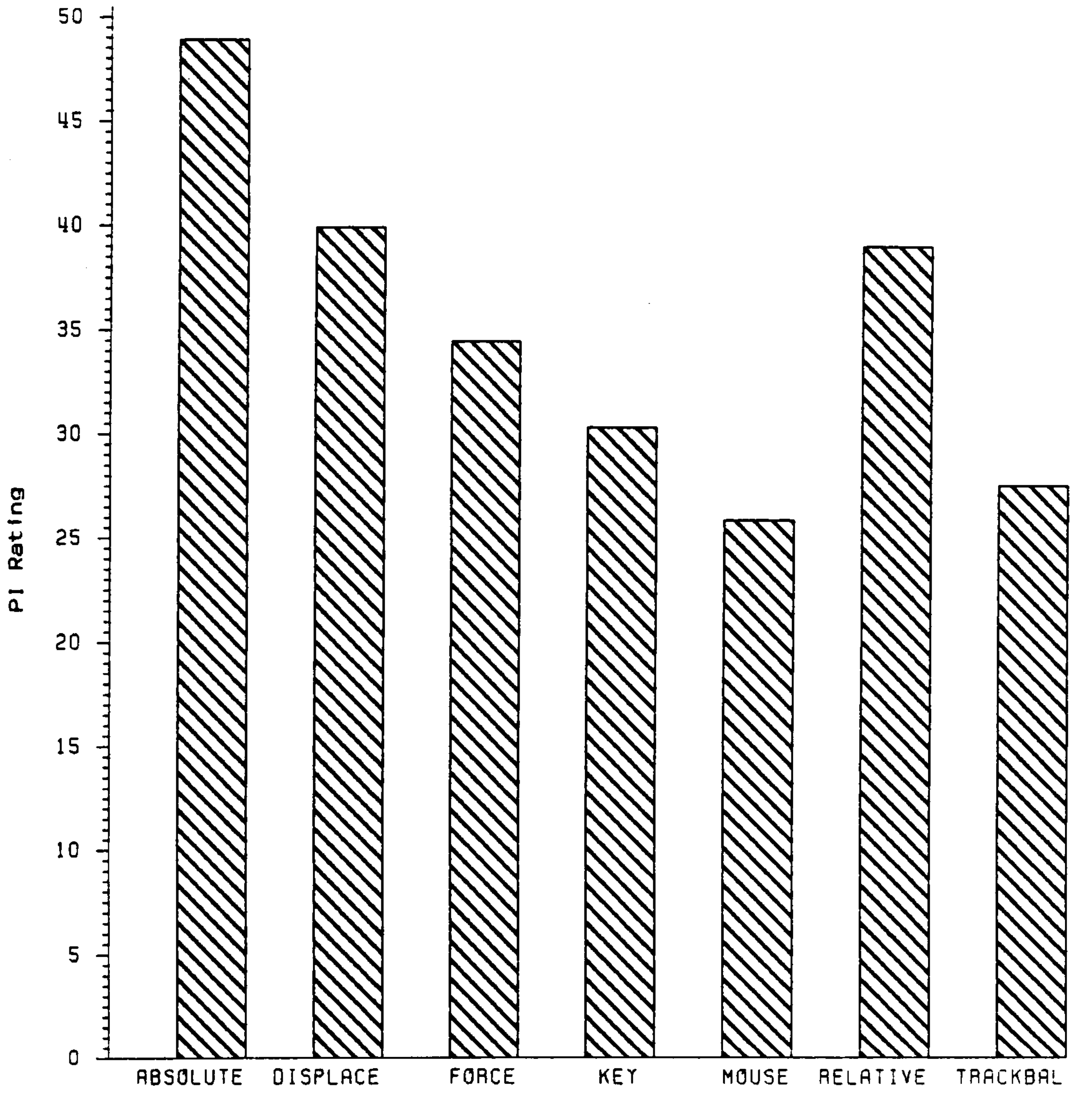

Figure 72. Comparison of devices on the Preference Index (PI).

DATA ANALYSIS AND RESULTS: GRAPHICS TASK

Three separate groups of analyses were performed on the data collected from the graphics editing tasks: (1) task completion time, (2) subjective ranks, and (3) bipolar scales.

Task Completion Time

For each of the seven types of graphics tasks, a separate analysis of variance (ANOVA) was performed on the cursor device (7) by trial block (3) model. The dependent measure, task completion time, was the average time to complete graphics editing tasks. Specifically, task time was the total time to complete a graphics task divided by the total number of editing changes attempted (seconds/edit).

Rectangles (RT). The ANOVA results for the RT task are given in Table 98 (Appendix B). The RT task required subjects to position rectangles within boundaries by changing the size and aspect ratio. As a result, the RT task was sensitive to both gross-positioning and "rubber-banding" performance with each device. The Cursor Device x Trial Block interaction ($F(10,50) = 3.96$, $p = 0.0005$), Cursor Device main effect ($F(5,25) = 8.35$, $p = 0.0001$), and Trial Block main effect ($F(2,10) = 18.11$, $p = 0.0005$) were significant. For the interaction and main effects, a post-hoc multiple comparison, using the Bonferroni-T Test, was performed on the task completion time means.

The Cursor Device by Trial Block interaction is shown in Figure 73 (Table 99). For the first trial block, the mouse and trackball perform better than the remaining four devices. For the second trial block, the trackball, mouse, and absolute touchpad perform better than the displacement joystick. For the last trial block the trackball is better for graphics editing than the displacement joystick. The most notable learning appears to occur with the absolute touchpad, especially between the first and second trial blocks. A possible explanation for this result may be the initial problems associated with finger pressure and position on the touchpad.

For the Cursor Device main effect, shown in Figure 74 (Table 100), the trackball provides faster rectangle positioning and "rubber-banding" performance than the absolute touchpad and both joysticks. In addition, the

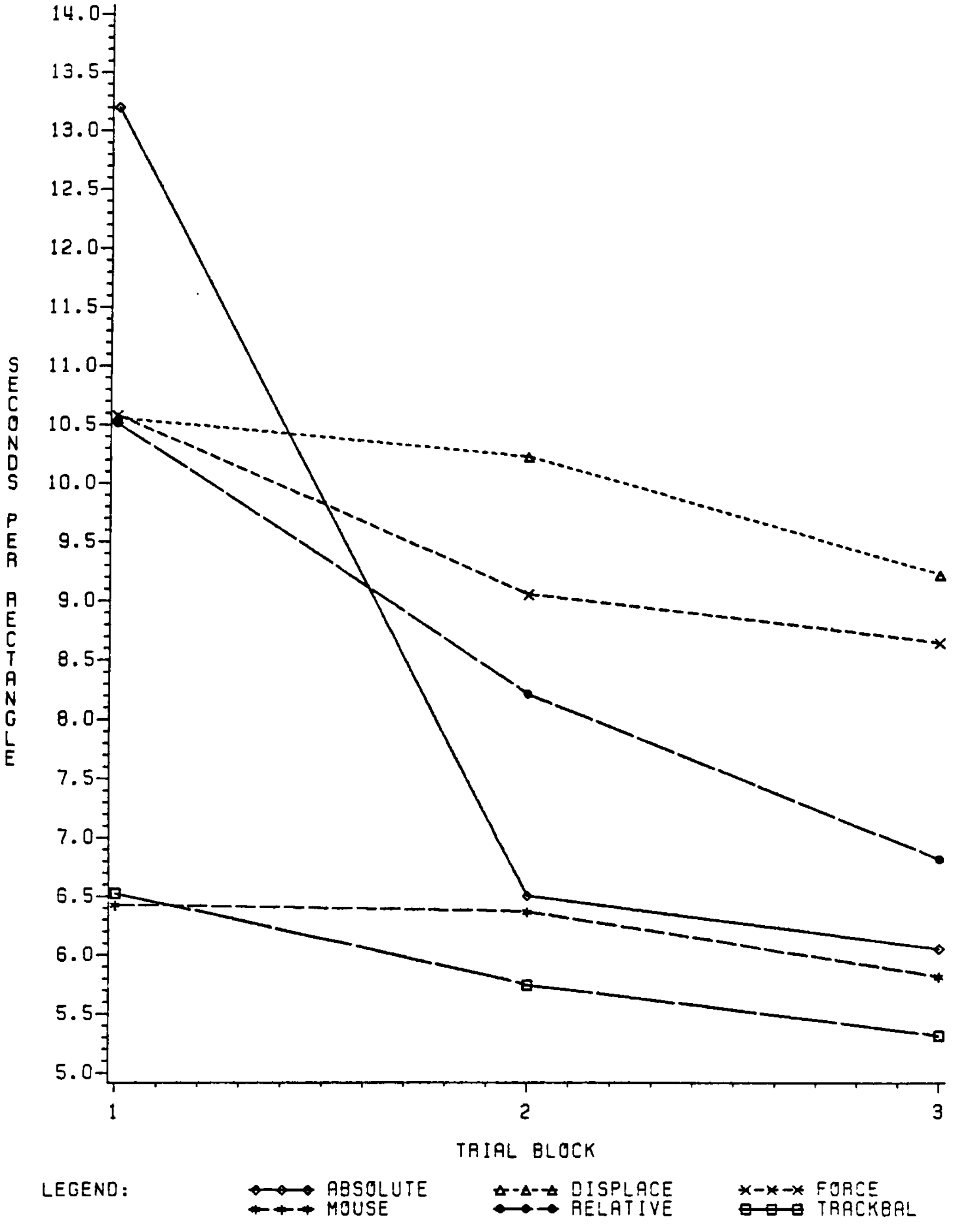

Figure 73. Comparison of devices across trial block for the RT task.

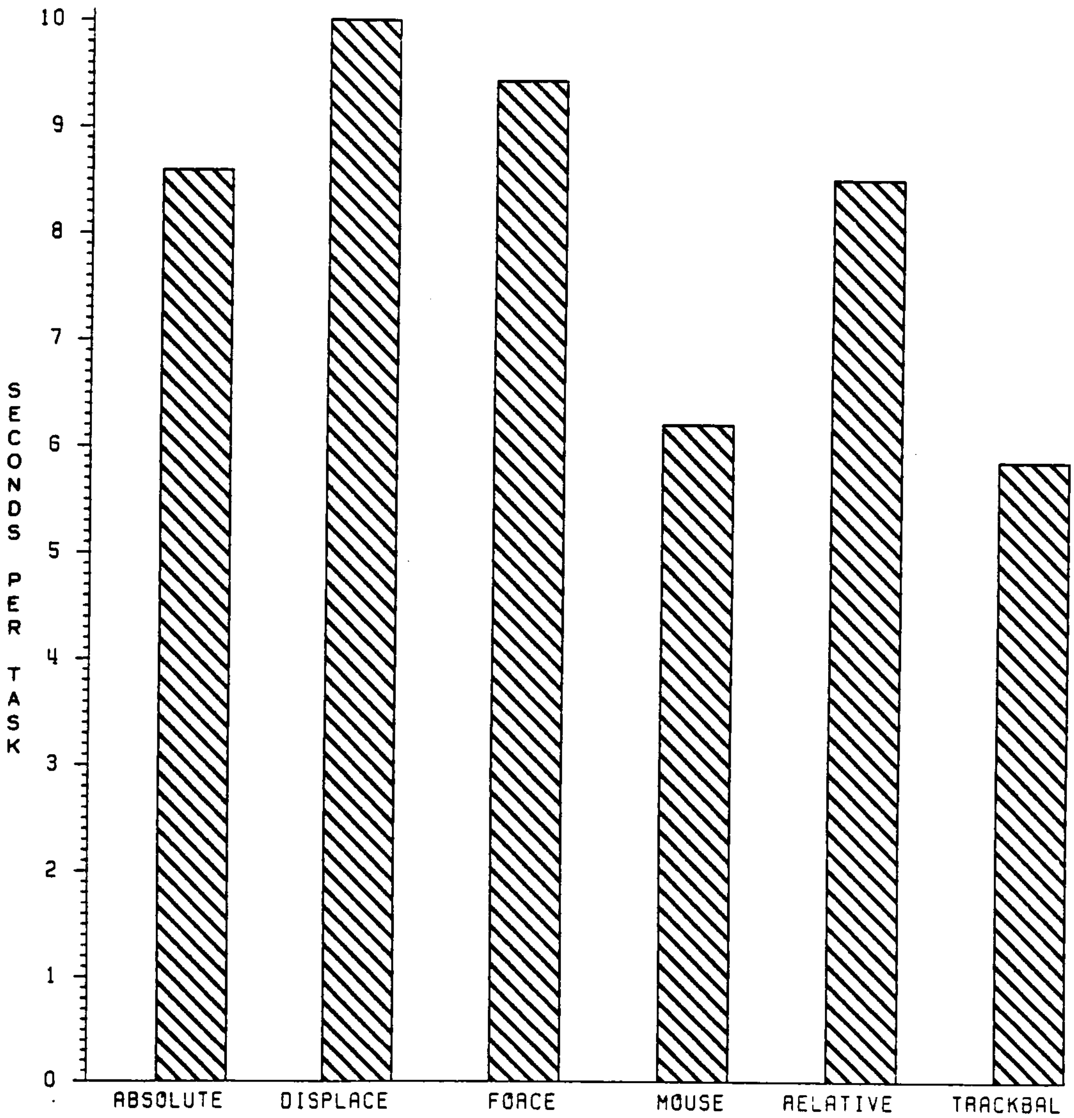

Figure 74. Comparison of devices for the RT task.

mouse is better than the displacement joystick. Of course, the Cursor Device main effect results must be considered with respect to the interaction results. The main effect of Trial Block, shown in Table 101, indicates asymptotic performance is reached by the second trial, averaged across all cursor devices.

Horizontal grid (HG) task. The ANOVA results for the HG task are given in Table 102 (Appendix B). The HG task was sensitive to the vertical positioning accuracy of each cursor device. The Cursor Device main effect ($F(5,25) = 3.01$, $p = 0.0293$), and Trial Block main effect ($F(2,10) = 8.92$, $p = 0.0060$) were significant. For the main effects, a Bonferroni-T Test was performed on the task completion time means.

For the main effect of Cursor Device, shown in Figure 75 (Table 103), no significant differences were found among cursor devices, which is probably due to the conservative nature of the Bonferroni-T statistic. The Trial Block main effect analysis indicates that asymptotic performance was reached by the second trial block, shown in Table 104.

Vertical grid (VG) task. The ANOVA results for the VG task are given in Table 105 (Appendix B). The VG task was

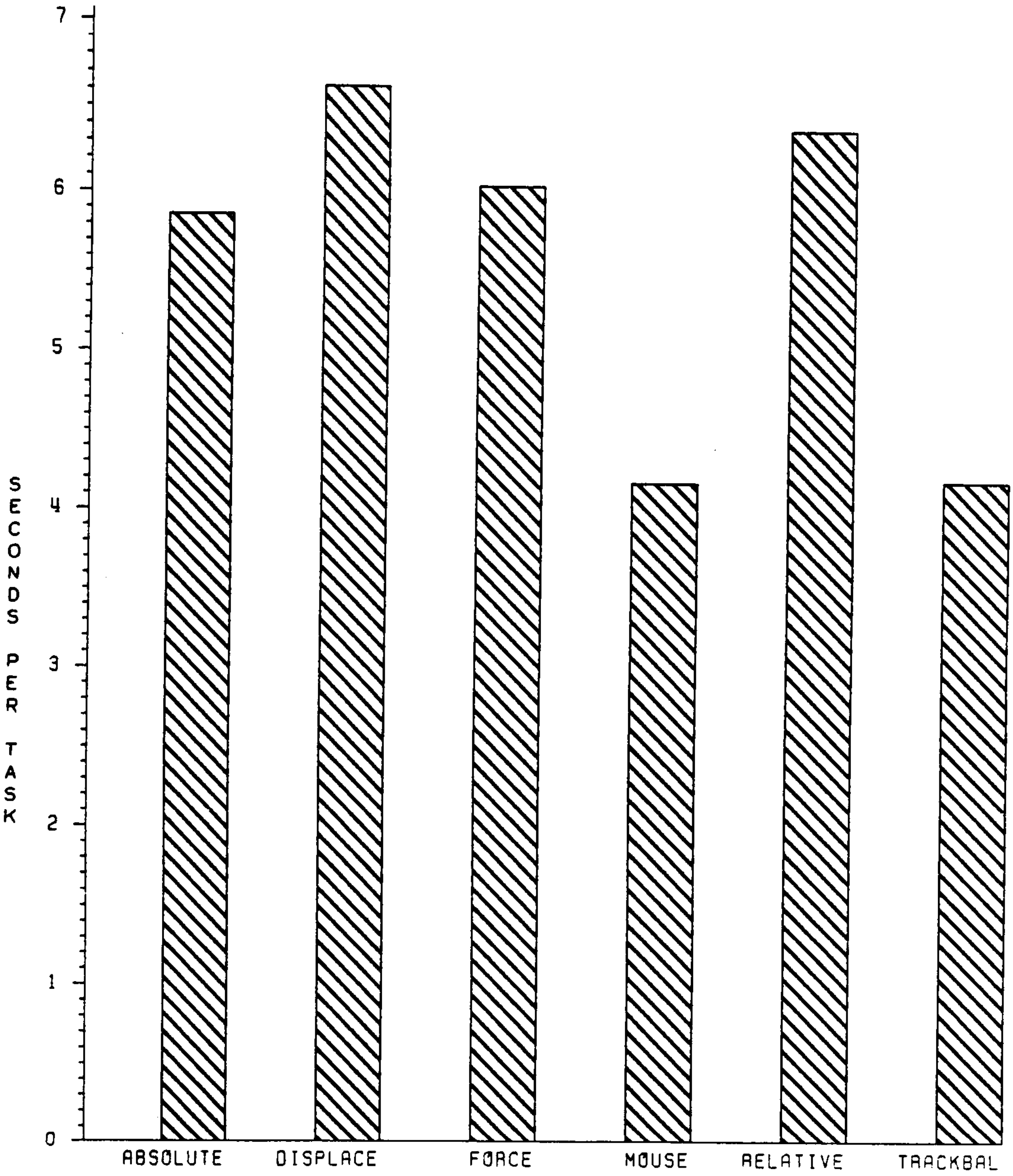

Figure 75. Comparison of devices for the HG task.

sensitive to the horizontal pixel-by-pixel positioning of the cursor devices. Only the Cursor Device main effect ($F(5,25) = 3.14$, $p = 0.0247$) was significant. The post-hoc Bonferroni-T Test (Table 106) indicated no differences among cursor devices, but the results are shown in Figure 76. The lack of statistically significant differences among devices is probably due to the conservative nature of the Bonferroni-T Test.

Angular grid (AG) task. The ANOVA results for the AG task are given in Table 107 (Appendix B). The AG task contained cursor positioning performance qualities of the HG and VG tasks in addition to the omni-directional "rubber-banding" skills required. Only the main effect of Cursor Device ($F(4,20) = 6.67$, $p = 0.0014$) was significant. Post-hoc testing was performed with the Bonferroni-T Test. (Note: Task completion time data for the relative touchpad was not used in the AG analysis, due to artifacts in the interface for this task. Specifically, random "spiking" occurred with the relative touchpad for several of the trial blocks, causing the angular line to jump unexpectedly. The result was to artifically lengthen task completion times for the relative touchpad. No other problems occurred with the other five devices on the AG

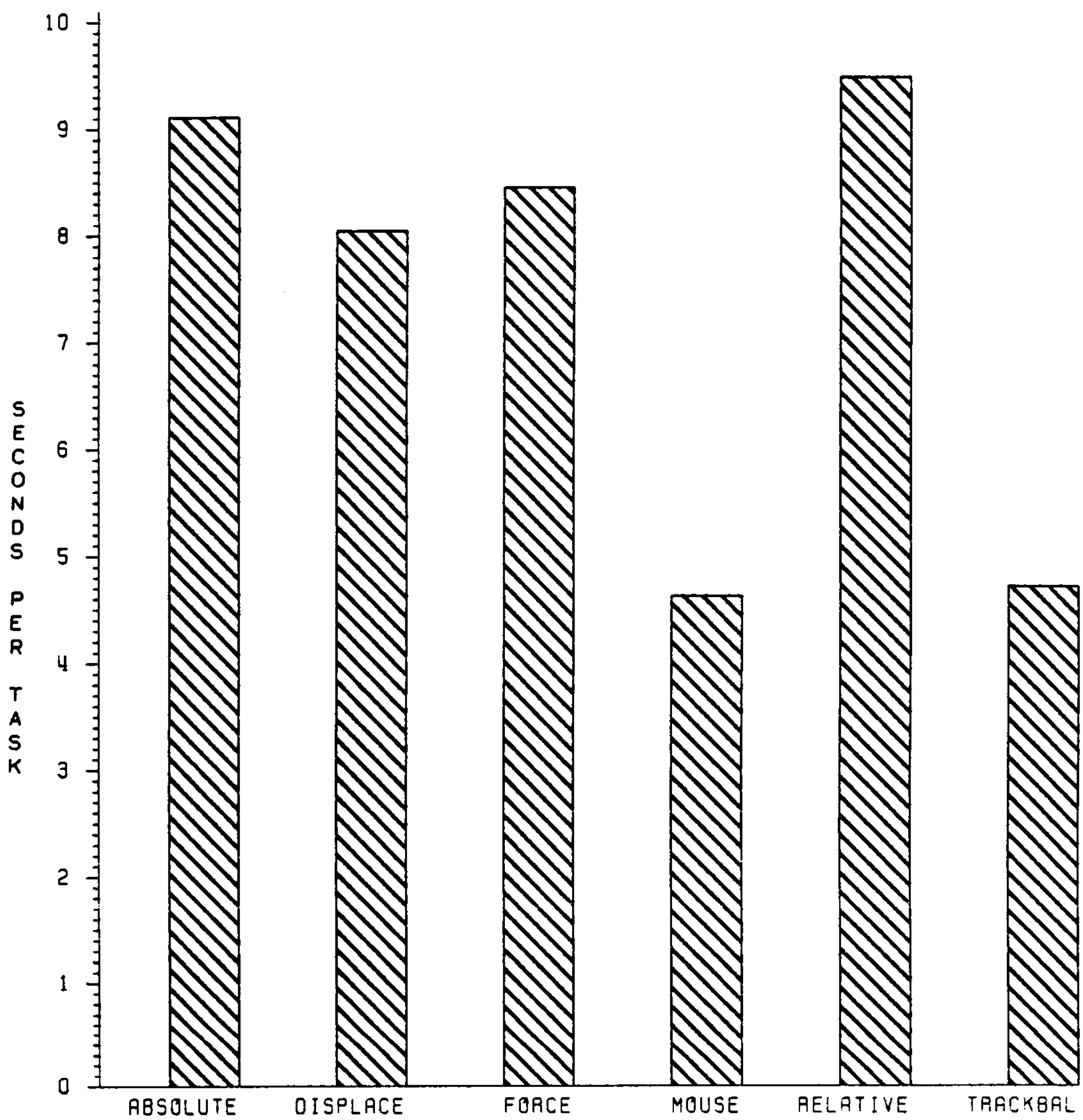

Figure 76. Comparison of devices for the VG task.

task and no other problems occurred for any of the devices on any other task.)

Results for the Cursor Device main effect, shown in Figure 77 (Table 108), indicate that the absolute touchpad is worse for angular line positioning than are the trackball and mouse. A possible explanation for these results is the apparent problem subjects had with pixel-by-pixel positioning with the absolute touchpad. Typically, to position the cursor on a pixel, as the AG task required, subjects either "rolled" their fingertips on the pad surface or used a fingernail. Both of these strategies were also apparent with the relative touchpad.

Fat bits (FB) task. The ANOVA results for the FB task are given in Table 109 (Appendix B). The FB task was, in reality, a target acquisition task similar in nature to the smallest target size (0.13 cm) and smallest target distance (2 cm) combination used in the target acquisition task comparison experiment. The Cursor Device main effect ($F(5,25) = 13.72$, $p = 0.0001$) and Trial Block main effect ($F(2,10) = 11.96$, $p = 0.0022$) were significant. For the main effects, a Bonferroni-T Test was performed on the task completion time means.

The main effect of Cursor Device, shown in Figure 78

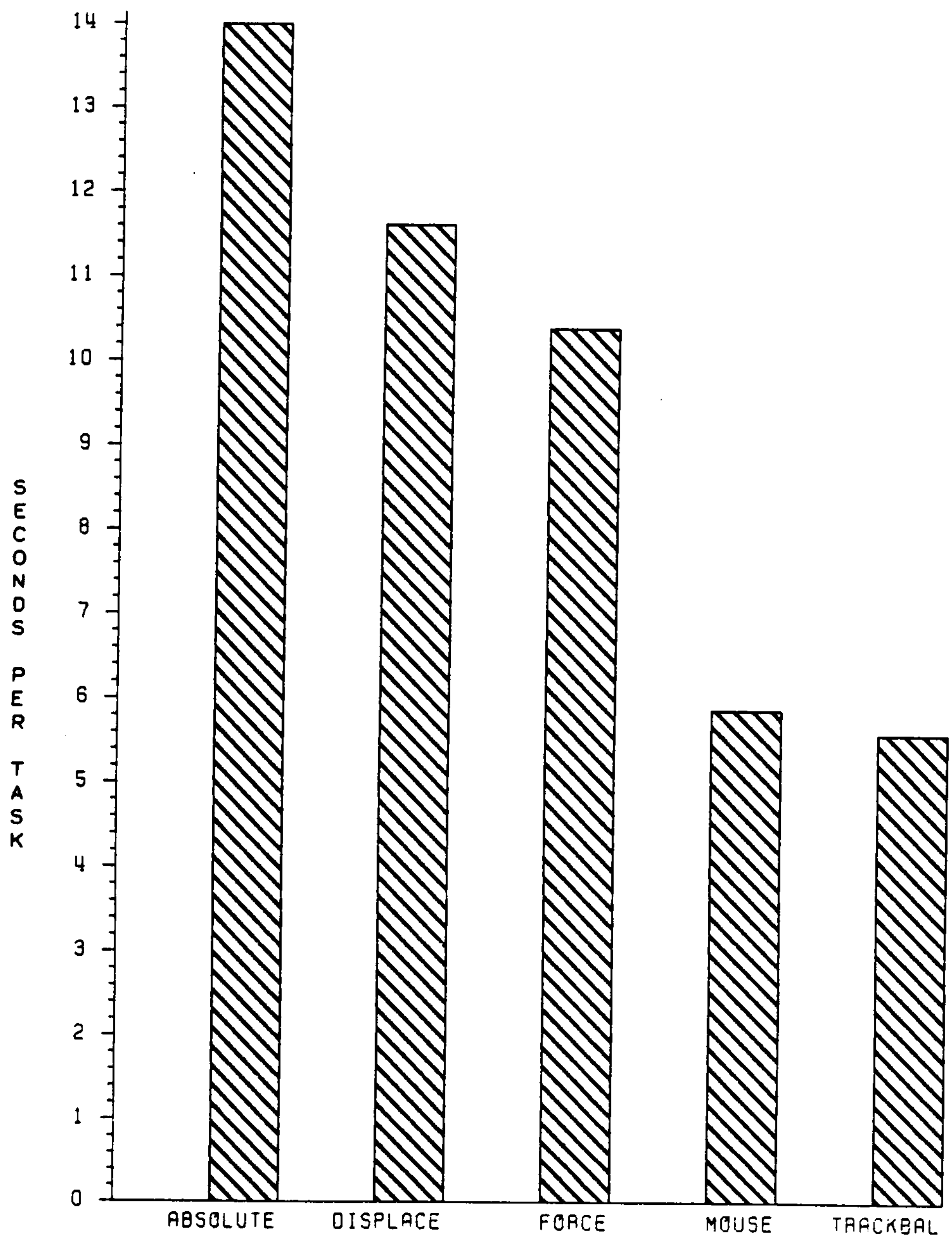

Figure 77. Comparison of devices for the AG task.

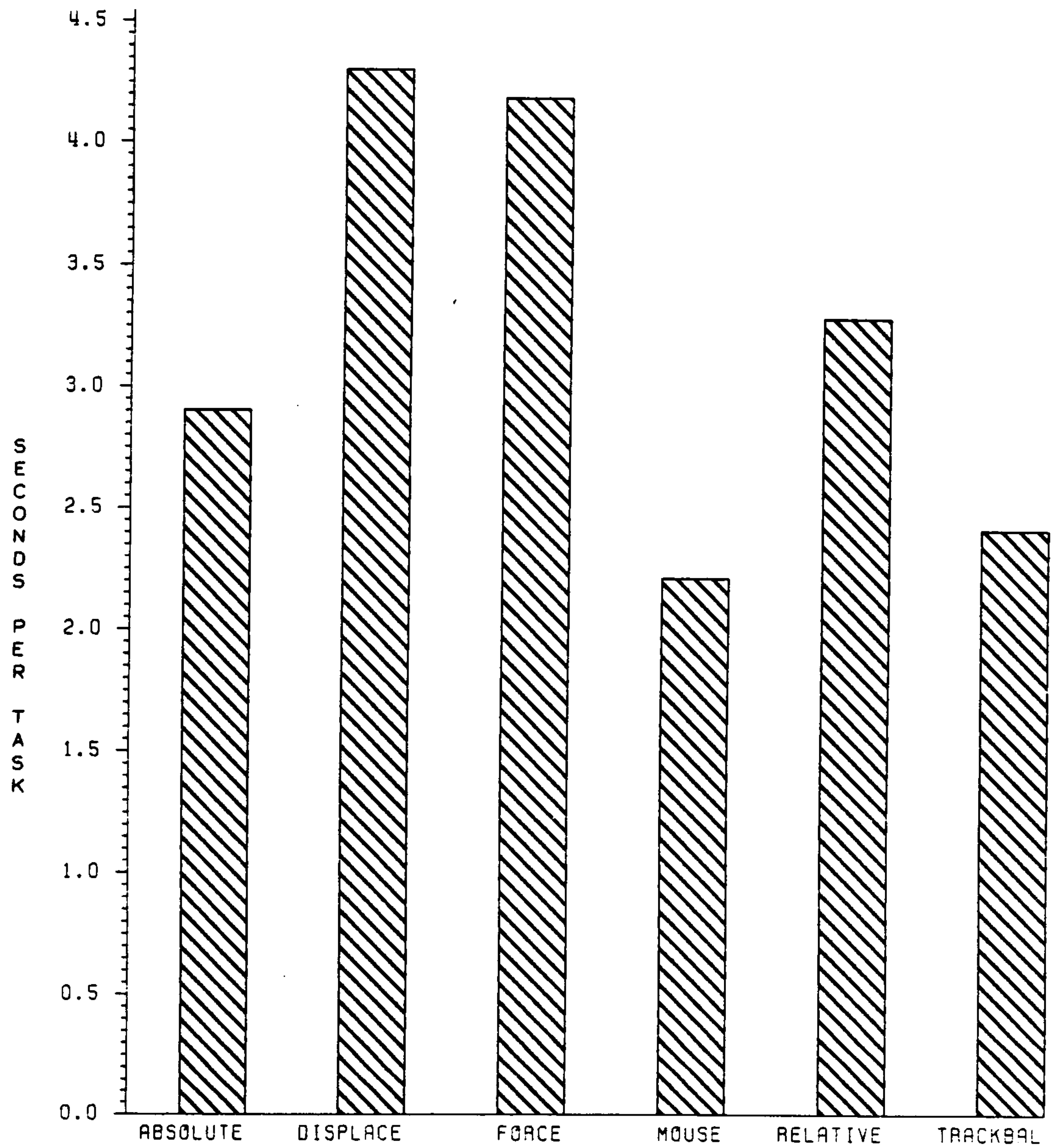

Figure 78. Comparison of devices for the FB task.

(Table 110), indicates that the two joysticks are poorer at acquiring the "pixel" targets than the mouse, trackball, and absolute touchpad. These results are similar to those associated with the target acquisition task for the smallest target size. The Trial Block main effect analysis indicated that asymptotic performance was reached by the second trial block, shown in Table 111.

Horizontal line (HL) task. ANOVA results for the HL task are given in Table 112 (Appendix B). The HL and VL tasks required subjects to perform both fine-positioning and "draw" short pixel segments. Therefore, it was sensitive to both positioning accuracy and the required qualities of a "natural" graphics drawing interface. Only the Trial Block main effect was significant ($F(2,10) = 7.97$, $p = 0.0085$). Post-hoc analysis indicated that, as with previous graphics tasks, asymptotic performance was reached by the second block (Table 113).

Vertical line (VL) task. The ANOVA results for the VL task, shown in Table 114 (Appendix B), indicate that drawing vertical lines is more sensitive than horizontal lines to differences among devices, although only the main effect of Cursor Device was significant ($F(5,25) = 6.72$, p

= 0.0004). For the main effect of Cursor Device a Bonferroni-T Test was performed.

As shown in Figure 79 (Table 115), the mouse performs better than the relative touchpad and the force joystick. In addition, the trackball performed better than the relative touchpad. This result is moderately suprising, as one might expect the relative touchpad to be a "natural" drawing interface since the actual fingertip is used to draw the lines. That is, the touchpads were the only devices which have an apparent direct connection between the device and screen; the mouse, trackball, and joysticks all have effectors of some kind.

Ranks

Data analysis. The six cursor devices were ranked by each subject on the same six criteria used for the target acquisition and text editing tasks. Each criterion was analyzed separately using the Friedman's Rank Sum Test. The results of the analyses indicated differences among the cursor devices for all criteria except positioning speed. Statistical results for the rank criteria, given in Tables 116 through 120 (Appendix B), indicated a critical rank sum of 17.7.

