

A Comparison of Two Control-Display Gain Measures for Head-Controlled Computer Input Devices

JOHN A. SCHAAB, ROBERT G. RADWIN,¹ and GREGG C. VANDERHEIDEN, *University of Wisconsin, Madison, Wisconsin*, and PER KROGH HANSEN, *Pointer Systems, Inc., Burlington, Vermont*

We compared two gain measures: One, defined as angle/angle (A/A) gain, is the ratio between the angle subtended by displacement of the cursor and the corresponding angle of head extension/flexion or rotation. The alternative measure, defined as displacement/angle (D/A) gain, is the ratio between the linear displacement of the cursor on the screen and the corresponding angle of head extension/flexion or rotation. A discrete target acquisition task using circular targets was used to compare control-display gain measures. Operator performance was evaluated for three viewing distances and three gain settings of each measure. Average movement time and root mean squared (RMS) cursor deviation from a straight line path increased as viewing distance increased for A/A gain settings 0.75 and 1.0. That no significant distance effect was observed for any of the D/A gain settings indicated that it might be more suitable to fix D/A gain rather than A/A gain for head-controlled computer input devices. Minimum movement time occurred for D/A gain settings of 0.5 cm/° and 0.67 cm/°. One explanation for the observed insensitivity of performance to changes in viewing distance with a fixed D/A gain may be that both angular head movement and the accompanying kinesthetic feedback do not change for a specified cursor displacement as viewing distance is changed.

INTRODUCTION

Head-controlled computer input devices, or *headpointers*, allow computer operators to maneuver a cursor in a graphical user interface using head movements instead of the hand movements that are usually needed for mice and trackballs. Head-controlled interfaces provide an alternative method of accessing a computer

and have been beneficial for some individuals with impaired upper-extremity control caused by spinal cord injury, degenerative muscular conditions, or cerebral palsy. The focus of this study is to examine characteristics of head motor control in order to provide information that will enhance performance of head-controlled computer input devices.

The linear relationship between movement time and the index of difficulty (ID) as described by Fitts' law has proven to be a robust predictor of various components of the human motor

¹ Requests for reprints should be sent to Robert G. Radwin, Department of Industrial Engineering, University of Wisconsin-Madison, 1513 University Ave., Madison, WI 53706.

system (Fitts, 1954; Fitts & Peterson, 1964). Langolf, Chaffin, and Foulke (1976) showed Fitts' law to be a good predictor of movement time for the finger, wrist, and arm. Fitts' law has also been shown to be a reliable predictor of movement time for computer-related tasks involving a variety of hand-operated input devices (Card, English, & Burr, 1978; Epps, 1986). Research on head-controlled computer interfaces and the human movement characteristics associated with them has received limited attention.

Jagacinski and Monk (1985) were among the first to report on a head-controlled computer interface. Their study used a helmet-mounted sight as a computer input device and found Fitts' law to adequately describe head movement. The results of their study indicated that movement time was slightly faster for head movements along the vertical and horizontal axes than for those along diagonal axes.

A discrete target acquisition task was developed by Radwin, Vanderheiden, and Lin (1990) to measure and evaluate the performance of various alternative computer input devices. The results of their study supported Jagacinski and Monk's findings that Fitts' law aptly described head movement in computer-related tasks and that performance for diagonal head movements was slower than for movements along the vertical or horizontal axis.

Andres and Hartung (1989) showed that head movement could be described using Fitts' law for a tapping task involving a chin stylus. Spitz (1990) used a prototype head-controlled computer input device to study users' ability to control cursor location by tilting their head. The results of that study also supported a Fitts' law relationship and showed tilting movements of the head to be less efficient than extension/flexion movements at longer movement amplitudes.

Selection of a control-display gain setting for a particular input device has been an important issue for designers of computer interfaces. Chapanis and Kinkade (1972) indicated the need to empirically determine optimum gain for an input device, given the complexities involved

within each system. The optimization of control-display gain has been the focus of several studies (Arnaut & Greenstein, 1986; Gibbs, 1962; Jenkins & Connor, 1949; Lin, Radwin, & Vanderheiden, 1992).

Typically the difference between hand- and head-controlled interfaces is that hand-controlled interfaces involve linear hand movement while the head remains stationary, whereas head-controlled interfaces involve head movements relative to a stationary display. As a result, the description of the control-display gain relationship for a head-controlled input device is different from that of traditional movements involving the upper extremities. An exception to this was Gibbs' (1962) study of joystick interfaces, in which control-display gain was defined as the ratio of angular movement of the display's cursor subtended at the user's eyes to corresponding angular movement of the joystick. Similarly, Jagacinski and Monk (1985), and later Lin et al. (1992), defined control-display gain for head-controlled interfaces as the ratio of the angle subtended by the displacement of the cursor to the viewing position and the corresponding angle of head extension/flexion or rotation.

Two measures of control-display gain for a head-controlled input device were the focus of the present study. One measure of headpointer gain, defined by Lin et al. (1992), will be referred to in this paper as *angle/angle* (A/A) gain because a fixed angle of cursor displacement corresponds to a fixed angle of head movement. An alternative measure proposed in this study will be referred to as *displacement/angle* (D/A) gain because a fixed displacement of the cursor corresponds to a fixed angle of head movement.

Figure 1 provides a representation of both A/A gain and D/A gain. The difference between the two approaches is that under variations in viewing distance, fixed A/A gain maintains a unitless ratio of output angle to input angle, whereas fixed D/A gain maintains a ratio of output displacement to input angle. The current study was designed to investigate the effect of viewing distance on each measure of gain.

