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Gain effects on performance using a head-controlled computer input device

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The purpose of this study was to use a Fitts' task to (1) determine how control-display gain influences performance using a head-controlled computer input device; (2) compare relative sensitivity to gain and optimal gain between head control and hand/arm control; and (3) investigate control–display gain interactions with other task factors including target width, movement amplitude and direction. The task was a discrete target acquisition task using circular targets of 2·9 mm, 8·1 mm, and 23·5 mm, movement amplitudes of 24·3 mm and 61·7 mm, and eight radial directions including 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. Each device was operated at four gain levels. Ten subjects participated. The results indicated that gain had a significant effect on movement time for both types of pointing devices and exhibited local minimums. Discrete target acquisition at all gains was aptly described using Fitts' Law for both input devices. The mouse gain resulting in minimum movement time and RMS cursor deviation was between 1·0 and 2·0. The minimum movement time and RMS cursor deviation for the head-controlled pointer occurred at a gain between 0·3 and 0·6. Average movement time at the optimal head-controlled pointer gain had a slope of 169 ms/bit and was more than 76% greater than at the optimal mouse gain with a slope of 135 ms/bit. In addition, average RMS displacement was more than 27% greater for the head-controlled pointer at its optimal gain setting than for the mouse. Gain had the greatest effect for small target widths and long movement amplitudes using the head-controlled pointer. Average movement time increased 37% when increasing the head-controlled pointer gain from 0·6 to 1·2 for the small target width, but only increased 0·3% when increasing gain for the large target width. Average movement time also increased 12% when decreasing the head-controlled pointer gain from 0·3 to 0·15 for the long movement amplitude, but decreased 0·3% when decreasing gain for the short movement amplitude.

1. Introduction

In order to enhance performance for individuals having physical disabilities by providing them with appropriate technology to compensate for their physical deficits, the understanding of human movement has become an important research direction in ergonomics and rehabilitation engineering. The growing number of service industries has increased use of computers and thus increased job opportunities for people with disabilities. While keyboard input strategies only require simple motor capability, some features of modern computer interfaces require a far greater degree of motor control. Graphics user interfaces using mouse input devices has especially limited people with impaired upper extremity movement capabilities from using these computers. Head-controlled pointing devices may help

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provide these people with a way to access these computer systems and work effectively in the modern workplace. The purpose of this investigation is to better understand the control factors of head motion in order to optimise performance using head-controlled computer input devices.

Extending the earlier findings of Woodworth (1899) who was especially interested in the relative limitations of human movement, Fitts (1954) developed the well known Fitts' Law which persuasively described the speed-accuracy tradeoff in human movement (Fitts and Peterson 1964). Fitts' Law was subsequently used for showing that various limb segments exhibited decreasing information processing rates as order of control increases (Langolf *et al.* 1976). Until recently, however, Fitts' Law has not been extended to head motion. Jagacinski and Monk (1985), and Andres and Hartung (1989) found that Fitts' law was a robust head movement time predictor. Radwin *et al.* (1990) developed a discrete movement target acquisition task based on Fitts' Law for evaluating alternative computer input devices, such as head-controlled pointers for movement impaired individuals. This method was shown useful for measuring subtle performance improvements when providing lateral torso support for a computer user with cerebral palsy.

Control-display gain was described by Gibbs (1962) as the relationship between movement of a control device (i.e., input movement) and its control element (i.e., cursor movement). Gain will be generally defined in this paper as the transfer function ratio between equivalent display and control movement parameters (D/C), such as displacement or rotation angle. The optimisation of this relationship has been a very important concern in designing human-machine interactive control systems (Jenkins and Connor 1949, Gibbs 1962, Morgan *et al.* 1963, Welford 1968, Poulton 1974, Shackel 1974, Langolf *et al.* 1976, Sheridan 1979, Buck 1980, Arnaut *et al.* 1986).

Numerous studies of control-display tasks concluded that movement time and D/C gain had a U-shape relationship, where the minimum movement time represented the optimum D/C gain (Jenkins and Connor 1949, Chapanis and Kinkade 1972, Poulton 1974, Perry and Voelcker 1989). Chapanis and Kinkade (1972) observed that optimum D/C gain may be affected by movement distance, tolerance and time delay. They found that increasing movement distance increased adjustment time, and increasing either target tolerance or time lags increased the optimum D/C gain. Perry and Voelcker (1989) recommended decreasing gain at lower speeds and increasing gain at higher speeds for improving user control of small movements and increasing speed for larger movements.

Jenkins and Connor (1949) maintained that the optimisation of D/C gain was a critical design factor affecting an operators' performance. They concluded that optimal D/C gain may save between 0·5 s to 5 s positioning time when compared with sub-optimal gains. Chapanis and Kinkade (1972) recommended that for applications where time and precision are critical, the optimum D/C gain must be established empirically. Epps (1986) compared six cursor control devices (mouse, absolute-mode touchpad, relative-mode touchpad, trackball, displacement joystick and force joystick) in a target acquisition task using Fitts' Law. Each device's control dynamics was considered optimised, including D/C gain, prior to the experiment. Card *et al.* (1978) compared four control devices (mouse, force joystick, step keys and text keys) in a text selection task, also considering the devices optimised for D/C gain.

Little data is available concerning performance degradation using computer input devices at sub-optimal gain. Furthermore, no data is available about the optimal gain for head-controlled computer input devices. This is important for designing computer interfaces that enhance performance for computer users having upper extremity movement impairments and who must depend on head-pointing computer input devices. The current study was designed to investigate the effects of gain to (1) determine how D/C gain influences the control performance using a head-controlled pointing device; (2) compare relative sensitivity to gain and optimal gain between head control and hand/arm contol; and (3) investigate control–display gain interactions with other task factors including target width, movement amplitude, and direction, using a Fitts' Law discrete target acquisition task.

2. Methods

2.1. *Subjects*

Ten subjects were recruited for this experiment. Six subjects were male and four were female ranging in age between 21 and 33. All subjects identified themselves as having normal neuromuscular function and having no visual impairments that might cause discomfort or difficulty focusing or concentrating on a computer monitor. All ten subjects described themselves as right-handed. Experience using a mouse ranged from 0 to 5 years. Subjects were paid on an hourly basis with a bonus for completing all the experiments.