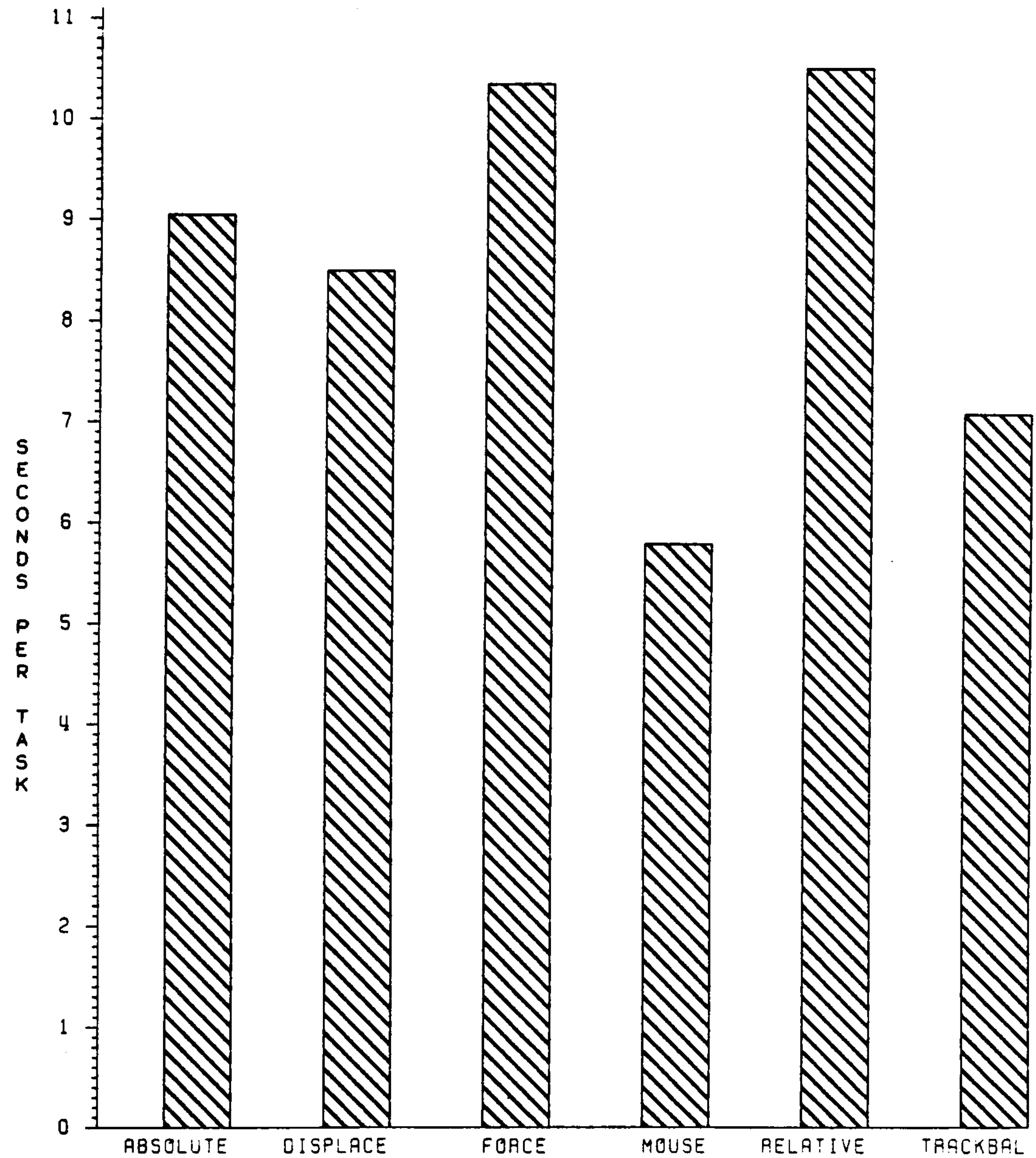

Figure 79. Comparison of devices for the VL task.

Results. Results for the five significant criteria are shown in Figure 80. Individual results are as follows:

(1) Preference ($S' = 21.24$, $p = 0.001$). The mouse and trackball are preferred over the absolute touchpad.

(2) Quality ($S' = 11.71$, $p = 0.04$). The subjects considered the mouse to be of higher quality than the absolute touchpad.

(3) Positioning speed ($S' = 5.81$, $p = 0.33$). No significant differences among devices.

(4) Positioning accuracy ($S' = 17.62$, $p = 0.004$). Subjects ranked the trackball and mouse as providing better cursor positioning accuracy than the absolute touchpad.

(5) Fatigue ($S' = 18.38$, $p = 0.003$). Subjects ranked the absolute touchpad as causing more fatigue than the trackball and mouse.

(6) Comfort ($S' = 19.43$, $p = 0.002$). Results for the comfort rank are similar to those for the fatigue criterion.

Bipolar Scales

Data analysis. As with the target acquisition and text editing analyses, the bipolar scale data were analyzed two different ways. First, a MANOVA was performed on the

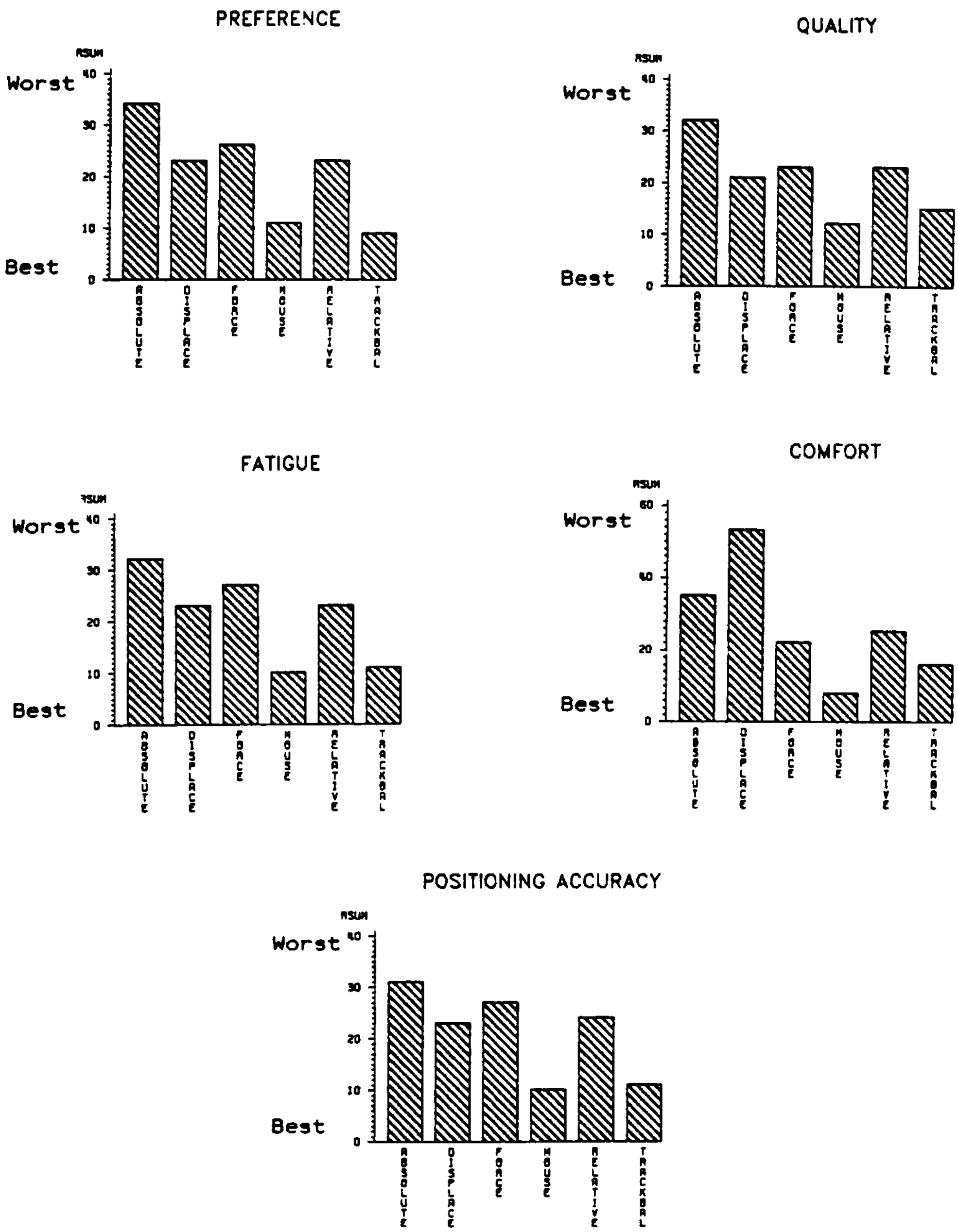

Figure 80. Comparison of devices ranked on the six criteria.

cursor device model, with the 10 scales the dependent measures. MANOVA results indicated significant differences among the scales (F[apprx](50,76) = 1.90, p = 0.0499). Separate ANOVAs were then performed on each of the scales. A summary of the MANOVA results, subsequent ANOVAs, and Bonferroni-T Tests are shown in Tables 121 through 131 (Appendix B).

Second, an ANOVA was performed on the Preference Index (PI) data. Results indicate significant differences among the seven devices (F(5,25) = 6.01, p = 0.0009). An ANOVA summary and subsequent post-hoc comparisons are given in Table 132 (Appendix B).

Results. Figure 81 shows results from the six (of 10) scales which indicated significant differences among cursor control devices. Individual scale results are as follows:

(1) Accurate (Inaccurate) (F(5,25) = 3.28, p = 0.0205). The mouse is considered more accurate than the absolute touchpad.

(2) Consistent (Inconsistent) (F(5,25) = 3.50, p = 0.0155). The mouse is considered to be more consistent for graphics than the relative touchpad.

(3) Comfortable (Uncomfortable) (F(5,25) = 6.77, p =

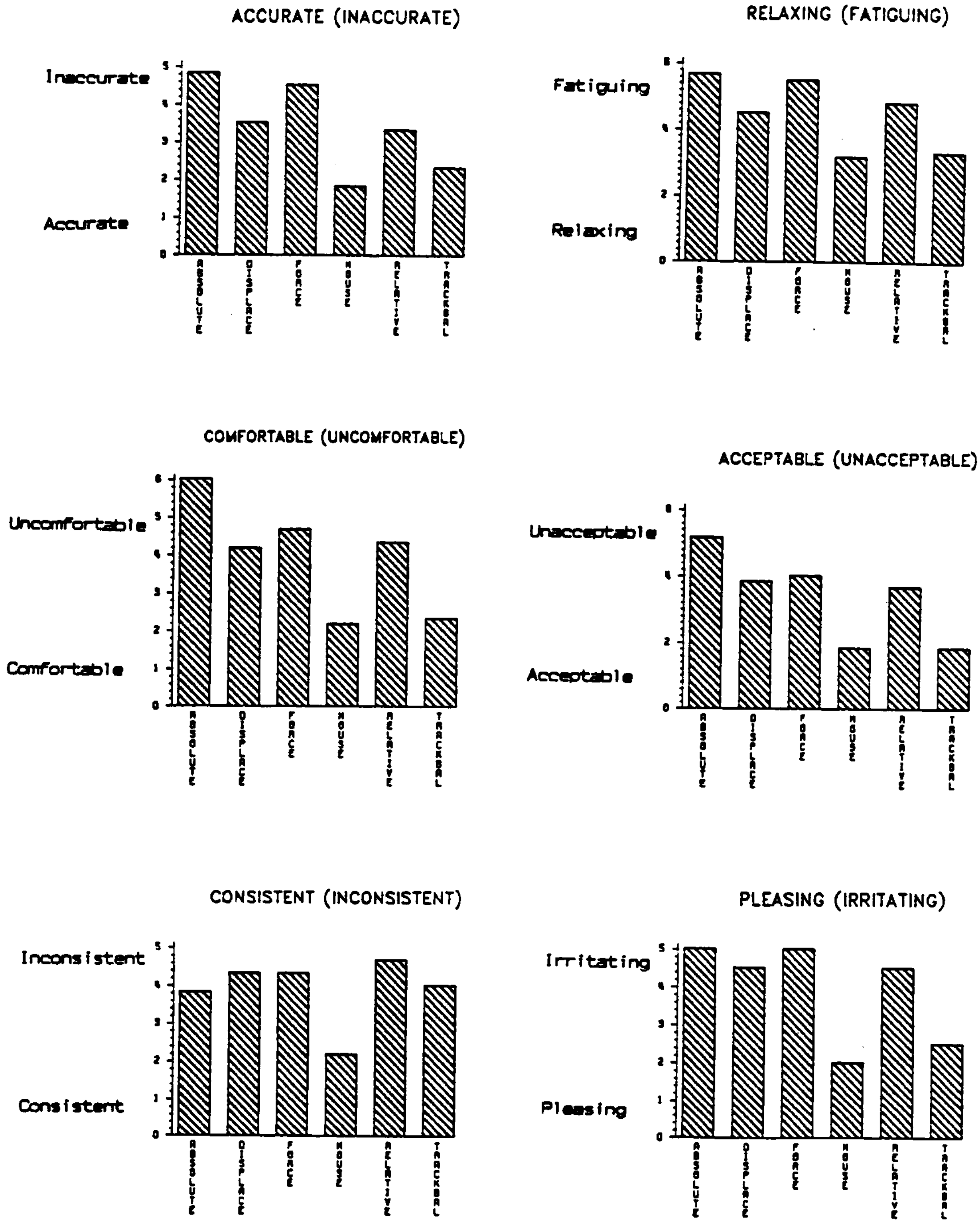

Figure 81. Comparison of devices on six bipolar scales.

0.0004) The mouse and trackball are rated as being more comfortable than the absolute touchpad.

(4) Relaxing (Fatiguing) ($F(5,25) = 4.68$, $p = 0.0038$). The trackball and mouse are perceived by subjects to be less fatiguing than the absolute touchpad. In addition, the mouse was rated better than the force joystick.

(5) Acceptable (Unacceptable) ($F(5,25) = 5.01$, $p = 0.0026$). The mouse and trackball are considered more acceptable than the absolute touchpad.

(6) Pleasing (Irritating) ($F(5,25) = 4.97$, $p = 0.0027$). Subjects find the mouse less irritating to use than the absolute touchpad and force joystick.

The PI analysis results, shown in Figure 82, indicate that, in general, subjects rate the mouse better than the absolute touchpad and force joystick. In addition, the trackball is rated better than the absolute touchpad (Table 132). The separate scale analyses and the overall PI indicate, quite strongly, the preference of the mouse and trackball for the various graphics tasks. The subjective measures of ranks and bipolar scales appear to agree with the performance of the cursor devices on the graphics tasks.

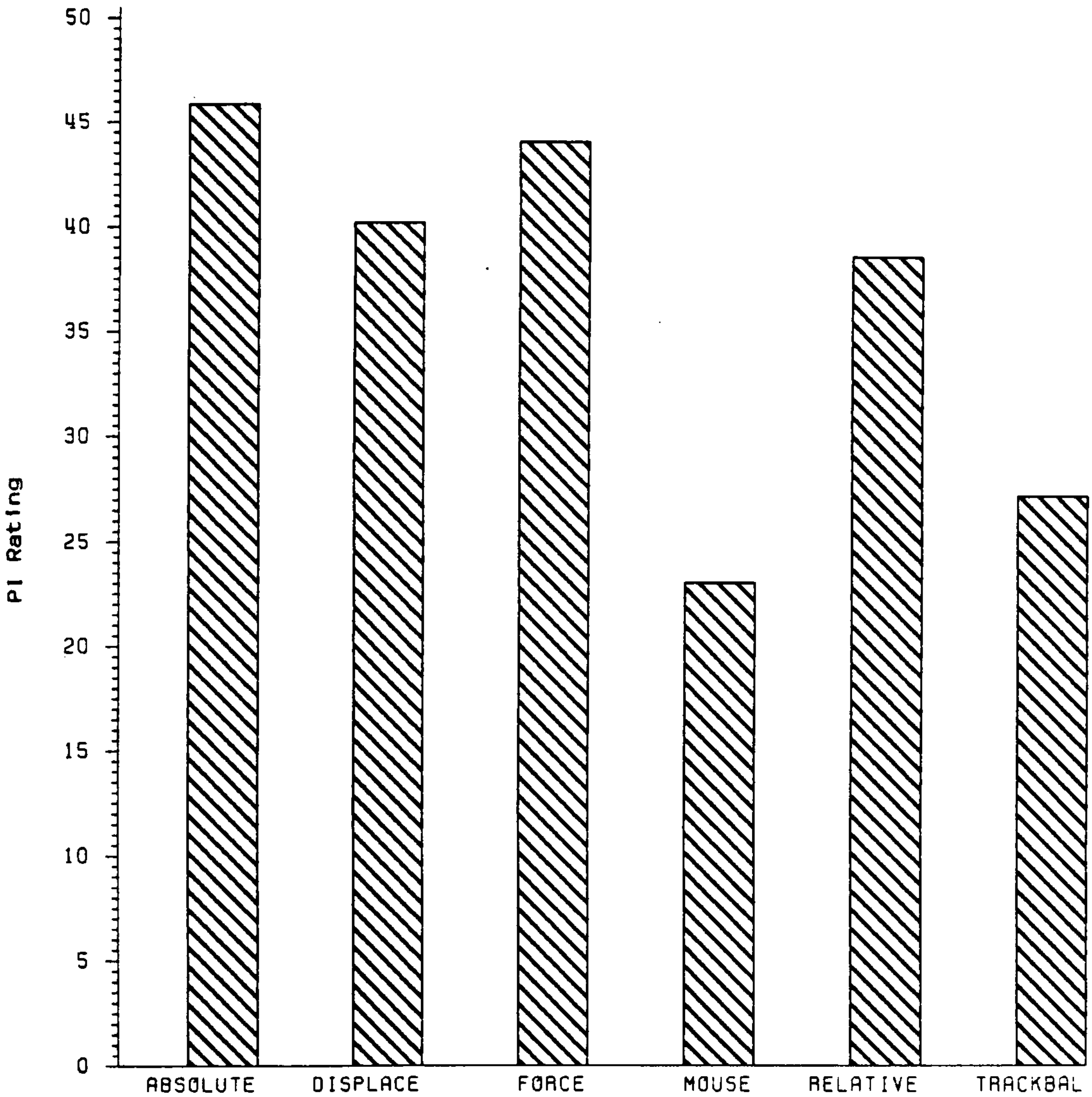

Figure 82. Comparison of devices on the Preference Index (PI).

DISCUSSION AND CONCLUSIONS

This discussion is divided into two parts: cursor device optimization and comparison of cursor devices.

Cursor Device Optimization

The device optimization portion of this research was performed so that a realistic, unbiased comparison of devices could be obtained. A secondary goal was to evaluate and interpret the influence of display/control dynamics on various cursor devices having different physical designs (i.e., effectors). Several interesting observations related to the interaction of device dynamics and the type of device effector are evident from the optimization results.

Perhaps the most interesting result is the variation in display/control dynamics for like devices. For example, the optimal dynamics for the force joystick are much "faster" than those for the displacement joystick (Figure 49). A possible explanation for this result is the inherent "zero-velocity" of the force joystick. More specifically, the user of a force joystick must only release the force joystick for the cursor to stop moving; the displacement joystick may require a slight control reversal, with the finger, to stop the cursor. Therefore, target overshoot may not be a problem with the faster dynamics for the force joystick, but may be a factor with the displacement joystick.

The optimal display/control dynamics associated with the relative touchpad and trackball are also interesting. Although both devices, when optimized, have a slightly exponential relationship between D:C gain and trackball/finger speed, the trackball's D:C range is much larger. As with the joysticks, the optimal dynamics may be related to the device effector. In essence, greater control of velocity scaling may be available with the trackball, as it has inherent inertia, zero-velocity capabilities, and is typically operated with fingertips. The touchpad must be operated with full hand movements. More specifically, the trackball can be released during cursor movement and the cursor will still continue to move on the screen for a certain distance, or alternately, the direction of the cursor can be reversed during movement with a change in fingertip movement on the trackball. As a result, faster (yet controllable) D:C dynamics may be possible. The touchpad, on the other hand, appears to require both fingertip and full hand movements. The required movement of the full hand, having larger mass than the finger, may hinder control reversals and fine cursor positioning. As a result, a slower touchpad velocity scaling might be needed to improve device/cursor control.

The problem of over-shoot/control reversals is also apparent with the mouse. Optimization results for the mouse indicate that the best velocity scaling was none. A possible reason for this result is that movements with the mouse are typically performed with the hand and lower arm. When velocity scaling is used with the mouse, stopping cursor movement may require a reversal in the direction of movement of the entire lower arm, again a larger-mass appendage.

A general rule regarding velocity scaling is evident from the extension of the force/displacement and trackball/touchpad/mouse optimization results. It appears that, as the movement and mass requirements to operate a specific device increase from fingertip to hand to lower arm, less velocity scaling is required to obtain optimal display/control dynamics; that is, the longer the body segment required to operate a cursor control device, the less velocity scaling is needed or desired.

Comparison of Cursor Devices

The primary goal of the three comparison studies was to determine the best cursor control device(s) for computer tasks. Three experimental tasks (target acquisition, text editing, and graphics editing) were used as a basis for collecting user performance and subjective preference data. A secondary goal of the study was to determine whether the results from the target acquisition comparison were generalizable to the specific tasks of text and graphics editing. The following discussion addresses these two goals with respect to the three dependent measures collected longitudinally across the three comparison experiments: (1) task completion time, (2) subjective ranks, and (3) bipolar scales.

Task completion time. The primary dependent measure for the three comparison studies was the time to complete specific tasks. For the target task, the time required to move a screen cursor into targets of various sizes and at various screen distances and to press an input button (TT, or seconds per target acquisition) was used. For the text editing task, the time required to move a cursor to a character or word within a text field and perform a text editing task (TCT, or seconds per edit) was used. For the graphics task, the time to perform one of seven various graphics editing tasks (TCT, seconds per edit) was the dependent measure. Since the three task completion times are similar in nature, one is able to compare cursor device performance <u>within</u> a task environment and <u>between</u> task environments.

The results from the <u>target acquisition</u> comparison show that, in general, subjects perform the task best with the mouse, trackball, and absolute touchpad (Figure 59); the worst performance is obtained with the rate-controlled joysticks. When the six devices are compared across target size, a measure of cursor positioning accuracy, differences among devices are very pronounced at the smallest target sizes. For example, the mouse and trackball are significantly better than all other devices at the smallest target size (Figure 57). Results at the second smallest target size are very similar, with the exception that the absolute touchpad improves, in terms of target positioning performance, relative to the trackball and mouse. As target size increases, differences among devices become less pronounced and, in fact, are not significant at the largest target size.

Comparison of cursor device performance at specific target sizes may be predictive of actual performance on tasks which require the acquisition of targets of these sizes. For example, the second to third target size range (0.27 to 0.54 cm) is representative of character sizes for text editing. The smallest target size (0.13 cm) represents the level of cursor positioning accuracy found in many graphics tasks. Therefore, one might expect that a comparison of cursor device performance at these two target sizes might predict results for text and graphics editing tasks.

A comparison of cursor devices across the four types of <u>text editing</u> files shows the mouse, trackball, and cursor keys as, generally, the best devices. Subjects, typically, can perform both the character deletion and actual text editing tasks faster (seconds per edit) with these three devices than with the touchpads, although the character delete (Figures 64 and 66) files appear to be more sensitive to device differences than the actual text editing files (Figures 68 and 69). By far the worst device is the absolute touchpad, as it is significantly worse than the trackball, mouse, and keys regardless of the file type. In addition, the rate-controlled, force joystick is better than the absolute touchpad for most file types.

Returning to the results from the target acquisition task at the 0.27 and 0.54 target sizes (Figure 57), the absolute touchpad is not significantly worse than the mouse and trackball, but is significantly better than the force joystick. That is, the results from the text editing comparison study for the touchpad are opposite to the predicted results based on the target acquisition comparison at target sizes representative of text editing.

A possible reason for this result is the interaction between the text editing task and the nature of the absolute touchpad device. First, the touchpad positions are positionally mapped to screen cursor positions. Second, cursor positioning errors related to lifting the finger from the touchpad surface (i.e., "fall-out" errors) were observed during sessions with the absolute touchpad on the text editing task. Third, the text editing task requires subjects to use the same hand which operated the touchpad to perform keyboard input. The combination of these three factors appeared to increase cursor positioning time. When the subject positioned the cursor over a given target character and lifted his/her finger to move the hand to the keyboard, the cursor would occasionally "jump" one character on the text field, due to fall-out error. The subject was then required to re-position the cursor over the target character by returning his/her finger to the touchpad, finding the exact position on the touchpad which corresponded to the target character, and position the cursor over the character. (Fall-out error was also observed for the relative touchpad, but the non-bitmapped nature reduced initial, or ballistic, cursor positioning on the text field.) For the target acquisition task, the subject's finger was always in contact with the touchpad surface, as the target selection input button was operated with the opposite hand. Therefore, fall-out problems were reduced.

For the graphics editing tasks, the conclusions for the best cursor device(s) differ slightly across the types of graphics tasks, which require various levels of cursor positioning acccuracy. For the rectangle (RT) task, which requires moderate cursor positioning accuracy, the trackball and mouse are the best devices for initial use (i.e., learning). As the subjects used the cursor devices on the RT task, the absolute touchpad performance improved dramatically (Figure 73). The fat bits (FB) task, which requires cursor positioning similar to the smallest target size and distance of the target acquisition task, indicates that the mouse, trackball, and absolute touchpad are better than the joysticks (Figure 78). The vertical line (VL) task, which requires a combination of fine cursor positioning with "draw" capability, indicates poor performance of the relative touchpad compared to the mouse and trackball (Figure 79). For the angular grid (AG) task, which requires pixel-by-pixel cursor positioning, the trackball and mouse are significantly better than the absolute touchpad (Figure 77). In general, the mouse and trackball are the best devices across all types of graphics tasks. The absolute touchpad performance degrades relative to the mouse and trackball as cursor positioning accuracy becomes important.

Again, the target acquisition results do not fully predict the performance results of the cursor devices for an actual graphics task. For moderate cursor positioning tasks (RT and FB), the order of cursor device performance is exactly that of the target acquisition task for the 0.13 target size (see Figures 57, 74, and 78). For the VL and AG tasks, which require fine cursor positioning, the target acquisition task results are poor predictors of actual graphics editing performance.

The predictive power of the target acquisition task for the text and graphics tasks can be further quantified using the Pearson's Product Moment Correlations. For the text editing task, the association between time to acquire a target at the 0.27-cm target size (an estimate of the size of a text character on the CRT) and the mean TCT from the four text files is quite low (r = 0.24, p = 0.65). The low correlation is probably due to the poor performance of the touchpads, especially the absolute mode, on the text tasks relative to the target acquisition task. For the graphics task, the association between TT at the 0.13-cm target size and the mean TCT for the seven graphics tasks (r = 0.80, p = 0.057) is much higher than the text task. Again, the touchpads did not perform as well on the graphics task, relative to the remaining devices, as the target task.

Subjective ranks. In general, the mouse and trackball are ranked best (i.e., lowest) across the target acquisition, text editing, and graphics tasks, although some differences are apparent for certain rank criteria (Figures 60, 70, and 80). For the preference criteria, the position of the absolute touchpad is third for the target acquisition task, but last for the text and graphics editing task; the displacement joystick is preferred more for the actual tasks than for the target acquisition task. The absolute touchpad, again, is ranked worse for quality for the text and graphics tasks than for the target acquisition task. For the positioning speed criterion, the mouse is ranked lower, relative to the trackball, for the text editing task compared to the target aquisition task. The displacement and force joystick ranks improve slightly, relative to the touchpads, from the target acquisition to the text/graphics tasks. For the positioning accuracy criteria, the two joysticks as a group change rank position relative to the two touchpads across tasks. Whereas the joysticks are ranked as worse than touchpads for the target task, the ranks improve for the graphics and, more noticably, for the text editing tasks. No rank differences are apparent across tasks for the fatigue criterion. Ranks for the comfort criteria, however, indicate a position change for the displacement joystick. Most noticable is the relatively poor rank for the displacement joystick on the graphics tasks as compared to the target and text editing tasks.

In general, it seems apparent that the subjective ranks, like the performance measures, vary depending on the task performed. In addition, the subjective ranks appear to mirror the performance results. That is, the devices which enable users to perform tasks well are ranked best; those devices which perform poorly are ranked worst.

Bipolar scales. For the most part, the bipolar scale and rank results are similar. The trackball and mouse are rated best on most scales, along with the cursor keys for the text editing task. In none of the three task environments are all 10 scales sensitive to cursor device differences (i.e., significant differences among devices). In addition, sensitive scales differ across the three task environments (see Figures 61, 71, and 81).

Only three scales are sensitive to differences among cursor devices for all three tasks. For the Accurate (Inaccurate) scale, relationships among scale values of devices remain constant across tasks, with the exception of the joysticks. In general, the joysticks are rated more accurate for the text editing task than for the graphics or target tasks. This result is not suprising, as the character target size for the text editing task is larger relative to graphics targets and the smallest target size for the acquisition task. The Acceptable (Unacceptable) scale was also sensitive across all tasks. In general, the joysticks are perceived as more acceptable for the text and graphics editing tasks than for the target acquisition task. In addition, the relative and absolute touchpads switch rating positions between the text/graphics and acquisition tasks, whereas the relative touchpad rating improve. For the Consistent (Inconsistent) scale, ratings among devices are very nearly identical for the target acquisition and graphics tasks. An improvement in the text editing rating associated with the joysticks is the most notable difference across tasks.

Three additional scales show differences among devices between the target and text editing tasks; these are Fast (Slow), Good (Bad), and Expensive (Inexpensive). In general, the differences in rating responses for these three scales reflect the improvement (i.e., decrease) of the joystick ratings from the target to text tasks. The Comfortable (Uncomfortable) and Pleasing (Irritating) scales were sensitive for only the graphics task.

For the most part, the performance of subjects on the three tasks and their Preference Index (PI) ratings are quite close. The association between the PI and the mean TCT for the text ($r = 0.99$, $p < 0.0001$) and graphics ($r = 0.97$, $p < 0.0001$) are quite strong. The association between the PI ratings on the target task and TT are significant ($r = 0.85$, $p = 0.029$), but not as strong as the actual tasks. The high correlation between subjective preference for cursor devices and the actual performace level may have interesting implications for computer industry "point of sale". More specifically, users of computer system cursor devices appear to be good judges of their own performance on actual text and graphics tasks.

General Conclusions

Based on the task completion time, subjective rank, and bipolar scale dependent measures, several general conclusions concerning the "best" cursor devices can be made. First, without exception, the mouse and trackball performed best across all three tasks. In addition, these two devices are generally preferred over the remaining devices. The cursor keys are typically grouped with the mouse and trackball on the text editing task only, and for a logical reason: cursor keys move only horizontally and vertically, the same way text is visually organized..

The conclusions related to the touchpads and joysticks are less straightforward. For example, the absolute touchpad performs quite well on the target acquisition task, but task completion times on the text editing and fine cursor positioning graphics tasks are poor. For the text task, this performance level appears to be due to the required use of a keyboard in conjunction with the absolute positioning, or bit-mapped, nature of the pad. For the high accuracy graphics tasks, the use of a finger as a pointing device on the touchpad surface results in very poor "pixel-by-pixel" cursor positioning.

Generally, the joysticks perform poorly on high accuracy cursor positioning tasks. However, for text editing and the acquisition of larger targets, the advantage of the mouse and trackball over the joysticks diminishes. In essence, joysticks are merely cursor keys with variable speed and oblique movement capability, a possible explanation for the relatively good performance of the joysticks on the text editing task.

Recommendations: Choosing a Cursor Control Device

With consideration to the limitations of the experiments discussed herein, the trackball and mouse appear to provide the best performance for a variety of computer tasks. In addition, users (subjects) seem to prefer these two devices over the remaining devices compared in this study. Although the results from this study appear, substantially, in favor of the mouse and trackball, one should consider these recommendations in the context of total system design.

The type of task being performed and frequency of cursor device use are very important considerations. For example, keyboard intensive tasks might dictate that a device which can be located on the keyboard, to reduce movement distances from keyboard to cursor device, should be used. If the task is cursor device intensive, one might choose a device which will reduce user fatigue.

The type of working environment may also affect the decision to use any one particular cursor control device for a specific application. In work situations where space is critical, one might choose the trackball over the mouse, as the trackball can be placed on the keyboard while the mouse requires space beside the workstation (i.e., greater "footprint"). On the other hand, input buttons located on the mouse allow users to choose system functions without moving the hand that operates the device; function/input buttons associated with the trackball must be located next to the device or operated with the opposite hand.

The harshness of the working environment may also affect the decision to use any one device. In environments with moisture or dirt, the optical mouse and trackball may be unnaceptable since neither of these devices can be "hardened" to make it impervious to the environment. The force joystick, displacement joystick, and touchpads <u>can</u> be hardened.

In essence, the decision to use any one specific device must be made with consideration to:

(1) task requirements (which include target sizes, target distances, frequency of cursor device use, and

possible interaction with keyboard use),

(2) space limitations of the workstation, and

(3) any extreme conditions which may be present in the work environment.

