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A Method for Evaluating Head-Controlled Computer Input Devices Using Fitts' Law

ROBERT G. RADWIN,[1] GREGG C. VANDERHEIDEN, *and* MEI-LI LIN, *University of Wisconsin, Madison, Wisconsin*

The discrete movement task employed in this study consisted of moving a cursor from the center of a computer display screen to circular targets located 24.4 and 110.9 mm in eight radial directions. The target diameters were 2.7, 8.1, and 24.2 mm. Performance measures included movement time, cursor path distance, and root-mean-square cursor deviation. Ten subjects with no movement disabilities were studied using a conventional mouse and a lightweight ultrasonic head-controlled computer input pointing device. Average movement time was 306 ms greater (63%) for the head-controlled pointer than for the mouse. The effect of direction on movement time for the mouse was relatively small compared with the head-controlled pointer, which was lowest at 90 and 270 deg, corresponding to head extension and head flexion, respectively. Average path distance and root mean square displacement was lowest at off-diagonal directions (0, 90, 180, and 270 deg). This methodology was also shown to be useful for evaluating performance using an alternative head-controlled input device for two subjects having cerebral palsy, and measured subtle performance improvements after providing a disabled subject with lateral torso support.

INTRODUCTION

The performance measures often used for evaluating computer input devices are speed and accuracy (English, Engelbart, and Berman, 1967). Goodwin (1975) measured and compared cursor positioning performance among cursor keys, a light pen, and a light gun while performing random and sequential pointing tasks representative of actual activities intended for these devices. Performance was measured for that study in terms of total task completion time. Each task consisted of a fixed number of movements to fixed-sized targets. The investigation found that performance was faster with the light pen or light gun than with the cursor keys.

Card, English, and Burr (1978) demonstrated that movement time using a mouse and joystick was adequately described using Fitts' law (Fitts, 1954; Fitts and Peterson, 1964). Epps (1986) compared six hand-operated cursor control devices using a target acquisition task based on Fitts' law. These included an absolute touchpad, a relative touchpad, a mouse, a trackball, a rate-controlled displacement joystick, and a rate-

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

controlled force joystick. The study demonstrated that the Fitts paradigm was apt for measuring target acquisition performance for all six devices. Jagacinski and Monk (1985) found that Fitts' law also described head movement using a helmet-mounted sight. That study, however, measured movement time wearing a heavy helmet weighing 15 N. Andres and Hartung (1989) used a Fitts' law paradigm to study head movements with a chin stick to depress keys on a keyboard. Although Fitts' law held for all these devices, Whitefield (1986) cautioned that situations other than discrete target selections, including many activities involved with these computer input devices, should not strictly conform to Fitts' law. Despite this limitation, Whitefield acknowledged that Fitts' law can be a useful means of comparing input pointing devices. Rosen, Goodenough-Trepangier, Getschow, and Felts (1986) studied movement-impaired subjects (with amyotrophic lateral sclerosis, head injury, and other conditions) and nonimpaired subjects performing a reciprocal tapping task in eight directions in order to assess movements relevant to special keyboard devices. They found that Fitts' law was also applicable for these disabled subjects.

The objective of this investigation was to develop a method for measuring and evaluating performance and for establishing norms using alternative head-controlled computer input devices intended for movement-impaired computer users. A Fitts' law discrete target acquisition task was considered for measuring and predicting movement time. Additional performance measures were cursor path distance and root-mean-square cursor deviation. In order to evaluate and compare alternative computer input interfaces for disabled individuals, it was first necessary to study subjects without movement disabilities in order to establish normal performance characteristics.

Performance of subjects without movement disabilities was compared with both a conventional mouse and an ultrasonic head-controlled computer input device. In order to test the potential of using this method for evaluating performance for persons with movement disabilities, an additional number of sets included two subjects with cerebral palsy. One disabled subject was provided with a thoracic support appliance for stabilizing trunk posture and tested to determine whether this method can measure subtle performance improvements.

METHODS

Experimental Task

A discrete movement target acquisition task was developed using computer input pointing devices and based on Fitts' law. The task was specifically designed for isolating discrete movements and not confounding measurements with more complex movements, such as dragging, clicking, and selecting, which are often performed using computer input pointing devices. The task was also specifically designed to accommodate people who have moderate to severe movement disabilities.

At the center of a computer display screen was a 5-mm-diameter circle designated as the HOME position. The objective of the task was to move a crosshair cursor from the HOME position to a circular target of varying diameter and location on the screen (see Figure 1). Subjects were instructed to move the cursor into the target region as quickly as possible. The task consisted of the following sequence of events:

(1) Subjects prepared for each trial by moving the cursor to the HOME position located at the center of the screen and posturing themselves in the specified manner for the next trial.