2.2. *Equipment*

The experiment task was programmed and performed on an Apple Macintosh II microcomputer using an Apple Color High-Resolution Model M0401 RGB monitor. The Macintosh II internal real-time clock, which was used for all timing operations, had a resolution of 1·25 ms. Cursor displacement was sampled at a rate of 32 Hz. The monitor, which was 640 horizontal pixels by 480 vertical pixels, had a resolution of 0·40625 mm per pixel resulting in an active video area of 235 mm horizontal by 176 mm vertical.

Two computer input devices were used in this experiment. They were (1) a conventional Apple Model A9M0331 mouse and (2) a specially modified Personics Corp. HeadMaster Model VCS 2000 ultrasonic head-controlled pointer. The mouse was used on a tabletop with a pad and the tracking acceleration feature was disabled. The head-controlled pointing device had an ultrasonic transmitting unit that sat on top of the monitor and sent signals to a lightweight headset that the user wore. This system translates changes in the user's head position into changes in the cursor position on the screen by tracking head rotation for horizontal cursor displacement and head extention and flexion for vertical cursor displacement. The head-controlled pointer was specially modified so vertical and horizontal sensitivity was equivalent and velocity control was disabled. Gain for both devices was controlled using software.

2.3. *Experimental design*

The discrete movement target acquisition task employed for this study was based on Fitts' Law and is described in full detail in Radwin *et al.* (1990). The HOME position was a 5 mm diameter circle located at the center of the computer display screen. The objective of the task was to move a cross-hair cursor from the HOME position to randomly located circular targets appearing on the screen as quickly as possible. Subjects used both the mouse and the head-controlled pointer for the same task.

Subjects were required to sit in an upright position in front of the computer monitor. When the conventional mouse was used the table height was raised or

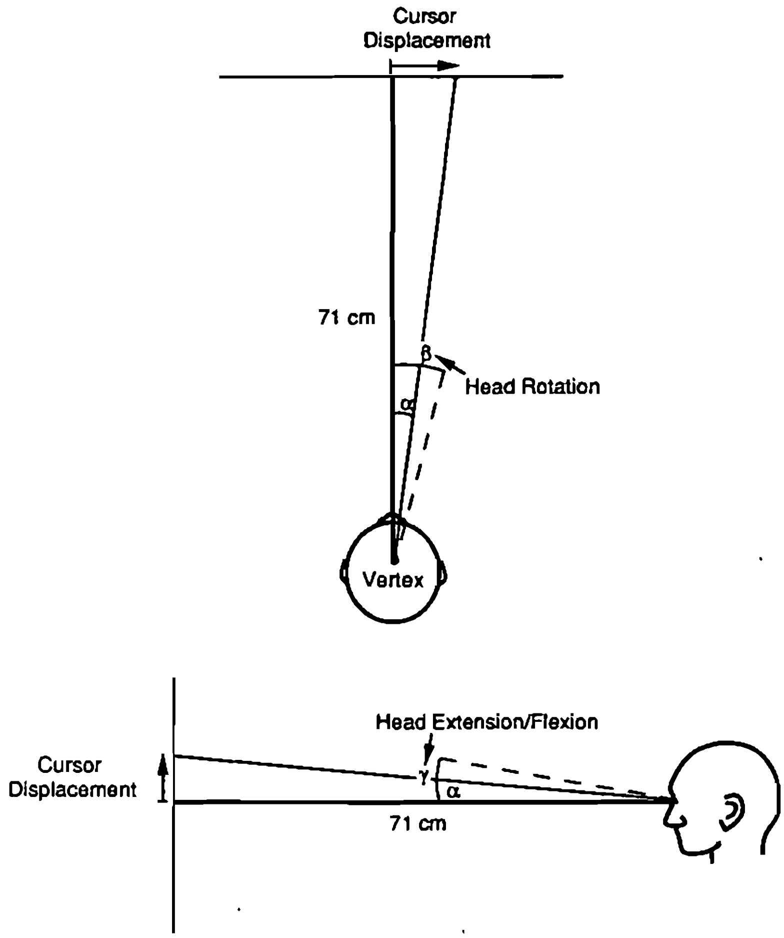

Figure 1. Head pointer gain was defined as the ratio of the corresponding visual angle subtended by the cursor displacement (α) to the angle of head rotation (β) or head extension/flexion (γ) for a given cursor displacement.

lowered to form a right angle between the lower and the upper arm in line with the torso, when holding the cursor in the HOME position. This was the required READY posture for starting a trial. When the ultrasonic head-controlled pointer was used, subjects were seated at a fixed distance of 71 cm in front of the monitor. The screen height was adjusted so subjects could face directly in line with the screen when the cursor was in the HOME position.

There were four additional independent variables including target width, movement amplitude, movement direction, and D/C gain. The three circular target width diameters were 2·9 mm, 8·1 mm, and 23·5 mm. Movement amplitude, defined as the distance between the center of the HOME position and the center of the targets, was 24·3 mm and 61·7 mm. Movement directions were eight equally spaced radial directions from the HOME position including 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° counter-clockwise, with respect to the right horizontal. These parameters resulted in Fitts' indices of difficulty of 1·0 bit, 2·5 bits, 4 bits, and 5·4 bits.

This experiment also included four gain levels for each device. The D/C gains for the mouse were 0·5, 1·0, 2·0, and 4·0, such that one unit of mouse displacement produced 0·5, 1·0, 2·0, and 4·0 units of cursor displacement, respectively. The D/C gain for head-controlled pointer was defined as the ratio of the corresponding operator visual angle subtended by the cursor displacement (α) to the degree of head rotation (β) or head extension/flexion (γ) (see figure 1). The gain levels included 0·15, 0·3, 0·6, and 1·2, such that one degree of head rotation and extension/flexion would produce 0·15, 0·3, 0·6, and 1·2 degrees of cursor displacement, respectively. The D/C gain ranges selected for this investigation covered what was considered the practical range of motion for each device. A mouse gain below 0·5 or a head-controlled pointer gain below 0·15 required movement beyond the active range of motion for reaching the farthest targets. A mouse gain above 4·0 or a head-controlled pointer gain above 1·2 resulted in excessive tremor and made precise positioning extremely difficult. Hence the lowest mouse gain corresponded to the lowest practical head pointer gain and the highest mouse gain corresponded to the highest practical head pointer gain.