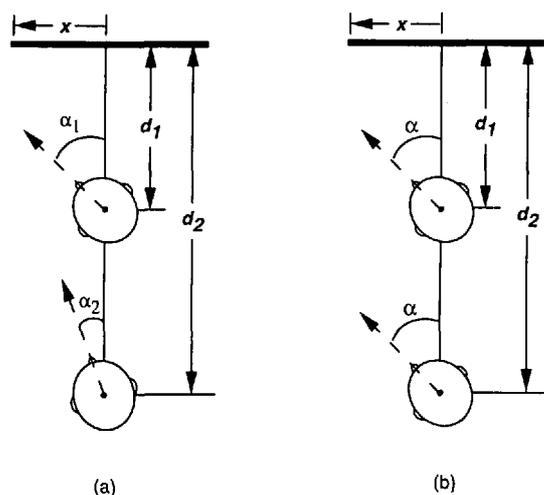


Figure 1. Head movement required to move the screen's cursor a distance x with (a) fixed A/A gain and (b) fixed D/A gain at different viewing distances. (a) A/A gain for a head-controlled computer input device is the ratio of the angle subtended by the displacement of the cursor back to the viewing position and the angle of head extension/flexion or rotation. $A/A \text{ gain} = \tan^{-1}(x/d_1)/\alpha_1$. (b) D/A gain is the ratio of linear cursor displacement on the screen and the angle of head extension/flexion or rotation. $D/A \text{ gain} = x/\alpha$. Observe that a fixed D/A gain maintains constant kinesthetic feedback regardless of viewing distance for identical cursor displacement.

One of the objectives of this study was to establish whether or not performance at various A/A gain settings for a head-controlled interface would be significantly affected by changes in the participant's viewing distance. The definition of A/A gain used in this study was similar to the definition Gibbs (1962) used for a joystick interface. That study found that the relationship between angular gain settings and movement times was similar for thumb, hand, and forearm control of a joystick; it concluded that the angular definition of gain provides a measure that could be generalized to these control movements. Gibbs (1962) tested participants only at a viewing distance of 60 cm and speculated that the display component of the gain calculation could be affected by amplitude changes between the display and the participant's eyes resulting from a change in viewing distance or optical magnification.

The second objective was to establish whether

or not performance at various D/A gain settings for a head-controlled interface would be significantly affected by changes in the participant's viewing distance. This alternative measure of gain defines the display component (i.e., cursor movement) of the gain calculation independent of the participant's viewing distance. As a result, changes in visual feedback will occur for a fixed D/A gain setting as viewing distance changes.

Changes in operator performance for small changes in viewing distance could reduce the effectiveness of such an interface because operators will rarely position themselves the same distance from the screen each time they use the device and will frequently adjust their seated posture as they perform various tasks. This is an important issue for computer interface designers because this type of effect can make the device more difficult to use and lead to customer dissatisfaction.

METHODS

Participants

Participating in the study were 12 able-bodied volunteers (six men and six women) ranging in age from 19 to 36 years (mean age 22.5 years). All stated that they had no previous conditions that would limit their voluntary range of head movement, and they wore their normal glasses or contact lenses. Participants volunteered for the study by responding to advertisements posted throughout the University of Wisconsin-Madison campus. All were considered novices in the use of head-controlled computer input devices. Participants were paid on an hourly basis and received an additional bonus for completing the entire experiment.

Apparatus

The experimental task was programmed and performed on a Apple Macintosh II microcomputer with an MC68020 processor. Movement times were measured using the Macintosh II internal real-time clock. The resolution of the timing routine was 1 ms. Participants viewed an Apple Two-Page Monochrome Monitor model

M1025. The display had a 1140×860 pixel resolution with 0.32987 mm/pixel. The screen was assumed to be flat for the purposes of this study.

A modified Personics Corporation model VCS 2000 ultrasonic head-controlled input device was used for this experiment. The transmitter unit was centered on top of and in the same vertical plane as the monitor. It emitted ultrasonic signals that were received by sensors in a headset worn by the user. The weight of the headset was 0.5 N; it was secured to the participant's head with a headband. This system measured the change in the operator's head position (i.e., extension/flexion and rotation) and translated this change into a displacement of the cursor on the computer screen. The velocity control of the input device was disabled to allow A/A gain and D/A gain to be controlled through software.

The headset of the input device was calibrated using a Keuffel & Esser Vectron digital surveying transit. The transit allowed the headset to be rotated in the vertical and horizontal planes with 0.0003° precision. No hardware noise from the input device was observed when the headset was perfectly stationary as measured by RMS cursor deviation.

Participants sat in a wheelchair in an upright position with their feet flat on the footrest and hands in their lap. This was the required Ready position for beginning a trial. Every participant's seated height was measured before each session, and the height of the monitor was adjusted so that the ultrasonic transmitter was at the same height as the top of the headset.

Experimental Task

A modified version of the Radwin et al. (1990) discrete movement target acquisition task based on Fitts' law was used in this study. At the center of the computer display, a 6.6-mm diameter circle was designated as the Home target. The objective of the task was to move the center of a 3.6-mm crosshair cursor from the Home position into circular targets of varying diameters and locations on the screen. Participants were instructed to move the cursor into the target as

quickly as possible. Instructions for the experimental task consisted of the following:

- (1) Move the cursor into the Home target at the center of the display and maintain the cursor inside. After 500 ms a short tone is sounded, accompanied by the presentation of a random target.
- (2) Continue holding the cursor inside the Home position for an additional 1.0 s until the Home position circle is removed from the display and a second tone is sounded, which is the Go signal. After the Go signal, move the cursor into the target as quickly as possible. The trial is reset if the cursor is moved outside the Home position at any time prior to the Go signal.
- (3) In order to successfully acquire a target, the center point of the cursor must be maintained within the circular target for a full 500 ms. Once the target has been successfully acquired, the circular target becomes transparent, leaving only its outline, which remains visible for an additional 500 ms.
- (4) After acquiring a target, prepare for the next trial by positioning the cursor inside the now-visible Home position and proceed as before.