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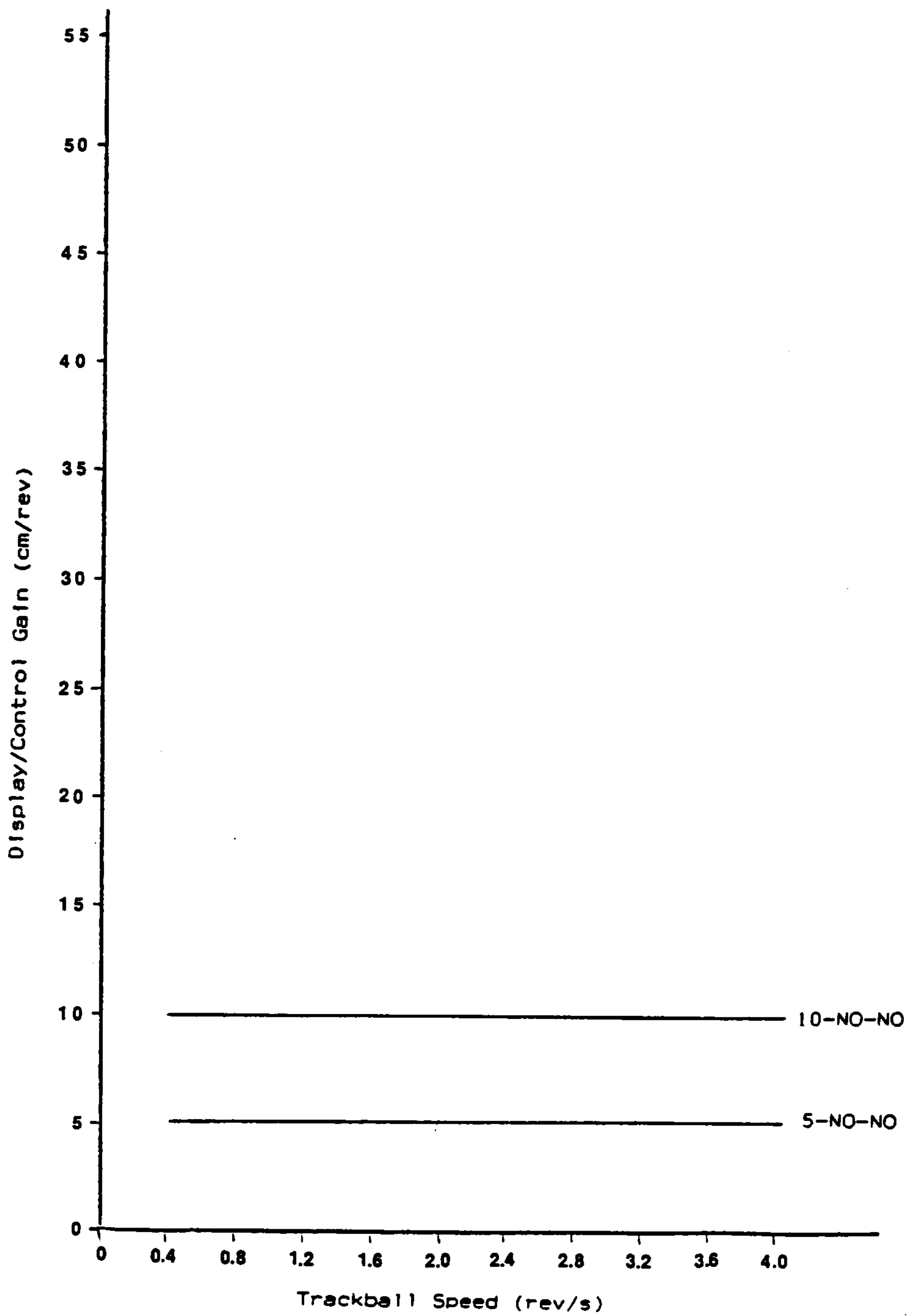
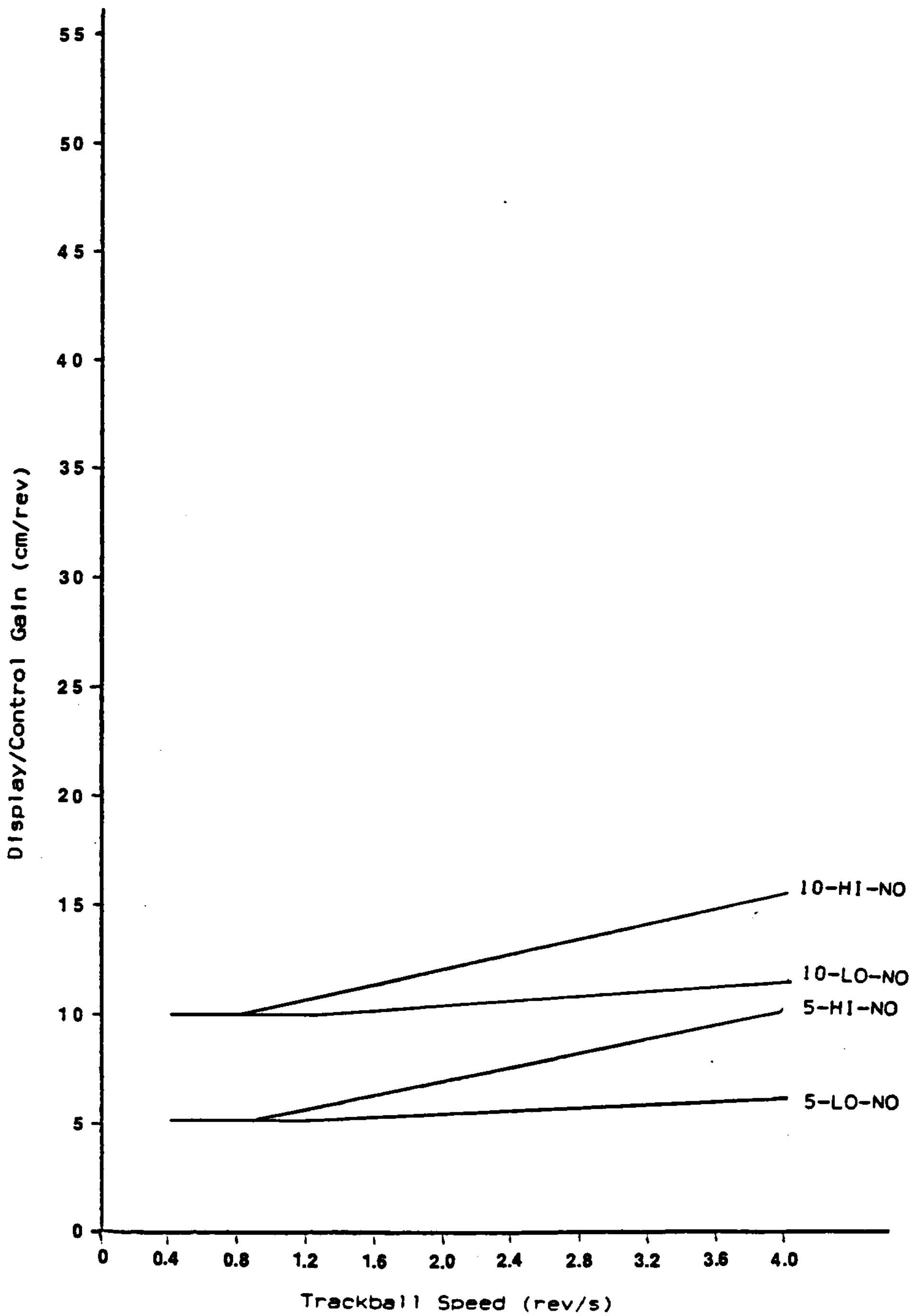
APPENDIX A:

Velocity Scale Relationships

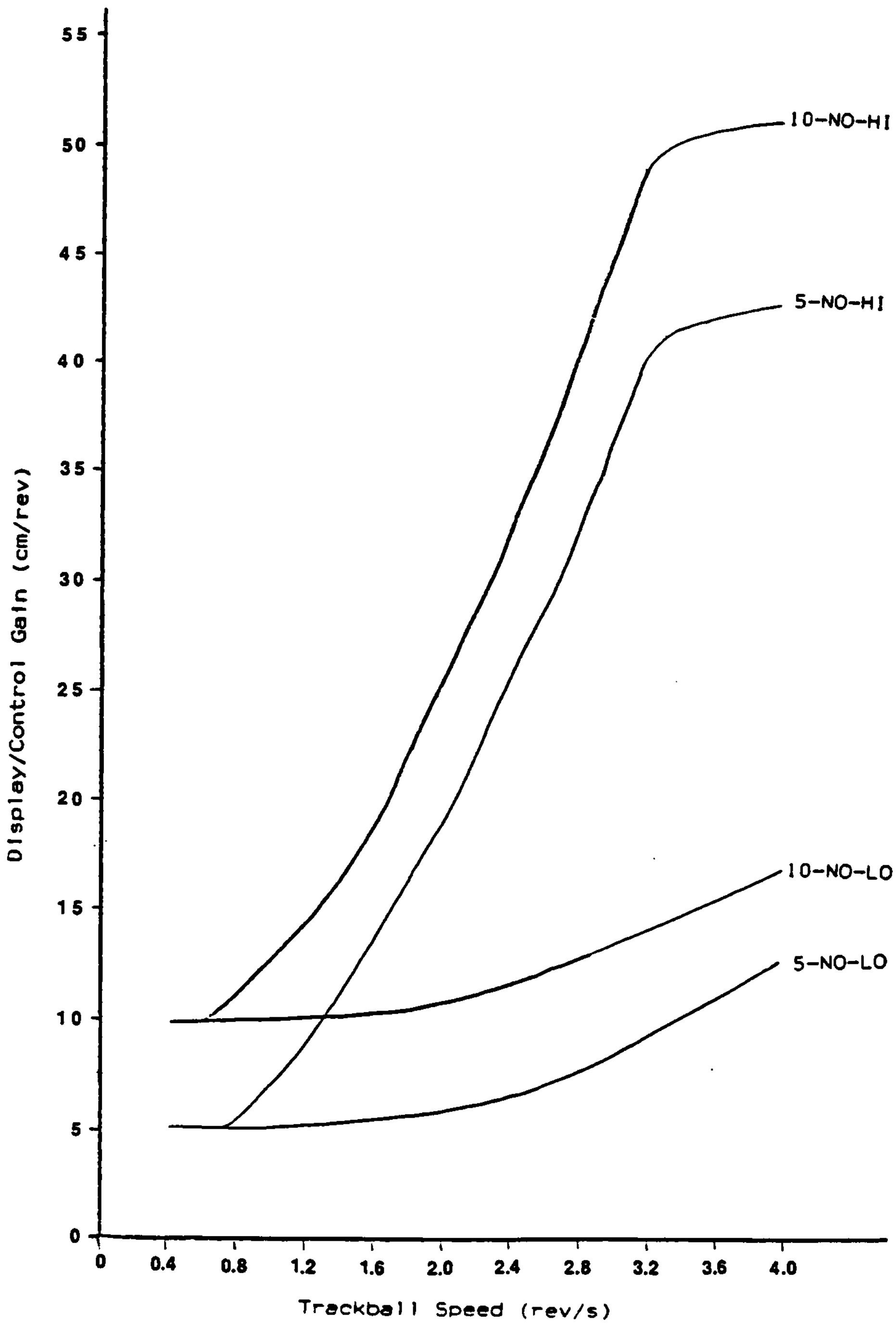
TRACKBALL: Zero-Order Velocity Scales



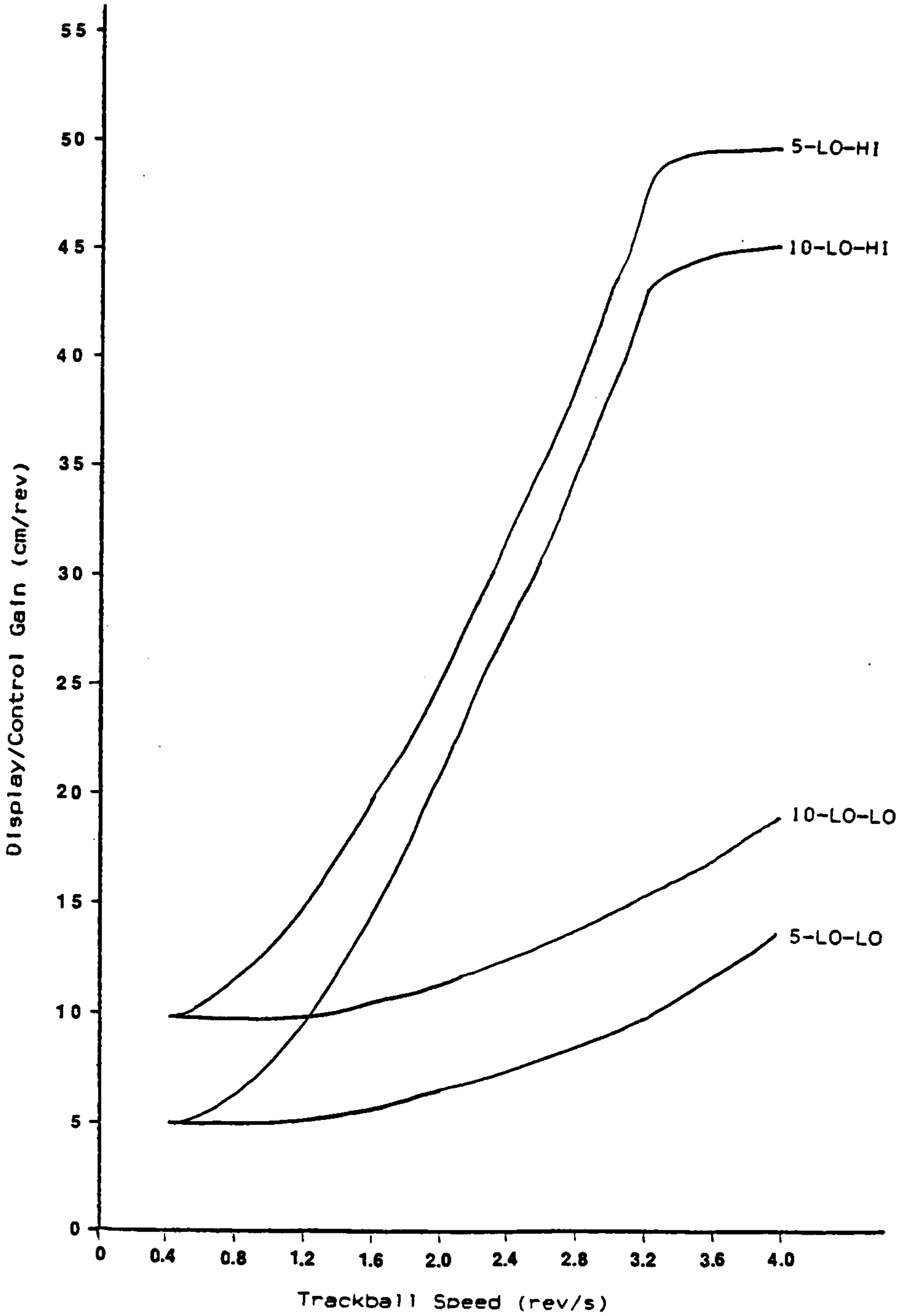
TRACKBALL: First-Order Velocity Scales



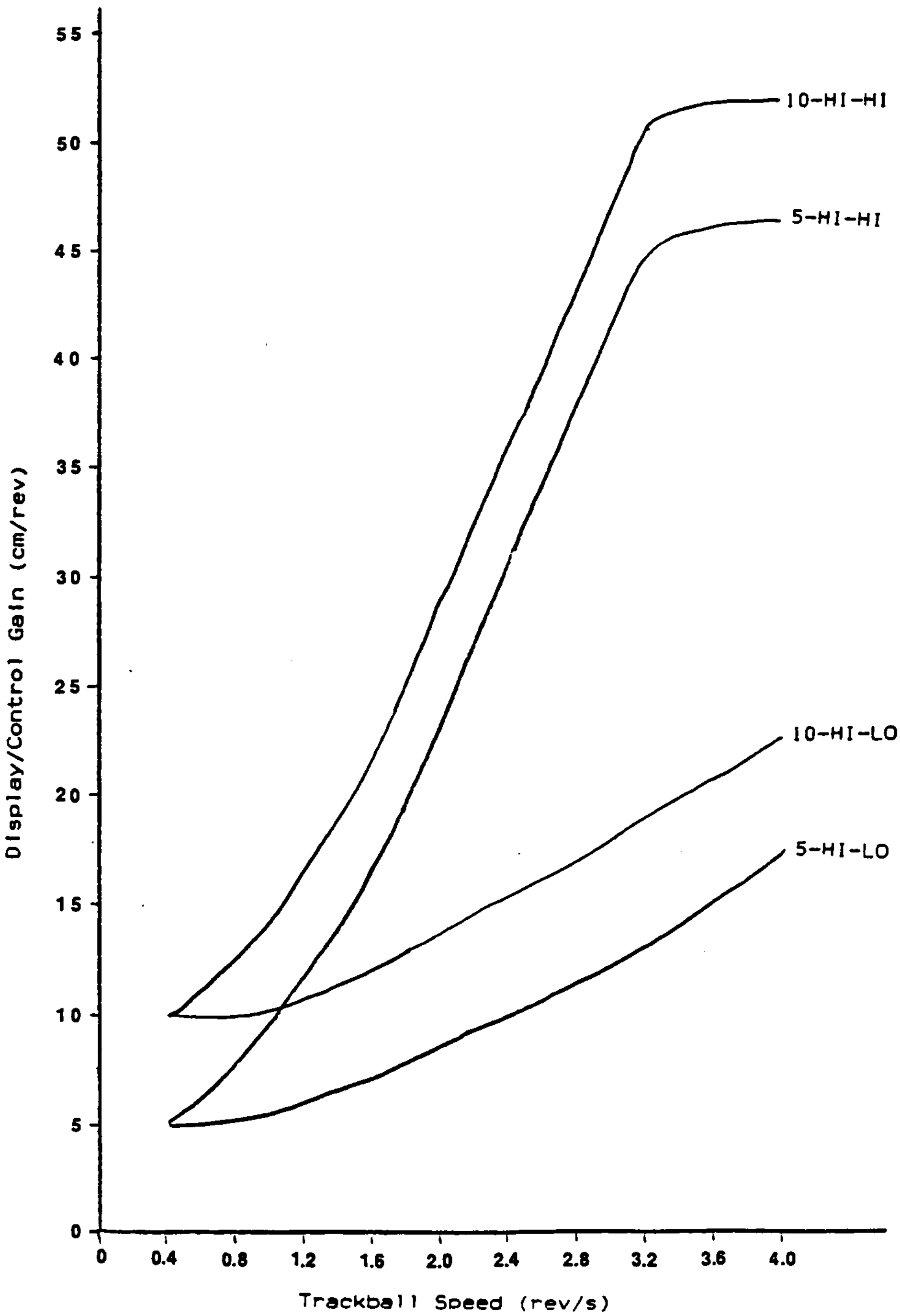
TRACKBALL: Pure Second-Order Velocity Scales



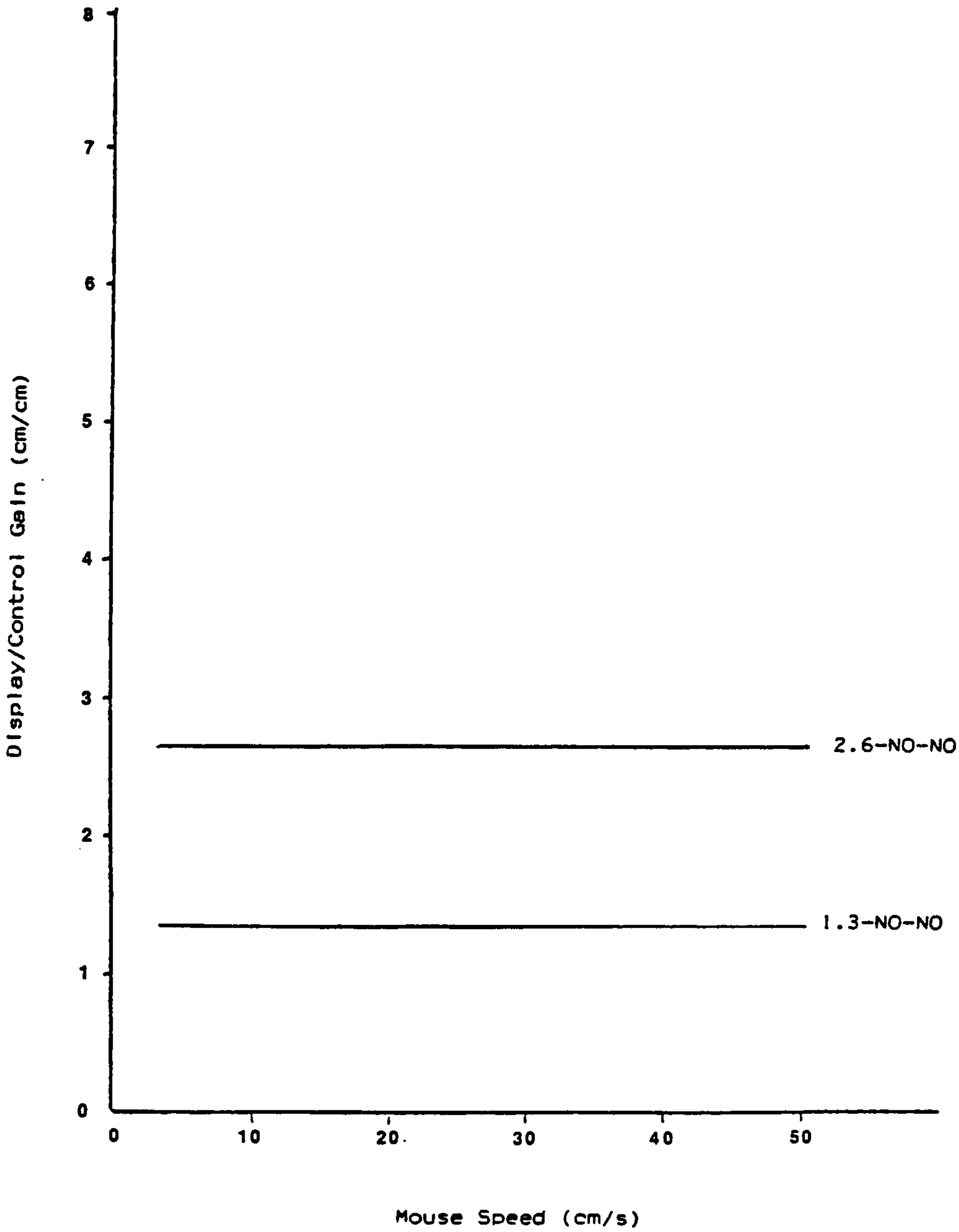
TRACKBALL: Low Second-Order Velocity Scales



TRACKBALL: High Second-Order Velocity Scales



MOUSE: Zero-Order Velocity Scales



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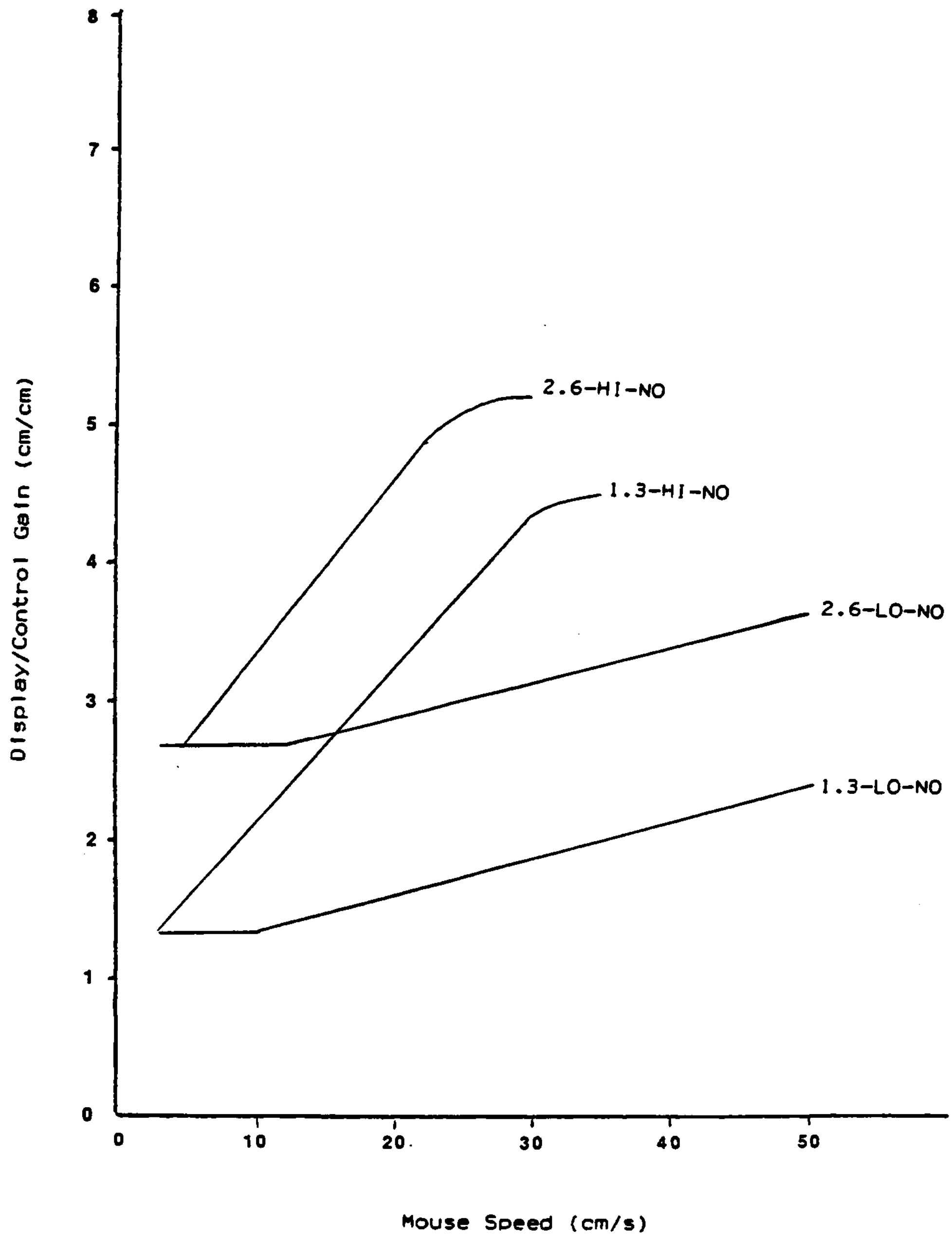

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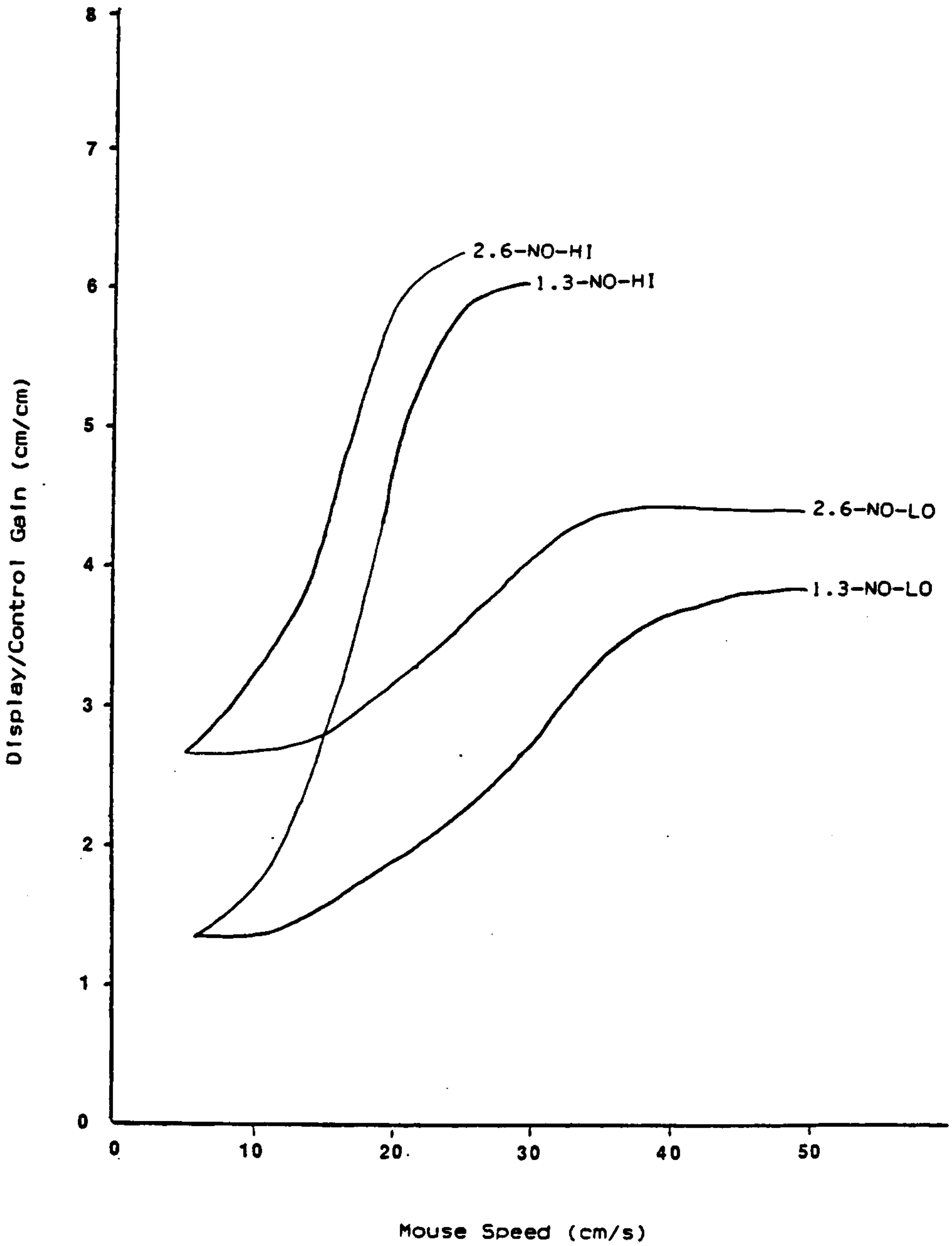

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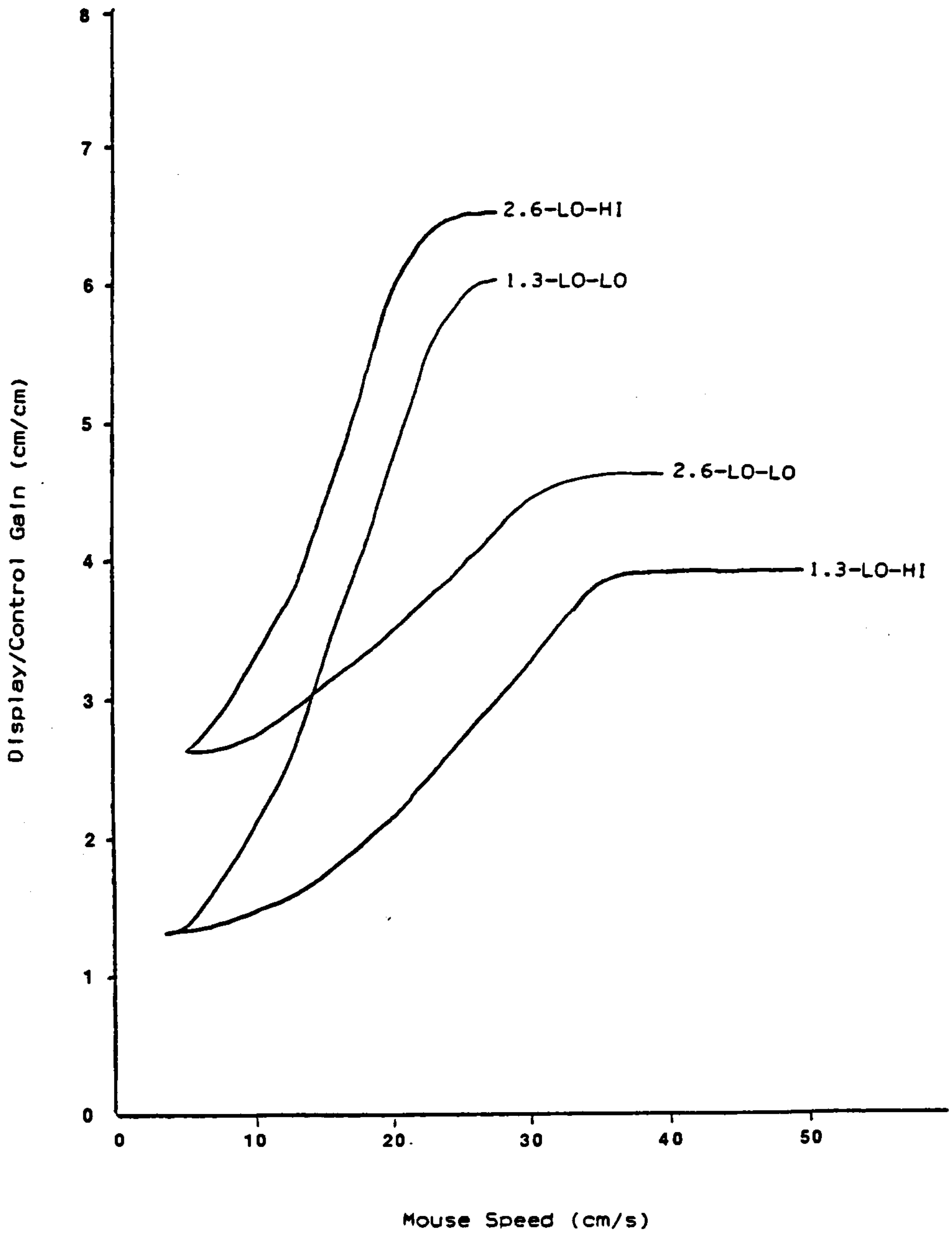
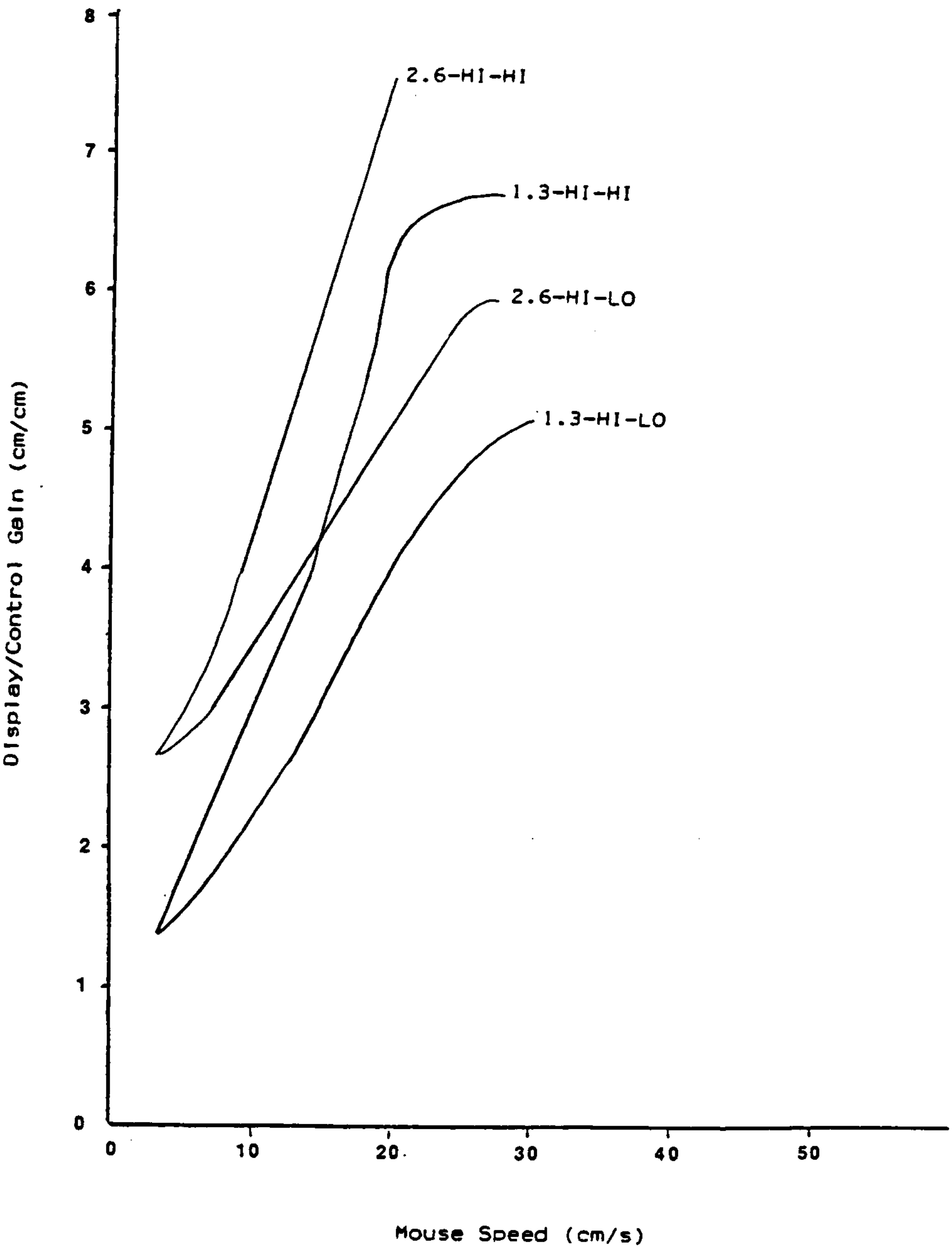
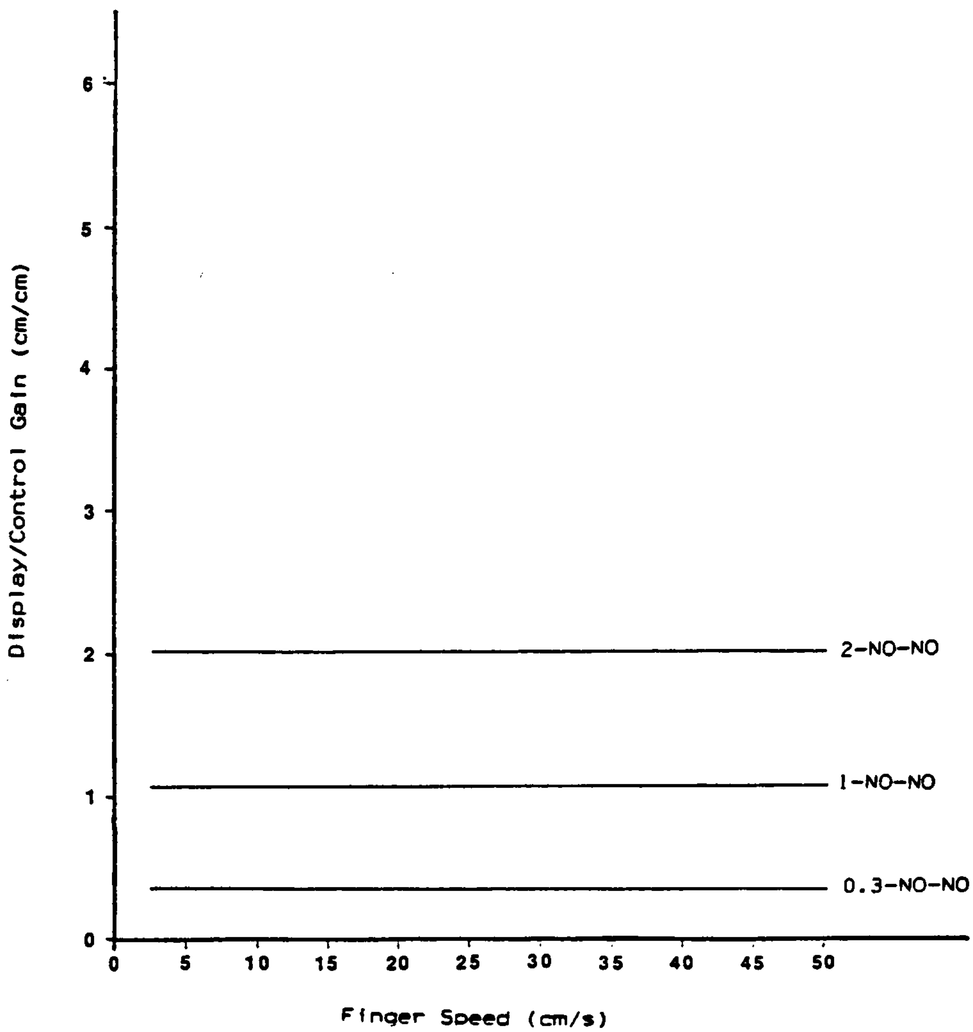