The three dependent variables in this experiment included movement time, cursor path distance and root mean square (RMS) cursor displacement. Movement time was defined as the time elapsed after the cursor moved outside the HOME position and when the target was successfully acquired. To acquire a target, subjects had to contain the cursor within a 5 mm region inside the target for at least 62·5 ms. If the cursor moved outside of the 5 mm region or outside of the target within 62·5 ms, the movement time counter would continue counting until the target was successfully acquired. Cursor path distance was defined as the length of the actual path traversed by the cursor, from the point where the cursor first left the HOME position to the point where the cursor moved across the target perimeter when the target was successfully acquired. Figure 2 illustrates the root mean square cursor displacement, where x_i was the distance between the ith sampling point on the actual cursor path and a straight line between the point on the HOME target where the cursor first left the HOME position and the point where the cursor was moved across the target perimeter, n was the number of the points sampled.

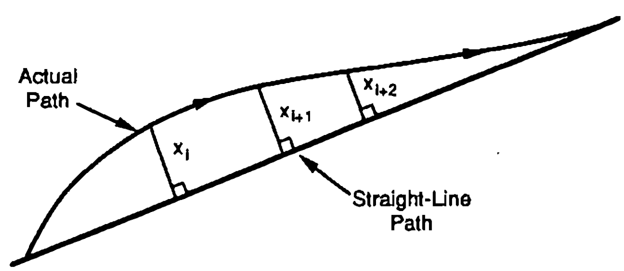

Figure 2. Root mean square cursor deviation was defined as the deviation from the straight line path drawn between the home position and target intersections such that RMS=

$$\sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}$$

The study was conducted in three experimental sessions, on three successive days per subject. At the beginning of the first session, an instructional set was provided for learning the experimental task and becoming familiar with the function of the two pointing devices. Data from the instructional set were not recorded. Two sets of 48 trials at four gain levels for each device, for a total of 16 learning sets (other than the two instructional sets) were included in the first session. Radwin *et al.* (1990) used the same experimental task and concluded that performance stabilised after 15 sets of 48 trials. The second and the third sessions used only one of the two pointing devices. Five subjects used the mouse in the second session and the head-controlled pointer in the third session. The other five subjects used these pointing devices in reverse order. The order that gain levels were presented was also counterbalanced among subjects. The mouse session consisted of 16 sets of 48 trials and lasted about 2·5 h including four warm-up sets (with one warm-up set at each gain level). The head-controlled pointer session also included 16 sets, including four sets (with one warm-up set) at each gain level, and lasted about 3 h. A 2 min rest break was provided between each set. In order to eliminate learning and warm-up effects, results were only based on data taken from the last three sets at every gain level for each input device.

A repeated measures full factorial experimental design was used, using subjects as a random effects blocking variable. Data was statistically analysed using analysis of variance. Movement time data was also fitted using least square regression and Fitts' Law.

3. Results

3.1. *Conventional mouse*

The effect of gain on average movement time for the mouse was statistically significant ($F(3,27)=12{\cdot}54$, $p<0{\cdot}01$) resulting in a local minimum average movement time between 486 ms (SD = 182 ms) for a mouse gain of 1·0 and 488 ms (SD = 195 ms) for a mouse gain of 2. The largest movement time of 529 ms (SD = 199 ms) occurred at a mouse gain of 0·5.

Increasing target width decreased average movement time from 678 ms (SD = 172 ms) for the small target width (2·9 mm) to 487 ms (SD = 135 ms) for the medium target width (8·1 mm), and to 342 ms (SD = 113 ms) for the large target width (23·5 mm) ($F(2,18)=286{\cdot}75$, $p<0{\cdot}01$). Figure 3 illustrates the interaction between gain × width on average movement time, which was statistically significant ($F(6,54)=10{\cdot}57$, $p<0{\cdot}01$). The smallest average movement time for the small target width (2·9 mm) was for a mouse gain of 1·0, which was 63 ms less ($p<0{\cdot}05$) than the average movement time at a 4·0 mouse gain. Average movement time for the medium target width (8·1 mm), however, was largest for a mouse gain of 0·5, which was 46 ms greater than for a mouse gain of 1·0 ($p<0{\cdot}05$), and 60 ms greater than for a 2·0 mouse gain ($p<0{\cdot}01$). Average movement time increased the most at the lowest mouse gain (0·5) for the large target width (23·5 mm), which was 39 ms, 44 ms and 50 ms greater than the average movement time at mouse gains of 1·0 ($p<0{\cdot}05$), 2·0 ($p<0{\cdot}01$), and 4·0 ($p<0{\cdot}01$), respectively (see figure 3).

Average movement time increased 195 ms ($F(1,9)=446{\cdot}99$, $p<0{\cdot}01$) when increasing movement amplitude from the short amplitude (24·3 mm) to the long amplitude (61·7 mm). The interaction between gain × amplitude on average movement time is plotted in figure 4, which was also statistically significant ($F(3,27)=4{\cdot}65$, $p<0{\cdot}01$). Average movement time for the long movement amplitude (61·7 mm) increased considerably at the lowest mouse gain (0·5), which was 124 ms

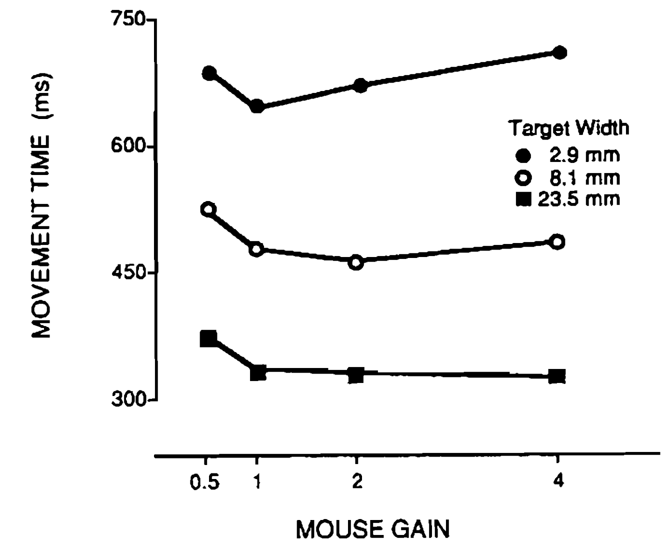

Figure 3. Average movement time plotted against mouse gain for three target widths.