Experimental Design

In the experiment we studied three levels of A/A gain and three levels of D/A gain. The A/A gain settings were 0.5, 0.75, and 1.0, such that 1° of head movement would produce 0.5° , 0.75° , and 1.0° of cursor movement, respectively. The D/A gain settings were 0.5 cm° , 0.67 cm° , and 1.0 cm° , such that 1° of head movement produced 0.5, 0.67, and 1.0 cm of cursor displacement on the monitor, respectively. Using three fixed levels of A/A gain and D/A gain supported direct exploration of the effect of viewing distance with each of these measures of gain.

Four additional independent variables were viewing distance, target width, movement amplitude, and movement direction. The three viewing distances were 50, 65, and 80 cm. Viewing distance was defined as the distance between the transmitter and the headset worn by the participant. The viewing distances were within the recommended range for VDT workstation distances adopted by AT&T Bell Laboratories (Sanders & McCormick, 1987). Diameters of the two circular targets were 3.9 and 14.5 mm. Target diameters were similar to the height of a 12-point capital letter (New York font) and a

floppy disk icon as they appear on the Apple two-page computer display.

The two movement amplitudes were 60 and 120 mm, which represented the distance from the center of the Home position to the center of the target. These parameters resulted in Fitts' indices of difficulty of 3.0 bits (W [target width] = 14.5 mm, A [movement amplitude] = 60 mm), 4.0 bits ($W = 14.5$ mm, $A = 120$ mm), 4.9 bits ($W = 3.9$ mm, $A = 60$ mm), and 5.9 bits ($W = 3.9$ mm, $A = 120$ mm). Movements were performed in eight radial directions measured from the Home position as 0° , 45° , 90° , 135° , 180° , 225° , 270° , and 315° counterclockwise with respect to the horizontal.

The cross-plot in Figure 2 shows that the two measures of gain are simple transformations of each other. Figure 2 indicates equivalent A/A gain values for fixed D/A gain levels and equivalent D/A gain values for fixed A/A gain levels at each viewing distance. Therefore, at any selected viewing distance, an equivalent value of D/A gain can be provided for a fixed value of A/A gain and vice versa.

The two dependent variables in this experi-

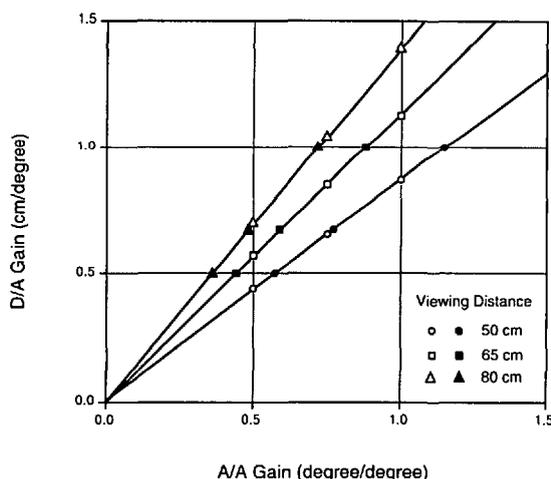


Figure 2. D/A gain plotted against A/A gain shows the transformation between the two gain measurements. The graph illustrates the relationship between the equations defining the two gain measures. The experimental conditions used in the present study for A/A gain and D/A gain have been added for reference. Solid symbols represent D/A gain conditions, and open symbols represent A/A gain conditions.

ment included movement time and root mean square (RMS) cursor deviation, which are described in detail in Radwin et al. (1990) and Lin et al. (1992). Movement time was defined as the time that elapsed after the cursor moved outside the Home position to when it was successfully positioned within the target. Movement time did not include the final 500 ms needed to acquire the target. If the cursor moved outside the target before 500 ms elapsed, the movement time counter continued running until the center point of the cursor remained within the target for a full 500 ms. RMS cursor deviation measured the sum-of-square difference in displacement between the cursor's actual path and the straight-line path. The straight-line path was measured from the point where the cursor exited the Home position to the point where it entered the target on successful acquisition. Cursor displacement for RMS was sampled at a rate of 32 Hz.

The experiment involved five experimental sessions for each participant. The first two sessions were designated for instruction and training so that participants could learn the experimental task and become familiar with each condition. During the two training sessions, participants performed 24 learning sets, each involving 32 trials per set, for a total of 786 trials. Radwin et al. (1990) used a similar experimental task and concluded that headpointer performance stabilized after 720 trials.

Actual data were collected during the last three sessions, which took approximately 1 h each. During a test session participants performed each experimental condition at a predetermined viewing distance for that session. Order of viewing distances was counterbalanced among the participants. At the beginning of each test session, participants received four warm-up sets, which included two A/A gain settings and two D/A gain settings. After completing the warm-up, participants experienced two replicates for each of the possible six sets (i.e., three levels of A/A gain and three levels of D/A gain) at the selected viewing distance. Half of them began each session controlling D/A gain settings,

followed by A/A gain settings; the order for the other half was the reverse. The order of presenting the A/A gain and D/A gain settings was counterbalanced for each participant.

The data were analyzed for each gain measure as a repeated-measures, full-factorial experiment in which participants were random-effect-blocking variables. Analysis of variance was performed using the BMDP statistical package. Movement time data were regressed against Fitts' index of difficulty.