(2) Subjects indicated they were ready to

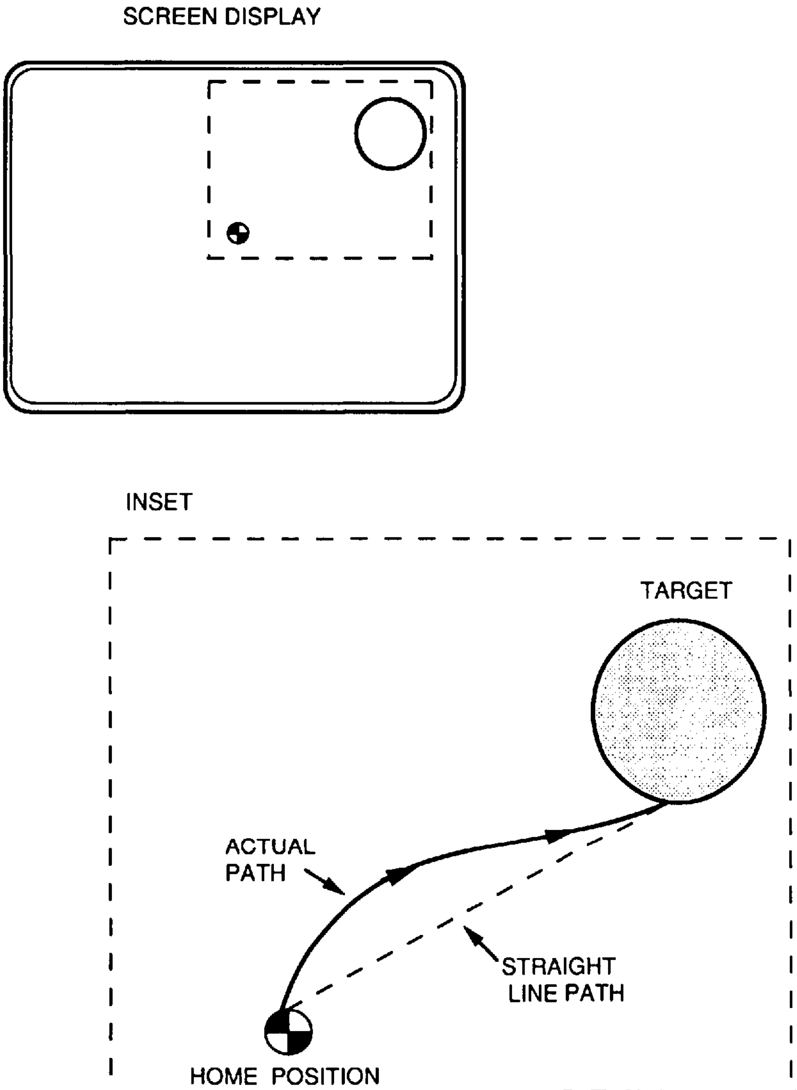

Figure 1. *Representation of computer display screen during target acquisition task.*

start a trial by keeping the cursor inside the HOME position for a full 2 s. If at any time they felt they were not prepared, they were able to move the cursor outside the HOME region before the 2 s had elapsed to prevent the trial from beginning.

(3) After the cursor had been inside the HOME position for 2 s, a solid circular target appeared on the screen. Subjects were instructed to continue holding the cursor inside the HOME position an additional 1.5 s until a tone sounded, which was the GO signal. This additional time enabled subjects to prepare for the subsequent movement. After the GO signal, subjects were instructed to move the cursor into the target area as quickly as possible. They were then required to maintain the cursor inside the target area, upon which

the solid target turned clear, displaying only the target outline and thus indicating to the subject that the target had been acquired successfully.

(4) After the target was acquired, subjects prepared for the next trial by moving the cursor back into the HOME region at the center of the screen, and the outline of the target was removed from the display.

Experimental Design

The experiment involved two types of computer input pointing devices (*P*). These included a conventional mouse pointer and an ultrasonic head-controlled pointer intended for use by computer users whose upper-extremity movement disabilities render them unable to use a mouse. The same task was performed using both pointing devices. The other independent variables were target diameter (*W*), movement amplitude (*A*), and movement direction (*D*). The experiment was a repeated-measures, full-factorial design in which subjects served as a random effects blocking variable.

Targets were located in eight different radial directions from the HOME position. These included angles of 0, 45, 90, 135, 180, 225, 270, and 315 deg with respect to the horizontal. The three target diameters measured 2.7, 8.1, and 24.2 mm. Movement amplitudes were 24.4 mm and 110.9 mm. The Fitts index of difficulty (ID) was determined for these movement amplitude and target diameter conditions. These conditions produced IDs of 1.0, 2.6, 3.2, 4.2, 4.8, and 6.4 bits.

Initial posture was fixed when the cursor was at the HOME position. Trials using the conventional mouse required subjects to sit in an upright position in the chair with the upper arm adducted and in line with the torso. The computer workstation table height was adjusted so that the forearm was at right angles with the upper arm. The screen height was independently adjustable from the table height and centered at eye level. Subjects were seated at a distance of 89 cm from the display screen. They were instructed to sit upright and face directly toward the screen before initiating a movement when using the head-controlled pointer.

The experiment was conducted in four experimental sessions per subject, each session lasting 2 h. A session included 15 sets of 48 trials, each consisting of all combinations of $W \times A \times D$ ($3 \times 2 \times 8$) presented in a counterbalanced order. A 2-min rest period was given between each set. Two consecutive sessions consisting of 15 sets each were conducted for each device. Half the subjects started the experiment using the mouse and the other half started the experiment using the head-controlled pointer. The first 15 sets for each input device were considered practice and were not included in the data analysis so as to stabilize task performance. Only the data obtained during the second and fourth sessions were used in the actual analysis. Data were averaged over every condition of $W \times A \times D$ for each subject, resulting in 15 replications for each input device per subject. A warmup set was always provided before each new session.

Ten subjects having no movement disabilities were randomly recruited by posting announcements in university buildings and classrooms. All subjects identified themselves as healthy adults between the ages of 21 and 32 years. Three were female and seven were male. All 10 described themselves as right-handed individuals. The amount of experience reported using a mouse pointing device ranged from none (two subjects) to five years of experience. Subjects were paid a small fee for participating.

Two additional subjects with cerebral palsy were recruited; they operated the head-controlled pointing input device for the same task previously described. One subject (CP1) was a 35-year-old male who had had spastic athetoid cerebral palsy since birth. This subject had no cognitive impairments, had completed two years of college coursework in computer science, and was a self-employed computer programmer who normally used a mouth stick as a computer keyboard access device. The second subject (CP2) was a 39-year-old male graduate student who had no experience using either a mouth stick or a head-controlled device.