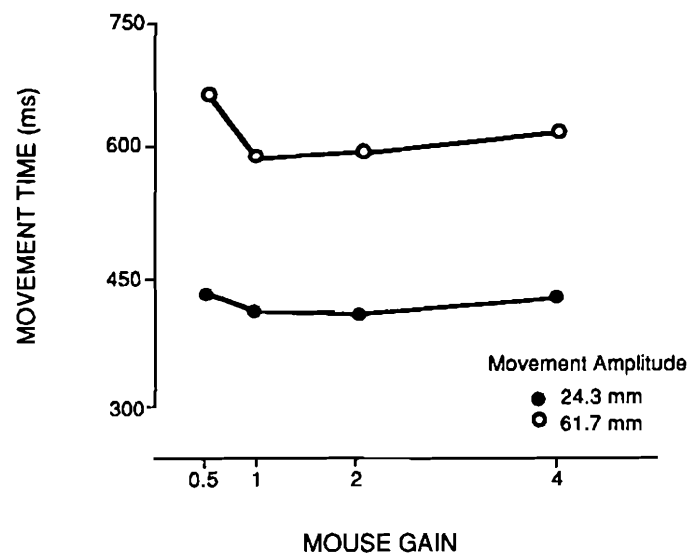

Figure 4. Average movement time plotted against mouse gain for two movement amplitudes.

and 123 ms greater than at mouse gains of 1·0 ($p<0·01$) and 2·0 ($p<0·01$), respectively.

The effect of direction on average movement time was also statistically significant ($F(7,63)=4·06$, $p<0·01$), however this effect only accounted for 0·4% of the total variance. The smallest average movement time was 481 ms (SD = 192 ms) at 0° and the largest movement time was 516 ms (SD = 205 ms) at 315°.

Discrete target acquisition at different gains was aptly described using Fitts' Law for the mouse pointer. The regression of movement time against index of difficulty at

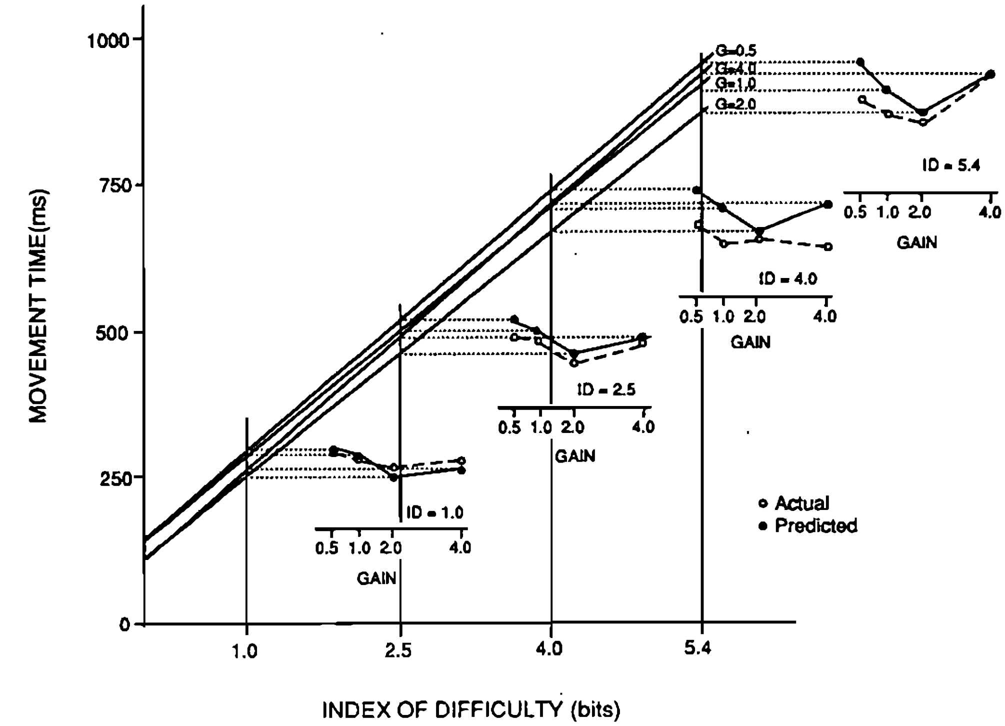

Figure 5. Fitts' Law regression lines for the four mouse gain levels. Average movement time at every gain level is plotted for each index of difficulty along with movement time predicted by the Fitts' Law model.

each gain level resulted in an average coefficient of variation of 0·99 for the mouse. The resulting Fitts' Law regression lines for each gain level are plotted in Figure 5. Movement time predicted by the Fitts' Law regression lines were projected against a gain abscissa along with average movement time measured for each index of difficulty level. The resulting curves all had local minimums in the proximity of a gains of 2 (See figure 5).

Average RMS displacement increased from 0·78 mm (SD=0·59 mm) for the short movement amplitude (24·3 mm) to 1·84 mm (SD=1·18 mm) for the long movement amplitude (61·7 mm) ($F(1,9)=105{\cdot}71$, $p<0{\cdot}01$). Increasing target width decreased average RMS displacement from 1·71 mm (SD=1·13 mm) of the small target width (2·9 mm), to 1·40 (SD=1·13 mm) for the medium target width (8·1 mm), and decreased to 0·82 mm (SD=0·71 mm) for the large target width (23·5 mm) ($F(2,18)=75{\cdot}42$, $p<0{\cdot}01$). The effect of direction on average RMS displacement was also statistically significant ($F(7,63)=24{\cdot}22$, $p<0{\cdot}01$). The smallest average RMS was 0·89 mm (SD=0·85 mm) at 0° and the largest RMS was 1·66 mm (SD=1·27 mm) at 45°. Scheffé multiple contrasts indicated that average RMS displacement was 0·61 mm larger at the diagonal directions including 45°, 135°, 225°, and 315° ($p<0{\cdot}01$) than at the off-diagonal directions (0°, 90°, 180°, and 270°). The effect of gain was marginally significant for average RMS displacement ($F(3,27)=2{\cdot}92$,

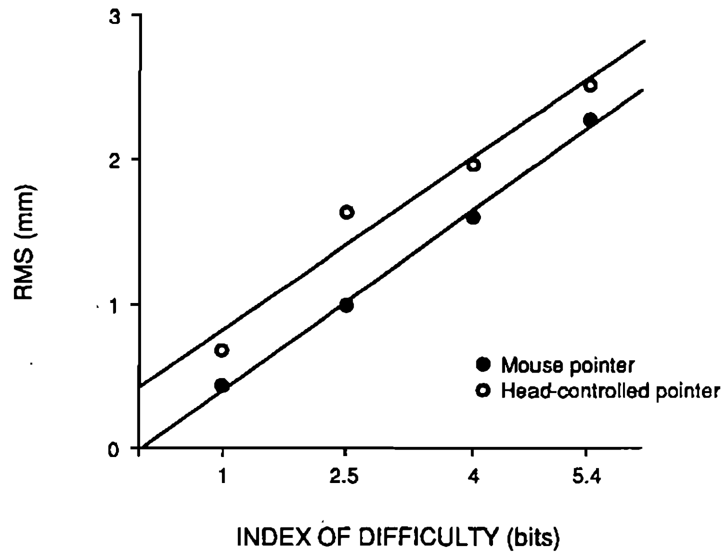

Figure 6. Average RMS cursor deviation plotted against Fitts' index of difficulty for the mouse and head-controlled pointer.