RESULTS

A/A Gain

The effect of A/A gain on movement time was statistically significant, $F(2, 22) = 18.34, p < .01$. Average movement time was 1079 ms ($SD = 199$ ms) for a setting of 0.5, 1124 ms ($SD = 210$ ms) for a setting of 0.75, and 1223 ms ($SD = 229$ ms) for a setting of 1.0. Pairwise contrasts showed that average movement time for A/A gain settings of 0.5 and 0.75 were significantly different from the average movement times for the A/A gain setting of 1.0 ($p < .01$). No signifi-

cant movement time difference was detected between A/A gain settings of 0.5 and 0.75.

Viewing distance had a significant effect on movement time, $F(2, 22) = 18.64, p < .01$. Average movement time was 1071 ms ($SD = 611$ ms) at 50 cm, 1117 ms ($SD = 664$ ms) at 65 cm, and 1238 ms ($SD = 815$ ms) at 80 cm. The interaction between A/A gain and viewing distance for average movement time was also statistically significant, $F(4, 44) = 9.13, p < .01$, and is shown in Figure 3a. Average movement time increased significantly for both A/A gain settings of 0.75 and 1.0 as viewing distance increased ($p < .01$). No significant difference was detected between viewing distances for an A/A gain of 0.5.

Fitts' index of difficulty significantly affected average movement time, $F(3, 33) = 304.32, p < .01$. Linear regression of average movement time against index of difficulty resulted in $R^2 = .98, F(1, 2) = 98.36, p < .01$. The interaction between A/A gain and the index of difficulty on average movement time was significant, $F(6, 66) = 10.43, p < .01$. Average movement time for A/A gain settings of 0.75 and 1.0 were respectively 195 ms and 352 ms greater than for an A/A gain

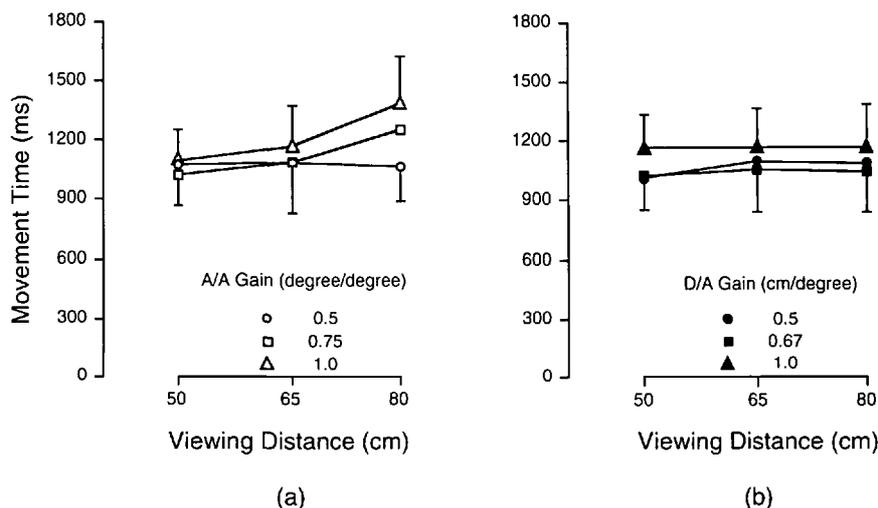


Figure 3. (a) Average movement time (ms) plotted against viewing distance for three A/A gain settings of a head-controlled input device. (b) Average movement time (ms) plotted against viewing distance for three D/A gain settings of a head-controlled input device.

of 0.5 with 4.9-bit movements ($p < .01$). Average movement time for an A/A gain of 1.0 was 220 ms greater than for an A/A gain of 0.5 with 5.9-bit movements ($p < .01$).

The interaction between viewing distance and index of difficulty on movement time was also significant, $F(6, 66) = 6.69$, $p < .01$. Average movement time at a viewing distance of 80 cm was 247 ms greater than at 50 cm and 207 ms greater than at 65 cm for a 4.9 bit index of difficulty ($p < .01$). Similarly, average movement time at a viewing distance of 80 cm was 327 ms greater than at 50 cm and 221 ms greater than at 65 cm for 5.9-bit movements ($p < .01$).

Table 1 summarizes coefficients resulting from stepwise linear regression ($p < .05$ to enter, $p > .01$ to remove) for movement time regressed against Fitts' index of difficulty, viewing distance, and gain. As the stepwise linear regression equation shows, A/A gain and the interaction among viewing distance, index of difficulty, and A/A gain significantly affect movement time. Target acquisition at each viewing distance for A/A gain was aptly described by Fitts' law. Regression of movement time against index of difficulty resulted in R^2 values of .99, .99, and .96 for respective viewing distances of 50 cm, 65 cm, and 80 cm.

Movement direction significantly affected movement time, $F(7,77) = 9.61$, $p < .01$. Diagonal movements (45°, 135°, 225°, and 315°) resulted in the largest average movement times, with a mean time of 1190 ms ($SD = 734$ ms). Off-diagonal movements (0°, 90°, 180°, and 270°) resulted in an average movement time of 1094 ms ($SD = 673$ ms).

The effect of A/A gain on average RMS dis-

placement was statistically significant, $F(2, 22) = 30.16$, $p < .01$. As A/A gain increased, average RMS displacement increased from 3.00 mm ($SD = 0.67$ mm) at a gain setting of 0.5 to 4.00 mm ($SD = 1.08$ mm) at a gain setting of 1.0. Average RMS displacement increased with viewing distance from 3.13 mm ($SD = 2.60$ mm) at a viewing distance of 50 cm to 3.97 mm ($SD = 3.69$ mm) at a distance of 80 cm, $F(2, 22) = 8.56$, $p < .01$.