The motor-impaired subjects were allowed to perform as many sets in one session as they could in comfort and without becoming tired, which was usually four to five sets per day. Practice sessions were conducted until the subjects had learned the task and their performance had stabilized, which occurred in four sessions. After the practice sessions, Subject CP1 completed 36 sets over a period of eight experimental sessions. Subject CP2 performed 18 sets over five experimental sessions. A warmup set was always provided at the beginning of each experimental session and was excluded from the analysis.

Subject CP1 had a tendency to exhibit a lateral bend to the right when seated in the wheelchair. After completion of the initial 36 sets, it was hypothesized that lateral trunk support might improve performance by helping to align the head's axis of rotation with the horizontal. Spherical thoracic support pads were attached to both sides of the wheelchair and an additional 18 trials were performed with the benefit of this orthotic device.

Dependent Variables

Movement time (MT) was defined as the time elapsed from just after the cursor moved outside the HOME region until the target perimeter was crossed when the target was successfully acquired. A target was considered successfully acquired if the cursor entered the target area and did not overshoot it but remained inside for at least 62.5 ms. If the cursor moved outside the target area in less than that time, the movement time counter continued until the cursor reentered the target and remained inside the target area until 62.5 ms had elapsed. This method was used in order to accommodate subjects with movement disabilities who may not be able to coordinate both moving the cursor and then pressing a button. The reported movement time does not include the time inside the target area.

Movement path distance (PD) was defined as the sum of periodically sampled cursor displacement magnitudes along the path the cursor traversed when acquiring a target, starting at the point at which the cursor first moved outside the HOME region to the point at which the cursor crossed the target perimeter upon successfully acquiring the target. The PD between the HOME region and target was included as a measure of cursor displacement along its actual path into the target region (see Figure 1). Root mean square (RMS) cursor deviation was measured using the sum of the squares of periodically sampled differences in displacement between the actual path the cursor traversed and a straight line drawn between the point at which the cursor first moved outside of the HOME region to the point at which the cursor crossed the target perimeter (see Figure 1). The RMS cursor deviation was included as a measure sensitive to deviation from the straight-line path between the HOME region and the target.

Equipment

The task was programmed and performed using an Apple Macintosh II microcomputer with a Moniterm Corp. Model VY1000 monitor. This display had 1280 × 960 pixel resolution with 0.26855 mm per pixel. The Macintosh II internal real-time clock was used for all timing operations; clock resolution was

1.25 ms. Cursor displacement for PD and RMS was sampled at a rate of 32 Hz.

The mouse was a conventional Apple Model A9M0331. Rate control and mouse acceleration were disabled. The ultrasonic head-controlled pointer was a Personics Corp. Model VCS 2000. Similar to a mouse, the head-controlled pointer was a relative displacement device and was extremely light, weighing only 0.5 N. It was designed for emulating a mouse pointer by tracking head rotation for horizontal cursor displacement and head extension-flexion for vertical cursor displacement. Sensitivity of the head pointer was maintained at the medium setting.

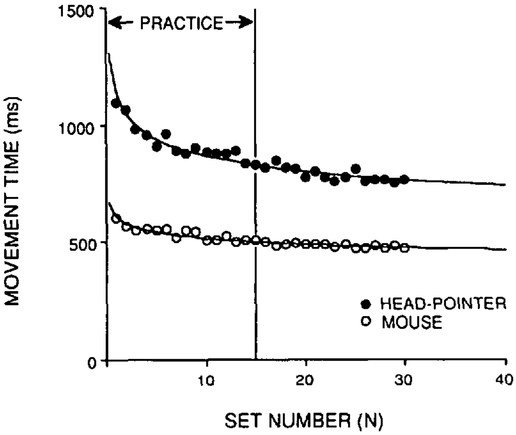

Figure 2. *Average movement time for the mouse and head-controlled pointer plotted against set number to indicate relative learning curves (10 subjects). The first 15 sets were considered practice and excluded from the analysis.*

RESULTS

Conventional Mouse and Head-Controlled Pointer—Nondisabled Subjects

The average MT was computed for each set of 48 trials and used to indicate relative learning for individual subjects performing the task. The average learning curves for 10 subjects each performing 30 consecutive sets using both the mouse and the head-controlled pointer are plotted in Figure 2. The linear regression model for the population learning curve was $MT(N) = 608\ N^{-0.07}$, $R^2 = 0.91$, for the mouse and $MT(N) = 1132\ N^{-0.11}$, $R^2 = 0.94$, for the head-controlled pointer, where $MT(N)$ is the average MT in ms for the Nth set, and N is the number of consecutive sets performed.

Average MT increased from 482 ms (SD = 263 ms) for the mouse to 788 ms (SD = 445 ms) for the head-controlled pointer, $F(1,9) = 127.56$, $p < 0.001$. Average MT also increased 86%, from 444 ms (SD = 304 ms) for the short movement amplitude condition to 826 ms (SD = 385 ms) for the long movement amplitude, $F(1,9) = 975.12$, $p < 0.001$. Increasing target diameter decreased average MT from 983 ms (SD = 398 ms) for the small target to 596 ms (SD = 249 ms) for the medium target and 327 ms (SD = 182 ms) for the large target, $F(2,18) = 491.71$, $p < 0.001$. The effect of direction on average MT was also statistically significant, $F(7,63 = 6.32$, $p < 0.001$, though the direction main effect accounted for only 0.3% of the total variance. The shortest average MT occurred at 90 deg (M = 586 ms, SD = 336 ms), which was 77 ms less than MT at 225 deg ($p < 0.01$) and 80 ms less than MT at 315 deg ($p < 0.01$).