$p<0{\cdot}05$). The average RMS cursor displacement at a gain of 4·0 was 0·28 mm (24%) greater than at a gain of 1·0. Average RMS displacement for the mouse is plotted against Fitt's index of difficulty in figure 6. Least squares regression of average RMS against index of difficulty resulted in the relationship: $\text{RMS} = -0{\cdot}02 + 0{\cdot}42\ ID$ ($R^2 = 0{\cdot}996$).

The interaction between amplitude × direction on average RMS displacement was also statistically significant ($F(7,63)=14{\cdot}31$, $p<0{\cdot}01$). The smallest average RMS displacement was 0·52 mm (SD=0·25 mm) at 180° and the largest RMS displacement was 0·98 mm (SD=0·81 mm) at 315° for the short movement amplitude (24·3 mm). Average RMS displacement increased 0·34 mm when moving the cursor along diagonal directions for the short movement amplitude ($p<0{\cdot}01$). The smallest average RMS displacement was 1·23 mm (SD=1·01 mm) at 0° and the largest RMS displacement was 2·38 mm (SD=1·54 mm) at 45° for the long movement amplitude (61·7 mm). The overall average RMS displacement increased 0·87 mm when moving the cursor along diagonal directions ($p<0{\cdot}01$). The interactions between amplitude × width, gain × width × direction, and width × amplitude × direction were also statistically significant ($p<0{\cdot}01$), but these effects were small in magnitude and each accounted for less than 1·25% of the total variance.

Movement amplitude was the predominant effect for cursor path distance, accounting for 89% of the total variance ($F(1,9)=14012{\cdot}41$, $p<0{\cdot}01$). The average cursor path distance was 23·07 mm (SD=6·25 mm) for the short movement amplitude (24·3 mm), while the average cursor path distance was 64 mm (SD=8·38 mm) for the long movement amplitude (61·7 mm). The effect of target width was also statistically significant ($F(2,18)=1563{\cdot}04$, $p<0{\cdot}01$). Average cursor path distance decreased from 49·41 mm (SD=21·82 mm) for the small target width (2·9 mm) to 45·17 mm (SD=20·84 mm) for the medium target width (8·1 mm), and to 36·04 mm (SD=20·45 mm) for the large target width (23·5 mm). The direction effect ($F(7,63)=12{\cdot}5$, $p<0{\cdot}01$), and the interaction effect between width × amplitude were

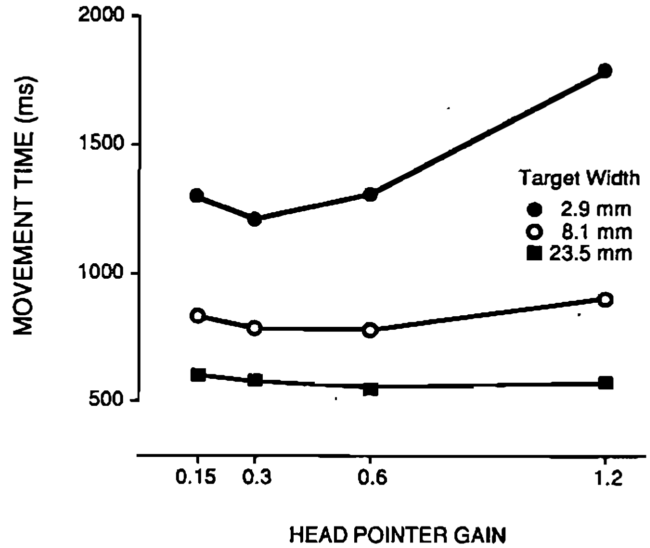

Figure 7. Average movement time plotted against head-controlled pointer gain for three target widths.

also statistically significant ($F(2,18)=24{\cdot}93$, $p<0{\cdot}01$), but they each accounted for less than 0·01% of the total variance. No significant gain effect ($F(3,27)=1{\cdot}94$, $p>0{\cdot}1$) was observed for average cursor path distance for the mouse.

3.2. *Head-controlled pointer*

The effect of gain on average movement time for head-controlled pointer was statistically significant ($F(3,27)=18{\cdot}94$, $p<0{\cdot}01$) having a local minimum between 859 ms (SD=383 ms) for a gain of 0·3 and 880 ms (SD=417 ms) for a gain of 0·6.

Increasing target width decreased average movement time ($F(2,18)=265{\cdot}22$, $p<0{\cdot}01$) from 1,400 ms (SD=542 ms) for the small target width (2·9 mm) to 823 ms (SD=254 ms) for the medium target width (8·1 mm), and to 579 ms (SD=206 ms) for the large target width (23·5 mm). Figure 7 illustrates the interaction between gain × width on average movement time, which was statistically significant ($F(6,54)=20{\cdot}40$, $p<0{\cdot}01$). The largest average movement time was at a head-controlled pointer gain of 1·2 for the small target width (2·9 mm), which was 579 ms greater than the average movement time at a head-controlled pointer gain of 0·3 ($p<0{\cdot}01$). For the medium target width (8·1 mm), the largest average movement time was also at a head-controlled pointer gain of 1·2, which was 126 ms greater than the average movement time at a head-controlled pointer gain of 0·6 ($p<0{\cdot}01$).