Average RMS displacement was significantly affected by the index of difficulty, $F(3, 33) = 75.84$, $p < .01$. Pairwise comparisons showed that the average RMS displacement for a 4.0-bit index of difficulty was 1.51 mm and 1.17 mm greater, respectively, than for indices of difficulty of 3.0 bits and 4.9 bits ($p < .01$). Similarly, the average RMS displacement for 5.9-bit movements was 1.57 and 1.23 mm greater, respectively, than for 3.0- and 4.9-bit movements ($p < .01$). A pairwise comparison for movement amplitude showed that average RMS displacement was 1.37 mm greater for 120-mm movements than for 60-mm movements ($p < .01$).

Movement direction also had a significant effect on average RMS displacement, $F(7, 77) = 88.55$, $p < .01$. Average RMS displacement for diagonal movements (45°, 135°, 225°, and 315°) was 4.96 mm ($SD = 3.49$ mm), which was greater than the average RMS displacement of 2.02 mm ($SD = 1.76$ mm) for off-diagonal movements (0°, 90°, 180°, and 270°). The interaction between the index of difficulty and movement direction was significant for average RMS displacement, $F(21, 231) = 3.17$, $p < .01$. Diagonal movements resulted in average RMS displacements that were 2.87, 3.76, 2.14, and 3.00

TABLE 1

Summary of Regression Models for Movement Time against Fitts' Index of Difficulty, Gain, and Viewing Distance

Gain	Regression Equation	R^2
A/A gain	$MT = -428.42 + 301.13(ID) - 324.50(G) + 2.09(ID)(D)(G)$.95
D/A gain	$MT = -624.88 + 343.08(ID) + 54.08(ID)(G)$.96

Note: MT = movement time (ms), ID = index of difficulty (bits), D = distance from the screen (cm), G = gain (unitless for A/A gain, cm/degree for D/A gain).

mm greater than off-diagonal movements at indices of difficulty of 3.0, 4.0, 4.9, and 5.9 bits, respectively.

D/A Gain

The D/A gain effect on average movement time was statistically significant, $F(2, 22) = 16.10$, $p < .01$. Average movement time was 1070 ms ($SD = 176$ ms) for a setting of 0.5 cm/°, 1047 ms ($SD = 186$ ms) for a setting of 0.67 cm/°, and 1169 ms ($SD = 189$ ms) for a setting of 1.0 cm/°. Pairwise contrasts showed that movement time for D/A gain settings of 0.5 and 0.67 cm/° were significantly different from that of 1.0 cm/° ($p < .01$). No significant difference was detected between D/A gain settings of 0.5 and 0.67 cm/°. In contrast to the results for A/A gain, the results for D/A gain failed to detect an effect attributable to viewing distance, $F(2, 22) = 0.72$, $p > .05$.

Average movement time was significantly affected by the index of difficulty, $F(3, 33) = 458.57$, $p < .01$. Linear regression of average movement time against index of difficulty resulted in $R^2 = .99$, $F(1, 2) = 234.95$, $p < .01$. The interaction between D/A gain and the index of difficulty for average movement time was significant, $F(6, 66) = 14.19$, $p < .01$. Average movement time for a D/A gain setting of 1.0 cm/° was 361 and 286 ms greater, respectively, than for 0.5 and 0.67 cm/° for movements with an index of difficulty of 4.9 bits ($p < .01$). Average movement time was 128 ms greater for a D/A gain setting of 1.0 cm/° when compared with a D/A gain setting of 0.5 cm/° for movements with an index of difficulty of 5.9 bits ($p < .01$). Stepwise linear regression for movement time against index of difficulty and D/A gain in Table 1 indicates D/A gain's effect on movement time slope.

The effect of movement direction on average movement time was statistically significant, $F(7, 77) = 11.96$, $p < .01$. Diagonal movements (45°, 135°, 225°, and 315°) resulted in the largest average movement times, with a mean time of 1134 ms ($SD = 658$ ms). Off-diagonal movements (0°, 90°, 180°, and 270°) resulted in an average movement time of 1056 ms ($SD = 633$ ms).

The effect of D/A gain on average RMS displacement was statistically significant, $F(2, 22) = 27.82$, $p < .01$. Average RMS displacement was 2.73 mm ($SD = 0.52$ mm) for a gain setting of 0.5 cm/°, 3.17 mm ($SD = 0.69$ mm) for a gain setting of 0.67 cm/°, and 3.71 mm ($SD = 0.75$ mm) for a gain setting of 1.0 cm/° ($p < .01$). Average RMS displacement was significantly affected by the index of difficulty, $F(3, 33) = 149.14$, $p < .01$. Average RMS displacements were 2.29 mm ($SD = 2.30$ mm) for 3.0-bit, 3.91 mm ($SD = 3.52$ mm) for 4.0-bit, 2.69 mm ($SD = 1.95$ mm) for 4.9-bit, and 3.92 mm ($SD = 2.66$ mm) for 5.9-bit movements. A pairwise comparison for movement amplitudes showed average RMS displacement to be 1.46 mm greater for 120-mm movements than for 60-mm movements ($p < .01$).

Movement direction also had a significant effect on average RMS displacement, $F(7, 77) = 112.38$, $p < .01$. Average RMS displacement for diagonal movements (45°, 135°, 225°, and 315°) was 4.50 mm ($SD = 3.06$ mm), which was 2.59 mm greater than the average RMS displacement of 1.91 mm ($SD = 1.62$ mm) for off-diagonal movements (0°, 90°, 180°, and 270°). The interaction between the index of difficulty and movement direction was significant for average RMS displacement, $F(21, 231) = 4.35$, $p < .01$. Diagonal movements resulted in average RMS displacements that were 2.44, 3.42, 1.87, and 2.61 mm greater than off-diagonal movements for respective indexes of difficulty of 3.0, 4.0, 4.9, and 5.9 bits. There was also a significant interaction between D/A gain and movement direction for average RMS displacement, $F(14, 154) = 5.50$, $p < .01$. Diagonal movements had average RMS displacements that were 1.97, 2.40, and 3.39 mm greater than respective off-diagonal movements at D/A gain settings of 0.5, 0.67, and 1.0 cm/°.