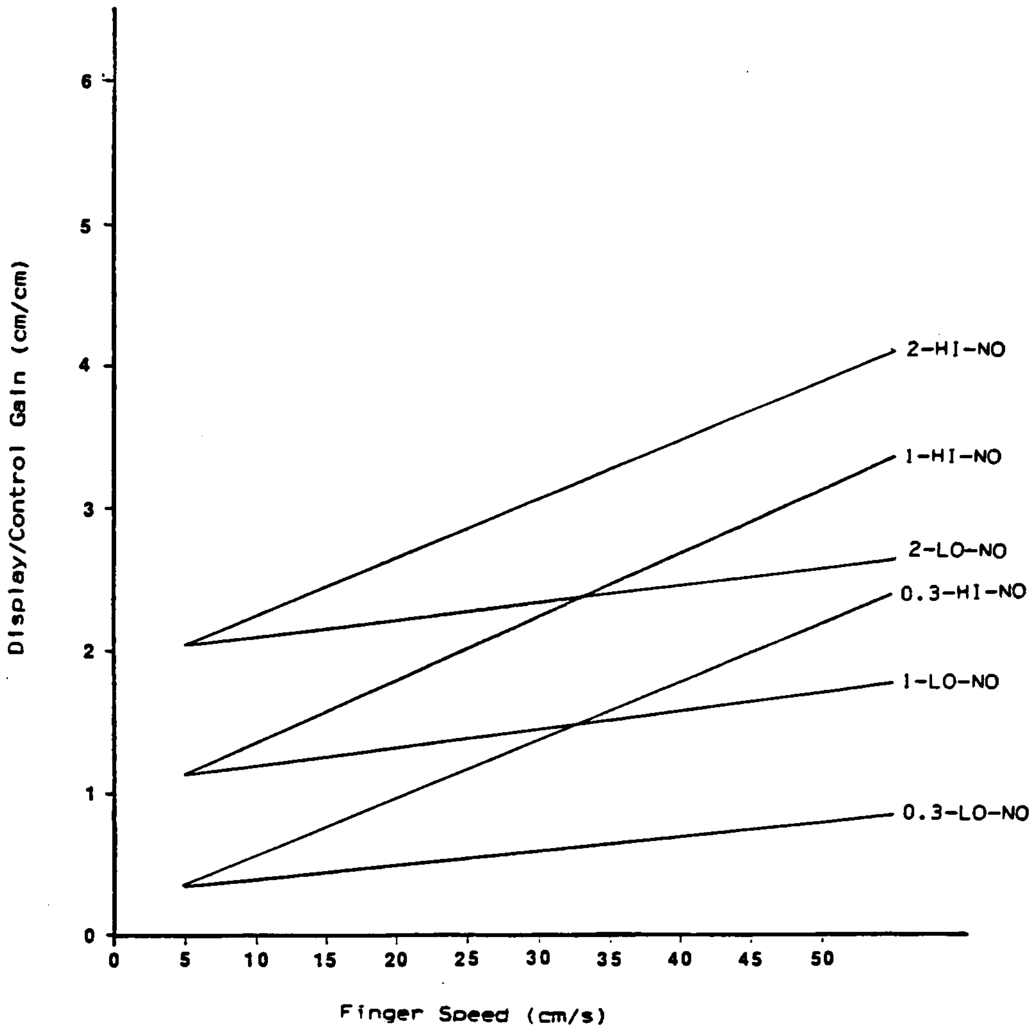
MOUSE: High Second-Order Velocity Scales



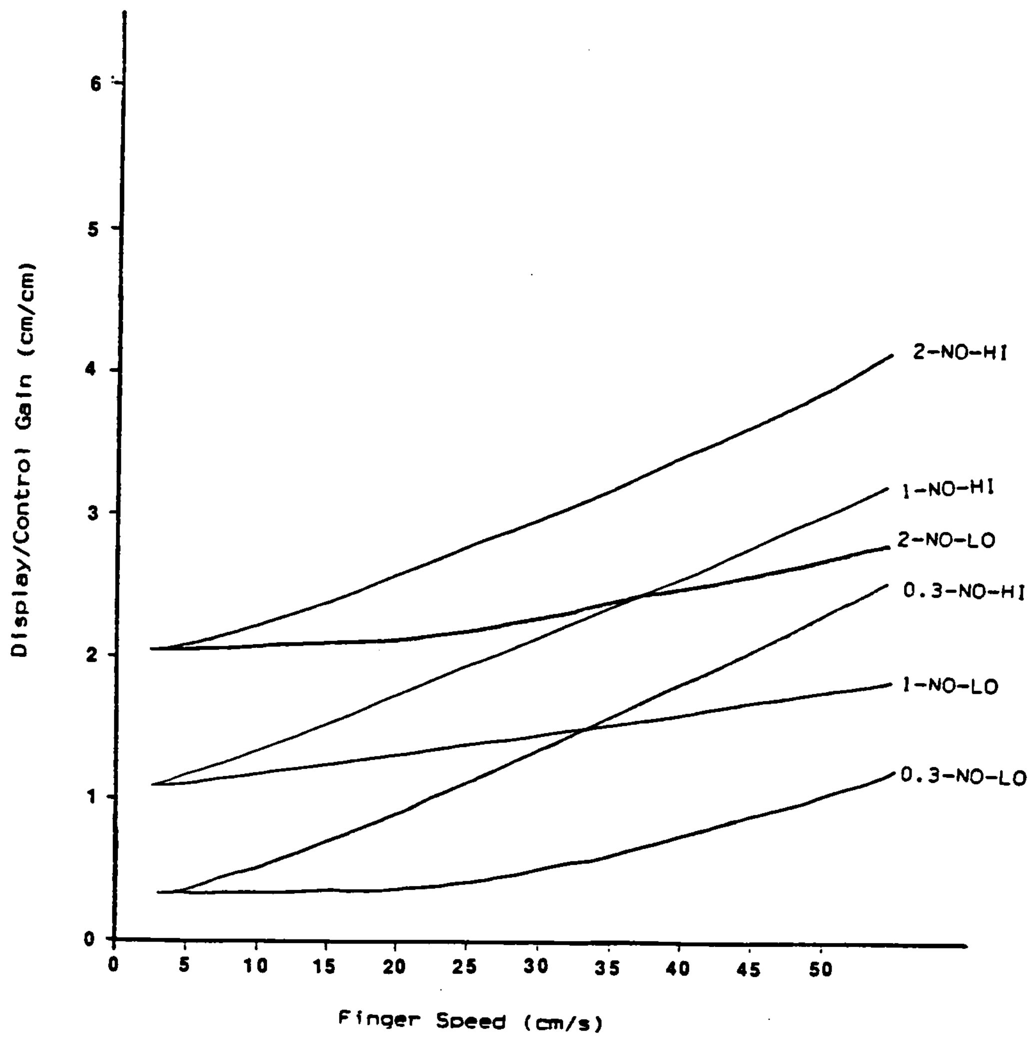
TOUCHPAD: Zero-Order Velocity Scales



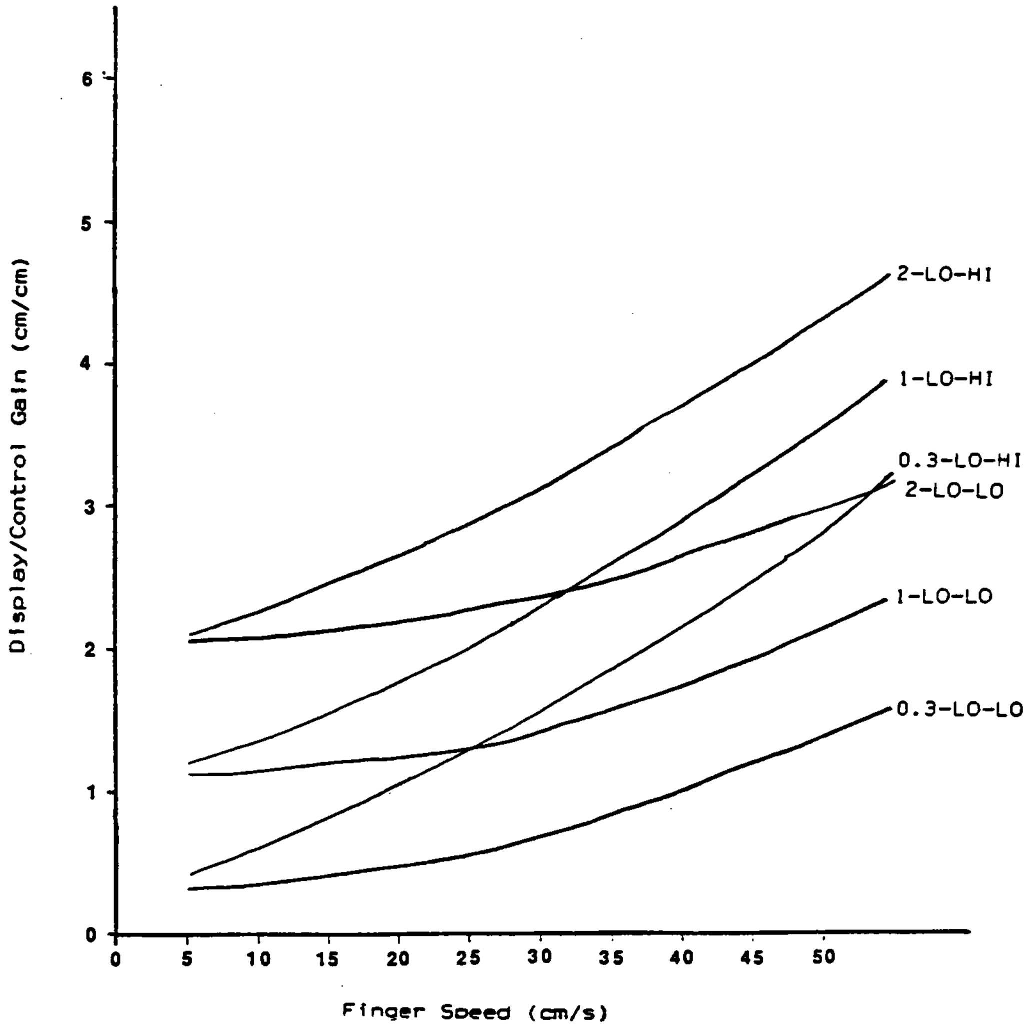
TOUCHPAD: First-Order Velocity Scales



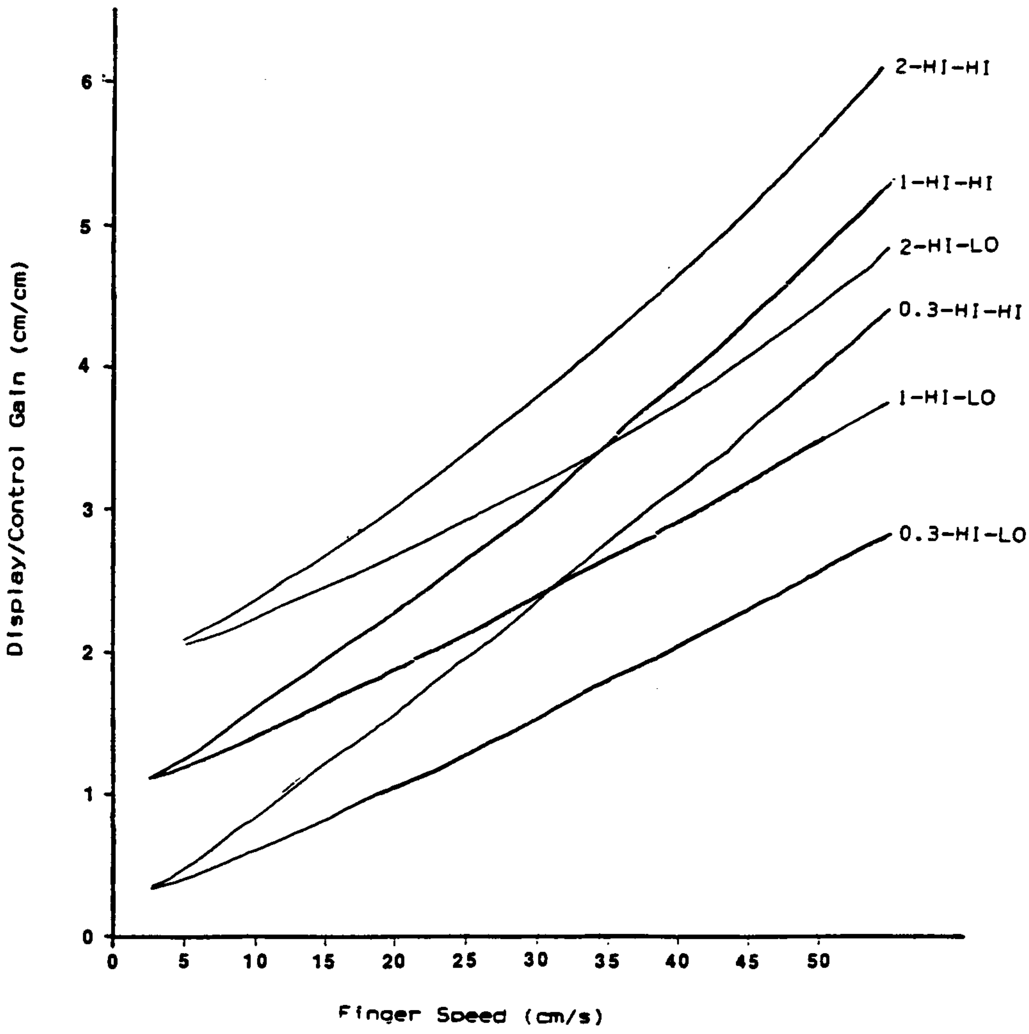
TOUCHPAD: Pure Second-Order Velocity Scales



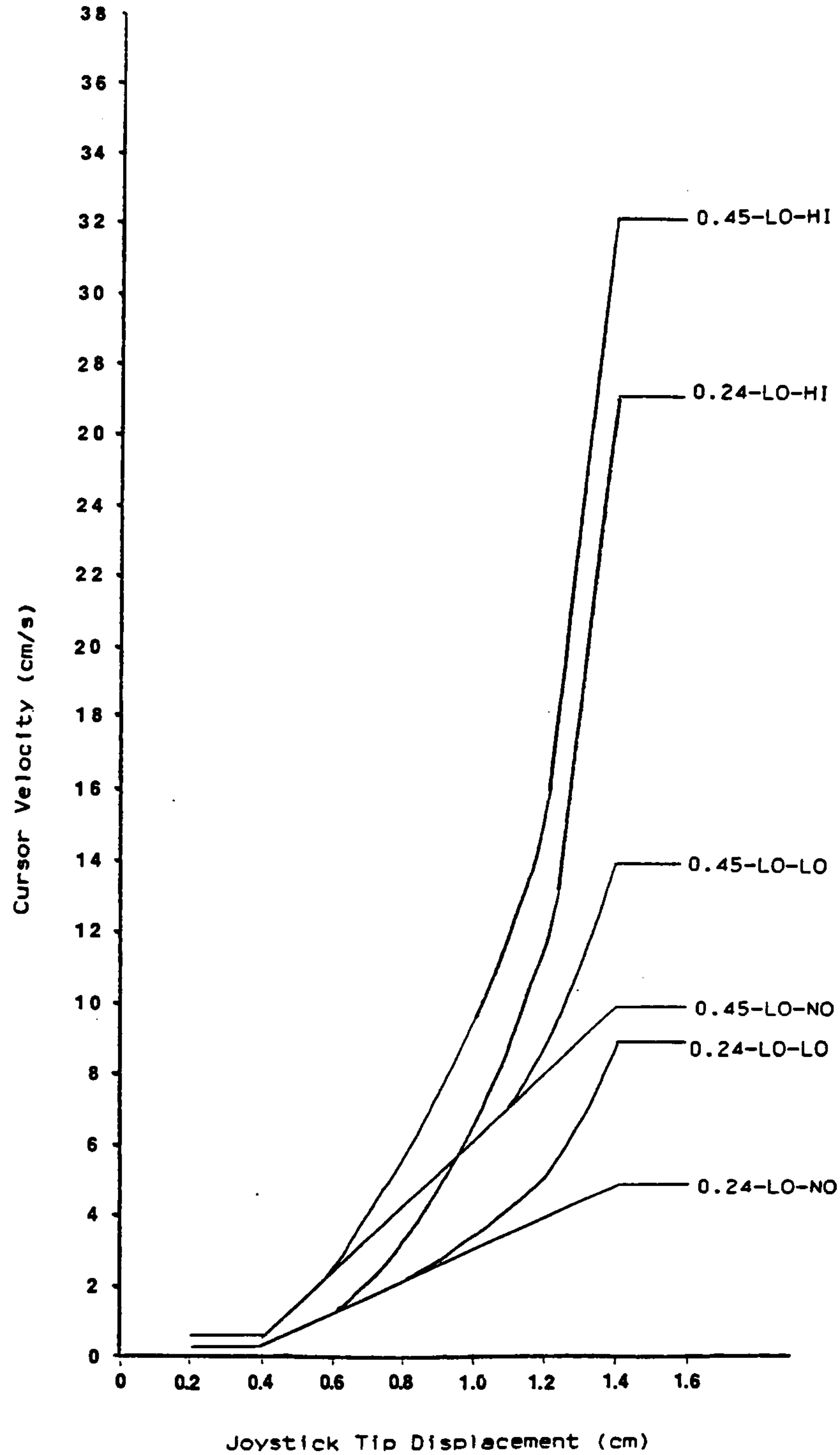
TOUCHPAD: Low Second-Order Velocity Scales



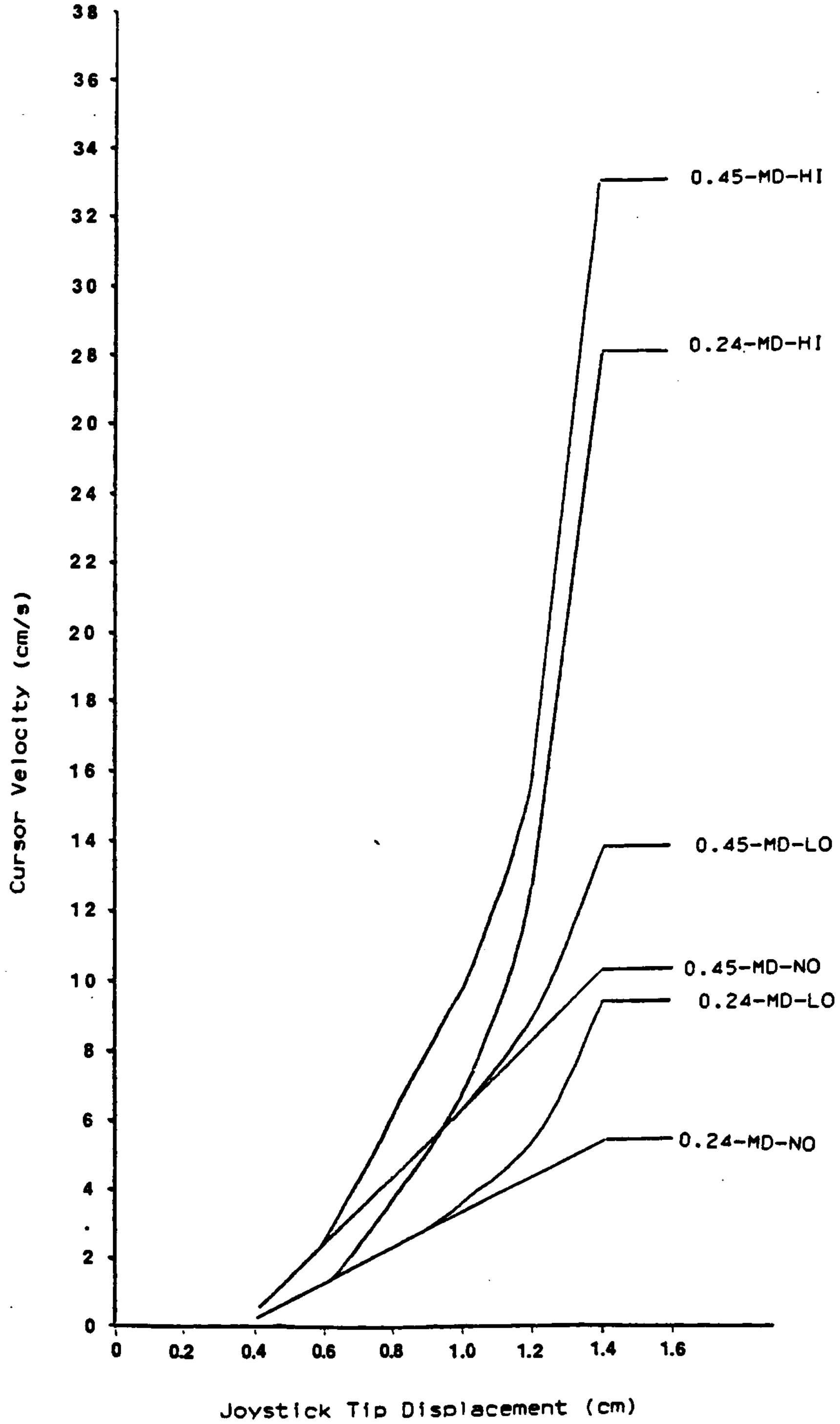
TOUCHPAD: High Second-Order Velocity Scales



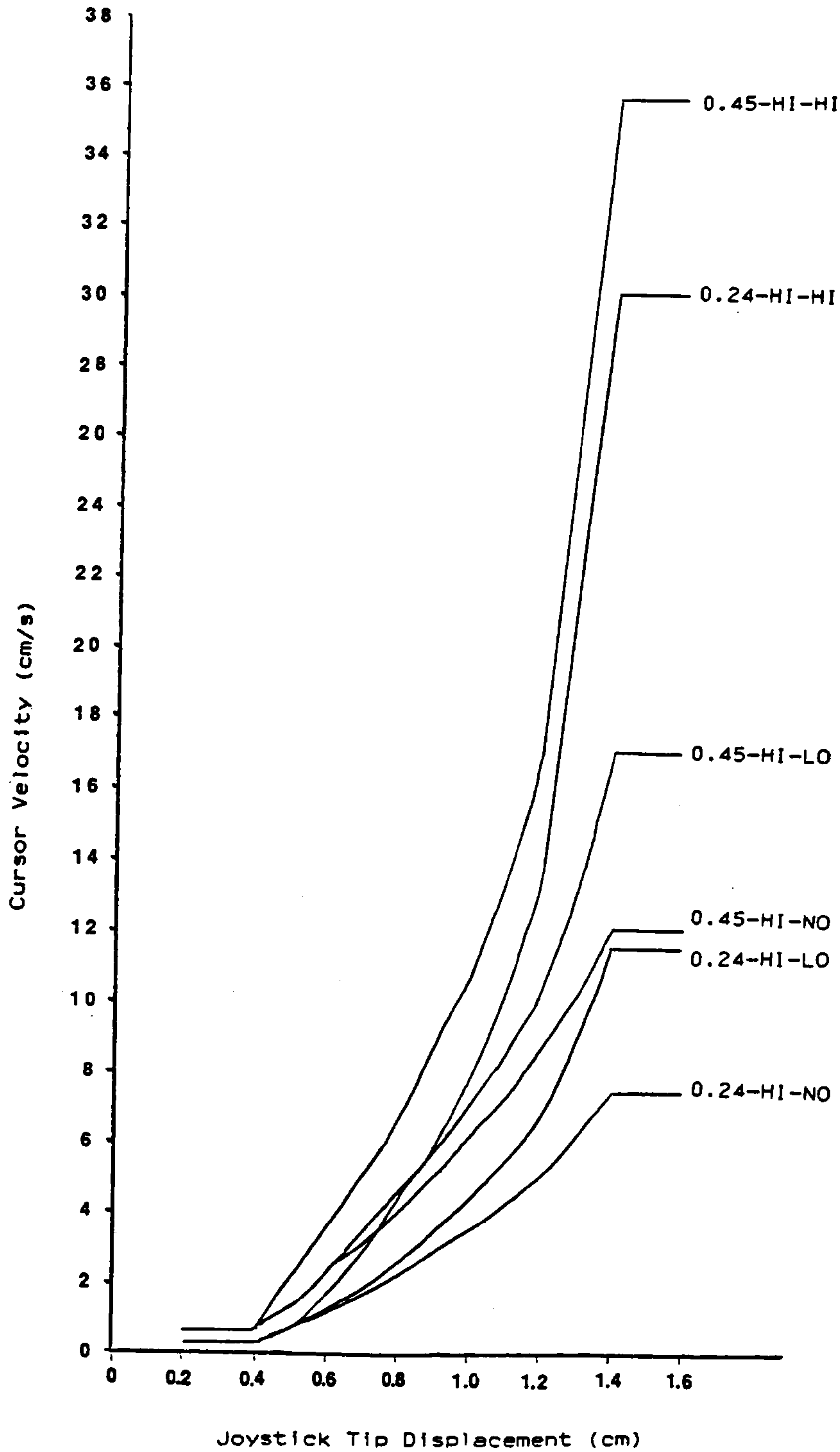
DISPLACEMENT JOYSTICK: Low First-Order Velocity Scales



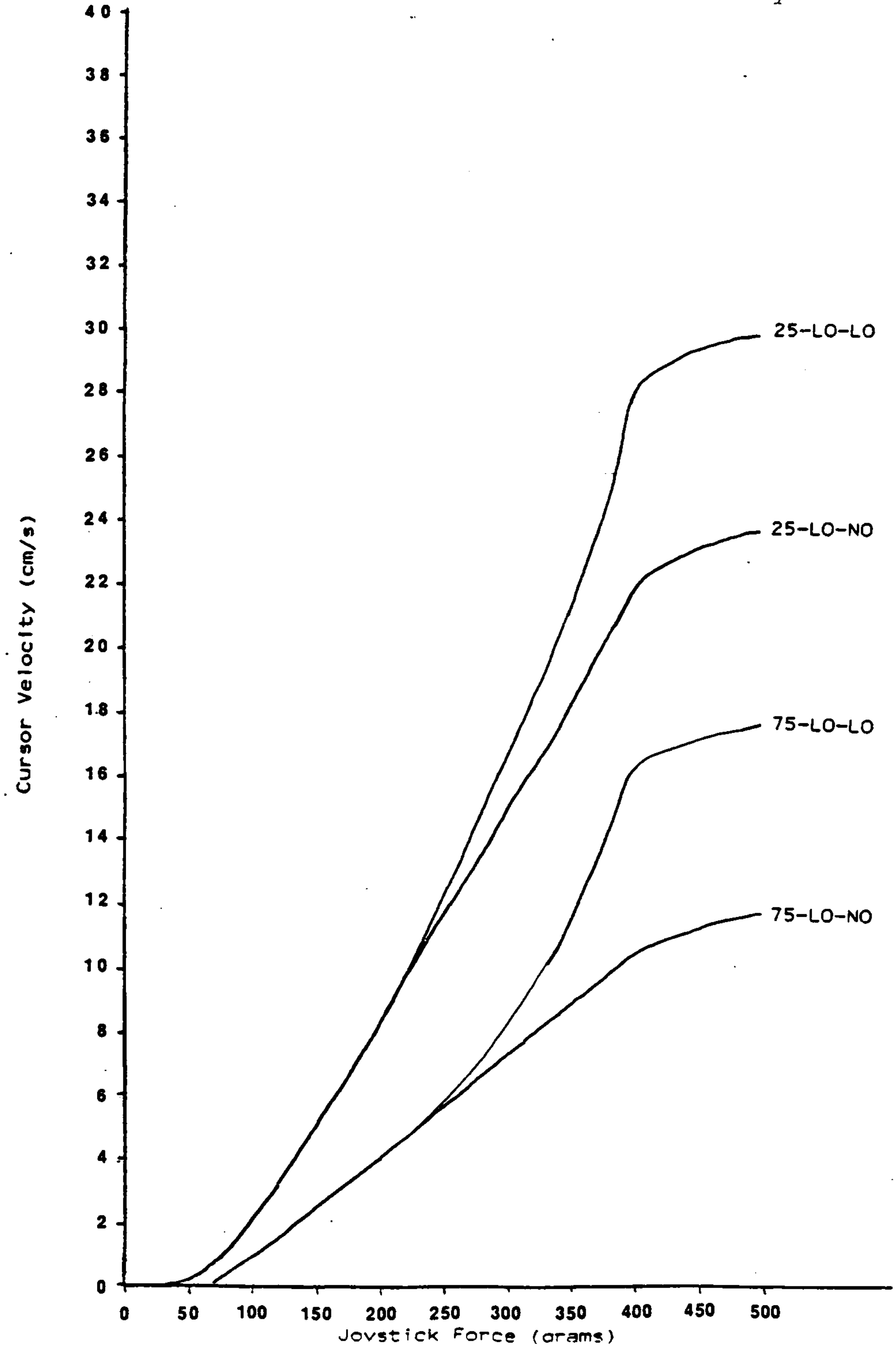
DISPLACEMENT JOYSTICK: Medium First-Order Velocity Scales



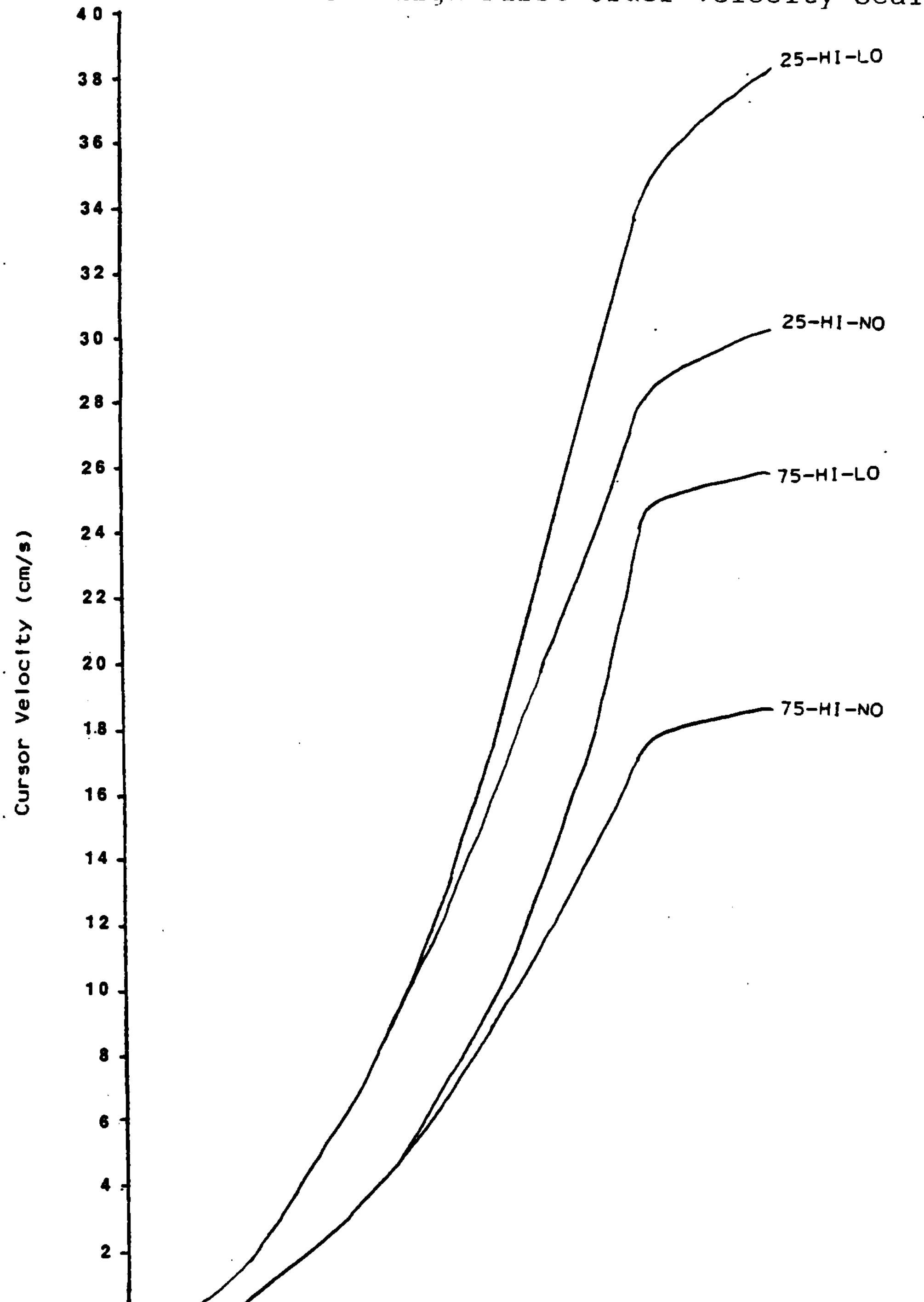
DISPLACEMENT JOYSTICK: High First-Order Velocity Scales



FORCE JOYSTICK: Low First-Order Velocity Scales



FORCE JOYSTICK: High First-Order Velocity Scales



APPENDIX B

Results of Statistical Analyses

TABLE 1

Trackball ANOVA Summary Table for Time to Target (TT)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	240473.4		
Within-subjects				
Velocity Scale (VS)	17	4367.1	1.25	0.2477
S*VS	85	3503.2		
Target Distance (TD)	3	1086672.6	198.43	0.0001
S*TD	15	5476.3		
Target Size (TS)	4	1059195.8	135.92	0.0001
S*TS	20	7792.5		
TS*TD	12	634.4	1.14	0.3500
S*TS*TD	60	558.8		
VS*TD	51	2723.6	4.06	0.0001
S*VS*TD	255	670.4		
VS*TS	68	2032.5	3.09	0.0001
S*VS*TS	340	657.6		
VS*TD*TS	204	351.6	0.72	0.9982
S*VS*TD*TS	1020	489.8		
Total	2159			

TABLE 2

Multiple Comparisons of Zero-Order Trackball Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS	
2.61	10-NO-NO	A
2.31	5-NO-NO	B

TS = 0.27

Mean TT	VS	
2.06	5-NO-NO	A
1.99	10-NO-NO	A

TS = 0.54

Mean TT	VS	
1.72	5-NO-NO	A
1.58	10-NO-NO	A

TS = 1.07

Mean TT	VS	
1.54	5-NO-NO	A
1.33	10-NO-NO	B

TS = 2.14

Mean TT	VS	
1.27	5-NO-NO	A
1.05	10-NO-NO	B

Mean TTs with the same letter within the same TS level are not significantly different.