The average movement time increased from 746 ms (SD=393 ms) for the small movement amplitude (24·3 mm) to 1122 ms (SD=529 ms) for the long movement amplitude (61·7 mm) ($F(1,9)=233{\cdot}94$, $p<0{\cdot}01$). The interaction between gain × amplitude on average movement time was also statistically significant ($F(3,27)=6{\cdot}61$, $p<0{\cdot}01$) and is plotted in figure 8. Average movement time significantly increased when the head-controlled pointer gain level increased for the small movement amplitude (24·3 mm)($p<0{\cdot}01$). Average movement time decreased 124 ms when head-controlled pointer gain increased from 0·15 to 0·3, and increased 236 ms when increasing gain to 1·2 for the long movement amplitude (61·7

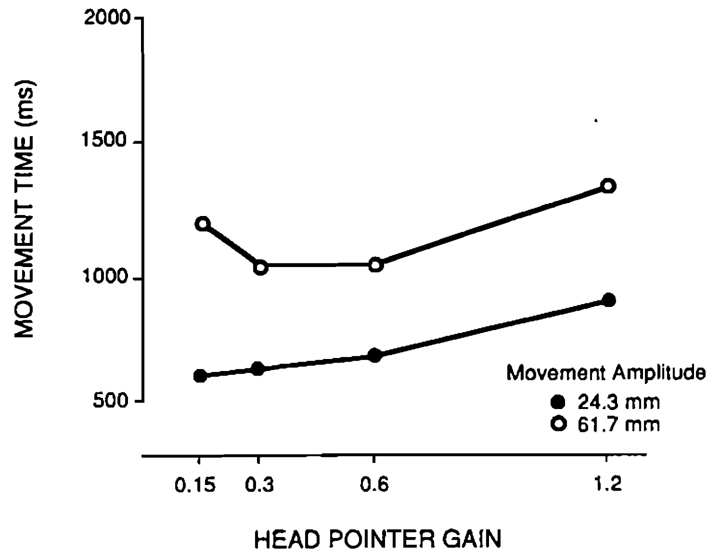

Figure 8. Average movement time plotted against head-controlled pointer gain for two movement amplitudes.

mm)($p<0{\cdot}01$). The interaction between amplitude × width was significant ($F(2,18)=18{\cdot}06$, $p<0{\cdot}01$), and this effect will be presented later in terms of Fitts' Law. The interaction between amplitude × direction was also significant ($F(7,63)=3{\cdot}37$, $p<0{\cdot}01$), but this effect accounted for less than 0·3% of total variance.

Although the direction effect was statistically significant ($F(7,63)=8{\cdot}54$, $p<0{\cdot}01$) it only accounted for less than 0·6% of the total variance. The smallest average movement time was 890 ms at 0° and the largest average movement time was 991 ms at 270°.

Discrete target acquisition at different gains was aptly described using Fitts' Law for the head-controlled pointer. The regression of movement time against index of difficulty at each gain level resulted in an average coefficient of variation of 0·94 for the head-controlled pointer (see figure 9). Movement time predicted by the Fitts' Law regression lines were projected against a gain abscissa along with average movement time measured for each index of difficulty level. The resulting curves had local minimums in the proximity of a 0·3 gain for indexes of difficulty greater than 2·5 (see figure 9).

The effect of gain on average RMS displacement was statistically significant ($F(3,27)=8{\cdot}43$, $p<0{\cdot}01$). Average RMS increased as gain increased from 0·15 (mean = 1·55 mm, SD = 1·21 mm) to 1·2 (mean = 2·02 mm, SD = 1·46 mm). Average RMS displacement increased from 1·12 mm (SD = 0·84 mm) for the short movement amplitude (24·3 mm) to 2·32 mm (SD = 1·46 mm) for the long movement amplitude (61·7 mm) ($F(1,9)=402{\cdot}82$, $p<0{\cdot}01$). Increasing target width decreased average RMS displacement from 1·98 mm (SD = 1·12 mm) for the small target width (2·9 mm), to 1·33 mm (SD = 1·32 mm) for the large target width (61·7 mm) ($F(2,18)=149{\cdot}85$, $p<0{\cdot}01$). The effect of direction on average RMS displacement was also statistically significant ($F(7,63)=35{\cdot}14$, $p<0{\cdot}01$). The average RMS displacement increased 1·23 mm ($p<0{\cdot}01$) when moving the cursor along diagonal

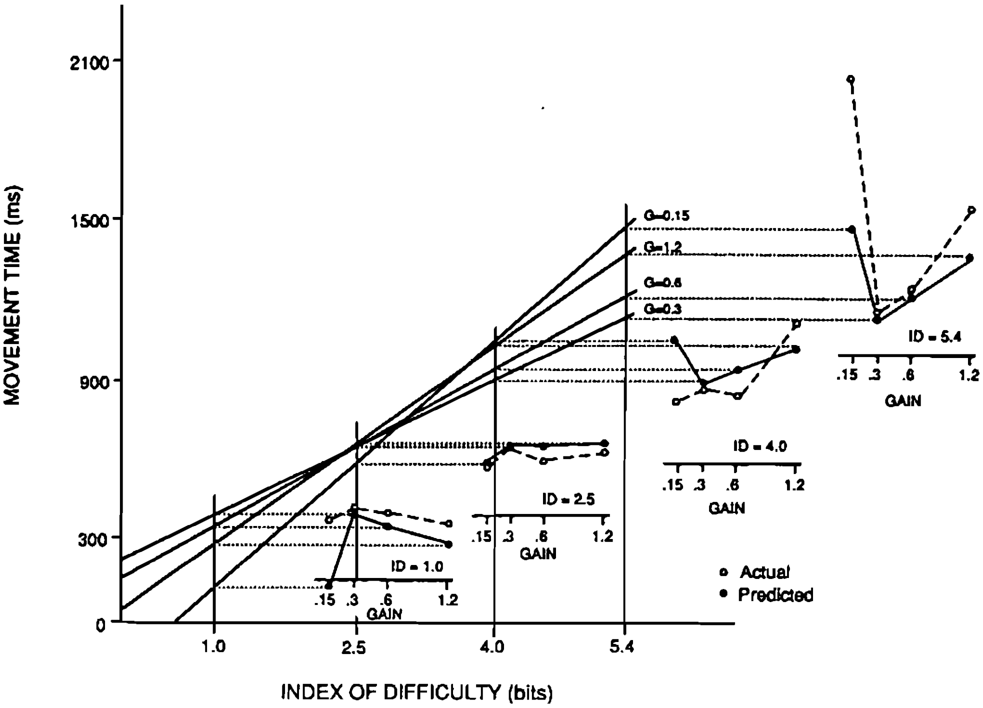

Figure 9. Fitts' Law regression lines for the four head pointer gain levels. Average movement time at every gain level is plotted for each index of difficulty along with movement time predicted by the Fitts' Law model.

directions (45°, 135°, 225°, and 315°) than when moving along off-diagonal directions (0°, 90°, 180°, and 270°).