Combined Data

At each viewing distance, a specific D/A gain setting is associated with a corresponding A/A gain setting (see Figure 2). In order to simultaneously examine data for both gains, the D/A

gain data were equated to their corresponding A/A gain setting for each viewing distance and plotted along with the original A/A gain data in Figure 4a. Similarly, the A/A gain data were equated to their corresponding D/A gain setting for each viewing and plotted along with the original D/A gain data in Figure 4b.

A least-squares quadratic polynomial was fitted to the movement time data in Figure 4a for each viewing distance because viewing distance has a significant effect on an A/A-gain-controlled headpointer. A single quadratic curve was fitted to the movement time data in Figure 4b because no significant viewing distance effect was found for the D/A-gain-controlled headpointer. The dotted vertical lines on these graphs identify the local minima of the fitted curves.

DISCUSSION

Arnaut and Greenstein (1990) determined from a study of control-display gain in trackball and touch-tablet interfaces that control-display gain was insufficient to predict performance by

itself. They concluded that optimization of a control-display interface must specify at least three of the four parameters involved (control target width, control amplitude, display target width, and display amplitude). In that study control amplitude, display amplitude, and display target width were manipulated so as to uniquely determine the fourth component, control target width.

The results of that experiment showed a significant three-way interaction among control amplitude, display amplitude, and display target width, which supported their hypothesis. Arnaut and Greenstein proposed using a task that provides a range of Fitts' indices of difficulty together with various levels of control-display gain as a method of optimizing the interface parameters. Using the index of difficulty to predict movement time for each gain level would specify three of the four control-display parameters and thus could be used to predict optimal settings.

In the present study we analyzed both sets of

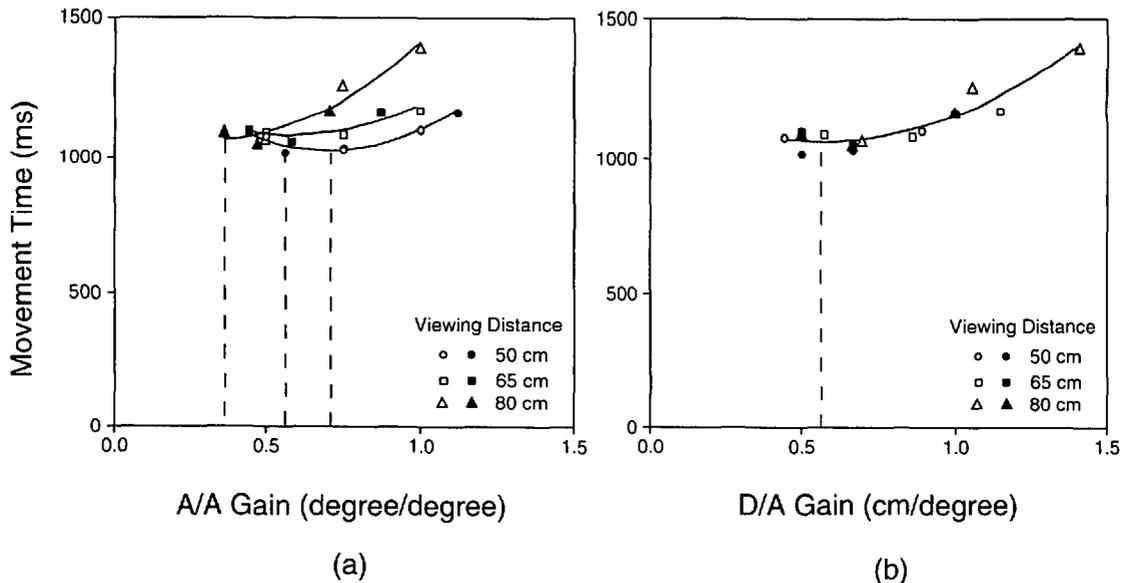


Figure 4. (a) Average movement time (ms) data from both data sets are plotted against equivalent A/A gain settings at each viewing distance. (b) Average movement time (ms) data from both data sets are plotted against equivalent D/A gain settings at each viewing distance. Solid symbols represent D/A gain conditions, and open symbols represent A/A gain conditions.

data using their respective control-display gain and Fitts' law relationship as suggested by Arnaut and Greenstein (1990). The study has been designed to model typical acquisition tasks that are involved in everyday use of a graphical user interface. The ability to effectively design a task on the display that models frequently used movements will fix both the display target width and the display amplitude, leaving either the control target width or control amplitude to be determined. Control amplitude was adjusted to provide the desired A/A gain or D/A gain setting in this study. Using a task that models typical movements on the computer's display allows a designer to focus on the control element of the interface, which this study has addressed.

The results from this study indicate that the head-controlled computer input device with high fixed A/A gain was significantly affected by viewing distance. The angle of head movement per unit of cursor displacement at a fixed A/A gain decreased as viewing distance increased. Consequently the target and display decreased in size both visually and kinesthetically. Increases in average movement time and RMS displacement for small increases in viewing distance indicated that the increase in leverage achieved by increasing viewing distance can lead to reductions in performance.

Fixed A/A gain of 1.0 is representative of a true headpointing computer interface. At this gain setting, the headpointer responds as if the user were pointing to images on the monitor with a beam of light (i.e., a variable-length pointer). The results showed performance for this type of device to be significantly affected by changes in viewing distance. As viewing distance increases, the operator's leverage increases, which, in this case, led to a degradation in performance.