Figure 3 illustrates average MT plotted against direction for both the mouse and the head-controlled pointer, showing the interaction between P and D, which was statistically significant, $F(7,63) = 10.71$, $p < 0.001$. Table 1 contains pairwise multiple contrasts between average MT for the mouse and the head-controlled pointer. Figure 4 illustrates the interaction between P and W. The effect of increasing target diameter was greater for the head-controlled pointer than for the mouse, $F(2,18) = 130.07$, $p < 0.001$. Average MT decreased 249 ms when the target size was increased from the small to medium diameter for the mouse, but average MT decreased 525 ms for the same target size in-

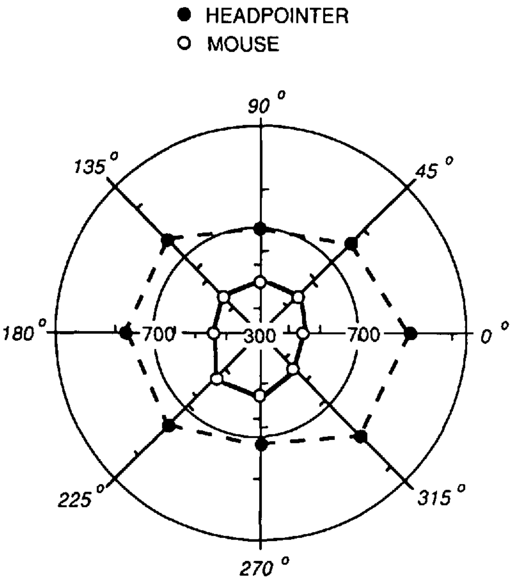

Figure 3. *Average movement time (ms) plotted in polar coordinates for both the mouse and head-controlled pointer against direction (10 subjects). Range around group means is indicated by tick marks on radial axes. Note that the center of the plot represents 300 ms.*

crease when using the head-controlled pointer (see Figure 4). Although the interaction between *D* and *W* was statistically significant, $F(14,126) = 5.75$, $p < 0.001$, the magnitude of this effect was very small, accounting for less than 0.3% of the variance. The interaction between *A* and *W* was also significant, $F(2,18) = 48.32$, $p < 0.001$, but this effect will be presented later using Fitts' law. Three-way interactions among $P \times D \times W$, $P \times D \times A$, and $P \times W \times A$ were statistically significant ($p < 0.001$); however, these effects were small in magnitude, and each accounted for less than 0.16% of the variance.

No significant pointing device effect, $F(1,9) = 15.37$, $p = 0.004$, was observed for average PD between the mouse ($M = 74.8$ mm, $SD = 47.5$ mm) and the head-controlled pointer ($M = 78.8$ mm, $SD = 47.7$ mm). Movement amplitude was the predominant effect, accounting for 97% of the variance, $F(1,9) = 8{,}615.67$, $p < 0.001$. The average PD for the 24.4-mm movement amplitude was 29.9 mm ($SD = 5.7$ mm), whereas the average PD for the 110.9-mm movement amplitude was 123.7 mm ($SD = 10.3$ mm). Although the decrease in average PD when increasing target diameter was statistically significant, $F(2,18) = 112.94$, $p < 0.001$, average PD decreased only 9.6 mm between the small and large targets. Average PD, which is plotted against direction angle in Figure 5, was statistically significant, $F(1,9) = 8.55$, $p < 0.001$. Pairwise multiple contrasts for the direction effect are given in Table 2. Although the interactions between *P* and *D*, $F(7,63) = 4.57$, $p < 0.001$; *A* and *W*, $F(2,18) = 16.63$, $p < 0.001$; and *A* and *D*, $F(7,63) = 5.43$, $p < 0.001$, were all statistically significant for PD, these effects each accounted for less than 0.1% of the total variance.

No significant pointing device effect was observed for average RMS, $F(1,9) = 13.08$, $p = 0.006$, between the mouse ($M = 1.2$ mm, $SD = 1.3$ mm) and the head-controlled pointer ($M = 1.8$ mm, $SD = 1.3$ mm). Although statistically significant, $F(2,18) = 20.92$, $p < 0.001$, average RMS decreased only 0.2 mm—from 1.6 mm ($SD = 1.3$ mm) to 1.4 mm ($SD = 1.4$ mm)—between the small and large target diameters, and *W* accounted for less than 1.0% of the variance. Average RMS increased 175%, from 0.8 mm ($SD = 0.5$ mm) to 2.2 mm ($SD = 1.6$ mm), when increasing movement amplitude, $F(1,9) = 86.51$, $p < 0.001$. Average RMS is plotted against direction angle in Figure 6. The effect of direction on RMS was statistically significant, $F(7,63) = 35.60$, $p < 0.001$. Pairwise multiple contrasts for the direction effect are included in Table 3.