The interaction between amplitude × direction on average RMS displacement was statistically significant ($F(7,63)=15{\cdot}85$, $p<0{\cdot}01$). At the short movement amplitude (24·3 mm), the smallest average RMS displacement was 0·53 mm (SD=0·46 mm) for 0° and the largest average RMS displacement was 1·58 mm (SD=1·03 mm) for 135°. The average RMS displacement was 0·34 mm greater when moving the cursor along diagonal directions than when moving along off-diagonal directions ($p<0{\cdot}01$). At the long movement amplitude (61·7 mm), the smallest average RMS displacement was 1·10 mm (SD=0·63 mm) for 0° and the largest average RMS displacement was 3·28 mm (SD=2·23 mm) for 315°. The average RMS displacement was 1·68 mm greater when moving the cursor along diagonal directions than when moving along off-diagonal directions for the long movement amplitude ($p<0{\cdot}01$). The interactions between width × amplitude, width × direction, and width × amplitude × direction on average RMS displacement were also statistically significant ($p<0{\cdot}01$), but these effects were small in magnitude and each accounted for less than 1% of the total variance. The average RMS cursor displacement is plotted against Fitts' index of difficulty in figure 6. Least squares regression of RMS against ID resulted in the linear relationship: RMS=0·41+0·040 ID ($R^2=0{\cdot}958$).

The gain effect on average cursor path distance was statistically significant

($F(3,27)=10{\cdot}4$, $p<0{\cdot}01$); however, it only accounted for 2% of the total variance. Movement amplitude was the predominant effect, accounting for 72% of the total variance ($F(1,9)=3288{\cdot}15$, $p<0{\cdot}01$). The average cursor path distance increased 45·85 mm when increasing movement amplitude from the short (24·3 mm) to the long (61·7 mm) amplitude. The effect of target width was also statistically significant ($F(2,18)=358{\cdot}85$, $p<0{\cdot}01$). Average cursor path distance decreased from 60·01 mm (SD=28·94 mm) for small target width (2·9 mm) to 39·85 mm (SD=24·19 mm) for large target width (23·5 mm). The interactions between gain × amplitude, gain × direction, and amplitude × direction were all statistically significant ($p<0{\cdot}01$); however they each accounted for less than 0·3% of the total variance.

4. Discussion

The D/C gain had a substantial effect on average movement time, especially for the head-controlled pointer, although the gain effect was not as great as target width and movement amplitude. A U-shaped relationship was observed for both the mouse and the head-controlled pointer. The optimal mouse gain was between 1·0 and 2·0 which was very similar to the findings of Epps (1986) who reported a optimal gain of 1·3 for an optical mouse. Arnaut *et al.* (1986) found that gain was rated in order of preference from 1·0, 0·875, 1·5, 2·0, and 2·5 for a touch tablet, with respect to ease of use and fatigue. Although Kantowitz and Elvers (1988) found that average movement time increased with gain for position control, they only studied gain levels of 1·0 and 2·0. In this investigation, average movement time also increased when mouse gain increased from 1·0 to 2·0. Furthermore, the lower mouse gain levels ($<1{\cdot}0$), with respect to optimal gain, resulted in larger average movement times than for the higher mouse gain levels ($>2{\cdot}0$). The magnitude of head-controlled pointer gain derived using the gain definition in this study was similar to the D/C ratio calculated using the definition proposed by Chapanis and Kinkade (1972) and varied by less than 0·2%. A head-controlled pointer gain level between 0·3 and 0·6 resulted in the smallest average movement time. The higher head-controlled pointer gain levels ($>0{\cdot}6$) resulted in a larger average movement time than the lower head-controlled pointer ($<0{\cdot}3$) gain levels with respect to the optimal gain setting.

Woodworth (1899) first described the speed–accuracy phenomenon by proposing that movement could be divided into two phases. The initial-adjustment phase (ballistic movement) covered most of the movement distance followed by the control phase (positioning movement) involving a series of feedback and adjustment processes in order to position into the target region. This explanation was supported by others (Welford 1968, Langolf *et al.* 1976, Sheridan 1979, Crossman and Goodeve 1983). In accordance with the two-phases movement control model, the outcome from this experiment resulted in both the average movement time and the average RMS displacement increasing when target width decreased. This was in fact the case for both devices and could be explained by reasoning that more precise positioning was required for entering the small tolerance target. Similarly movement time and RMS displacement increased as movement amplitude increased.

Buck (1980) claimed that a large proportion of the movement time is spent on secondary corrective movements, and that the D/C gain should not affect corrective movements necessary when using a joystick-oscilloscope system for a target alignment task. This hypothesis was rejected by Arnaut *et al.* (1986) who conducted a study to assess the effects of D/C gain on performance for a target selection task using a touch tablet. The results indicated that D/C gain between 0·875 and 1·0 produced better target selection performance, especially for small targets.

Data from this study also indicated that a high gain level would greatly increase both the average movement time and average RMS displacement for small targets using either pointing device, especially for the head-controlled pointer. The gain effect was therefore particularly important for individuals having physical disabilities who must depend on head-pointing device. These results may be explained by increased tremor produced by the combination of high gain and a small tolerance. Higher gain levels decreased average movement time for acquiring large targets, however (see figures 3 and 7). In fact, for the large target width (23·5 mm), the average movement time was still decreasing up to a mouse gain of 4·0, while the smallest average movement time for the head-controlled pointer gain was 0·6. The decrease in movement time at high gains was anticipated because of the decreased requirement for positioning movement and the increase in ballistic movement for large targets.

The average movement time and average RMS displacement increased when movement amplitude increased. Since ballistic movement likely dominated most of the average movement time for the mouse at long movement amplitudes (61·7 mm), the lower gain levels would be expected to result in larger movement times. In this study, that was only true for the mouse pointer. The average movement time and average RMS at a head-controlled pointer gain of 1·2, which was considered a very high gain within the practical range, was in fact greater than at the lower gain levels, even for the long movement amplitude. The interaction between gain and movement amplitude on cursor path distance followed a similar pattern as RMS displacement. One explanation for this result was that tremor during head motion, especially for the high gain conditions, caused a considerable increase in positioning error and thus deteriorated the benefit of high gain for ballistic movement. In order to fully undestand the interaction between gain and ballistic movement and positioning movement on movement time, further investigations should be conducted considering individual movement as two control phases, including ballistic and positioning movements at different gain levels.