The Long-Range Optical Pointer (LROP) is an example of a true headpointing computer interface, in that it uses a long-range light pen to point to different images on the screen. The LROP has been shown to be a viable option for individuals with high spinal cord injuries, polio, and muscular dystrophy (Angelo, Deterding, & Weisman, 1991; Smith et al., 1989). The results

of the current study indicate that a head-positioning computer interface would be preferable to a true headpointing interface such as the LROP, because performance was improved for A/A gain settings less than unity.

Langolf and Hancock (1975) found Fitts' law to be a good predictor of human performance in microscopic work in which the display magnification was greater than unity. Their study showed that changes in microscopic power did not significantly affect movement time for movements within the microscope's field. The apparatus used by Langolf and Hancock required participants to physically place a small part into fixed targets while monitoring the movements through a microscope with magnifications ranging from $3.5\times$ to $15\times$. Fixing control movement while adjusting display movement through magnification in that study is analogous to fixing D/A gain while changing viewing distance in the present study. The control movement for a selected D/A gain setting remains constant (i.e., head extension/flexion or rotation) as viewing distance is changed, whereas the visual angle associated with the constant cursor displacement changes. D/A gain provides an alternative measure of controlling a headpointer interface and maintains a fixed amount of linear cursor displacement per degree of head rotation. Chapanis and Kinkade (1972) used a definition similar to D/A gain to define the control-display ratio for rotary knobs, in that they measured the control element in revolutions of the knob and the display element in inches.

Crossman and Goodeve (1983) studied feedback in hand movements and addressed feedback mechanisms that included external (visual) and internal (kinesthetic) feedback. In one experiment participants rotated a control device around the long axis of the forearm and aligned a pointer on an illuminated target. During the middle portion of the task, the pointer was removed from the participant's view. Crossman and Goodeve concluded from their study that for short periods, positional control can be maintained entirely with the kinesthetic system.

They also exposed participants to changes in control-display gain during a reciprocal positioning task with the same apparatus. The results of that experiment showed that participants overshoot the target for the first cycle following an increase in gain from a low to a high level, and that they approached the target more slowly for the first cycle following a decrease in gain from high to low. Crossman and Goodeve (1983) reported that participants adjusted at a relatively slow pace, involving several motion cycles, to the effect of rapid gain changes. They hypothesized from these results that the relationship between visual and kinesthetic feedback must slowly recalibrate itself with the removal or scale change of visual information. Although the experimental conditions of the current study did not examine the effect of rapid gain changes, the significant viewing distance effect for A/A gain indicates that users could experience rapid changes in performance when making small adjustments in their viewing distance. Further research is needed to determine how rapid changes in gain affect head-controlled input devices.

Fitts (1954) considered the motor system to include the visual and proprioceptive feedback loops that allow individuals to monitor their activities. Analysis of the D/A gain data in the current study failed to detect a significant effect attributable to viewing distance (see Figure 3b). Head extension/flexion or head rotation at a selected D/A gain setting remains constant for a specified cursor displacement regardless of viewing distance, though the visual angle will change. The observed insensitivity of performance with a fixed D/A gain to changes in viewing distance may be explained by the fact that both angular head movement and the accompanying kinesthetic feedback at a specified D/A gain do not change as viewing distance is changed. The D/A gain data also suggest that stable performance can be maintained while visual feedback is modified at different viewing distances. This result is similar to the findings of Langolf and Hancock (1975) regarding changes in optical magnification of microscope work.

Both kinesthetic and visual feedback vary for fixed A/A gain as viewing distance changes. Kinesthetic feedback varies because A/A gain maintains a fixed ratio of the angle of cursor displacement and the angle of head movement for each viewing distance. Head movement is adjusted for a defined task as viewing distance is changed in order to maintain the fixed ratio between the angle of cursor displacement and the angle of head movement (see Figure 1). Visual feedback varies as a result of changes in viewing distance.

The lack of feedback continuity for fixed A/A gain at different viewing distances provides an explanation for the variance in performance found in this study. Figure 4b superimposes the transformed A/A gain movement time data onto the D/A gain movement time data. Transforming the A/A gain movement time data to a D/A gain scale removes the effect of viewing distance. This result suggests that maintaining adequate kinesthetic feedback for head-controlled movements is an important factor with regard to performance.

Figure 4b shows that the smallest average movement times occurred for D/A gain settings of 0.5 to 0.67 $\text{cm}/^\circ$. Lin et al. (1992) reported that a head-controlled pointer gain level between 0.3 and 0.6 resulted in the smallest average movement times. That study was performed at a viewing distance of 71 cm, which resulted in equivalent D/A gain settings of 0.37 and 0.74 $\text{cm}/^\circ$ for the respective A/A gain settings 0.3 and 0.6. The results from the present study support their findings when their data are analyzed on a D/A gain scale. Clearly, once the amount of head movement associated with a specified cursor displacement is beyond some optimal level, performance will decrease. Determining this optimal gain level will be dependent on each individual's abilities.

The importance of maintaining adequate kinesthetic feedback for head-controlled movements could be argued based on the results from the low A/A gain setting. The current study failed to detect a significant viewing distance effect for an A/A gain setting of 0.5. As Figure 2 illustrates, the A/A gain setting of 0.5 transforms

to equivalent D/A gains of 0.44 cm/° at 50 cm, 0.57 cm/° at 65 cm, and 0.70 cm/° at 80 cm. Each of these D/A gain settings was within the optimal range identified earlier. This provides an explanation for the stability of performance across viewing distance with an A/A gain of 0.5.

One difference between the present study and that of Lin et al. (1992) was that it did not evaluate participants over the same range of A/A gain settings. Using viewing distance as a variable created limitations on the range of A/A gain settings that could be tested in the present study. An example of this limitation was that at a viewing distance of 50 cm, A/A gain settings below 0.5 made it difficult for participants to move the cursor to the edge of the screen because of the extreme range of head movement that was required.