VS = Velocity Scale: Zero-Order	+ 1st Order	+ 2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 3

Multiple Comparisons of First-Order Trackball Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS		
2.41	10-LO-NO	A	
2.39	10-HI-NO	A	
2.20	5-HI-NO	B	
2.18	5-LO-NO	B	

TS = 0.27

Mean TT	VS		
1.95	5-LO-NO	A	
1.95	10-LO-NO	A	
1.92	10-HI-NO	A	B
1.80	5-HI-NO		B

TS = 0.54

Mean TT	VS		
1.71	5-LO-NO	A	
1.54	5-HI-NO	B	
1.52	10-HI-NO	B	
1.51	10-LO-NO	B	

TS = 1.07

Mean TT	VS		
1.48	5-LO-NO	A	
1.40	5-HI-NO	A	B
1.30	10-HI-NO		B
1.29	10-LO-NO		B

TS = 2.14

Mean TT	VS	
1.19	5-LO-NO	A
1.10	5-HI-NO	A
1.09	10-LO-NO	A
1.06	10-HI-NO	A

Mean TTs with the same letter within the same TS level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 4

Multiple Comparisons of Pure Second-Order Trackball Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS		
2.58	10-NO-LO	A	
2.28	10-NO-HI	B	
2.17	5-NO-HI	B	
2.17	5-NO-LO	B	

TS = 0.27

Mean TT	VS	
1.91	5-NO-HI	A
1.90	10-NO-LO	A
1.88	5-NO-LO	A
1.86	10-NO-HI	A

TS = 0.54

Mean TT	VS	
1.57	5-NO-LO	A
1.57	10-NO-LO	A
1.56	5-NO-HI	A
1.47	10-NO-HI	A

TS = 1.07

Mean TT	VS	
1.38	5-NO-HI	A
1.33	5-NO-LO	A
1.28	10-NO-LO	A
1.24	10-NO-HI	A

TS = 2.14

Mean TT	VS		
1.14	5-NO-LO	A	
1.07	5-NO-HI	A	B
1.03	10-NO-LO	A	B
0.98	10-NO-HI		B

Mean TTs with the same letter within the same TS level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 5

Multiple Comparisons of Low First- Plus Second-Order Trackball Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS		
2.45	10-LO-HI	A	
2.29	10-LO-LO	B	
2.24	5-LO-HI	B	
2.21	5-LO-LO	B	

TS = 0.27

Mean TT	VS		
2.00	10-LO-HI	A	
1.90	5-LO-LO	A	B
1.87	10-LO-LO	A	B
1.81	5-LO-HI		B

TS = 0.54

Mean TT	VS		
1.60	5-LO-HI	A	
1.59	10-LO-HI	A	
1.55	5-LO-LO	A	
1.55	10-LO-LO	A	

TS = 1.07

Mean TT	VS		
1.36	5-LO-HI	A	
1.32	5-LO-LO	A	
1.29	10-LO-HI	A	
1.25	10-LO-LO	A	

TS = 2.14

Mean TT	VS		
1.13	5-LO-LO	A	
1.07	5-LO-HI	A	B
1.04	10-LO-HI	A	B
0.98	10-LO-LO		B

Mean TTs with the same letter within the same TS level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 6

Multiple Comparisons of High First- Plus Second-Order Trackball Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS		
2.52	10-HI-LO	A	
2.46	10-HI-HI	A	
2.14	5-HI-LO	B	
2.11	5-HI-HI	B	

TS = 0.27

Mean TT	VS		
2.01	10-HI-LO	A	
1.93	10-HI-HI	A	B
1.80	5-HI-LO	A	B
1.80	5-HI-HI		B

TS = 0.54

Mean TT	VS	
1.51	5-HI-LO	A
1.50	5-HI-HI	A
1.46	10-HI-LO	A
1.44	10-HI-HI	A

TS = 1.07

Mean TT	VS	
1.29	5-HI-HI	A
1.25	5-HI-LO	A
1.20	10-HI-LO	A
1.15	10-HI-HI	A

TS = 2.14

Mean TT	VS	
1.01	5-HI-HI	A
1.00	5-HI-LO	A
0.96	10-HI-LO	A
0.91	10-HI-HI	A

Mean TTs with the same letter within the same TS level are not significantly different.

VS = Velocity Scale:

Zero-Order	+	1st Order	+	2nd Order
5 = 5.0 D:C gain		NO = None		NO = None
10 = 10.0 D:C gain		LO = Low		LO = Low
		HI = High		HI = High

TABLE 7

Multiple Comparisons of Zero-Order Trackball Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS	
1.18	10-NO-NO	A
1.06	5-NO-NO	A

TD = 4 cm

Mean TT	VS	
1.44	10-NO-NO	A
1.43	5-NO-NO	A

TD = 8 cm

Mean TT	VS	
2.03	5-NO-NO	A
1.90	10-NO-NO	A

TD = 16 cm

Mean TT	VS	
2.59	5-NO-NO	A
2.33	10-NO-NO	B

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 8

Multiple Comparisons of First-Order Trackball Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS	
1.15	10-LO-NO	A
1.14	10-HI-NO	A
1.12	5-HI-NO	A
1.12	5-LO-NO	A

TD = 4 cm

Mean TT	VS	
1.43	10-LO-NO	A
1.40	10-HI-NO	A
1.36	5-LO-NO	A
1.36	5-HI-NO	A

TD = 8 cm

Mean TT	VS	
1.91	5-LO-NO	A
1.77	10-HI-NO	B
1.75	10-LO-NO	B
1.75	5-HI-NO	B

TD = 16 cm

Mean TT	VS	
2.41	5-LO-NO	A
2.26	10-LO-NO	B
2.22	10-HI-NO	B
2.19	5-HI-NO	B

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 9

Multiple Comparisons of Pure Second-Order Trackball Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.23	10-NO-HI	A	
1.15	10-NO-LO	A	B
1.12	5-NO-HI	A	B
1.04	5-NO-LO		B

TD = 4 cm

Mean TT	VS	
1.46	10-NO-LO	A
1.45	5-NO-LO	A
1.42	10-NO-HI	A
1.41	5-NO-HI	A

TD = 8 cm

Mean TT	VS	
1.86	10-NO-LO	A
1.81	5-NO-LO	A
1.77	5-NO-HI	A
1.63	10-NO-HI	B

TD = 16 cm

Mean TT	VS	
2.22	5-NO-LO	A
2.21	10-NO-LO	A
2.14	5-NO-HI	A
1.98	10-NO-HI	B

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale: Zero-Order + 1st Order + 2nd Order

Zero-Order	1st Order	2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 10

Multiple Comparisons of Low First- Plus Second-Order Trackball Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.26	10-LO-HI	A	
1.15	5-LO-HI	A	B
1.12	5-LO-LO		B
1.10	10-LO-LO		B

TD = 4 cm

Mean TT	VS	
1.45	10-LO-HI	A
1.44	5-LO-HI	A
1.40	10-LO-LO	A
1.37	5-LO-LO	A

TD = 8 cm

Mean TT	VS	
1.79	5-LO-LO	A
1.77	10-LO-HI	A
1.71	10-LO-LO	A
1.70	5-LO-HI	A

TD = 16 cm

Mean TT	VS	
2.21	5-LO-LO	A
2.19	10-LO-LO	A
2.17	10-LO-HI	A
2.17	5-LO-HI	A

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale:	Zero-Order	+	1st Order	+	2nd Order
	5 = 5.0 D:C gain		NO = None		NO = None
	10 = 10.0 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 11

Multiple Comparisons of High First- Plus Second-Order Trackball Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.30	10-HI-HI	A	
1.22	10-HI-LO	A	B
1.14	5-HI-HI		B
1.13	5-HI-LO		B

TD = 4 cm

Mean TT	VS	
1.43	10-HI-LO	A
1.42	10-HI-HI	A
1.40	5-HI-LO	A
1.38	5-HI-HI	A

TD = 8 cm

Mean TT	VS	
1.74	10-HI-LO	A
1.68	10-HI-HI	A
1.67	5-HI-LO	A
1.65	5-HI-HI	A

TD = 16 cm

Mean TT	VS		
2.12	10-HI-LO	A	
2.00	5-HI-HI	A	B
1.99	5-HI-LO	A	B
1.93	10-HI-HI		B

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale: Zero-Order	+ 1st Order	+ 2nd Order
5 = 5.0 D:C gain	NO = None	NO = None
10 = 10.0 D:C gain	LO = Low	LO = Low
	HI = High	HI = High

TABLE 12

ANOVA Summary Table for Mouse Time-to-Target (TT)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	97511.0		
Within-subjects				
Velocity Scale (VS)	17	6872.7	1.16	0.3122
S*VS	85	5911.2		
Target Distance (TD)	3	678328.3	153.98	0.0001
S*TD	15	4405.4		
Target Size (TS)	4	2187675.8	217.77	0.0001
S*TS	20	10045.7		
VS*TD	51	2688.1	1.46	0.0315
S*VS*TD	255	1842.1		
VS*TS	68	4538.7	1.92	0.0001
S*VS*TS	340	2358.2		
TS*TD	12	4005.7	2.07	0.0331
S*TS*TD	60	1937.2		
VS*TD*TS	204	1875.2	1.13	0.1286
S*VS*TD*TS	1020	1665.2		
Total	2159			

TABLE 13

Multiple Comparisons of Zero-Order Mouse Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS	
3.21	2-NO-NO	A
2.37	1-NO-NO	B

TS = 0.27

Mean TT	VS	
2.20	2-NO-NO	A
1.92	1-NO-NO	B

TS = 0.54

Mean TT	VS	
1.52	2-NO-NO	A
1.47	1-NO-NO	A

TS = 1.07

Mean TT	VS	
1.17	1-NO-NO	A
1.12	2-NO-NO	A

TS = 2.14

Mean TT	VS	
0.95	2-NO-NO	A
0.93	1-NO-NO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 14

Multiple Comparisons of First-Order Mouse Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS		
2.88	2-LO-NO	A	
2.69	1-HI-NO	A	
2.64	2-HI-NO	A	
2.34	1-LO-NO	B	

TS = 0.27

Mean TT	VS		
2.26	2-LO-NO	A	
2.05	2-HI-NO	A	B
1.99	1-HI-NO	A	B
1.95	1-LO-NO		B

TS = 0.54

Mean TT	VS	
1.58	2-HI-NO	A
1.50	2-LO-NO	A
1.48	1-HI-NO	A
1.48	1-LO-NO	A

TS = 1.07

Mean TT	VS	
1.31	1-LO-NO	A
1.28	1-HI-NO	A
1.17	2-HI-NO	A
1.13	2-LO-NO	A

TS = 2.14

Mean TT	VS	
0.95	1-HI-NO	A
0.94	1-LO-NO	A
0.93	2-HI-NO	A
0.92	2-LO-NO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 15

Multiple Comparisons of Pure Second-Order Mouse Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS		
3.17	2-NO-HI	A	
2.98	2-NO-LO	A	
2.61	1-NO-HI	B	
2.48	1-NO-LO	B	

TS = 0.27

Mean TT	VS	
2.16	2-NO-HI	A
2.09	1-NO-HI	A
2.06	2-NO-LO	A
1.93	1-NO-LO	A

TS = 0.54

Mean TT	VS		
1.79	1-NO-LO	A	
1.68	1-NO-HI	A	B
1.64	2-NO-HI	A	B
1.48	2-NO-LO		B

TS = 1.07

Mean TT	VS	
1.26	1-NO-LO	A
1.24	1-NO-HI	A
1.24	2-NO-HI	A
1.10	2-NO-LO	A

TS = 2.14

Mean TT	VS	
1.04	1-NO-HI	A
1.01	1-NO-LO	A
0.97	2-NO-HI	A
0.91	2-NO-LO	A

Mean TT's with the same letter within a TS level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 16

Multiple Comparisons of Low First-Order Plus Second-Order Mouse Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS	
3.00	2-LO-HI	A
2.94	2-LO-LO	A
2.78	1-LO-HI	B
2.45	1-LO-LO	B

TS = 0.27

Mean TT	VS		
2.25	2-LO-HI	A	
2.13	2-LO-LO	A	B
1.97	1-LO-LO		B
1.95	1-LO-HI		B

TS = 0.54

Mean TT	VS	
1.67	2-LO-HI	A
1.54	1-LO-LO	A
1.51	1-LO-HI	A
1.48	2-LO-LO	A

TS = 1.07

Mean TT	VS	
1.26	1-LO-HI	A
1.21	2-LO-HI	A
1.14	2-LO-LO	A
1.12	1-LO-LO	A

TS = 2.14

Mean TT	VS	
1.02	1-LO-LO	A
1.01	1-LO-HI	A
0.95	2-LO-HI	A
0.90	2-LO-LO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale	0th Order +	1st Order +	2nd Order
	1 = 1.3 D:C gain	NO = None	NO = None
	2 = 2.6 D:C gain	LO = Low	LO = Low
		HI = High	HI = High

TABLE 17

Multiple Comparisons of High First-Order Plus Second-Order Mouse Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS	
3.03	2-HI-HI	A
2.84	2-HI-LO	A B
2.57	1-HI-HI	B C
2.56	1-HI-LO	C

TS = 0.27

Mean TT	VS	
2.20	2-HI-LO	A
2.11	2-HI-HI	A
2.03	1-HI-LO	A
1.93	1-HI-HI	A

TS = 0.54

Mean TT	VS	
1.77	2-HI-HI	A
1.72	2-HI-LO	A
1.72	1-HI-LO	A
1.65	1-HI-HI	A

TS = 1.07

Mean TT	VS	
1.32	1-HI-LO	A
1.29	2-HI-HI	A
1.28	1-HI-HI	A
1.27	2-HI-LO	A

TS = 2.14

Mean TT	VS	
1.03	1-HI-HI	A
0.96	2-HI-LO	A
0.96	1-HI-LO	A
0.95	2-HI-HI	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 18

Multiple Comparisons of Zero-Order Mouse Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS	
1.54	2-NO-NO	A
1.13	1-NO-NO	B

TD = 4 cm

Mean TT	VS	
1.73	2-NO-NO	A
1.36	1-NO-NO	B

TD = 8 cm

Mean TT	VS	
1.80	2-NO-NO	A
1.66	1-NO-NO	A

TD = 16 cm

Mean TT	VS	
2.16	1-NO-NO	A
2.12	2-NO-NO	A

Mean TTs with the same letter within a TD are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.0 D:C gain		NO = None		NO = None
	2 = 2.0 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 19

Multiple Comparisons of First-Order Mouse Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS	
1.46	2-HI-NO	A
1.45	2-LO-NO	A
1.20	1-LO-NO	B
1.19	1-HI-NO	B

TD = 4 cm

Mean TT	VS	
1.58	2-LO-NO	A
1.55	2-HI-NO	A
1.51	1-LO-NO	A
1.47	1-HI-NO	A

TD = 8 cm

Mean TT	VS	
1.98	1-HI-NO	A
1.73	2-LO-NO	B
1.66	1-LO-NO	B
1.63	2-HI-NO	B

TD = 16 cm

Mean TT	VS	
2.19	2-LO-NO	A
2.07	1-HI-NO	A
2.05	2-HI-NO	A
2.04	1-LO-NO	A

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 20

Multiple Comparisons of Pure Second-Order Mouse Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS		
1.45	2-NO-LO	A	
1.41	2-NO-HI	A	
1.30	1-NO-LO	A	
1.27	1-NO-HI	A	

TD = 4 cm

Mean TT	VS		
1.70	2-NO-HI	A	
1.62	2-NO-LO	A	
1.49	1-NO-HI	A	B
1.38	1-NO-LO		B

TD = 8 cm

Mean TT	VS	
1.89	2-NO-HI	A
1.83	1-NO-HI	A
1.78	2-NO-LO	A
1.73	1-NO-LO	A

TD = 16 cm

Mean TT	VS	
2.38	1-NO-LO	A
2.34	2-NO-HI	A
2.33	1-NO-HI	A
1.98	2-NO-LO	B

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 21

Multiple Comparisons of Low First-Order Plus Second-Order Mouse Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS		
1.48	2-LO-HI	A	
1.38	2-LO-LO	A	B
1.31	1-LO-HI	A	B
1.15	1-LO-LO		B

TD = 4 cm

Mean TT	VS	
1.66	2-LO-HI	A
1.61	2-LO-LO	A
1.52	1-LO-LO	A
1.47	1-LO-HI	A

TD = 8 cm

Mean TT	VS	
1.84	2-LO-HI	A
1.82	1-LO-HI	A
1.79	2-LO-LO	A
1.73	1-LO-LO	A

TD = 16 cm

Mean TT	VS	
2.28	2-LO-HI	A
2.21	1-LO-HI	A
2.08	2-LO-LO	A
2.07	1-LO-LO	A

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 22

Multiple Comparisons of High First-Order Plus Second-Order Mouse Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS	
1.47	2-HI-HI	A
1.46	2-HI-LO	A
1.33	1-HI-HI	A
1.29	1-HI-LO	A

TD = 4 cm

Mean TT	VS		
1.76	2-HI-HI	A	
1.67	2-HI-LO	A	B
1.53	1-HI-LO		B
1.49	1-HI-HI		B

TD = 8 cm

Mean TT	VS	
1.86	2-HI-HI	A
1.83	1-HI-LO	A
1.78	1-HI-HI	A
1.76	2-HI-LO	A

TD = 16 cm

Mean TT	VS	
2.30	2-HI-LO	A
2.23	2-HI-HI	A
2.22	1-HI-LO	A
2.18	1-HI-HI	A

Mean TTs with the same letter within a TD level are not significantly different.

VS = Velocity Scale	0th Order	+	1st Order	+	2nd Order
	1 = 1.3 D:C gain		NO = None		NO = None
	2 = 2.6 D:C gain		LO = Low		LO = Low
			HI = High		HI = High

TABLE 23

ANOVA Summary Table for Touchpad Time to Target (TT)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	528795.0		
Within-subjects				
Velocity Scale (VS)	26	17288.8	0.97	0.5144
S*VS	130	17847.8		
Target Distance (TD)	3	1290762.6	127.49	0.0001
S*TD	15	10124.4		
Target Size (TS)	4	3937814.0	98.86	0.0001
S*TS	20	39831.4		
VS*TD	78	6402.6	4.36	0.0001
S*VS*TD	390	1469.3		
VS*TS	104	3469.6	1.18	0.1264
S*VS*TS	520	2939.8		
TS*TD	12	5938.3	4.08	0.0001
S*TS*TD	60	1457.2		
VS*TD*TS	312	1651.6	1.13	0.0804
S*VS*TD*TS	1560	1465.3		
Total	3239			

TABLE 24

Multiple Comparisons of Zero-Order Touchpad Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.65	2-NO-NO	A	
1.42	.3-NO-NO	B	
1.30	1-NO-NO	B	

TD = 4 cm

Mean TT	VS		
1.78	.3-NO-NO	A	
1.72	2-NO-NO	A	B
1.56	1-NO-NO		B

TD = 8 cm

Mean TT	VS	
2.48	.3-NO-NO	A
2.15	2-NO-NO	B
2.00	1-NO-NO	B

TD = 16 cm

Mean TT	VS	
3.59	.3-NO-NO	A
2.48	2-NO-NO	B
2.40	1-NO-NO	B

Mean TTs with the same letter within a given TD are not significantly different.

VS = Velocity Scale	0th order	+	1st Order	+	2nd Order
	.3 = 0.33 D:C gain		NO = None		NO = None
	1 = 1.0 D:C gain		LO = Low		LO = Low
	2 = 2.0 D:C gain		HI = High		HI = High

TABLE 25

Multiple Comparisons of First-Order Touchpad Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.53	.3-HI-NO	A	
1.45	2-LO-NO	A	
1.42	2-HI-NO	A	
1.38	1-HI-NO	A	
1.38	1-LO-NO	A	
1.34	.3-LO-NO	A	

TD = 4 cm

Mean TT	VS		
1.75	2-LO-NO	A	
1.64	2-HI-NO	A	B
1.64	.3-LO-NO	A	B
1.64	.3-HI-NO	A	B
1.59	1-HI-NO	A	B
1.47	1-LO-NO		B

TD = 8 cm

Mean TT	VS		
2.09	.3-LO-NO	A	
2.03	.3-HI-NO	A	B
1.97	2-HI-NO	A	B
1.97	2-LO-NO	A	B
1.86	1-HI-NO		B
1.84	1-LO-NO		B

TD = 16 cm

Mean TT	VS	
2.60	.3-LO-NO	A
2.39	2-LO-NO	B
2.32	1-LO-NO	B
2.25	2-HI-NO	B
2.23	.3-HI-NO	B
2.19	1-HI-NO	B

Mean TTs with the same letter within a given TD are not significantly different.

VS = Velocity Scale	0th order	+	1st Order	+	2nd Order
	.3 = 0.33 D:C gain		NO = None		NO = None
	1 = 1.0 D:C gain		LO = Low		LO = Low
	2 = 2.0 D:C gain		HI = High		HI = High

TABLE 26

Multiple Comparisons of Pure Second-Order Touchpad Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.56	2-NO-HI	A	
1.52	2-NO-LO	A	
1.45	.3-NO-HI	A	B
1.37	1-NO-LO	A	B
1.27	1-NO-HI		B
1.25	.3-NO-LO		B

TD = 4 cm

Mean TT	VS	
1.70	1-NO-HI	A
1.69	.3-NO-HI	A
1.63	2-NO-HI	A
1.60	2-NO-LO	A
1.58	1-NO-LO	A
1.52	.3-NO-LO	A

TD = 8 cm

Mean TT	VS				
2.22	1-NO-LO	A			
2.08	.3-NO-HI	A	B		
1.99	2-NO-LO		B	C	
1.88	.3-NO-LO		B	C	D
1.80	1-NO-HI			C	D
1.78	2-NO-HI				D

TD = 16 cm

Mean TT	VS			
2.42	.3-NO-HI	A		
2.41	1-NO-LO	A		
2.38	2-NO-LO	A	B	
2.34	.3-NO-LO	A	B	
2.19	1-NO-HI		B	C
2.09	2-NO-HI			C

Mean TTs with the same letter within a given TD are not significantly different.

VS = Velocity Scale	0th order +	1st Order +	2nd Order
	.3 = 0.33 D:C gain	NO = None	NO = None
	1 = 1.0 D:C gain	LO = Low	LO = Low
	2 = 2.0 D:C gain	HI = High	HI = High

TABLE 27

Multiple Comparisons of Low First- Plus Second-Order Touchpad Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.61	.3-LO-HI	A	
1.50	2-LO-LO	A	B
1.44	1-LO-HI	A	B
1.43	2-LO-HI	A	B
1.40	1-LO-LO		B
1.31	.3-LO-LO		B

TD = 4 cm

Mean TT	VS		
1.73	.3-LO-HI	A	
1.68	2-LO-LO	A	B
1.63	.3-LO-LO	A	B
1.58	1-LO-HI	A	B
1.57	2-LO-HI	A	B
1.50	1-LO-LO		B

TD = 8 cm

Mean TT	VS	
2.06	.3-LO-HI	A
2.04	2-LO-LO	A
1.97	1-LO-LO	A
1.90	.3-LO-LO	A
1.88	2-LO-HI	A
1.87	1-LO-HI	A

TD = 16 cm

Mean TT	VS		
2.37	.3-LO-LO	A	
2.35	.3-LO-HI	A	B
2.33	2-LO-LO	A	B
2.31	1-LO-LO	A	B
2.28	2-LO-HI	A	B
2.15	1-LO-HI		B

Mean TTs with the same letter within a given TD are not significantly different.

VS = Velocity Scale   0th order + 1st Order + 2nd Order

0th order	1st Order	2nd Order
.3 = 0.33 D:C gain	NO = None	NO = None
1 = 1.0 D:C gain	LO = Low	LO = Low
2 = 2.0 D:C gain	HI = High	HI = High

TABLE 28

Multiple Comparisons of High First- Plus Second-Order Touchpad Velocity Scales Across Target Distances

TD = 2 cm

Mean TT	VS		
1.59	.3-HI-HI	A	
1.49	.3-HI-LO	A	
1.45	2-HI-LO	A	
1.44	2-HI-HI	A	
1.43	1-HI-LO	A	
1.40	1-HI-HI	A	

TD = 4 cm

Mean TT	VS		
1.92	.3-HI-HI	A	
1.85	2-HI-LO	A	
1.79	1-HI-HI	A	B
1.78	2-HI-HI	A	B
1.77	1-HI-LO	A	B
1.60	.3-HI-LO		B

TD = 8 cm

Mean TT	VS		
2.16	2-HI-HI	A	
2.16	.3-HI-HI	A	
2.00	2-HI-LO	A	B
1.96	1-HI-LO	A	B
1.95	.3-HI-LO		B
1.90	1-HI-HI		B

TD = 16 cm

Mean TT	VS	
2.52	.3-HI-HI	A
2.29	2-HI-LO	B
2.19	1-HI-LO	B
2.18	2-HI-HI	B
2.14	1-HI-HI	B
2.09	.3-HI-LO	B

Mean TTs with the same letter within a given TD are not significantly different.

VS = Velocity Scale	0th order	+ 1st Order	+ 2nd Order
	.3 = 0.33 D:C gain	NO = None	NO = None
	1 = 1.0 D:C gain	LO = Low	LO = Low
	2 = 2.0 D:C gain	HI = High	HI = High

TABLE 29

ANOVA Summary Table for Displacement Joystick Time to Target (TT)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	896777.7		
Within-subjects				
Velocity Scale (VS)	17	59869.6	1.70	0.0590
S*VS	85	35295.8		
Target Distance (TD)	3	1033227.1	270.13	0.0001
S*TD	15	7527.0		
Target Size (TS)	4	8027061.0	144.40	0.0001
S*TS	20	55590.0		
VS*TD	51	8532.1	2.28	0.0001
S*VS*TD	255	3745.8		
VS*TS	68	9422.0	1.56	0.0058
S*VS*TS	340	6035.8		
TS*TD	12	7572.9	1.61	0.1138
S*TS*TD	60	4703.7		
VS*TD*TS	204	3280.3	0.94	0.7220
S*VS*TD*TS	1020	3507.6		
Total	2159			

TABLE 30

Multiple Comparisons of Low First-Order Joystick Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS	
4.87	.45-LO-HI	A
4.66	.45-LO-NO	A B
4.65	.24-LO-NO	A B
4.49	.45-LO-LO	A B
4.36	.24-LO-LO	B
4.32	.24-LO-HI	B

TS = 0.27

Mean TT	VS	
3.91	.45-LO-HI	A
3.56	.45-LO-NO	A B
3.52	.24-LO-NO	A B
3.46	.24-LO-HI	B
3.40	.24-LO-LO	B
3.40	.45-LO-LO	B

TS = 0.54

Mean TT	VS	
3.13	.45-LO-HI	A
2.60	.45-LO-NO	B
2.53	.45-LO-LO	B
2.35	.24-LO-NO	B
2.34	.24-LO-HI	B
2.30	.24-LO-LO	B

TS = 1.07

Mean TT	VS	
1.82	.24-LO-NO	A
1.80	.45-LO-HI	A
1.69	.45-LO-NO	A
1.66	.24-LO-HI	A
1.60	.45-LO-LO	A
1.56	.24-LO-LO	A

TS = 2.14

Mean TT	VS	
1.48	.24-LO-NO	A
1.23	.45-LO-NO	A
1.18	.45-LO-HI	A
1.13	.45-LO-LO	A
1.11	.24-LO-HI	A
1.09	.24-LO-LO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS=Velocity Scale: Minimum Cursor Velocity + 1st Order + 2nd Order

Minimum Cursor Velocity	1st Order	2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 31

Multiple Comparisons of Medium First-Order Joystick Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS				
5.36	.45-MD-HI	A			
4.66	.45-MD-LO	B			
4.42	.45-MD-NO	B	C		
4.35	.24-MD-NO	B	C		
4.13	.24-MD-HI		C	D	
3.87	.24-MD-LO			D	

TS = 0.27

Mean TT	VS		
4.04	.45-MD-HI	A	
3.86	.45-MD-LO	A	
3.81	.24-MD-HI	A	
3.32	.45-MD-NO	B	
3.28	.24-MD-NO	B	
3.18	.24-MD-LO	B	

TS = 0.54

Mean TT	VS			
3.13	.45-MD-HI	A		
2.79	.45-MD-LO	A	B	
2.60	.24-MD-HI		B	
2.53	.45-MD-NO		B	
2.44	.24-MD-NO		B	C
2.06	.24-MD-LO			C

TS = 1.07

Mean TT	VS			
2.20	.45-MD-HI	A		
2.02	.45-MD-LO	A	B	
1.72	.24-MD-NO		B	C
1.71	.24-MD-HI		B	C
1.58	.24-MD-LO		B	C
1.56	.45-MD-NO			C

TS = 2.14

Mean TT	VS	
1.39	.24-MD-NO	A
1.15	.24-MD-LO	A
1.14	.45-MD-HI	A
1.13	.45-MD-LO	A
1.13	.24-MD-HI	A
1.11	.45-MD-NO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS=Velocity Scale:

Minimum Cursor Velocity	+ 1st Order	+ 2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 32

Multiple Comparisons of High First-Order Joystick Velocity Scales Across Target Size

TS = 0.13

Mean TT	VS					
5.29	.45-HI-LO	A				
5.14	.45-HI-HI	A	B			
4.79	.45-HI-NO		B	C		
4.45	.24-HI-HI			C	D	
4.17	.24-HI-NO				D	E
3.83	.24-HI-LO					E

TS = 0.27

Mean TT	VS			
4.03	.45-HI-HI	A		
3.74	.24-HI-HI	A	B	
3.70	.45-HI-LO	A	B	
3.70	.45-HI-NO	A	B	
3.32	.24-HI-LO		B	C
3.26	.24-HI-NO			C

TS = 0.54

Mean TT	VS			
2.94	.45-HI-HI	A		
2.86	.24-HI-HI	A		
2.69	.45-HI-NO	A	B	
2.68	.45-HI-LO	A	B	
2.34	.24-HI-NO		B	C
2.12	.24-HI-LO			C

TS = 1.07

Mean TT	VS		
2.05	.45-HI-HI	A	
1.79	.24-HI-HI	A	B
1.75	.45-HI-LO	A	B
1.73	.45-HI-NO	A	B
1.57	.24-HI-NO		B
1.51	.24-HI-LO		B

TS = 2.14

Mean TT	VS	
1.22	.24-HI-NO	A
1.20	.24-HI-HI	A
1.19	.45-HI-LO	A
1.12	.45-HI-HI	A
1.12	.45-HI-NO	A
1.10	.24-HI-LO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS=Velocity Scale: Minimum Cursor Velocity + 1st Order + 2nd Order

Minimum Cursor Velocity	1st Order	2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 33

Multiple Comparisons of Low First-Order Joystick Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS	
2.38	.45-LO-HI	A
2.17	.45-LO-NO	A B
2.05	.45-LO-LO	B
2.03	.24-LO-HI	B
1.94	.24-LO-NO	B
1.86	.24-LO-LO	B

TD = 4 cm

Mean TT	VS	
2.71	.45-LO-HI	A
2.43	.45-LO-NO	A B
2.34	.45-LO-LO	B
2.31	.24-LO-LO	B
2.20	.24-LO-HI	B
2.18	.24-LO-NO	B

TD = 8 cm

Mean TT	VS	
3.04	.45-LO-HI	A
2.93	.24-LO-HI	A B
2.86	.45-LO-NO	A B
2.86	.24-LO-NO	A B
2.76	.45-LO-LO	A B
2.66	.24-LO-LO	B

TD = 16 cm

Mean TT	VS	
4.07	.24-LO-NO	A
3.79	.45-LO-HI	A B
3.53	.45-LO-NO	B C
3.36	.45-LO-LO	C D
3.35	.24-LO-LO	C D
3.16	.24-LO-HI	D

Mean TTs with the same letter within a TD level are not significantly different.