The results showed significant effects of gain of Fitts' Law slopes for both pointing devices. Arnaut and Greenstein (1987) maintained that optimisation of a control-display interface must specify at least three of four design parameters including (1) control amplitude; (2) control target width; (3) display amplitude; and (4) display target width. Since D/C gain be definition only involves two of these four parameters, it is insufficient alone as a specification for optimisation, according to their criteria. Since this study used a Fitts' Law discrete movement task, the determination of the optimum D/C gain should be sufficient in specification for optimisation of performance because the task involved manipulating both target width and movement amplitude, in addition to gain.

Gan and Hoffmann (1988) studied visually controlled and ballistic movement using a repetitive discrete tapping task about the elbow with movement amplitude ranging from 4 cm to 25 cm. Visual controlled movement included visual feedback for path correction where as ballistic movement was so rapid in that path correction was impossible. They found that the approximate boundary between these two classes of movements was at an ID between 2 bits to 4·5 bits. This boundary changed with movement amplitude. Movements for IDs less than this boundary were considered ballistic, while movements for higher IDs were considered in visually controlled region. They also maintained that since Fitts' equation was applicable only to visually controlled movements, it was likely that Fitt's Law would not apply for movement times less than about 200 ms, which was the lag necessary for visual feedback. Since the study reported in this paper included movement amplitudes as short as 2·43 cm, and the shortest average movement time for ID = 1 for the mouse pointer was 250 ms, visual control may have still been involved because of the short movement amplitude. In other words, the Fitts' equation should still be applicable at the conditions of ID = 1 for the current study.

When considering the significant effects of D/C gain, performance using the mouse and the head-controlled pointer can only be fairly compared when they are operating at their optimal gain settings. It is also important to keep in mind the definition for mouse gain differed from head-controlled pointer gain. According to these results optimal mouse gain was between 1·0 and 2·0 and optimal head-controlled pointer gain was between 0·3 and 0·6. Since this experiment did not cover levels in between, the comparison in performance between the two devices was based only on the best performance measured, which was at mouse gain of 1·0, and at head-controlled pointer gain of 0·3. Average movement time was more than 76% greater at the optimal head-controlled pointer gain of 0·3 (M = 859 ms, SD = 383 ms) with a Fitts' slope of 169 ms/bit, than at the optimal mouse gain of 1·0 (M = 486 ms, SD = 182 ms) with a Fitts' slope of 135 ms/bit. In addition, average RMS displacement was more than 27% greater for the head-controlled pointer at its optimal gain (M = 1·498 mm, SD = 1·107 mm) than for the mouse (M = 1·175 mm, SD = 1·056).

Although the index of difficulty accounted for 74% of the movement time variance for the conventional mouse and 62% of the variance for the head-controlled pointer, the gain effect accounted for only 1·4% of the variance for the mouse and 8% of total variance for the head-controlled pointer. In addition, the gain effect on RMS displacement and cursor path distance was significant for the head-controlled pointer but not for the mouse. These results suggested that optimal gain was a more important factor affecting performance using a head-controlled pointer than a conventional mouse.

An important aspect of this work is to learn about the characteristics of head motor control in order to enhance performance of head-controlled computer input devices for individuals with physical disabilities. One obvious need for head-controlled instruments are for people with upper extremeties movement impairments. Another not so obvious use is for people who have cerebral palsy. Vaughan *et al.* (1988) used electromyography for measuring muscle contraction levels to examine voluntary control of the masseter and orbicularis oris muscle activities in cerebral palsied individuals. They concluded that people with cerebral palsy have similar poor control over both muscles. They further suggested that the cerebral palsied subjects' voluntary motor deficits did not result from abnormal muscle spindle based reflexes, but was related to the inability to learn the relationship between the motor commands to the muscles and the resulting perceptual consequences of the movement. Neilson and McCaughey (1982) made similar conclusions. They studied the dissociation between functional control of movement and ability to regulate spasm and spasticity and concluded that spasm and spasticity were not the primary cause of movement disability in cerebral palsied subjects, but rather the inability to formulate and communicate appropriate motor command to specific muscles. Often head motor control is less affected by cerebral palsy than upper limb control, making head-controlled pointers and mouth sticks a viable alternative for computer access. Motor control for target acquisition tasks, compounded by spasticity and muscle spasms, may represent increased degrees of movement complexity for individuals with cerebral palsy, and gain might be an even more important control factor in human-machine interface design for these people (Radwin *et al.* 1990). Future research will study movement impaired subjects using the head-controlled pointers under different gain conditions.

5. Conclusions

Gain had a significant effect on movement time for both the mouse and the head-controlled pointer. The optimal mouse gain was between 1·0 and 2·0 and the optimal head-controlled pointer gain was between 0·3 and 0·6. Low mouse gains (<1·0) should be avoided because it increased task time demands, while high mouse gains (>2·0) increased RMS error. For similar reasons, high head-controlled pointer gains (>0·6) should be avoided because of increased RMS error and subsequently increased task time, particularly for small targets.

Data from the study indicated that movement time was always less for the mouse than for the head-controlled pointer at all the gain levels tested. Average movement time was more than 76% greater for the head-controlled pointer than for the mouse at optimal gain settings.

The lower mouse gain levels (<1·0), with respect of the optimal gain, resulted in larger average movement times than at the higher mouse gain levels (>2·0). The higher head-controlled pointer gain levels (>0·6) resulted in greater average movement times than for the lower head-controlled pointer gain levels (<0·3) with respect to the optimal gain settings.

Fitts' Law aptly described movement time at all gain levels for both input devices. The lowest Fitts' Law slopes occurred at the optimal gain levels for the mouse pointer and at indices of difficulty greater than 2·5 for the head-controlled pointer. Gain accounted for 8% of the total variance of average movement time for the head-controlled pointer and only 1·4% of the variance for the mouse. Optimal gain improved performance using the head-controlled pointer by more than 21%. These results indicated that optimal gain was more important for the head-controlled pointer than for the conventional mouse in terms of movement time.

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