The interaction between *D* and *A* on RMS cursor deviation was statistically significant, $F(7,63) = 15.59$, $p < 0.001$; average RMS increased 0.5 mm when moving to diagonal target direction (45, 135, 225, and 315 deg) for the short movement amplitude and increased

TABLE 1

Pairwise Contrasts for Average Movement Time (ms) between Direction and Pointing Device Conditions (10 Subjects)

Direction (deg)	Direction (deg) 45	90	135	180	225	270	315
Head-controlled pointer							
0	−35*	−124***	−27	−42***	−12	−68***	27
45		−89***	8	−8	23	−33	62***
90			97***	81***	112***	56***	151***
135				−16	15	−41**	54***
180					30	−25	69***
225						−56***	39**
270							95***
Mouse							
0	38**	22	7	24	63***	64***	31
45		−16	−31	−14	26	26	−6
90			−15	2	41***	42***	9
135				17	56***	57***	24
180					39**	40**	7
225						0	−32
270							−32

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

1.7 mm when moving to diagonal targets for the long movement amplitude. Although the interactions $D \times P$, $F(7,63) = 14.38$, $p < 0.001$; $D \times W$, $F(14,63) = 14.05$, $p < 0.001$; $P \times D \times A$, $F(7,63) = 4.53$, $p < 0.001$; and $D \times W \times A$, $F(14,126) = 16.39$, $p < 0.001$, were all statistically significant, each accounted for less than 3.0% of the total variance.

Linear regression models were produced for predicting individual subject perfor-

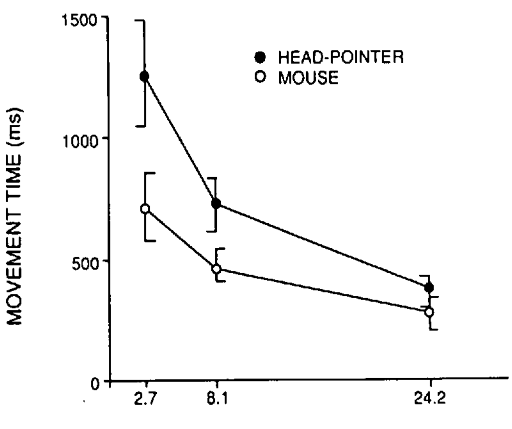

Figure 4. *Average movement time plotted against target diameter for the mouse and head-controlled pointer (10 subjects). Range around the group means is indicated by error bars.*

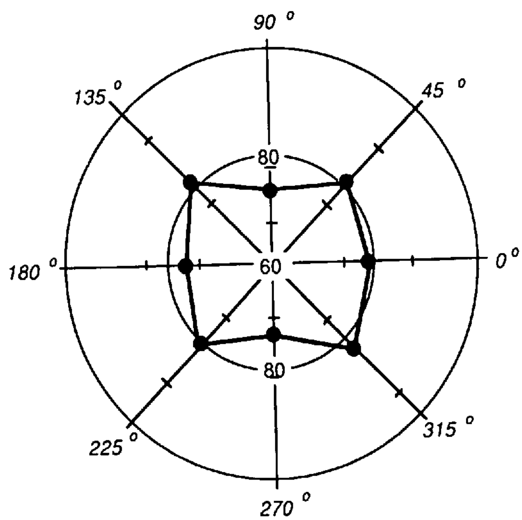

Figure 5. *Average PD (mm) plotted in polar coordinates against direction (10 subjects). Note that the center of the plot represents 60 mm. Range around the group means is indicated by tick marks on radial axes.*

TABLE 2

Pairwise Multiple Contrasts for Average Path Distance (mm) between Direction Conditions (10 Subjects)

Direction (deg)	Direction (deg)						
	45	90	135	180	225	270	315
0	2.0	−3.4	0.6	−2.2	0.3	−2.0	2.5
45		−5.4***	−1.4	−4.3**	−1.7	−4.0**	0.4
90			4.0**	1.1	3.7*	1.4	5.8***
135				−2.8	−0.3	−2.6	1.9
180					2.6	0.3	4.7***
225						−2.4	2.1
270							4.4**

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.

mance for each of the 16 $P \times D$ combinations using Fitts' law. The regression of average MT against ID for each individual subject produced a good linear fit, resulting in an average coefficient of variation of 0.94. The average slope for the mouse was 147 ms/bit, which increased to 240 ms/bit for the head-controlled pointer, $F(1,9) = 102.72, p < 0.001$. Linear regression models were also computed from the population average MT over all eight directions, and are listed in Table 4.

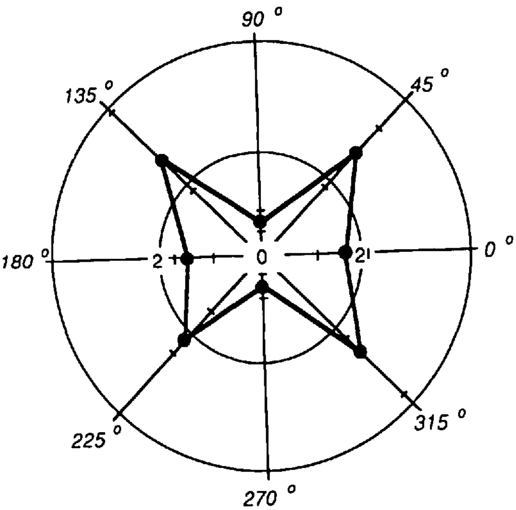

Figure 6. *Average RMS (mm) deviation plotted in polar coordinates against direction (10 subjects). Range around the group means is indicated by tick marks on radial axes.*

Head-Controlled Pointer—Cerebral Palsy Subjects

The learning curve for motor-impaired Subject CP1 performing 40 consecutive sets of 48 trials was $MT(N) = 3936\, N^{-0.31}$, $R^2 = 0.50$, where $MT(N)$ is the average MT in ms for the Nth set and N is the number of consecutive sets performed. The learning curve for Subject CP2 performing 18 consecutive sets of trials was $MT(N) = 4761\, N^{-0.12}, R^2 = 0.55$.