VS=Velocity Scale: Minimum Cursor Velocity + 1st Order + 2nd Order

Minimum Cursor Velocity	1st Order	2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 34

Multiple Comparisons of Medium First-Order Joystick Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS	
2.75	.45-MD-HI	A
2.22	.45-MD-LO	B
2.09	.45-MD-NO	B C
2.06	.24-MD-HI	B C
1.87	.24-MD-NO	C D
1.58	.24-MD-LO	D

TD = 4 cm

Mean TT	VS	
2.84	.45-MD-HI	A
2.74	.45-MD-LO	A
2.42	.24-MD-HI	B
2.32	.45-MD-NO	B C
2.10	.24-MD-LO	C
2.07	.24-MD-NO	C

TD = 8 cm

Mean TT	VS	
3.21	.45-MD-HI	A
3.12	.45-MD-LO	A B
2.82	.24-MD-HI	B C
2.65	.45-MD-NO	C
2.64	.24-MD-NO	C
2.63	.24-MD-LO	C

TD = 16 cm

Mean TT	VS	
3.95	.24-MD-NO	A
3.89	.45-MD-HI	A
3.52	.45-MD-LO	B
3.40	.24-MD-HI	B C
3.27	.45-MD-NO	B C
3.15	.24-MD-LO	C

Mean TTs with the same letter within a TD level are not significantly different.

VS=Velocity Scale: Minimum Cursor Velocity + 1st Order + 2nd Order

Minimum Cursor Velocity	1st Order	2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 35

Multiple Comparisons of High First-Order Joystick Velocity Scales Across Target Distance

TD = 2 cm

Mean TT	VS			
2.51	.45-HI-HI	A		
2.42	.45-HI-LO	A	B	
2.29	.45-HI-NO	A	B	
2.07	.24-HI-HI		B	C
1.78	.24-HI-LO			C
1.71	.24-HI-NO			C

TD = 4 cm

Mean TT	VS	
2.89	.45-HI-HI	A
2.64	.45-HI-NO	A
2.61	.24-HI-HI	A
2.60	.45-HI-LO	A
2.23	.24-HI-NO	B
2.03	.24-HI-LO	B

TD = 8 cm

Mean TT	VS			
3.11	.24-HI-HI	A		
3.10	.45-HI-HI	A		
3.01	.45-HI-LO	A	B	
2.74	.24-HI-NO		B	C
2.65	.45-HI-NO			C
2.65	.24-HI-LO			C

TD = 16 cm

Mean TT	VS		
3.71	.45-HI-HI	A	
3.67	.45-HI-LO	A	B
3.64	.45-HI-NO	A	B
3.44	.24-HI-HI	A	B
3.38	.24-HI-NO		B
3.05	.24-HI-LO	C	

Mean TTs with the same letter within a TD level are not significantly different.

VS=Velocity Scale: Minimum Cursor Velocity + 1st Order + 2nd Order

Minimum Cursor Velocity	1st Order	2nd Order
0.24 cm/s	LO=Low	NO=None
0.45 cm/s	MD=Medium	LO=Low
	HI=High	HI=High

TABLE 36

ANOVA Summary Table for Force Joystick Time to Target (TT)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	643995.0		
Within-subjects				
Velocity Scale (VS)	7	55294.0	2.46	0.0365
S*VS	35	22461.9		
Target Distance (TD)	3	679486.4	48.94	0.0001
S*TD	15	13882.7		
Target Size (TS)	4	5544422.5	85.34	0.0001
S*TS	20	64967.8		
VS*TD	21	5043.0	0.87	0.6280
S*VS*TD	105	5791.6		
VS*TS	28	23758.0	2.49	0.0003
S*VS*TS	140	9537.9		
TS*TD	12	8632.4	1.49	0.1548
S*TS*TD	60	5808.5		
VS*TD*TS	84	4699.2	0.73	0.9627
S*VS*TD*TS	420	6467.6		
Total	959			

TABLE 37

Multiple Comparisons of Low First-Order Joystick Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS	
6.08	75-LO-NO	A
6.05	75-LO-LO	A
5.03	25-LO-NO	B
4.59	25-LO-LO	B

TS = 0.27

Mean TT	VS	
3.88	75-LO-NO	A
3.75	75-LO-LO	A
3.40	25-LO-NO	A
3.31	25-LO-LO	A

TS = 0.54

Mean TT	VS	
2.53	75-LO-NO	A
2.35	75-LO-LO	A
2.29	25-LO-LO	A
2.25	25-LO-NO	A

TT = 1.07

Mean TT	VS	
1.75	75-LO-NO	A
1.66	25-LO-NO	A
1.60	25-LO-LO	A
1.53	75-LO-LO	A

TS = 2.14

Mean TT	VS	
1.22	75-LO-NO	A
1.20	25-LO-LO	A
1.18	25-LO-NO	A
1.14	75-LO-LO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale: Minimum Force + 1st Order + 2nd Order

Minimum Force	1st Order	2nd Order
25 grams	LO = Low	NO = None
75 grams	HI = High	LO = Low

TABLE 38

Multiple Comparisons of High First-Order Joystick Velocity Scales Across Target Sizes

TS = 0.13

Mean TT	VS	
6.26	75-HI-LO	A
5.92	75-HI-NO	A
4.96	25-HI-NO	B
4.57	25-HI-LO	B

TS = 0.27

Mean TT	VS		
3.95	75-HI-NO	A	
3.93	75-HI-LO	A	
3.43	25-HI-NO	A	B
3.24	25-HI-LO		B

TS = 0.54

Mean TT	VS	
2.58	75-HI-LO	A
2.47	25-HI-NO	A
2.42	75-HI-NO	A
2.30	25-HI-LO	A

TS = 1.07

Mean TT	VS	
1.84	25-HI-LO	A
1.70	75-HI-LO	A
1.63	25-HI-NO	A
1.60	75-HI-NO	A

TS = 2.14

Mean TT	VS	
1.31	25-HI-LO	A
1.20	25-HI-NO	A
1.19	75-HI-NO	A
1.19	75-HI-LO	A

Mean TTs with the same letter within a TS level are not significantly different.

VS = Velocity Scale: Minimum Force + 1st Order + 2nd Order

Minimum Force	1st Order	2nd Order
25 grams	LO = Low	NO = None
75 grams	HI = High	LO = Low

TABLE 39

Multiple Comparisons for the Force Joystick Velocity Scale Main Effect

Mean TT	VS				
3.15	75-HI-LO	A			
3.09	75-LO-NO	A	B		
3.01	75-HI-NO	A	B	C	
2.96	75-LO-LO	A	B	C	D
2.74	25-HI-NO		B	C	D
2.70	25-LO-NO		B	C	D
2.65	25-HI-LO			C	D
2.60	25-LO-LO				D

Mean TTs with the same letter are not significantly different.

VS = Velocity Scale: Minimum Force + 1st Order + 2nd Order

Minimum Force	1st Order	2nd Order
25 grams	LO = Low	NO = None
75 grams	HI = High	LO = Low

TABLE 40

ANOVA Summary Table for Trial Block Analysis Based on Time to Target (TT) for Target Acquisition Task

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	2.975		
Within-Subjects				
Device (DEV)	5	31.3012	29.38	0.0001
S*DEV	55	1.0653		
Trial Block (BK)	4	5.4276	46.17	0.0001
S*BK	44	0.1176		
DEV*BK	20	0.2566	2.47	0.0007
S*DEV*BK	220	0.1037		
Total	359			

TABLE 41

Results of Bonferroni-T Test for Cursor Device x Trial Block Interaction Based on Target Acquisition Time to Target (TT)

MSE=0.1037 df=220 N=12 C=60 Alpha=0.05 T=3.33

Critical Difference = 0.438 s

Absolute Touchpad

Mean TT	Block	
3.154	1	A
2.334	2	B
2.105	3	B
1.979	4	B
1.946	5	B

Trackball

Mean TT	Block	
2.033	1	A
1.813	2	A
1.784	3	A
1.832	4	A
1.811	5	A

Displacement Joystick

Mean TT	Block	
3.965	1	A
3.482	2	B
3.494	3	B
3.497	4	B
3.466	5	B

Force Joystick

Mean TT	Block	
3.855	1	A
3.279	2	B
3.332	3	B
3.075	4	B
3.136	5	B

Optical Mouse

Mean TT	Block	
2.272	1	A
1.906	2	A B
1.944	3	A B
1.780	4	B
1.700	5	B

Relative Touchpad

Mean TT	Block	
3.199	1	A
2.594	2	B
2.569	3	B
2.438	4	B
2.356	5	B

Mean TT with the same letters within a single trial block are not significantly different.

TABLE 42

Results of the Bonferroni-T Test for Trial Block Main Effect Based on Target Acquisition Time to Target (TT)

MSE=0.1176 df=44 N=72 C=10 Alpha=0.05 T=2.96

Critical Difference = 0.169 s

Mean TT	Block	
3.079	1	A
2.568	2	B
2.538	3	B
2.433	4	B
2.403	5	B

Mean TT with the same letter are not significantly different.

Each trial block contains 40 trials.

TABLE 43

ANOVA Summary Table for Main Analysis Based on Targe Acquisition Time to Target (TT)

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	11.414		
Within-Subjects				
Device (DEV)	5	122.614	32.92	0.0001
S*DEV	55	3.725		
Target Distance (TD)	3	84.404	261.59	0.0001
S*TD	33	0.323		
Target Size (TS)	4	396.588	305.98	0.0001
S*TS	44	1.296		
DEV*TD	15	1.690	5.95	0.0001
S*DEV*TD	165	0.284		
DEV*TS	20	14.163	25.25	0.0001
S*DEV*TS	220	0.584		
TS*TD	12	0.309	1.30	0.2276
S*TS*TD	132	0.238		
DEV*TS*TD	60	0.229	1.07	0.3354
S*DEV*TS*TD	660	0.214		
Total	1439			

TABLE 44

Results of Bonferroni-T Test for Cursor Device x Target Size Interaction Based on Target Acquisition Time to Target (TT)

MSE=0.5841 df=220 N=48 C=75 Alpha=0.05 T=3.39

Critical Difference = 0.529 s

Target size = 0.13 cm

Mean TT	Device	
5.975	DISPLACE	A
5.846	FORCE	A
4.338	RELATIVE	B
3.471	ABSOLUTE	C
2.773	MOUSE	D
2.596	TRACKBAL	D

Target size = 0.27 cm

Mean TT	Device	
4.613	DISPLACE	A
3.981	FORCE	B
3.018	RELATIVE	C
2.576	ABSOLUTE	C D
2.274	MOUSE	D
2.149	TRACKBAL	D

Target size = 0.54 cm

Mean TT	Device	
3.244	DISPLACE	A
2.822	FORCE	A
2.193	RELATIVE	B
1.833	ABSOLUTE	B
1.742	TRACKBAL	B
1.709	MOUSE	B

Target size = 1.07 cm

Mean TT	Device	
2.169	DISPLACE	A
2.036	FORCE	A B
1.638	RELATIVE	B C
1.469	ABSOLUTE	B C
1.448	TRACKBAL	B C
1.349	MOUSE	C

Target size = 2.14 cm

Mean TT	Device	
1.421	DISPLACE	A
1.343	FORCE	A
1.255	RELATIVE	A
1.116	TRACKBAL	A
1.107	ABSOLUTE	A
1.058	MOUSE	A

Mean TT with the same letters within a single target size are not significantly different.

TABLE 45

Results of Bonferroni-T Test for Cursor Device x Target Distance Interaction Based on Target Acquisition Time to Target (TT)

MSE=0.284 df=165 N=60 C=60 Alpha=0.05 T=3.41

Critical Difference = 0.332 s

Target distance = 2 cm

Mean TT	Device	
2.741	DISPLACE	A
2.537	FORCE	A
1.983	ABSOLUTE	B
1.817	RELATIVE	B
1.420	MOUSE	C
1.327	TRACKBAL	C

Target distance = 4 cm

Mean TT	Device		
3.167	DISPLACE	A	
2.898	FORCE	A	
2.323	RELATIVE	B	
1.979	ABSOLUTE	C	
1.658	TRACKBAL	C	D
1.604	MOUSE		D

Target distance = 8 cm

Mean TT	Device	
3.647	DISPLACE	A
3.392	FORCE	A
2.588	RELATIVE	B
2.167	ABSOLUTE	C
1.979	TRACKBAL	C
1.920	MOUSE	C

Target distance = 16 cm

Mean TT	Device	
4.382	DISPLACE	A
3.996	FORCE	B
3.107	RELATIVE	C
2.402	ABSOLUTE	D
2.387	MOUSE	D
2.277	TRACKBAL	D

Mean TT with the same letters within a single target distance are not significantly different.

TABLE 46

Results of the Bonferroni-T Test for Cursor Device Main Effect Based on Target Acquisition Time to Target (TT)

MSE=3.7251 df=55 N=240 C=15 Alpha=0.05 T=3.07

Critical Difference = 0.541 s

Mean TT	Device		
3.484	DISPLACE	A	
3.206	FORCE	A	
2.489	RELATIVE	B	
2.091	ABSOLUTE	B	C
1.833	MOUSE		C
1.810	TRACKBAL		C

Mean TT with the same letter are not significantly different.

TABLE 47

Results of the Friedman's Two-Way Rank Sum Test for Preference.

K=6 N=12 S′=39.53 $p < 0.001$

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device			
62	DISPLACE	A		
51	FORCE	A	B	
50	RELATIVE	A	B	
49	ABSOLUTE	A	B	
27	TRACKBAL		B	C
13	MOUSE			C

Mean Rank Sums with the same letter are not significantly different.

TABLE 48

Results of the Friedman's Two-Way Rank Sum Test for Comfort.

K=6 N=12 S'=27.95 $p < 0.001$

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device			
55	RELATIVE	A		
51	DISPLACE	A	B	
51	FORCE	A	B	
49	ABSOLUTE	A	B	
29	TRACKBAL		B	C
17	MOUSE			C

Mean Rank Sum with the same letter are not significantly different.

TABLE 49

Results of the Friedman's Two-Way Rank Sum Test for Quality.

K=6 N=12 S'=24.42 p=0.001

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device	
57	DISPLACE	A
50	RELATIVE	A
48	ABSOLUTE	A
47	FORCE	A
32	TRACKBAL	A B
18	MOUSE	B

Mean Rank Sums with the same letter are not significantly different.

TABLE 50

Results of the Friedman's Two-Way Rank Sum Test for Positioning Speed.

K=6 N=12 S'=25.14 $p < 0.001$

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device		
56	FORCE	A	
55	DISPLACE	A	
47	RELATIVE	A	B
46	ABSOLUTE	A	B
25	MOUSE		B
23	TRACKBAL		B

Mean Rank Sum with the same letter are not significantly different.

TABLE 51

Results of the Friedman's Two-Way Rank Sum Test for Positioning Accuracy.

K=6 N=12 S'=25.43 $p < 0.001$

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device		
59	DISPLACE	A	
59	FORCE	A	
41	ABSOLUTE	A	B
40	RELATIVE	A	B
28	TRACKBAL		B
25	MOUSE		B

Mean Rank Sums with the same letter are not significantly different.

TABLE 52

Results of the Friedman's Two-Way Rank Sum Test for Fatigue.

K=6 N=12 S'=42.29 $p < 0.001$

Critical Difference = 26.1 (Alpha=0.05)

Rank Sum	Device			
62	ABSOLUTE	A		
53	DISPLACE	A		
53	RELATIVE	A		
47	FORCE	A	B	
20	TRACKBAL		B	C
17	MOUSE			C

Mean Rank Sums with the same letter are not significantly different.

TABLE 53

MANOVA Summary Table for 10 Bipolar Scale Ratings

```
    H = ANOVA SS&CP Matrix for : DEV
    E = ANOVA SS&CP Matrix for : S*DEV
    P = Dependent measures =   10
    Q = Hypothesis df      =    5
    NE = Error df          =   55
    S = MIN(P,Q)           =    5
    M = 0.5(ABS(P-Q)-1)    =  2.0
    N = 0.5(NE-P-1)        = 22.0

Wilks' Criterion          L = DET(E)/DET(H+E) = 0.2496

F(approximation) = (U*Z-2B)/(P*Q)*(1-L**1/Z)/L**1/Z

    with  df[DEV] = P*Q = 50    df[S*DEV] = U*Z-2B = 213

F(50,213) = 1.52          p = 0.0230
```

TABLE 54

ANOVA Summary Table for ACCURATE (INACCURATE) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	6.589		
Within-Subjects				
Device (DEV)	5	9.447	4.78	0.0011
S*DEV	55	1.974		
Total	71			

Results of the Bonferroni-T Test for ACCURATE (INACCURATE)

MSE=1.974 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.76

Mean Scale Value	Device		
4.00	FORCE	A	
3.67	DISPLACE	A	
3.58	ASSOLUTE	A	
3.16	RELATIVE	A	B
2.58	TRACKBAL	A	B
1.58	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 55

ANOVA Summary Table for FAST (SLOW) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	4.408		
Within-Subjects				
Device (DEV)	5	9.514	4.39	0.0020
S*DEV	55	2.168		
Total	71			

Results of the Bonferroni-T Test for FAST (SLOW)

MSE=2.168 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.84

Mean Scale Value	Device		
4.00	DISPLACE	A	
3.83	FORCE	A	
3.75	RELATIVE	A	
2.92	TRACKBAL	A	B
2.75	ABSOLUTE	A	B
1.67	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 56

ANOVA Summary Table for CONSISTENT (INCONSISTENT) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	4.499		
Within-Subjects				
Device (DEV)	5	6.114	3.41	0.0094
S*DEV	55	1.793		
Total	71			

Results of the Bonferroni-T Test for CONSISTENT (INCONSISTENT)

MSE=1.793 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.67

Mean Scale Value	Device		
3.67	RELATIVE	A	
3.25	DISPLACE	A	B
3.08	FORCE	A	B
2.92	ABSOLUTE	A	B
2.33	TRACKBAL	A	B
1.67	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 57

ANOVA Summary Table for NATURAL (UNNATURAL) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	6.419		
Within-Subjects				
Device (DEV)	5	12.955	6.99	0.0001
S*DEV	55	1.853		
Total	71			

Results of the Bonferroni-T Test for NATURAL (UNNATURAL)

MSE=1.853 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.71

Mean Scale Value	Device		
4.42	DISPLACE	A	
4.33	FORCE	A	
3.50	RELATIVE	A	B
2.50	TRACKBAL		B
2.42	ABSOLUTE		B
2.00	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 58

ANOVA Summary Table for COMFORTABLE (UNCOMFORTABLE) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	7.207		
Within-Subjects				
Device (DEV)	5	7.689	3.09	0.0158
S*DEV	55	2.489		
Total	71			

Results of the Bonferroni-T Test for COMFORTABLE (UNCOMFORTABLE)

MSE=1.853 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.98

Mean Scale Value	Device	
4.50	FORCE	A
4.25	ABSOLUTE	A
4.08	RELATIVE	A
3.67	DISPLACE	A
2.67	TRACKBAL	A
2.67	MOUSE	A

Mean Scale Values with the same letter are not significantly different.

TABLE 59

ANOVA Summary Table for RELAXING (FATIGUING) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	4.640		
Within-Subjects				
Device (DEV)	5	8.258	6.35	0.0001
S*DEV	55	1.301		
Total	71			

Results of the Bonferroni-T Test for RELAXING (FATIGUING)

MSE=1.301 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.43

Mean Scale Value	Device		
4.75	FORCE	A	
4.75	ABSOLUTE	A	
4.75	RELATIVE	A	
4.33	DISPLACE	A	B
3.25	TRACKBAL		B
2.92	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 60

ANOVA Summary Table for ACCEPTABLE (UNACCEPTABLE) Bipolar Scale Ratings

Source	df	MS	F	p
<u>Between-Subjects</u>				
Subject (S)	11	3.196		
<u>Within-Subjects</u>				
Device (DEV)	5	11.747	5.28	0.0005
S*DEV	55	2.226		
Total	71			

Results of the Bonferroni-T Test for ACCEPTABLE (UNACCEPTABLE)

MSE=2.226 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.87

Mean Scale Value	Device		
3.83	FORCE	A	
3.83	DISPLACE	A	
3.50	RELATIVE	A	
2.75	ABSOLUTE	A	B
2.00	TRACKBAL	A	B
1.50	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 61

ANOVA Summary Table for PLEASING (IRRITATING) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	6.798		
Within-Subjects				
Device (DEV)	5	6.289	2.62	0.0341
S*DEV	55	2.404		
Total	71			

Results of the Bonferroni-T Test for ACCEPTABLE (UNACCEPTABLE)

MSE=2.404 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.94

Mean Scale Value	Device	
4.58	FORCE	A
4.25	RELATIVE	A
4.08	DISPLACE	A
3.67	ABSOLUTE	A
3.00	TRACKBAL	A
2.75	MOUSE	A

Mean Scale Values with the same letter are not significantly different.

TABLE 62

ANOVA Summary Table for GOOD (BAD) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	3.879		
Within-Subjects				
Device (DEV)	5	13.034	5.19	0.0006
S*DEV	55	2.512		
Total	71			

Results of the Bonferroni-T Test for GOOD (BAD)

MSE=2.512 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.99

Mean Scale Value	Device			
4.58	FORCE	A		
3.83	DISPLACE	A	B	
3.58	RELATIVE	A	B	C
3.00	ABSOLUTE	A	B	C
2.17	TRACKBAL		B	C
1.83	MOUSE			C

Mean Scale Values with the same letter are not significantly different.

TABLE 63

ANOVA Summary Table for EXPENSIVE (INEXPENSIVE) Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	1.438		
Within-Subjects				
Device (DEV)	5	3.614	3.22	0.0128
S*DEV	55	1.123		
Total	71			

Results of the Bonferroni-T Test for EXPENSIVE (INEXPENSIVE)

MSE=1.123 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 1.33

Mean Scale Value	Device		
4.17	DISPLACE	A	
3.92	FORCE	A	B
3.75	ABSOLUTE	A	B
3.58	TRACKBAL	A	B
3.42	RELATIVE	A	B
2.58	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 64

ANOVA Summary Table for Preference Index (PI): Combined Bipolar Scale Ratings

Source	df	MS	F	p
Between-Subjects				
Subject (S)	11	353.9		
Within-Subjects				
Device (DEV)	5	738.0	7.74	0.0001
S*DEV	55	95.3		
Total	71			

Results of the Bonferroni-T Test for PI

MSE=95.3 dF=55 N=12 C=15 Alpha=0.05 T=3.07

Critical Difference = 12.23

Mean Scale Value	Device			
41.4	FORCE	A		
39.3	DISPLACE	A		
37.7	RELATIVE	A	B	
33.8	ABSOLUTE	A	B	
27.0	TRACKBAL		B	C
21.2	MOUSE			C

Mean Scale Values with the same letter are not significantly different.

TABLE 65

ANOVA Results for the Single Screen/Character Delete (SS/CD) Files

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	22.09		
Within-subjects				
Device (DEV)	6	51.95	11.92	0.0001
S*DEV	36	4.36		
Trial Block (BLK)	2	83.76	21.77	0.0001
S*BLK	12	3.85		
DEV*BLK	12	7.56	3.16	0.0012
S*DEV*BLK	72	2.39		
Total	146			

TABLE 66

Results of the Bonferonni-T Test for Cursor Device by Trial Block Interaction based on the SS/CD Files

MSE=2.394 df=72 N=7 C=63 Alpha=0.05 T=3.50

Critical Difference = 2.89

Trial Block One

TCT	Device		
13.41	ABSOLUTE	A	
8.40	DISPLACE	B	
8.21	RELATIVE	B	C
7.24	FORCE	B	C
6.89	MOUSE	B	C
5.91	KEY	B	C
5.48	TRACKBAL		C

Trial Block Two

TCT	Device		
8.10	ABSOLUTE	A	
6.48	RELATIVE	A	B
6.45	DISPLACE	A	B
6.14	FORCE	A	B
5.17	KEY		B
4.83	TRACKBAL		B
4.36	MOUSE		B

Trial Block Three

TCT	Device		
7.05	ABSOLUTE	A	
5.95	DISPLACE	A	B
5.76	FORCE	A	B
5.62	RELATIVE	A	B
5.45	KEY	A	B
4.38	TRACKBAL	A	B
4.12	MOUSE		B

Mean Task Completion Times (TCT) with the same letter within a trial block are not significantly different.

TABLE 67

Results of the Bonferonni-T Test for Cursor Device Main Effect based on the SS/CD Files

MSE=4.357 df=36 N=21 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.10

TCT	Device	
9.52	ABSOLUTE	A
6.94	DISPLACE	B
6.77	FORCE	B
6.38	RELATIVE	B
5.51	KEY	B
5.12	TRACKBAL	B
4.90	MOUSE	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 68

Results of the Bonferonni-T Test for Trial Block Main Effect based on the SS/CD Files

MSE=3.847 df=12 N=49 C=3 Alpha=0.05 T=2.78

Critical Difference = 1.10

TCT	Block	
7.93	1	A
5.93	2	B
5.48	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 69

ANOVA Results for the Multiple Screen/Character Delete Files

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	8.49		
Within-subjects				
Device (DEV)	6	39.87	18.27	0.0001
S*DEV	36	2.18		
Trial Block (BLK)	2	19.88	46.58	0.0001
S*BLK	12	0.43		
DEV*BLK	12	2.27	2.48	0.0088
S*DEV*BLK	72	0.91		
Total	146			

TABLE 70

Results of the Bonferonni-T Test for Cursor Device by Trial Block Interaction based on the MS/CD Files

MSE=0.913 df=72 N=7 C=63 Alpha=0.05 T=3.50

Critical Difference = 1.78

Trial Block One

TCT	Device		
11.63	ABSOLUTE	A	
8.96	DISPLACE	B	
8.74	RELATIVE	B	
8.21	FORCE	B	C
6.95	KEY		C
6.86	TRACKBAL		C
6.77	MOUSE		C

Trial Block Two

TCT	Device				
10.27	ABSOLUTE	A			
7.92	DISPLACE		B		
7.45	FORCE		B	C	
7.33	RELATIVE		B	C	D
7.14	KEY		B	C	D
5.95	TRACKBAL			C	D
5.66	MOUSE				D

Trial Block Three

TCT	Device			
8.45	ABSOLUTE	A		
8.06	RELATIVE	A	B	
7.94	DISPLACE	A	B	
6.59	FORCE		B	C
6.42	KEY		B	C
6.13	MOUSE			C
5.98	TRACKBAL			C

Mean Task Completion Times (TCT) with the same letter within a trial block are not significantly different.

TABLE 71

Results of the Bonferonni-T Test for Cursor Device Main Effect based on the MS/CD Files

MSE=2.182 df=36 N=21 C=21 Alpha=0.05 T=3.27

Critical Difference = 1.49

TCT	Device		
10.12	ABSOLUTE	A	
8.27	DISPLACE	B	
8.05	RELATIVE	B	
7.42	FORCE	B	C
6.84	KEY	B	C
6.26	TRACKBAL		C
6.19	MOUSE		C

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 72

Results of the Bonferonni-T Test for Trial Block Main Effect based on the MS/CD Files

MSE=0.428 df=12 N=49 C=3 Alpha=0.05 T=2.78

Critical Difference = 0.37

TCT	Block	
8.30	1	A
7.39	2	B
7.08	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 73

ANOVA Results for the Single Screen/Text Edit Files

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	39.96		
Within-subjects				
Device (DEV)	6	38.24	4.17	0.0028
S*DEV	36	9.18		
Trial Block (BLK)	2	39.95	8.59	0.0028
S*BLK	12	4.65		
DEV*BLK	12	7.29	2.75	0.0040
S*DEV*BLK	72	2.65		
Total	146			

TABLE 74

Results of the Bonferonni-T Test for Cursor Device by Trial Block Interaction based on the SS/TE Files

MSE=2.657 df=72 N=7 C=63 Alpha=0.05 T=3.50

Critical Difference = 3.05

Trial Block One

TCT	Device		
15.17	ABSOLUTE	A	
11.76	FORCE	B	
11.55	RELATIVE	B	
10.79	DISPLACE	B	
10.74	MOUSE	B	
9.50	TRACKBAL	B	
9.24	KEY	B	

Trial Block Two

TCT	Device		
11.76	DISPLACE	A	
11.55	ABSOLUTE	A	
11.13	RELATIVE	A	B
9.40	KEY	A	B
9.26	FORCE	A	B
9.24	TRACKBAL	A	B
8.10	MOUSE		B

Trial Block Three

TCT	Device		
11.31	ABSOLUTE	A	
10.10	DISPLACE	A	
10.00	KEY	A	B
9.79	FORCE	A	B
9.55	RELATIVE	A	B
8.24	MOUSE		B
7.36	TRACKBAL		B

Mean Task Completion Times (TCT) with the same letter within a trial block are not significantly different.

TABLE 75

Results of the Bonferonni-T Test for Cursor Device Main Effect based on the SS/TE Files

MSE=9.181 df=36 N=21 C=21 Alpha=0.05 T=3.27

Critical Difference = 3.06

TCT	Device		
12.68	ABSOLUTE	A	
10.88	DISPLACE	A	B
10.74	RELATIVE	A	B
10.27	FORCE	A	B
9.54	KEY		B
9.02	MOUSE		B
8.70	TRACKBAL		B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 76

Results of the Bonferonni-T Test for Trial Block Main Effect based on the SS/TE Files

MSE=4.650 df=12 N=49 C=3 Alpha=0.05 T=2.78

Critical Difference = 1.21

TCT	Block		
11.25	1	A	
10.06	2	A	B
9.48	3		B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 77

ANOVA Results for the Multiple Screen/Text Edit Files

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	48.43		
Within-subjects				
Device (DEV)	6	34.94	5.84	0.0003
S*DEV	36	5.99		
Trial Block (BLK)	2	21.01	9.46	0.0034
S*BLK	12	2.22		
DEV*BLK	12	3.01	1.39	0.1905
S*DEV*BLK	72	2.16		
Total	146			

TABLE 78

Results of the Bonferonni-T Test for Cursor Device Main Effect based on the MS/TE Files

MSE=5.988 df=36 N=21 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.47

TCT	Device		
14.67	ABSOLUTE	A	
12.65	RELATIVE	A	B
12.48	DISPLACE	A	B
11.81	FORCE		B
11.45	KEY		B
11.11	TRACKBAL		B
10.89	MOUSE		B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 79

Results of the Bonferonni-T Test for Trial Block Main Effect based on the MS/TE Files

MSE=2.22 df=12 N=49 C=3 Alpha=0.05 T=2.78

Critical Difference = 0.84

TCT	Block	
12.90	1	A
11.88	2	B
11.68	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 80

Results of the Friedman's Two-way Rank Sum Test for Preference

K=6 N=6 S'=21.18 p=0.002

Critical Difference = 24.0

Rank Sum	Device			
43	RELATIVE	A		
41	ABSOLUTE	A	B	
31	DISPLACE	A	B	C
26	FORCE	A	B	C
20	TRACKBAL	A	B	C
18	KEY		B	C
17	MOUSE			C

Rank Sums with the same letter are not significantly different.

TABLE 81

Results of the Friedman's Two-way Rank Sum Test for Quality

K=6 N=6 S'=17.69 p=0.008

Critical Difference = 24.0

Rank Sum	Device		
42	RELATIVE	A	
40	ABSOLUTE	A	B
28	FORCE	A	B
27	DISPLACE	A	B
24	TRACKBAL	A	B
18	KEY		B
17	MOUSE		B

Rank Sums with the same letter are not significantly different.

TABLE 82

Results of the Friedman's Two-way Rank Sum Test for Positioning Speed

K=6 N=6 S'=13.71 p=0.04

Critical Difference = 24.0

Rank Sum	Device		
40	KEY	A	
37	RELATIVE	A	B
29	ABSOLUTE	A	B
28	MOUSE	A	B
26	FORCE	A	B
21	DISPLACE	A	B
15	TRACKBAL		B

Rank Sums with the same letter are not significantly different.

TABLE 83

Results of the Friedman's Two-way Rank Sum Test for Positioning Accuracy

K=6 N=6 S'=25.53 p=0.001

Critical Difference = 24.0

Rank Sum	Device		
45	ABSOLUTE	A	
38	RELATIVE	A	
31	DISPLACE	A	B
26	FORCE	A	B
24	MOUSE	A	B
24	TRACKBAL	A	B
8	KEY		B

Rank Sums with the same letter are not significantly different.