The interaction between the index of difficulty and viewing distance for the A/A gain data significantly affected movement time. The results showed that for the higher indices of difficulty, which were associated with small target widths, movement time increased as viewing distance increased. As previously mentioned, the amount of head rotation required for a headpointing task will decrease for a specified A/A gain setting as viewing distance is increased. Increasing viewing distance to the point at which head tremor begins to affect acquisition of small targets provides an explanation for the observed effect. As the required head movement decreases for the task (i.e., viewing distance increases), head tremor may affect performance because smaller head movements are required to displace the cursor, possibly making it more difficult to stabilize.

An interaction effect between the index of difficulty and D/A gain showed a significant effect when D/A gain was increased for movements involving the higher degrees of difficulty. The results showed average movement times for the D/A gain setting 1.0 cm/° to be significantly greater than the lower settings when movements were made to the small target. Similarly, a significant interaction between the index of

difficulty and A/A gain was found that showed average movement times for an A/A gain of 0.5 to be significantly lower than the higher settings when movements were made to the small target. Lin et al. (1992) found that high gain levels for a head-controlled input device can greatly increase average movement time and average RMS displacement when acquiring small targets. Further study is needed to explore the interaction gain and target width.

The movement direction effect for both A/A gain and D/A gain showed significant increases in average movement time and in average RMS displacement for diagonal movements (45°, 135°, 225°, and 315°) when compared with off-diagonal movements (0°, 90°, 180°, and 270°). These results support the findings of previous studies (Jagacinski & Monk, 1985; Lin et al., 1992; Radwin et al., 1990). Off-diagonal movements require one to coordinate muscle groups associated with either head rotation or head extension/flexion. The direction effect along the diagonal may be caused by the need to simultaneously coordinate muscle groups associated with both head rotation and head extension/flexion (Radwin et al., 1990).

Average RMS displacement was significantly affected by the interaction between movement direction and the index of difficulty in both the A/A gain and the D/A gain studies. At each index of difficulty, diagonal movements resulted in larger average RMS cursor displacements when compared with off-diagonal movements. The differences between diagonal and off-diagonal movements became greater for large movement amplitudes and large target widths. A larger target width appeared to create a greater deviation from the straight-line path by allowing the cursor to be positioned farther away from the center of the target when the target is acquired.

This study involved fully able-bodied participants. The data should provide general guidance on the range and type of gain needed for a head-controlled computer input device. Future studies are needed that include participants who

have movement impairments to ensure that these results are applicable.

CONCLUSIONS

A head-controlled computer input device with fixed A/A gain, defined in this study, was significantly affected by changes in viewing distance. Average movement time and RMS cursor deviation increased for A/A gain settings of 0.75 and 1.0 as viewing distance increased. A specified A/A gain setting for a head-controlled interface results in less head rotation for acquiring a target as viewing distance increases, which may cause movements at greater viewing distances to be more affected by head tremor. Analysis of D/A gain, defined in this study, for a head-controlled input device failed to show a significant viewing distance effect.

Optimal D/A gain settings for this study were between 0.5 and 0.67 cm^o. The results indicate that at high D/A gain settings (1.0 cm^o), significant increases in average movement time and RMS cursor displacement occur. Results from a previous study by Lin et al. (1992) suggest that optimal D/A gain may be within the range of 0.37 to 0.74 cm^o. Further research is needed to determine optimal D/A gain settings.

Head tremor is likely to have a significant impact on user performance of head-controlled computer input devices. For tasks demanding precise movements, gain will need to be adjusted to compensate for head tremor in order to accommodate the user's abilities. In addition, for cases in which head tremor does affect performance, changes to the task design (i.e., increase in target width and decrease in target amplitude) should be considered.

Performance for both the A/A gain and the D/A gain head-controlled interface were significantly affected by movement direction. Average movement time and average RMS cursor displacement significantly increased for diagonal movements, which involve a combination of head rotation and head extension/flexion.

Based on the results of this study, we recommend that control-display gain for a head-

controlled computer input device maintain a constant amount of linear cursor displacement per unit of head extension/flexion or rotation. Optimal control-display gains should be determined clinically for each individual, but it appears that the value is less than 1.0 and, possibly, less than 0.67. The significant viewing distance effect for A/A gain indicates that fixing the A/A gain for a head-controlled interface would not be preferable for users who frequently adjust their viewing position when working at a computer. The significant viewing distance effect indicates that users could experience rapid changes in performance when making small adjustments to their viewing distance. Therefore, from a practical perspective, implementing fixed D/A gain would be preferable to fixing A/A gain for head-controlled computer interfaces.

ACKNOWLEDGMENTS

Funding for this project was provided by a subcontract from Pointer Systems, Inc., under grant 2 R44 NS26965-02A3 from the National Institute of Neurological Disorders and Stroke.

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- John A. Schaab is an ergonomist at Intel Corporation, Hillsboro, Oregon. He received his M.S. in industrial engineering from the University of Wisconsin-Madison in 1994.
- Robert G. Radwin is a professor in the Department of Industrial Engineering at the University of Wisconsin-Madison. He received his Ph.D. in industrial and operations engineering from the University of Michigan in 1986.
- Gregg C. Vanderheiden is a professor in the Department of Industrial Engineering at the University of Wisconsin-Madison, where he received his Ph.D. in rehabilitation technology in 1984.
- Per Krogh Hansen is principal at Pointer Systems, Inc., in Burlington, Vermont. He received his M.S.E.E. in electrical engineering from the Technical University of Copenhagen in 1976.

Date received: August 23, 1994

Date accepted: April 7, 1996