The average MT for Subject CP1 is plotted against direction in Figure 7 for task performance both with and without lateral torso support. Average MT was greatest for movement in the 0-deg direction and smallest at 90 deg, with MT 1250 ms greater at 0 deg than at 90 deg without torso support (see Figure 7). Similar findings resulted for PD and RMS: average PD was 166.2 mm greater at the 0-deg direction than at 90 deg, and average RMS was 5.8 mm greater at 0 deg than at 90 deg.

The average MT for Subject CP1 decreased 467 ms after torso support was provided, $F(1,2496) = 52.22$, $p < 0.001$. The resulting task performance improvement when the thoracic support pads were used to straighten the subject's posture is shown in Figure 7. Similarly, average PD decreased 49.4 mm, $F(1,2496) = 31.26$, $p < 0.001$, and average RMS decreased 1.1 mm, $F(1,2496) = 20.11, p$

TABLE 3

Pairwise Multiple Contrasts for Average Root Mean Square Distance (mm) between Direction Conditions (10 Subjects)

Direction (deg)	Direction (deg)						
	45	90	135	180	225	270	315
0	1.2***	−0.5	0.8***	−0.1	0.5	−0.6**	0.8***
45		−1.6***	−0.3	−1.2***	−0.6**	−1.7***	−0.3
90			1.3***	0.4	1.0***	−0.1	1.3***
135				−0.9***	−0.3	−1.4***	0.0
180					0.6**	−0.5	0.9***
225						−1.1***	0.3
270							1.4***

** $p < 0.05$; *** $p < 0.01$.

< 0.001, after the thoracic support pads were installed on the subject's wheelchair.

Linear regression models based on Fitts' law for MT versus ID were MT = −545 + 584 ID ms, R^2 = 0.94, for Subject CP1 and MT = −99 + 1145 ID ms, R^2 = 0.97, for Subject CP2. Regression models for MT at each direction for Subject CP1 are given in Table 5. The average slope decreased 213 ms/bit and the slope at 0 deg decreased 409 ms/bit when torso support was provided.

DISCUSSION

Although computer input pointing devices (joysticks, light pens, mice, tablets, touchpads, touchscreens, trackballs, etc.) and graphics-based operating systems using iconic images can make computers easier to learn and more efficient for fully able persons, these same advancements can hamper computer accessibility for individuals with movement impairments such as motor coor-

TABLE 4

Summary of MT Regression Models for Movement Time against Fitts' Index of Difficulty (10 Subjects)

Pointing Device	Direction (deg)	Slope (ms/bit)	Intercept (ms)	R^2
Mouse	0	139	−60	0.987
	45	149	−61	0.986
	90	140	−45	0.970
	135	138	−51	0.996
	180	137	−31	0.972
	225	169	−109	0.970
	270	153	−49	0.968
	315	151	−76	0.995
Head pointer	0	268	−168	0.943
	45	240	−98	0.932
	90	203	−51	0.966
	135	244	−103	0.944
	180	236	−91	0.956
	225	247	−101	0.936
	270	216	−40	0.965
	315	262	−117	0.949

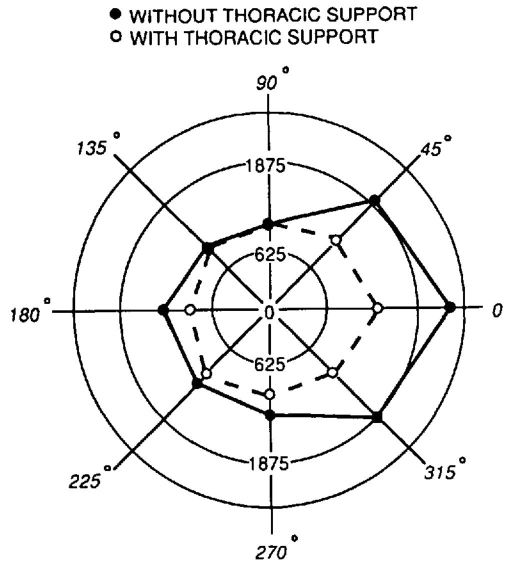

Figure 7. *Average movement time (ms) for cerebral palsy Subject CP1 both with and without postural support, plotted in polar coordinates against direction.*

dination disorders, paralysis, or spasticity. Because these devices require a certain degree of motor control, upper extremity weakness and reduced manual dexterity can diminish a disabled person's capability for using these interfaces and associated software. Computer input devices previously available for motor-impaired computer users rely primarily on keyboard input strategies (Lee and Vanderheiden, 1987) or are so slow that their users are unable to meaningfully participate or compete in regular education and employment settings. Alternative mouse devices, such as head-controlled pointers and locators, are now becoming commercially available and are intended to help mildly to moderately impaired individuals, especially those with cerebral palsy or upper-spinal injuries (Berliss, Borden, and Vanderheiden, 1989).

Before an alternative input device for a person with a motor impairment can be selected and evaluated by a therapist working with such an individual, it is necessary to have an objective measure of performance. Each disability is different. To determine which strategy of a number of potential interventions is most appropriate for a specific individual with special capabilities, it is necessary to have a quantitative metric for comparing performance using these devices. Furthermore, determining the optimum settings for a particular individual requires an objective measure that is reliable and should also have predictive properties.

The results of this study indicate that a discrete movement target acquisition task based on Fitts' law can be useful for evaluating and comparing alternative computer input pointing devices for subjects having no movement disabilities. The disabled subject results demonstrated that this task can also be performed by individuals with severe movement disabilities and that the method was sensitive enough for measuring subtle performance differences that could not be easily discerned visually.