TABLE 84

Results of the Friedman's Two-way Rank Sum Test for Fatigue

K=6 N=6 S′=23.02 $p<0.001$

Critical Difference = 24.0

Rank Sum	Device			
44	RELATIVE	A		
41	ABSOLUTE	A	B	
29	DISPLACE	A	B	C
28	FORCE	A	B	C
21	MOUSE	A	B	C
19	TRACKBAL		B	C
14	KEY			C

Rank Sums with the same letter are not significantly different.

TABLE 85

Results of the Friedman's Two-way Rank Sum Test for Comfort

K=6 N=6 S'=17.88 p=0.006

Critical Difference = 24.0

Rank Sum	Device		
41	RELATIVE	A	
41	ABSOLUTE	A	B
30	FORCE	A	B
26	DISPLACE	A	B
22	TRACKBAL	A	B
19	MOUSE	A	B
17	KEY		B

Rank Sums with the same letter are not significantly different.

Table 86

MANOVA Summary Table for the 10 Bipolar Ratings

```
    H = ANOVA SS&CP Matrix for : DEV
    E = ANOVA SS&CP Matrix for : S*DEV
    P = Dependent Measures =    10
    Q = Hypothesis df      =     6
    NE = Error df          =    36
    S = MIN(P,Q)           =     6
    M = 0.5(ABS(P-Q)-1)    =   1.5
    N = 0.5(NE-P-1)        =  12.5

Wilks' Criterion            L = DET(E)/DET(H + E) = 0.2496

    W = -(NE-0.5(P-Q+1))*LN(L)         = 101.15
    U = NE-0.5(P-Q+1)                  =  33.5
    Z = SQRT((P*P*Q*Q-4)/(P*P+Q*Q-5)=   5.24
    B = (P*Q-2)/4                      =  14.5

F(approximation) = (U*Z-2B)/(P*Q)*(1-L**1/Z)/L**1/Z

    With df[DEV] = P*Q = 60      df[S*DEV] = U*Z-2B = 146

F(60,146) = 1.90            p = 0.0010
```

TABLE 87

ANOVA Summary Table for Accurate (Inaccurate) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	4.40		
Within-subjects				
Device (DEV)	6	19.54	12.40	0.0001
S*DEV	36	1.58		
Total	48			

Results of the Bonferonni-T Test for Accurate (Inaccurate)

MSE=1.576 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.19

Mean Scale Value	Device			
6.29	ABSOLUTE	A		
4.14	DISPLACE	A	B	
4.00	RELATIVE		B	
3.00	FORCE		B	C
2.57	TRACKBAL		B	C
1.71	MOUSE			C
1.43	KEY			C

Mean Scale Values with the same letter are not significantly different.

TABLE 88

ANOVA Summary Table for Fast (Slow) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	6.54		
Within-subjects				
Device (DEV)	6	8.93	5.42	0.0004
S*DEV	36	1.67		
Total	48			

Results of the Bonferonni-T Test for Fast (Slow)

MSE=1.647 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.24

Mean Scale Value	Device		
5.00	KEY	A	
4.71	ABSOLUTE	A	
3.71	DISPLACE	A	B
3.29	RELATIVE	A	B
3.14	FORCE	A	B
2.29	MOUSE		B
2.00	TRACKBAL		B

Mean Scale Values with the same letter are not significantly different.

TABLE 89

ANOVA Summary Table for Consistent (Inconsistent) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	4.56		
Within-subjects				
Device (DEV)	6	19.37	7.28	0.0001
S*DEV	36	2.66		
Total	48			

Results of the Bonferonni-T Test for Consistent (Inconsistent)

MSE=2.660 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.85

Mean Scale Value	Device				
6.14	ABSOLUTE	A			
4.86	RELATIVE	A	B		
4.43	DISPLACE	A	B	C	
3.57	FORCE	A	B	C	D
3.14	TRACKBAL		B	C	D
1.71	MOUSE			C	D
1.57	KEY				D

Mean Scale Values with the same letter are not significantly different.

TABLE 90

ANOVA Summary Table for Natural (Unnatural) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	3.03		
Within-subjects				
Device (DEV)	6	5.27	1.49	0.2110
S*DEV	36	3.55		
Total	48			

TABLE 91

ANOVA Summary Table for Comfortable (Uncomfortable) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	4.37		
Within-subjects				
Device (DEV)	6	4.52	1.25	0.3044
S*DEV	36	3.61		
Total	48			

TABLE 92

ANOVA Summary Table for Relaxing (Fatiguing) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	6.76		
Within-subjects				
Device (DEV)	6	1.85	1.88	0.1116
S*DEV	36	0.98		
Total	48			

TABLE 93

ANOVA Summary Table for Acceptable (Unacceptable) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	4.56		
Within-subjects				
Device (DEV)	6	6.42	3.02	0.0171
S*DEV	36	2.13		
Total	48			

Results of the Bonferonni-T Test for Acceptable (Unacceptable)

MSE=2.128 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.55

Mean Scale Value	Device		
4.86	ABSOLUTE	A	
3.86	RELATIVE	A	B
3.71	DISPLACE	A	B
3.00	FORCE	A	B
2.43	TRACKBAL	A	B
2.43	KEY	A	B
2.29	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 94

ANOVA Summary Table for Pleasing (Irritating) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	7.76		
Within-subject				
Device (DEV)	6	6.09	2.53	0.0380
S*DEV	36	2.41		
Total	48			

Results of the Bonferonni-T Test for Pleasing (Irritating) ommitted due to non-significance.

TABLE 95

ANOVA Summary Table for Good (Bad) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	4.78		
Within-subjects				
Device (DEV)	6	6.54	3.49	0.0081
S*DEV	36	1.88		
Total	48			

Results of the Bonferonni-T Test for Good (Bad)

MSE=1.877 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.39

Mean Scale Value	Device		
4.71	ABSOLUTE	A	
4.29	RELATIVE	A	B
3.57	DISPLACE	A	B
3.14	FORCE	A	B
2.43	TRACKBAL	A	B
2.43	KEY	A	B
2.29	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 96

ANOVA Summary Table for Expensive (Inexpensive) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	3.37		
Within-subjects				
Device (DEV)	6	7.90	5.32	0.0085
S*DEV	36	1.49		
Total	48			

Results of the Bonferonni-T Test for Expensive (Inexpensive)

MSE=1.485 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 2.13

Mean Scale Value	Device		
5.43	KEY	A	
4.29	FORCE	A	B
4.29	DISPLACE	A	B
3.43	TRACKBAL	A	B
3.00	MOUSE		B
2.57	ABSOLUTE		B
2.57	RELATIVE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 97

ANOVA Summary Table for Preference Index (PI)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	6	264.7		
Within-subjects				
Device (DEV)	6	458.3	4.25	0.0025
S*DEV	36	107.9		
Total	48			

Results of the Bonferonni-T Test for Preference Index (PI)

MSE=107.87 df=36 N=7 C=21 Alpha=0.05 T=3.27

Critical Difference = 18.15

Mean Scale Value	Device		
48.86	ABSOLUTE	A	
39.86	DISPLACE	A	B
39.00	RELATIVE	A	B
34.43	FORCE	A	B
30.29	KEY		B
27.57	TRACKBAL		B
25.86	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 98

ANOVA Results for the Rectangles (RT) Files

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	26.68		
Within-subjects				
Device (DEV)	5	51.91	8.35	0.0001
S*DEV	25	6.22		
Trial Block (BLK)	2	68.03	18.11	0.0005
S*BLK	10	3.76		
DEV*BLK	10	12.20	3.96	0.0005
S*DEV*BLK	50	3.08		
Total	107			

TABLE 99

Results of the Bonferonni-T Test for Cursor Device by Trial Block Interaction based on the RT Task

MSE=3.081 df=50 N=6 C=45 Alpha=0.05 T=3.52

Critical Difference = 3.52

Trial Block One

TCT	Device		
13.20	ABSOLUTE	A	
10.58	FORCE	A	
10.55	DISPLACE	A	
10.51	RELATIVE	A	
6.52	TRACKBAL	B	
6.42	MOUSE	B	

Trial Block Two

TCT	Device		
10.22	DISPLACE	A	
9.05	FORCE	A	B
8.21	RELATIVE	A	B
6.50	ABSOLUTE		B
6.36	MOUSE		B
5.74	TRACKBAL		B

Trial Block Three

TCT	Device		
9.22	DISPLACE	A	
8.65	FORCE	A	B
6.81	RELATIVE	A	B
6.05	ABSOLUTE	A	B
5.81	MOUSE	A	B
5.31	TRACKBAL		B

Mean Task Completion Times (TCT) with the same letter within a trial block are not significantly different.

TABLE 100

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the RT Task

MSE=6.217 df=25 N=18 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.70

TCT	Device			
10.00	DISPLACE	A		
9.43	FORCE	A	B	
8.58	ABSOLUTE	A	B	
8.51	RELATIVE	A	B	C
6.20	MOUSE		B	C
5.86	TRACKBAL			C

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 101

Results of the Bonferonni-T Test for Trial Block Main Effect Based on the RT Task

MSE=3.7558 df=10 N=36 C=3 Alpha=0.05 T=2.87

Critical Difference = 1.31

TCT	Block	
9.63	1	A
7.68	2	B
6.98	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 102

ANOVA Results for the Horizontal Grid (HG) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	16.87		
Within-subjects				
Device (DEV)	5	21.35	3.01	0.0293
S*DEV	25	7.10		
Trial Block (BLK)	2	9.37	8.92	0.0060
S*BLK	10	1.05		
DEV*BLK	10	1.29	1.22	0.3020
S*DEV*BLK	50	1.06		
Total	107			

TABLE 103

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the HG Task

MSE=7.103 df=25 N=18 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.88

TCT	Device	
6.61	DISPLACE	A
6.36	RELATIVE	A
6.02	FORCE	A
5.85	ABSOLUTE	A
4.17	TRACKBAL	A
4.16	MOUSE	A

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 104

Results of the Bonferonni-T Test for Trial Block Main Effect Based on the HG Task

MSE=1.051 df=10 N=36 C=3 Alpha=0.05 T=2.87

Critical Difference = 0.69

TCT	Block	
6.09	1	A
5.36	2	B
5.12	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 105

ANOVA Results for the Vertical Grid (VG) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	40.49		
Within-subjects				
Device (DEV)	5	85.46	3.14	0.0247
S*DEV	25	27.24		
Trial Block (BLK)	2	13.75	3.27	0.0807
S*BLK	10	4.20		
DEV*BLK	10	3.89	0.83	0.6003
S*DEV*BLK	50	4.67		
Total	107			

TABLE 106

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the VG Task

MSE=27.236 df=25 N=18 C=15 Alpha=0.05 T=3.24

Critical Difference = 5.64

TCT	Device	
9.48	RELATIVE	A
9.11	ABSOLUTE	A
8.45	FORCE	A
8.04	DISPLACE	A
4.71	TRACKBAL	A
4.62	MOUSE	A

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 107

ANOVA Results for the Angular Grid (AG) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	46.71		
Within-subjects				
Device (DEV)	4	242.54	6.67	0.0014
S*DEV	20	36.36		
Trial Block (BLK)	2	9.26	3.05	0.0923
S*BLK	10	3.03		
DEV*BLK	8	3.26	0.88	0.5421
S*DEV*BLK	40	3.71		
Total	89			

TABLE 108

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the AG Task

MSE=26.336 df=20 N=18 C=10 Alpha=0.05 T=3.15

Critical Difference = 6.34

TCT	Device		
13.99	ABSOLUTE	A	
11.61	DISPLACE	A	B
10.389	FORCE	A	B
5.87	MOUSE		B
5.58	TRACKBAL		B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 109

ANOVA Results for the Fat Bits (FB) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	2.26		
Within-subjects				
Device (DEV)	5	13.90	13.72	0.0001
S*DEV	25	1.01		
Trial Block (BLK)	2	2.59	11.96	0.0022
S*BLK	10	0.22		
DEV*BLK	10	0.18	0.51	0.8723
S*DEV*BLK	50	0.36		
Total	107			

TABLE 110

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the FB Task

MSE=1.103 df=25 N=18 C=15 Alpha=0.05 T=3.24

Critical Difference = 1.08

TCT	Device		
4.30	DISPLACE	A	
4.18	FORCE	A	
3.28	RELATIVE	A	B
2.90	ABSOLUTE		B
2.41	TRACKBAL		B
2.21	MOUSE		B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 111

Results of the Bonferonni-T Test for Trial Block Main Effect Based on the FB Task

MSE=0.216 df=10 N=36 C=3 Alpha=0.05 T=2.87

Critical Difference = 0.31

TCT	Block	
3.52	1	A
3.11	2	B
3.02	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 112

ANOVA Results for the Horizontal Line (HL) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	102.67		
Within-subjects				
Device (DEV)	5	29.22	2.34	0.0713
S*DEV	25	12.49		
Trial Block (BLK)	2	16.51	7.97	0.0085
S*BLK	10	2.07		
DEV*BLK	10	3.71	0.66	0.7518
S*DEV*BLK	50	5.58		
Total	107			

TABLE 113

Results of the Bonferonni-T Test for Trial Block Main Effect Based on the HL Task

MSE=2.071 df=10 N=36 C=3 Alpha=0.05 T=2.87

Critical Difference = 0.97

TCT	Block	
9.22	1	A
8.11	2	B
7.99	3	B

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 114

ANOVA Results for the Vertical Lines (VL) Task

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	16.57		
Within-subjects				
Device (DEV)	5	61.38	6.72	0.0004
S*DEV	25	9.14		
Trial Block (BLK)	2	6.79	3.78	0.0598
S*BLK	10	1.80		
DEV*BLK	10	4.61	1.05	0.4200
S*DEV*BLK	50	4.41		
Total	107			

TABLE 115

Results of the Bonferonni-T Test for Cursor Device Main Effect Based on the VL Task

MSE=9.139 df=25 N=18 C=15 Alpha=0.05 T=3.24

Critical Difference = 3.27

TCT	Device			
10.50	RELATIVE	A		
10.34	FORCE	A	B	
9.04	ABSOLUTE	A	B	C
8.49	DISPLACE	A	B	C
7.08	TRACKBAL		B	C
5.79	MOUSE			C

Mean Task Completion Times (TCT) with the same letter are not significantly different.

TABLE 116

Results of the Friedman's Two-way Rank Sum Test for Preference

K=6 N=6 S'=21.24 p=0.001

Critical Difference = 17.7

Rank Sum	Device		
34	ABSOLUTE	A	
26	FORCE	A	B
23	RELATIVE	A	B
23	DISPLACE	A	B
11	MOUSE		B
9	TRACKBAL		B

Rank Sums with the same letter are not significantly different.

TABLE 117

Results of the Friedman's Two-way Rank Sum Test for Quality

K=6 N=6 S'=11.71 p=0.04

Critical Difference = 17.7

Rank Sum	Device		
32	ABSOLUTE	A	
23	FORCE	A	B
23	RELATIVE	A	B
21	DISPLACE	A	B
15	TRACKBAL	A	B
12	MOUSE		B

Rank Sums with the same letter are not significantly different.

TABLE 118

Results of the Friedman's Two-way Rank Sum Test for Positioning Accuracy

K=6 N=6 S'=17.62 p=0.004

Critical Difference = 17.7

Rank Sum	Device		
31	ABSOLUTE	A	
27	FORCE	A	B
24	RELATIVE	A	B
23	DISPLACE	A	B
11	TRACKBAL		B
10	MOUSE		B

Rank Sums with the same letter are not significantly different.

TABLE 119

Results of the Friedman's Two-way Rank Sum Test for Fatigue

K=6 N=6 S'=18.38 p=0.003

Critical Difference = 17.7

Rank Sum	Device		
32	ABSOLUTE	A	
27	FORCE	A	B
23	DISPLACE	A	B
23	RELATIVE	A	B
11	TRACKBAL		B
10	MOUSE		B

Rank Sums with the same letter are not significantly different.

TABLE 120

Results of the Friedman's Two-way Rank Sum Test for Comfort

K=6 N=6 S′=19.43 p=0.002

Critical Difference = 17.7

Rank Sum	Device		
35	RELATIVE	A	
25	ABSOLUTE	A	B
22	FORCE	A	B
20	DISPLACE	A	B
16	TRACKBAL		B
8	MOUSE		B

Rank Sums with the same letter are not significantly different.

Table 121

MANOVA Summary Table for the 10 Bipolar Ratings

```
    H = ANOVA SS&CP Matrix for : DEV
    E = ANOVA SS&CP Matrix for : S*DEV
    P = Dependent Measures =     10
    Q = Hypothesis df      =      5
    NE = Error df          =     25
    S = MIN(P,Q)           =      5
    M = 0.5(ABS(P-Q)-1)    =    2.0
    N = 0.5(NE-P-1)        =    7.0

Wilks' Criterion              L=DET(E)/DET(H=E)=0.0430

    W = -(NE-0.5(P-Q+1))*LN(L)          =  69.22
    U = NE-0.5(P-Q+1)                   =  22.0
    Z = SQRT((P*P*Q*Q-4)/(P*P+Q*Q-5) =   4.56
    B = (P*Q-2)/4                       =  12.0

F(approximation) = (U*Z-2B)/(P*Q)*(1-L**1/Z)/L**1/Z

    With df[DEV] = P*Q = 50        df[S*DEV] = U*Z-2B = 76

F(50,76) = 1.90               p = 0.0499
```

TABLE 122

ANOVA Summary Table for Accurate (Inaccurate) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	2.51		
Within-subjects				
Device (DEV)	5	8.24	3.28	0.0205
S*DEV	25	2.51		
Total	35			

Results of the Bonferonni-T Test for Accurate (Inaccurate)

MSE=2.511 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.97

Mean Scale Value	Device		
4.83	ABSOLUTE	A	
4.50	FORCE	A	B
3.50	DISPLACE	A	B
3.33	RELATIVE	A	B
2.33	TRACKBAL	A	B
1.83	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 123

ANOVA Summary Table for Fast (Slow) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	9.11		
Within-subjects				
Device (DEV)	5	4.04	2.33	0.0725
S*DEV	25	1.74		
Total	35			

TABLE 124

ANOVA Summary Table for Consistent (Inconsistent) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	8.31		
Within-subjects				
Device (DEV)	5	4.78	3.50	0.0155
S*DEV	25	1.36		
Total	35			

Results of the Bonferonni-T Test for Consistent (Inconsistent)

MSE=1.364 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.19

Mean Scale Value	Device		
4.67	RELATIVE	A	
4.33	FORCE	A	B
4.33	DISPLACE	A	B
4.00	TRACKBAL	A	B
3.83	ABSOLUTE	A	B
2.17	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 125

ANOVA Summary Table for Natural (Unnatural) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	2.89		
Within-subjects				
Device (DEV)	5	7.43	3.09	0.0262
S*DEV	25	2.40		
Total	35			

Results of the Bonferonni-T Test for Natural (Unnatural)

MSE=2.401 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.90

Mean Scale Value	Device	
5.00	ABSOLUTE	A
4.50	FORCE	A
4.33	DISPLACE	A
3.50	RELATIVE	A
2.67	TRACKBAL	A
2.17	MOUSE	A

Mean Scale Values with the same letter are not significantly different.

TABLE 126

ANOVA Summary Table for Comfortable (Uncomfortable) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	0.44		
Within-subjects				
Device (DEV)	5	12.84	6.77	0.0004
S*DEV	25	1.90		
Total	35			

Results of the Bonferonni-T Test for Comfort (Uncomfortable)

MSE=1.900 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.58

Mean Scale Value	Device		
6.00	ABSOLUTE	A	
4.67	FORCE	A	B
4.33	RELATIVE	A	B
4.17	DISPLACE	A	B
2.33	TRACKBAL		B
2.17	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 127

ANOVA Summary Table for Relaxing (Fatiguing) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	1.07		
Within-subjects				
Device (DEV)	5	6.73	4.68	0.0038
S*DEV	25	1.44		
Total	36			

Results of the Bonferonni-T Test for Relaxing (Fatiguing)

MSE=1.44 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.25

Mean Scale Value	Device			
5.67	ABSOLUTE	A		
5.50	FORCE	A	B	
4.83	RELATIVE	A	B	C
4.50	DISPLACE	A	B	C
3.33	TRACKBAL		B	C
3.17	MOUSE			C

Mean Scale Values with the same letter are not significantly different.

TABLE 128

ANOVA Summary Table for Acceptable (Unacceptable) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	2.98		
Within-subjects				
Device (DEV)	5	10.38	5.01	0.0026
S*DEV	25	2.07		
Total	35			

Results of the Bonferonni-T Test for Acceptable (Unacceptable)

MSE=2.071 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.70

Mean Scale Value	Device		
5.16	ABSOLUTE	A	
4.00	FORCE	A	B
3.83	DISPLACE	A	B
3.67	RELATIVE	A	B
1.83	TRACKBAL		B
1.83	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 129

ANOVA Summary Table for Pleasing (Irritating) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	0.78		
Within-subjects				
Device (DEV)	5	10.45	4.97	0.0027
S*DEV	25	2.10		
Total	35			

Results of the Bonferonni-T Test for Pleasing (Irritating)

MSE=2.103 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.72

Mean Scale Value	Device		
5.00	ABSOLUTE	A	
5.00	FORCE	A	
4.50	DISPLACE	A	B
4.50	RELATIVE	A	B
2.50	TRACKBAL	A	B
2.00	MOUSE		B

Mean Scale Values with the same letter are not significantly different.

TABLE 130

ANOVA Summary Table for Pleasing Good (Bad) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	1.78		
Within-subjects				
Device (DEV)	5	7.24	4.59	0.0042
S*DEV	25	1.58		
Total	35			

Results of the Bonferonni-T Test for Good (Bad)

MSE=1.578 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference = 2.35

Mean Scale Value	Device	
4.33	ABSOLUTE	A
4.17	DISPLACE	A
4.17	FORCE	A
3.67	RELATIVE	A
2.00	TRACKBAL	A
2.00	MOUSE	A

Mean Scale Values with the same letter are not significantly different.

TABLE 131

ANOVA Summary Table for Pleasing Expensive (Inexpensive) Bipolar Scale Ratings

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	5.24		
Within-subjects				
Device (DEV)	5	2.18	1.20	0.3387
S*DEV	25	1.82		
Total	25			

TABLE 132

ANOVA Summary Table for Preference Index (PI)

Source	df	MS	F	p
Between-subjects				
Subjects (S)	5	47.3		
Within-subjects				
Device (DEV)	5	516.2	6.01	0.0009
S*DEV	25	85.8		
Total	35			

Results of the Bonferonni-T Test for Preference Index (PI)

MSE=85.82 df=25 N=6 C=15 Alpha=0.05 T=3.24

Critical Difference =17.35

Mean Scale Value	Device			
45.83	ABSOLUTE	A		
44.00	FORCE	A	B	
40.17	DISPLACE	A	B	C
38.50	RELATIVE	A	B	C
27.17	TRACKBAL		B	C
23.00	MOUSE			C

Mean Scale Values with the same letter are not significantly different.

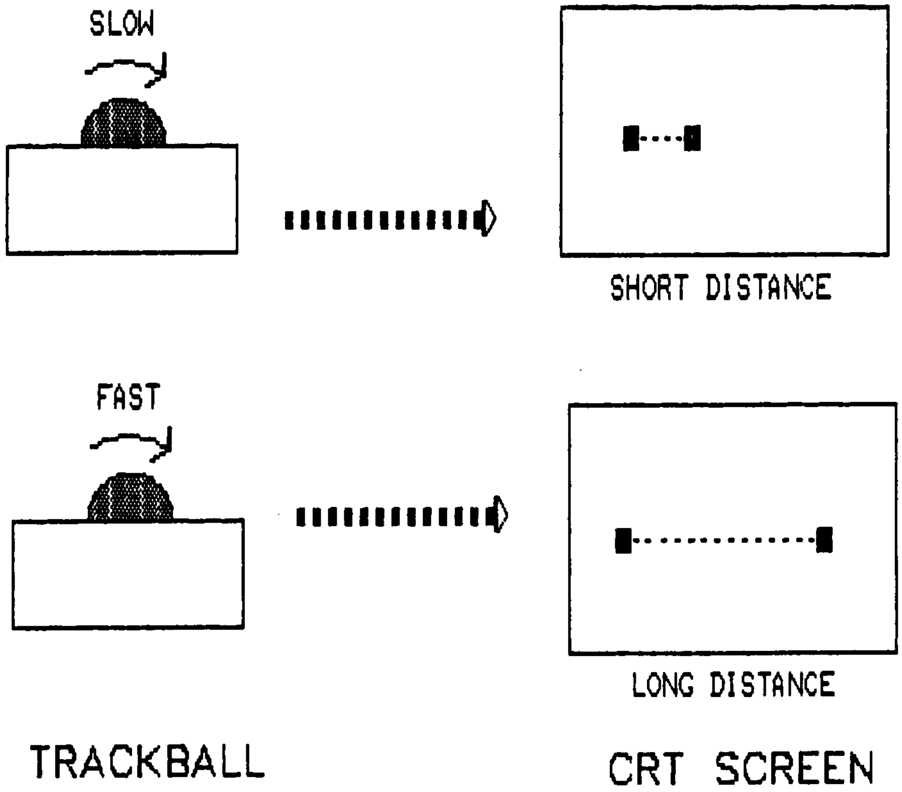
APPENDIX C:

Instructions for the Seven Cursor Control Devices

TRACKBALL

The trackball is operated by rolling the ball in the direction in which you want the cursor to move on the screen. The faster the trackball is rolled the further the cursor will move on the screen. The relationship between the amount of trackball rotation and the distance the cursor will move on the screen is dependent on the speed with which the ball is rotated. (SEE DRAWING). If you roll the trackball slowly, the cursor will move a short distance for a given rotation of the ball. If you roll the trackball fast, the cursor will move a long distance for the same given rotation of the ball.

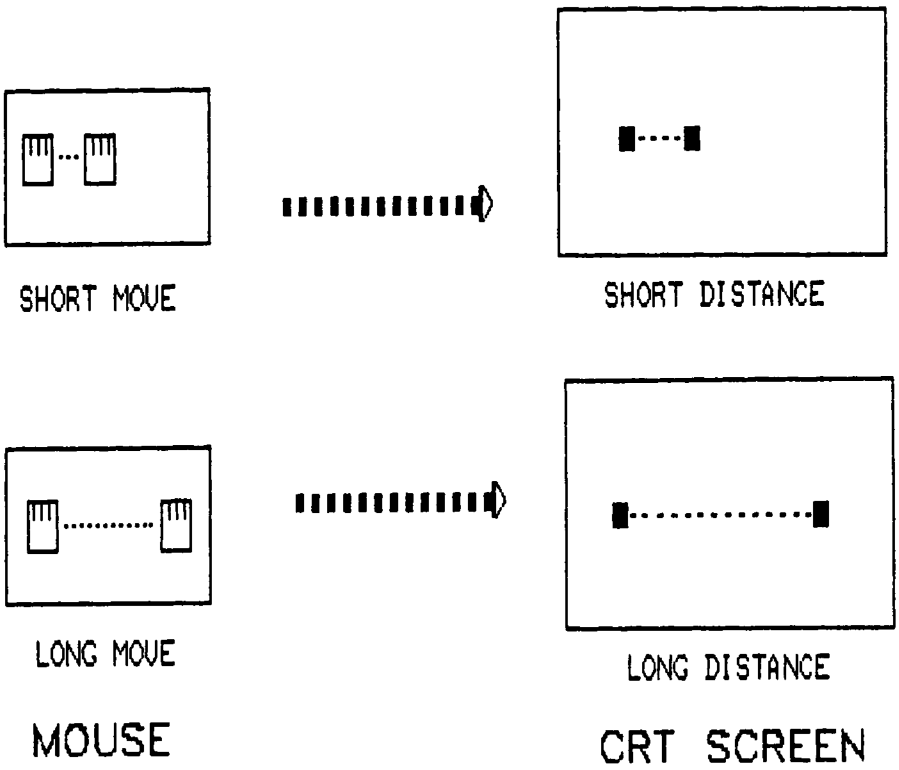
ANY QUESTIONS????


SLOW
SHORT DISTANCE
FAST
LONG DISTANCE
TRACKBALL
CRT SCREEN

MOUSE

The mouse is operated by sliding it across the surface of the blue pad in the direction in which you want the cursor to move. The distance with which the mouse is moved is approximately equal to the distance which the cursor moves on the screen. If you pick up the mouse and move it to a new position on the blue pad, the cursor position on the screen will not change.

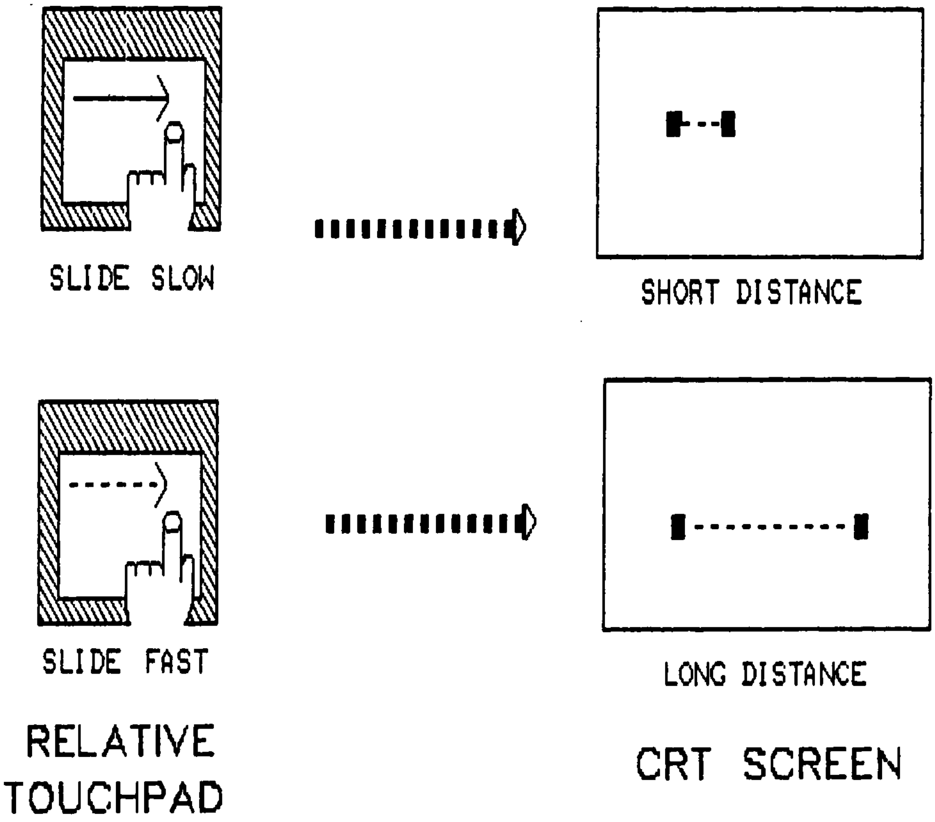
ANY QUESTIONS???


SHORT MOVE
SHORT DISTANCE
LONG MOVE
LONG DISTANCE
MOUSE
CRT SCREEN

RELATIVE TOUCHPAD

The relative touchpad is operated by sliding your finger (moderate fingertip pressure) across the pad in the direction in which you want the cursor to move. The faster you slide your finger across the pad the farther the cursor will move on the screen. The relationship between the distance you slide your finger across the touchpad and the distance the cursor will move on the screen is dependent on the speed with which you slide your finger across the touchpad. (SEE DRAWING). If you slide your finger slowly, the cursor will move a short distance for a given finger distance moved. If you slide your finger fast, the cursor will move a long distance for the same given finger distance moved.

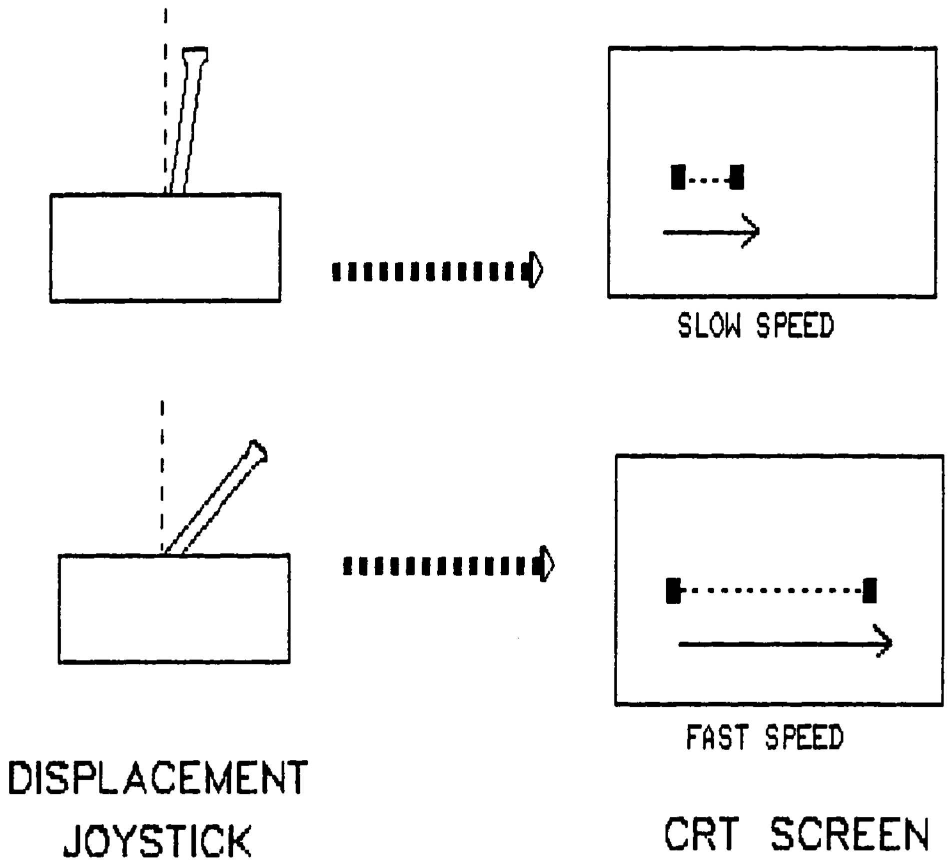
ANY QUESTIONS???