Based on the learning curves obtained for subjects with no movement disabilities, 15 training sets (720 trials) were adequate for attaining stable performance using both the mouse and the head-controlled pointer. Although the rate of learning was slightly higher for the head-controlled pointer than for the mouse, initial average MT for the head-controlled pointer was 524 ms greater than for the mouse, and comparable performance was not achieved in 30 sets of trials (see Figure 2). For both devices, average MT had improved less than 1% between two consecutive trials before data were collected for analysis. Card et al. (1978) found that performance using a mouse and a joystick stabilized within 60 blocks of 20 consecutive trials per block (1200 trials). Epps (1986) found no significant improvement in performance after only 2 blocks of 40 trials (80 trials).

Learning was more rapid for Subject CP1

TABLE 5

Summary of MT Regression Models for Movement Time against Fitts' Index of Difficulty for Cerebral Palsy Subject CP1

Postural Support	*Direction (deg)*	*Slope (ms/bit)*	*Intercept (ms)*	R^2
No torso support	0	923	−1089	0.896
	45	763	−861	0.821
	90	369	−202	0.932
	135	369	−181	0.908
	180	541	−539	0.870
	225	532	−560	0.941
	270	506	−461	0.928
	315	672	−465	0.812
Torso support	0	514	−441	0.977
	45	356	−64	0.956
	90	378	−280	0.928
	135	336	−142	0.947
	180	309	−111	0.917
	225	366	−187	0.878
	270	386	−350	0.917
	315	327	−57	0.978

than for the subjects having no movement impairments, presumably because of previous experience using a mouth-stick pointer for keyboard access. The learning rate for Subject CP2, who had no previous experience with a mouth-stick, was similar to the learning rate measured for the subjects with no movement disabilities. Although learning to use the head-controlled pointer was more rapid for Subject CP1, performance among trials was more variable. Initial average MT for Subject CP1 was as high as 3936 ms, and in 40 sets of trials average MT was reduced to 1612 ms and never reached the performance of the nonimpaired subjects (788 ms). On some individual trials, however, MT was actually less for Subject CP1 than on certain individual trials for subjects without movement impairments. Average MT for Subject CP2 was 3487 ms, which was greater than MT for both the nonimpaired subjects and Subject CP1.

For subjects having no movement disabilities, performance was always better using the mouse as compared with the head-controlled pointer. Average MT was 63% greater for the head-controlled pointer than for the mouse. The differences in PD and RMS between the mouse and head-controlled pointer, however, were relatively small in magnitude and considered insignificant. When Card et al. (1978) compared a mouse with a number of other input pointing devices, performance using the mouse was also superior: the mouse exceeded the joystick, text keys, and step keys with respect to faster movement time and had the lowest error rate. The disabled subject was unable to use the mouse, so no comparison between the head-controlled pointer and the mouse was possible. The average MT measured for disabled Subject CP1 clearly extended beyond the range for nonimpaired subjects (see Figures 3 and 7).

The effect of direction on average MT for the mouse was relatively small in magnitude (see Figure 3), having the greatest difference—64 ms—between 270 and 0 deg (see Table 1). Target approach angle on MT was not significant when a mouse was used for rectangular targets in the Card et al. (1978) study, though it took subjects slightly longer to position the joystick when the target was approached diagonally. The head-controlled pointer average MT in this study was as much as 151 ms less at the 90-deg direction than at 315 deg, and MT was significantly less at 90 deg than at all other movement directions (see Table 1). Furthermore, average MT for the head-controlled pointer at 270 deg was 95 ms less than average MT at 315 deg, and also significantly less than MT at 0, 90, 135, and 225 deg (see Table 1). Hence average MT using the head pointer was lowest at directions of 90 and 270 deg (see Figure 3), corresponding to head extension and flexion, respectively.

Average PD versus direction (see Figure 5) was lowest at 90, 180, and 270 deg. Greater PD values tended to correspond to diagonal movements at 45, 135, 225, and 315 deg, whereas the shorter PD values corresponded with horizontal and vertical motion. Significantly reduced PD at 0 deg, however, was not observed (see Figure 5). Similarly, RMS cursor deviation displayed this same type of pattern (see Figure 6), in which RMS was smallest at 0, 90, 180, and 270 deg and greatest at 45, 135, 225, and 315 deg.

These direction differences may have occurred because movement in the diagonal directions included combined movements of lateral head rotation and head flexion/extension, using muscle groups involved in both horizontal and vertical actions. Horizontal motion using the mouse was predominantly forearm motion, whereas vertical motion was predominantly upper-arm movement. Although the direction effect on MT for the mouse was small, direction had a relatively large effect on PD and RMS. Schmidtke and Stier (1961) found that motions involving predominantly the forearm were faster than movements involving predominantly the upper arm.

The results from the current investigation agreed with the findings of Jagacinski and Monk (1985). Their study similarly found that MT using a helmet-mounted sight was greater for diagonal directions than for off-diagonal directions. Two muscle activation models were considered. Under serial activation, a diagonal target was reached using orthogonal pairs of muscle groups for horizontal and vertical movements in succession. The parallel activation model assumed that two muscle groups would be activated simultaneously. Although the outcome of the Jagacinski and Monk study strictly rejected both models, it could not reject a combination of the two. The results obtained in this study indicate greater PD and RMS measurements, in addition to increased MT, for diagonal directions than for off-diagonal directions for head movement. These results indicate that the cursor displacement path was greater for movement in diagonal directions, as measured by increased PD. In addition, increased deviation from the straight-line path was also indicated by increased RMS for diagonal directions. Hence larger MT values obtained for the diagonal directions were associated with greater movement trajectories, which agrees with the theory for a combination of series and parallel muscle activation.

Discrete target acquisition for both the mouse and the head-controlled pointer was aptly described for all subjects using Fitts' law. The plot in Figure 8 compares MT averaged over all directions for subjects with no movement disabilities using both the mouse and head-controlled pointer, and for cerebral palsy Subject CP1 using the head-controlled pointer both with and without lateral torso support. The smallest slope resulted when using the mouse (147 ms/bit) which increased when using the head-controlled pointer (240 ms/bit) for subjects having no movement disabilities. The slope for Subject CP1 was lowest when the torso was supported (369 ms/bit)

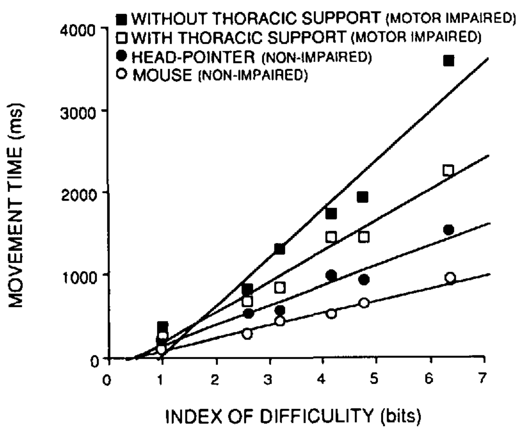

Figure 8. *Average movement time plotted against Fitts' index of difficulty.*

and increased when the torso was unsupported (584 ms/bit). The slope for Subject CP2 was even greater (1145 ms/bit); however, Subject CP2 had less training than did Subject CP1.

Use of a thoracic support device dramatically improved performance for the disabled subject tested. Because this movement-impaired individual tended to lean to the right in the wheelchair, movement toward the right-hand side was constrained when using the head-controlled pointer. Lateral rotation of the torso with respect to the horizontal and, consequently, to the plane of the head-controlled pointer's ultrasonic receiver meant that cursor movement in the 0-deg direction actually involved both rotation and flexion of the head, similar to movement along a diagonal direction for someone with upright posture. After alignment of the torso with the vertical plane, performance improved as a result of the reorientation and increased stability of the body in the wheelchair. This large effect can be observed in Figure 7. Both the average MT and the symmetry of the polar plot of movement time versus direction were improved.

The slope in the Fitts' law relationship tends to increase for increasing degrees of motor complexity. Langolf, Chaffin, and Foulke (1976) found that Fitts' law held for finger, wrist, and arm movements, and that the respective slopes increased for increasing orders of control. The cerebral palsy subjects using the head-controlled pointer without torso support represented the highest order of control complexity in this study because of involvement of the head, neck, and torso in accomplishing the movement task. Use of the torso support reduced the degree of movement complexity and thus resulted in decreasing the Fitts' law slope (see Figure 8).

Whitfield, Ball, and Bird (1983) compared performance between an on-screen and off-screen touch input device in selection and target acquisition tasks. They were unable to describe their data using Fitts' law for a serial random target acquisition task without controlling posture by having subjects return to a home position before each target was presented. For that reason a discrete target acquisition task was adopted for this study.

The Fitts' law slope for the ultrasonic device used in this study was 60 ms less than for a helmet-mounted pointer (Jagacinski and Monk, 1985), though the intercept for the ultrasonic head-pointer was 250 ms greater than the intercept for the helmet-mounted pointer. This resulted in lower MT predictions for the ultrasonic device at larger ID values and in greater MT predictions for the ultrasonic device at smaller ID values. These results may be explained by the increased weight of the helmet-mounted pointer, which was 30 times heavier than the ultrasonic head pointer used in this study and may have increased the Fitts' law slope (Langolf et al., 1976). Because the head-pointing device used in this study weighed only 0.5 N, the results were more representative of actual head movement.

The task used in this study was specifically designed to accommodate individuals with movement disabilities. In pointing tasks it is common to have some type of confirmation (switch closure or long delay) to differentiate pointing behavior to the target from transient target crossings when acquiring surrounding targets. Sequential movements involved in coordinating mouse button-pressing after reaching a target were not studied. Rather than have subjects indicate they had acquired a target by pressing the mouse button, as was done in previous investigations using pointing devices (Card et al., 1978), target acquisition in this study was accomplished by maintaining the cursor inside the target area for 62.5 ms. This paradigm provided a task that eliminated potential error introduced from movement sequencing effects by providing a single, discrete movement to a target as opposed to the more complex motor task of sequentially acquiring a target and then pressing the button. This was particularly necessary for testing subjects with movement disabilities that might severely limit coordinating a response button press following a discrete movement. These type activities will be addressed in future investigations.

CONCLUSIONS

Average movement time for 10 subjects having no movement disabilities was 63% greater when using a head-controlled pointer than when using a conventional mouse. Although the effect of direction was relatively small for the mouse, performance using the head-controlled pointer was affected by direction. Movement time, path distance, and root mean square displacement increased when movement was performed in diagonal directions corresponding to motion involving head rotation combined with head extension/flexion. The direction effect was asymmetric for one disabled subject, apparently caused by a tendency to bend the torso to the right.

Fitts' law aptly described movement time behavior observed for all subjects without movement impairments and for two subjects with cerebral palsy. Furthermore, the slope of the Fitts' law relationship was lower for the mouse than for the head-controlled pointer. The slope was reduced for a cerebral palsy subject after lateral torso support was provided. This demonstrated that the task was useful as an evaluative instrument for the selection and comparison of alternative pointing devices for movement-impaired individuals, and that it also shows promise for evaluating modifications in the workplace for individuals with movement disabilities using head-controlled input devices. This study also provided stable baseline performance characteristics for use of these two input devices by users without movement disabilities.

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