SLIDE SLOW
SHORT DISTANCE
SLIDE FAST
LONG DISTANCE
RELATIVE TOUCHPAD
CRT SCREEN

DISPLACEMENT JOYSTICK

The displacement joystick is operated by pushing the stick in the direction in which you want the cursor to move. The farther you displace the stick, the faster the cursor will move on the screen. The relationship between the amount of joystick displacement and the speed the cursor will move on the screen is dependent on the distance the joystick is moved. (SEE DRAWING). If you move the joystick a little, the cursor will move slowly. If you move the joystick a lot, the cursor will move quickly across the screen.

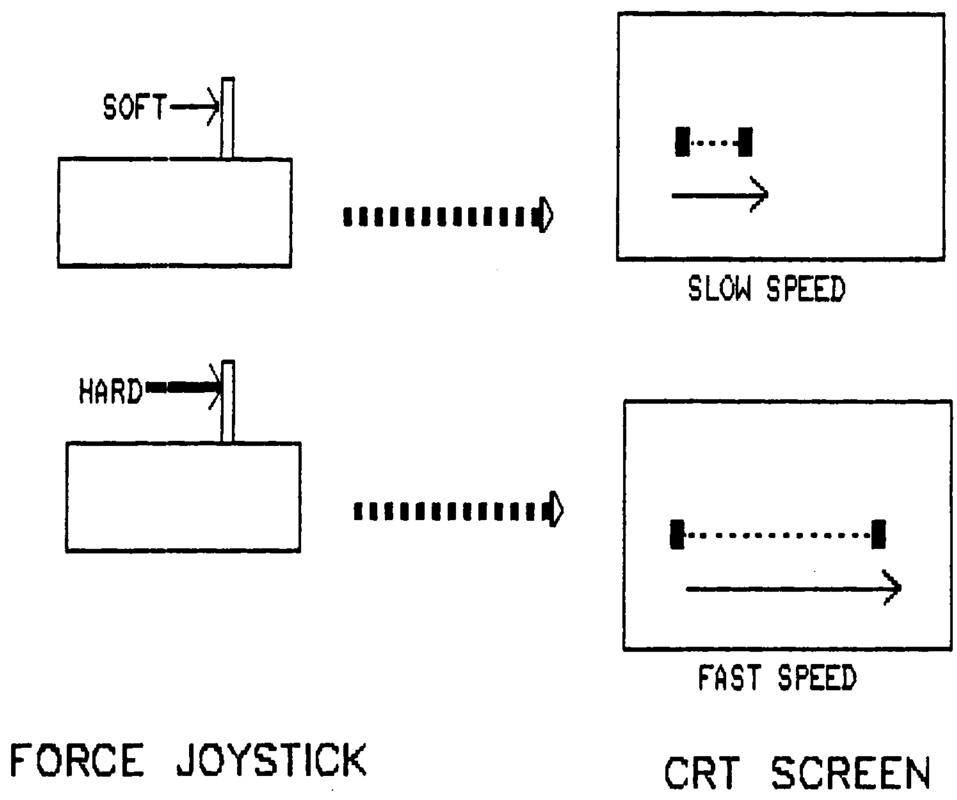
ANY QUESTIONS???


SLOW SPEED
FAST SPEED
DISPLACEMENT
JOYSTICK
CRT SCREEN

FORCE JOYSTICK

The force joystick is operated by pushing the stick in the direction in which you want the cursor to move. The harder you push the stick the faster the cursor will move on the screen. The relationship between the amount of joystick pressure and the speed the cursor will move on the screen is dependent on the pressure with which the joystick is pushed. (SEE DRAWING). If you push the joystick softly, the cursor will move slowly. If you push the joystick hard, the cursor will move quickly across the screen.

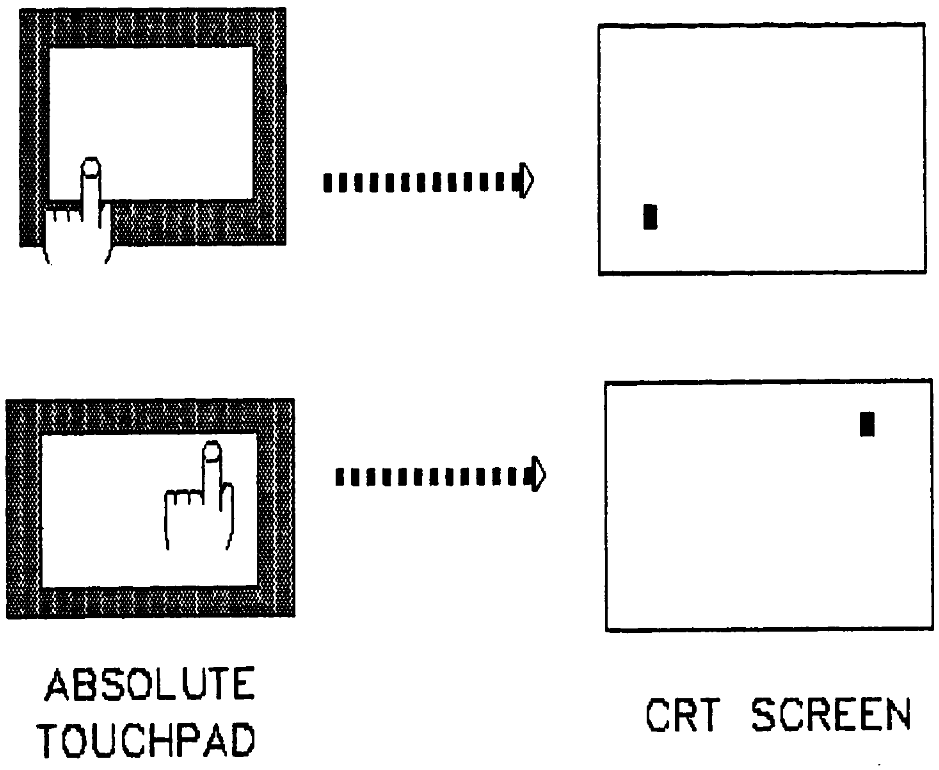
ANY QUESTIONS???


SOFT
HARD
SLOW SPEED
FAST SPEED
FORCE JOYSTICK
CRT SCREEN

ABSOLUTE TOUCHPAD

The absolute touchpad is operated by sliding your finger (moderate fingertip pressure) or moving your finger to the position on the pad which corresponds to the cursor position on the screen. Each position on the pad corresponds (i.e., is "mapped") to a specific position on the screen. (SEE DRAWING). If you place your finger in the lower left-hand corner of the pad the cursor will appear in the corresponding lower left-hand corner of the screen. If you slide or move your finger to the top right hand corner of the pad, the cursor will move to the corresponding upper right-hand corner of the screen.

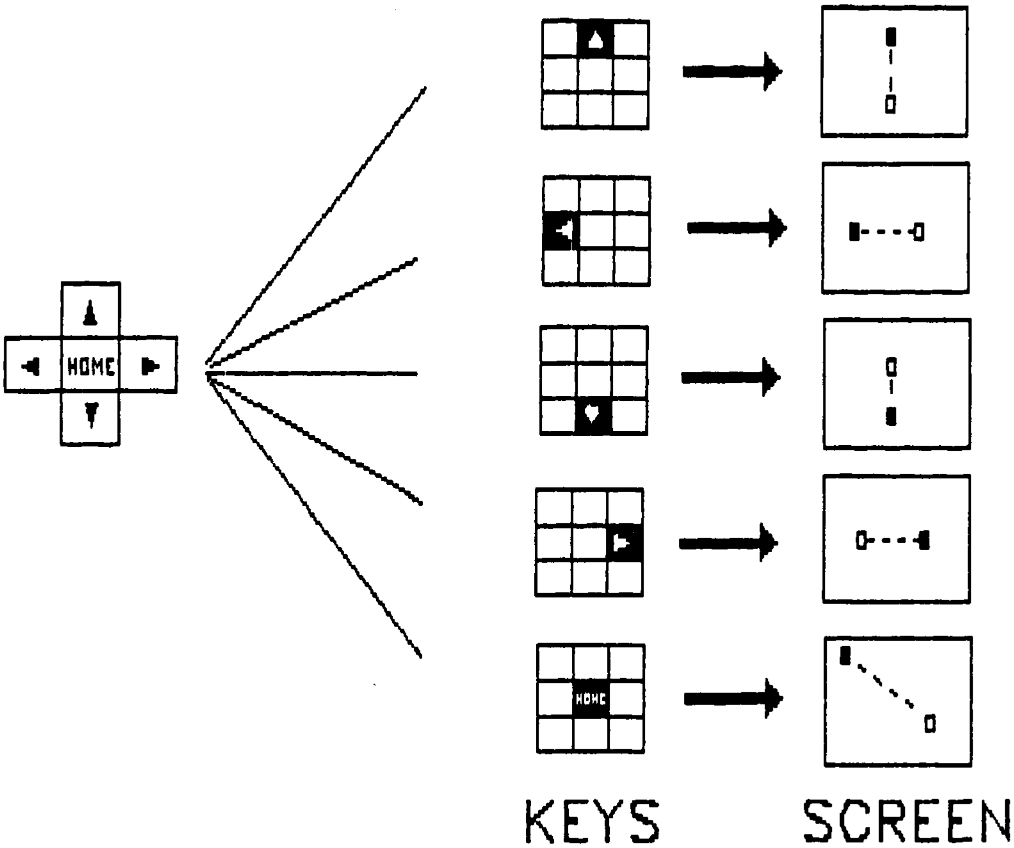
ANY QUESTIONS???


ABSOLUTE
TOUCHPAD
CRT SCREEN

CURSOR KEYS

The cursor keys are operated by pressing one of the four directional keys. The direction which the cursor will move is shown by the direction of the arrow on each key (SEE DRAWING). If you briefly press a key, the cursor will move only one character. If you hold the key down, the cursor will move across the screen. If you press the HOME key, the cursor will move to the top left position on the screen.

ANY QUESTIONS???


HOME
HOME
KEYS
SCREEN

APPENDIX D:

Instructions for the Bipolar Scales

INSTRUCTIONS: SCALES

After you use each cursor device, you will be asked to judge each on a series of descriptive scales.

Here is an example of how to use the scales:

If you feel that a certain cursor device is VERY CLOSELY RELATED to one end of the scale, you should place your check mark as follows:

GOOD :__X__:_____:_____:_____:_____:_____:_____: BAD

or

GOOD :_____:_____:_____:_____:_____:_____:__X__: BAD

If you feel that a certain cursor device is QUITE CLOSELY RELATED to one end of the scale, you should place your check mark as follows:

GOOD :_____:__X__:_____:_____:_____:_____:_____: BAD

or

GOOD :_____:_____:_____:_____:_____:__X__:_____: BAD

If you feel that a certain cursor device is ONLY SLIGHTLY RELATED to one end of the scale, you should place your check mark as follows:

GOOD :_____:_____:__X__:_____:_____:_____:_____: BAD

or

GOOD :_____:_____:_____:_____:__X__:_____:_____: BAD

The direction toward which you check, of course, depends on which of the two ends of the scales seem to be most characteristic of how you feel about each cursor device.

If you feel that a certain cursor device is NEUTRAL between the ends of the scale, or the scale is COMPLETELY IRRELEVANT, you should place your check-mark as follows:

GOOD : _____ : _____ : _____ : __X__ : _____ : _____ : _____ : BAD

IMPORTANT

1) Place your check-mark in the middle of the spaces, not on the boundaries:

this / not this

GOOD : _____ : _____ : __X__ : _____ : _____X_____ : _____ : BAD

2) Be sure you check each scale: DO NOT OMIT ANY.

3) Never put more than one check-mark on each scale.

APPENDIX E:

Instructions for the PFM Editor

INSERT CHARACTER / WORD:

(1) Position cursor over character or space which the inserted character/word should begin.

(2) Press [INSERT] key.

(3) Type characters, words, and spaces to be inserted.

DELETE CHARACTER:

(1) Position cursor over character to be deleted.

(2) Press [DELETE CHAR] key.

DELETE WORD:

(1) Position cursor over the first character of the word to be deleted.

(2) Press [DELETE WORD] key.

(3) Insert periods (.) commas (,) or spaces, if needed.

REPLACE CHARACTERS:

(1) Position cursor over the first character of the incorrect characters to be replaced.

(2) Type over incorrect characters with correct characters.

REPLACE WORD:

(1) Position cursor over the first character of the word to be replaced.

(2) Press [DELETE WORD] then [INSERT] keys

(3) Insert new word plus periods (.) commas (,) or spaces, if needed.

UNDO: If you hit the [DELETE WORD] key by mistake.

Press the [UNDO] key and the word will reappear.

PAGE DOWN: Press [PAGE DOWN] to make 11 lines (1/2 screen) of text on the screen move UP

PAGE UP: Press [PAGE UP] to make 11 lines (1/2 screen) of text on the screen move DOWN

* FINISH FILE: Press [ESC] then [Q] then [A] [Y] keys

EDITING EXAMPLES

Delete Character

X relies primarilly on the apprenticeship strategy. Limiting

Insert Character

X access to traiing is, however, the basic strategy of a
n

Replace Character

X leading union-like organization, the American Medical

Delete Word

X Corporation, and ~~and~~ seems to have made possible a high return to

Insert Word

X the skills of physicians ^ bargaining or strikes. The
without

Replace Word

X closest approach to this strategy ~~between~~ the true unions is
among

Multiple Edits

XX the combination of appprenticeship and ~~the~~ licensing in such

APPENDIX F:

Examples of the Text Editing Tasks

Without wholly denying the relevance of such psychological explanations, one can also explain favoritism along economic lines. The downward inflexibility of wages and the instability of the demand for labor in many industries create frequent periods of excess labor suupply in the pre-union era. Firms therefore had to ~~to~~ ration jobs among applicants or among their workers. They did not want to use price rationing; this would have required substantial wage cuts that would have seemed to workers and to the public and that could have stimulated the organization of unions. The idea of using seniority in layoffs seems not to have ~~affected~~ to employers of manual labor. In the absence of any other device, the foreman was lfet to use his own criteria. If the career incentives for running an efficient shop were great enough, he could lay off the least able workers first, according to his own assessment of ability. Or he could use his power to increase his personal satisfaction, through graft or favoritism.

A major exception to the usual political position of the labor movement took place in 1972, when the AFL-CIO did not endorse either presidential candidate and would not permit its state and local bodies to make endorsements. Leaders of several major national unions, including most of the building trades unions, supported President Nixon for re-election, and a leader of the New York building trades, Peter Brennan, became Secretary of Labor in the second Nixon administration.

This departure from the general rule had little to do with domestic political issues. It took place largely because the labor movement supported the Republican administration position on the war in Viet Nam, and Democratic candidate George McGovern was a peace candidate. By 1976, the AFL-CIO was once again back in the Democratic camp.

The political position of unions as a whole is that of favoring increased state ~~participation~~ intervention in the economy through extension of such programs as social security, public housing, public power, minimum wage laws, and the like, but not extending to the large-scale public ownership of mining, manufacturing, or distributive industries. In fighting for such things as improved unemployment insurance programs for the use of income taxes rather than sales taxes in financing state and local governments, the unions represent the interest of a group much broader than their own membership. On many of these issues, they are the only effecive lobby representing low-income urban people, for there are not strong political organizations of consumers or of non-union workers. Although the positions taken by unions on particular issues may not always be in the interest of the community as a whole, at least as it is construed by other groups, it does seem to be in the public interest to have some strong group that will act as the champion of the underdog.

Many of the measures ~~which~~ that unions have supported are in the immediate economic interests of union members. Others, however, represent a more general ideological position whose application in particular areas works against the short-run interests of the members. Thus unions have backed high price supports for agricultural commodities, a position that is contrary to the immediate interests of union members both as consumers of farm products and as workers in the industries that process and distribute them.

The AFL-CIO maintains a Washington staff to present labor's position to Congress and to the administrative agencies of the federal government. In addition, ~~most~~ major unions have their national headquarters in Washington and others maintain Washington representatives for this purpose. The AFL-CIO state ~~base~~ organizations usually maintain similar offices at state capitals. At the local level such unions as the building codes and licensing laws, maintain close contact with local political organizations.

The effectiveness of any lobby depends not so much on the cogency of its arguments as on its ability to deliver votes, money, or both to party organizations or candidates. Unions typically endorse candidates for office and attempt to persuade their members to vote for them. Ordinarily the endorsement is made not by the unions as such, but by a subsidiary body of the AFL-CIO, the Committee on Political Education (COPE). COPE usually endorses Democrats and union members usually vote for Democrats. However, this is not good evidence of the success of COPE; there is a strong coincidence of natural preferences between the unions and their members, arising from the well-known differences in party preference by socioeconomic class (outside the South). The union member typically votes Democratic because of the traditions of his family, his ethnic group, or his neighborhood rather than because the union urges him to, and many loyal union members have doubts about the right of unions to make political endorsements. When a union leader attempts to sway his members against their natural inclination, he almost always fails. The most celebrated case is that of John L. Lewis, who in 1940 supported Wendell Willkie for president against Franklin D. Roosevelt and who resigned as president of the CIO when it became apparent that CIO members had overwhelmingly ignored his position in casting their ballots. The effectiveness of union political activity therefore lies largely in getting union members registered and in seeing that they remember to vote rather than in persuading them to alter their positions.

Unions support candidates by articles, editorials, and cartoons in union papers; by programs at union meetings; by having union staff do precinct work; and by contributing money to campaign funds. The Taft-Hartley Law prohibits the use of dues funds for contributions to candidates for federal office, so that voluntary contributions are collected to support such candidates. At the state and local level, contributions are made from union treasuries.

In some states, unions have played an important part in the internal affairs of the Democratic party, though there is probably only one case (Michigan) where unions have had anything resembling control of a major political ~~of~~ party at the state level. Even in Michigan, where union influence in politics has reached its highest level, union leaders have usually not done well as candidates for public office. The members of unions are still a minority in the electorate in the most highly industrialized states. Unions have been most successful when they have supported some one sympathetic with their position who has not been a career union leader.

The role of unions in politics has long seemed a menacing one to American conservatives, probably because they have typically overrated its effecitveness. Yet the major farm and business interests have always played an important political role, and it was only natural for unions to seek to do ~~similarly~~. likewise. Perhaps it would be good for American democracy if economic interest groups all stayed out of politics, though this is surely debatable. It does seem clear, however, that if some producer groups are to have strong political influence, it is best for the consumer for all of them to have influence. Since consumers have seldom had an effective lobby of their own, they may get some protection from conflicts of interest among producer lobbies.

It would be highly unfortunate for American democracy if any part of the electorate came to feel that the machinery of government did not permit its interests to be adequately represented, so that it felt it necessary to oppose the system of government as a whole. The participation of unions in politics can help to prevent workers from developing such a feeling, and thus can inhibit the growth of anti-democratic political movements among workers.

APPENDIX G:

Distribution of Text Edits

Distribution of text editing changes for MS/CD and MS/TE files:

	CHARACTER	WORD	Total
INSERT	3	3	6
DELETE	3	3	6
REPLACE	3	3	6
Total	9	9	18

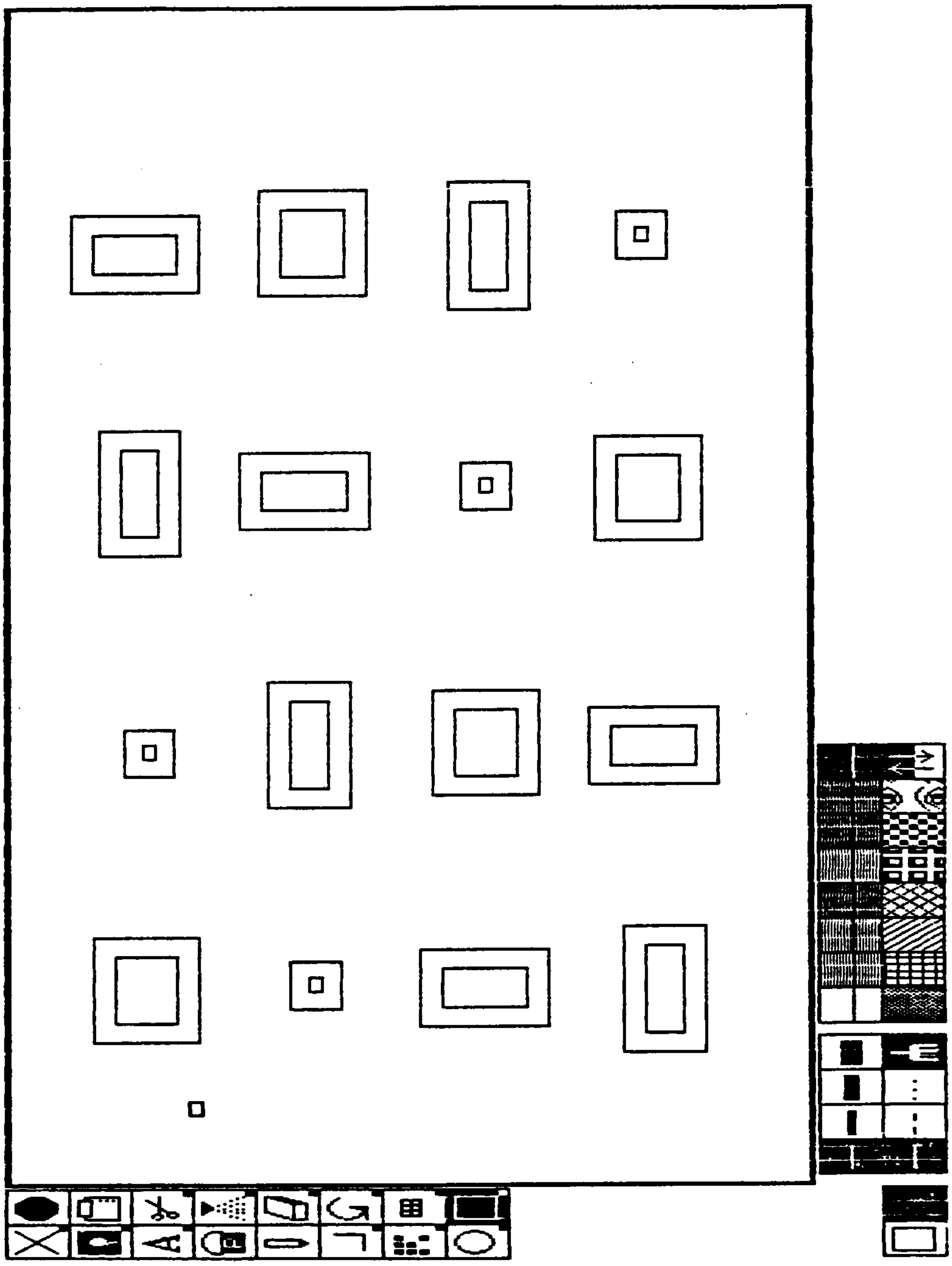
Distribution of distance between lines of text edits:

LINE #		% OCCURRENCE
0		13
1	26	13
2		7
3	14	7
4		4
5		4
6		4
7	16	4
8		3
9		3
10		3
11		3
12		3
13		3
14		3
15	24	3
16		2
17		2
18		2
19		2
20		2
21		2
22		2
23		2
24		2
25	20	2
Total	100 %	

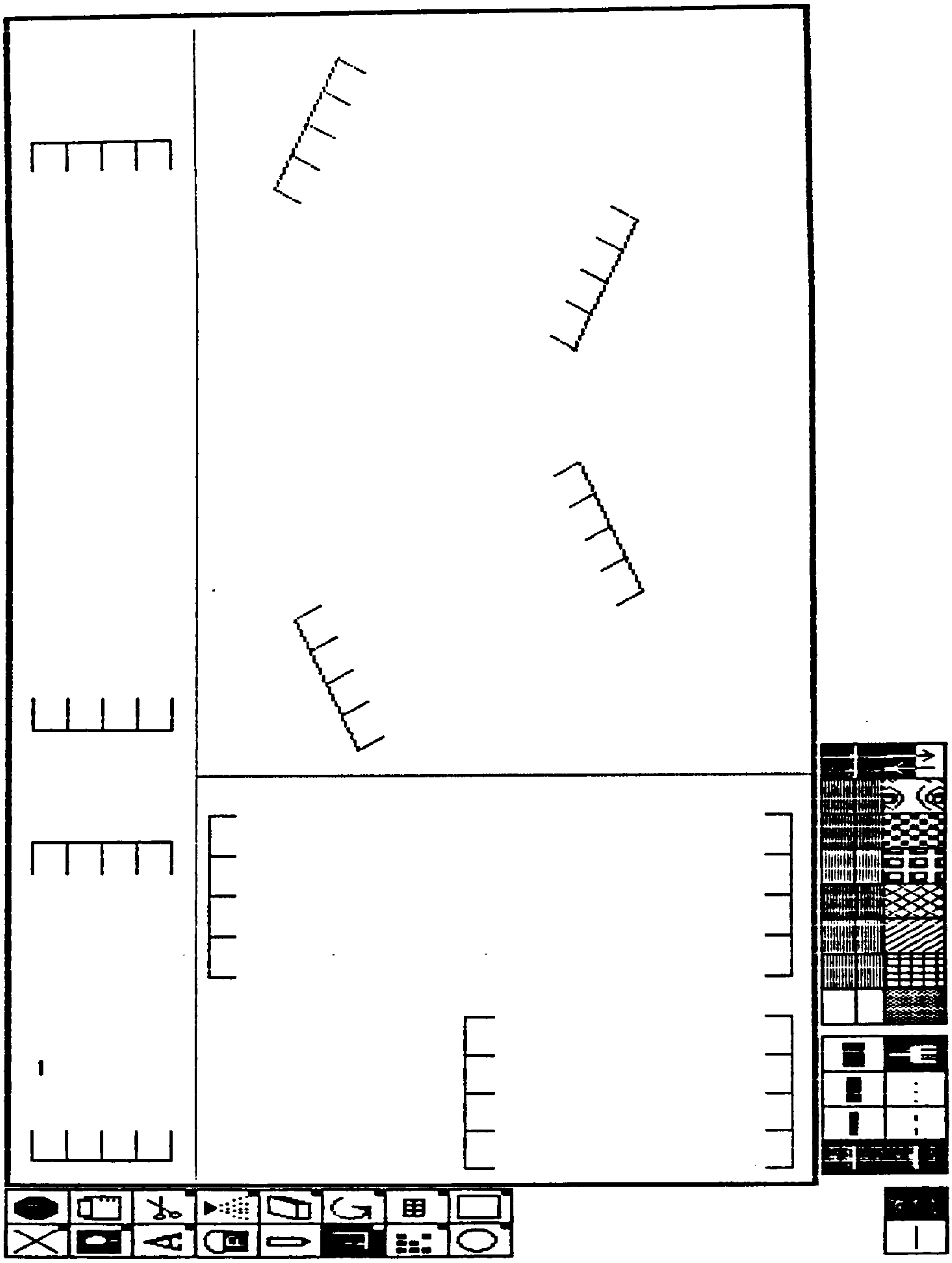
AAPENDIX H

Examples of the Graphics Tasks

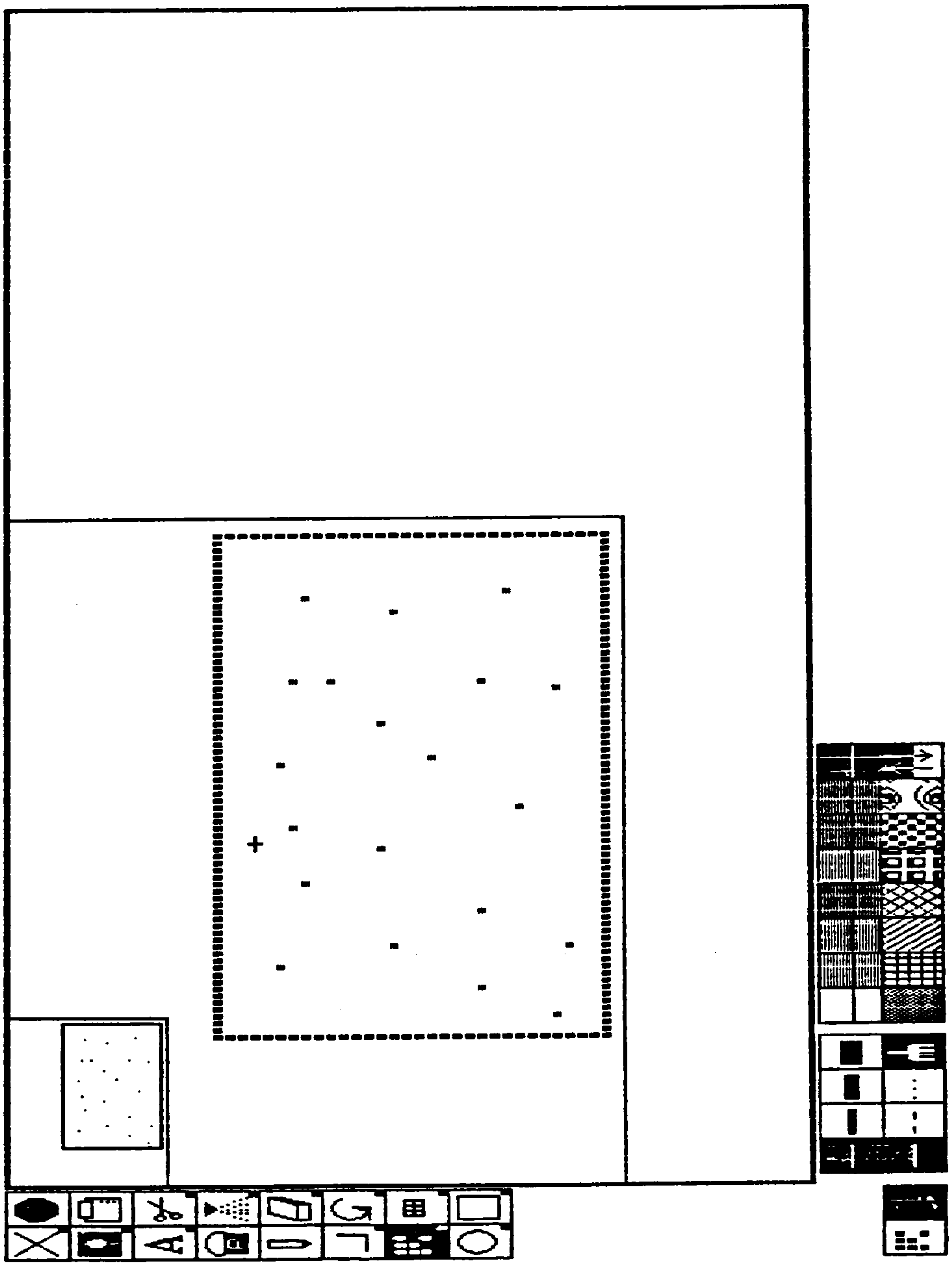
RECTANGLES



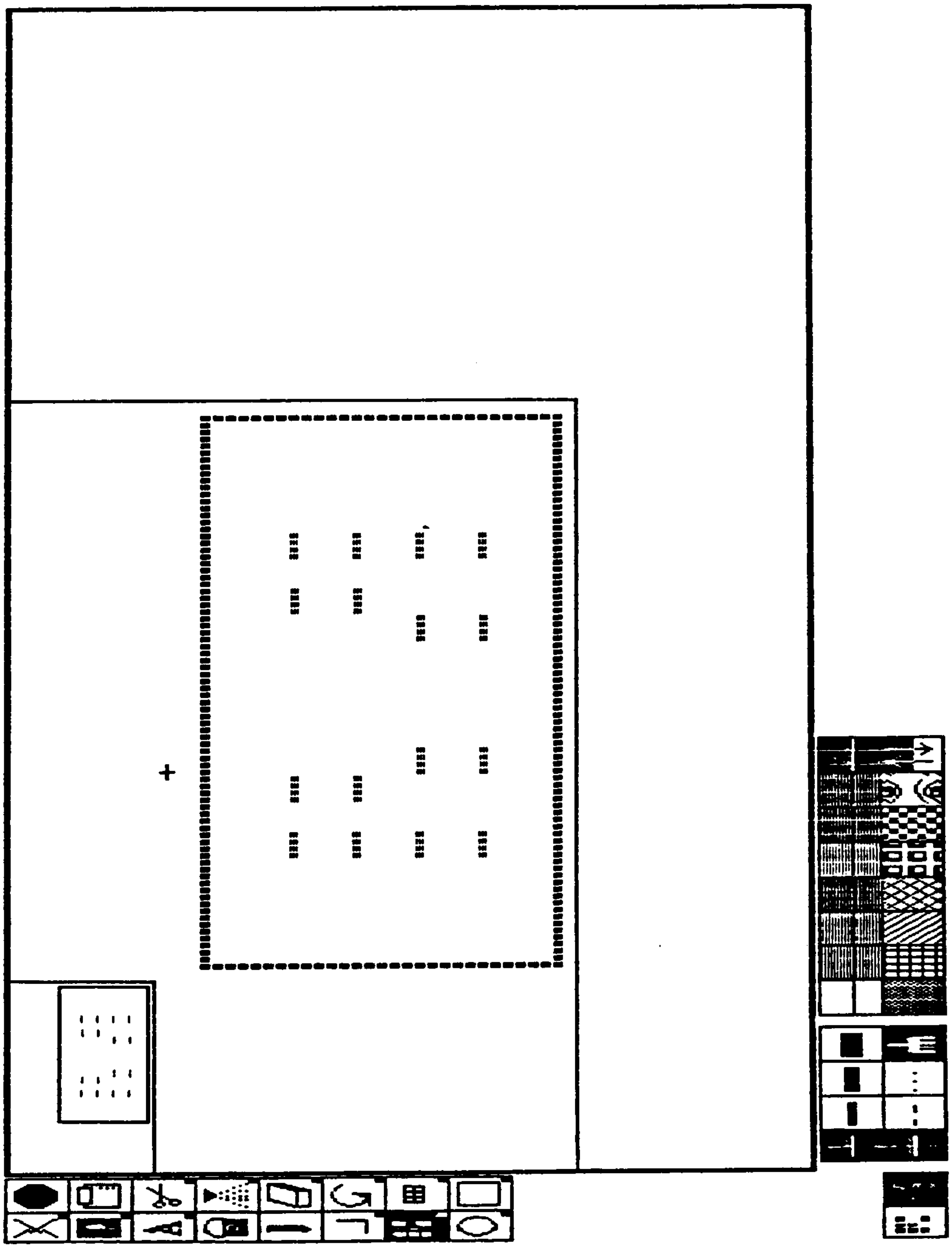
GRIDS



FATBITS



LINES



The vita has been removed from the scanned document