A Comparison of Area Pointing and Goal Crossing for People with and without Motor Impairments

Jacob O. Wobbrock
The Information School
University of Washington
Mary Gates Hall, Box 352840
Seattle, WA 98195
wobbrock@u.washington.edu

Krzysztof Z. Gajos
Department of Computer Science & Engineering
University of Washington
The Paul G. Allen Center, Box 352350
Seattle, WA 98195
kgajos@cs.washington.edu

ABSTRACT

Prior work has highlighted the challenges faced by people with motor impairments when trying to acquire on-screen targets using a mouse or trackball. Two reasons for this are the difficulty of positioning the mouse cursor within a confined area, and the challenge of accurately executing a click. We hypothesize that both of these difficulties with area pointing may be alleviated in a different target acquisition paradigm called "goal crossing." In goal crossing, users do not acquire a confined area, but instead pass over a target line. Although goal crossing has been studied for able-bodied users, its suitability for people with motor impairments is unknown. We present a study of 16 people, 8 of whom had motor impairments, using mice and trackballs to do area pointing and goal crossing. Our results indicate that Fitts' law models both techniques for both user groups. Furthermore, although throughput for able-bodied users was higher for area pointing than for goal crossing (4.72 *vs.* 3.61 bits/s), the opposite was true for users with motor impairments (2.34 *vs.* 2.88 bits/s), suggesting that goal crossing may be viable for them. However, error rates were higher for goal crossing than for area pointing under a strict definition of crossing errors (6.23% *vs.* 1.94%). Subjective results indicate a preference for goal crossing among motor-impaired users. This work provides the empirical foundation from which to pursue the design of crossing-based interfaces as accessible alternatives to pointing-based interfaces.

ACM Categories & Subject Descriptors: H.5.2. [**Information interfaces and presentation**]: User interfaces – *input devices and strategies*. K.4.2. [**Computers and society**]: Social issues – *assistive technologies for persons with disabilities*.

General Terms: Design, Experimentation, Human Factors.

Keywords: Target acquisition, area pointing, goal crossing, Fitts' law, Steering law, throughput, mouse, trackball.

1. INTRODUCTION

Graphical user interfaces are often difficult to use for people with motor impairments. One cause of this difficulty is the challenge of acquiring on-screen targets with the mouse cursor. On-screen targets, such as buttons, menus, scrollbars, and text fields,

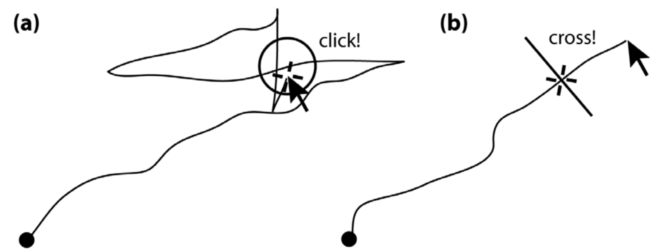

Figure 1. (a) Users with motor impairments often have difficulty acquiring area targets, as shown in this figure adapted from a study by Hwang et al. [11]. **(b)** In goal crossing, the need for acquiring a confined area and clicking is removed; goals must only be passed.

consume a finite amount of screen area and require the user to move inside that area before these widgets can be activated. Under most circumstances, a subsequent click is necessary to actually acquire the targets. This target acquisition process must occur countless times in the course of regular computer use. We call this familiar scheme "area pointing." (It may similarly be called "mouse pointing" or "point-and-click"; we prefer "area pointing" for its symmetry to "goal crossing.")

Prior research has clearly demonstrated the difficulty people with motor impairments may have with area pointing. Both parts of the process—moving to within a target and then activating it—can be troublesome. Hwang et al. [11] showed that motor-impaired users often pass over or slip out of their target as they try to position their cursor inside it (Figure 1a). Trewin and Pain [26] reported that 15 of 20 subjects with motor impairments had difficulty pointing and clicking with the mouse. In fact, they showed that 28.1% of mouse clicks contained movement *during* the click itself. (Trewin et al. considered this enough of a problem to address it later in their *Steady Clicks* system [27].) Trewin and Pain hastened to point out that although many of their subjects had tried mousing alternatives, subjects often preferred standard mice or trackballs to specialized devices because of these devices' familiarity, availability, and ubiquity. This is consistent with other findings showing high abandonment and low adoption rates of specialized devices, even among those who clearly need them [15,22,23]. Thus, it is crucial to improve the effectiveness of *ordinary* input devices for people with motor impairments by fundamentally changing how these devices can be used.

In that spirit, this paper presents a study of "goal crossing" as an alternative to area pointing for performing target acquisition. In goal crossing, a user does not have to move within a confined area and execute a click. Instead, the user simply moves over a goal line (Figure 1b). As a result, goal crossing may be a promising fundamental alternative to area pointing for people with motor impairments.

This paper investigates this hypothesis in a study of goal crossing and area pointing with mice and trackballs involving 16 people, 8 of whom have motor impairments. Our results confirm the promise of goal crossing for people with disabilities, showing that their throughput was better for crossing than for pointing despite the opposite being true for able-bodied users. Besides this discovery, our study also shows that Fitts' law accurately models pointing and crossing performance by people with motor impairments. Furthermore, subjective results indicate a preference for goal crossing over area pointing by people with motor impairments. These findings provide an empirical foundation upon which to base the pursuit of accessible crossing-based user interface designs. Although many practical design challenges await such efforts, this study shows that pursuing them may be worthwhile.

2. RELATED WORK

To date, goal crossing has been modeled and studied only for able-bodied users. In developing their Steering law, Accot and Zhai [1] first proposed goal crossing and showed that it followed Fitts' law [5], given here as MacKenzie's popular Shannon formulation [19]:

$$MT = a + b \log_2\left(\frac{A}{W} + 1\right) \quad (1)$$

Fitts' law predicts the movement time *MT* required to acquire a target of size *W* at a distance *A* in a rapid aimed movement (Figure 2a). Note that the size constraint *W* in a crossing task is orthogonal, rather than collinear, to the movement axis (Figure 2b). In Equation 1, *a* and *b* are regression coefficients determined empirically. The $\log_2$ term is called the index of difficulty (*ID*), measured in *bits*. Higher indices mean more difficult tasks. The ratio 1/*b* is the index of performance (*IP*), or *throughput*, and is measured in *bits/second*. This quantity provides a way to compare crossing and pointing results. It also supports comparisons with prior experiments, since throughput is task-independent.

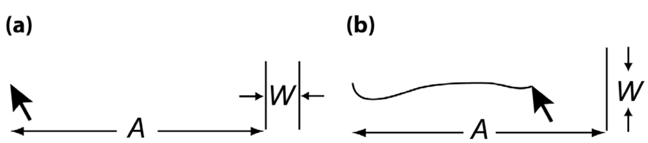

Figure 2. (a) In a classic Fitts' law task, the constraint imposed by *W* is collinear to the movement axis. **(b)** In goal crossing, the constraint is orthogonal to the movement axis.

Rapid aimed movements of the kind assumed by Fitts' law are called "closed loop" because the subject can adjust their unfolding motion by performing corrections along the way. This contrasts with an "open loop" movement akin to "throwing a dart," in which a subject's initial ballistic action determines the entire path of motion. Prior research differs in the extent to which it claims that movements by people with motor impairments can be modeled by Fitts' law, since such people's ability to make closed loop corrections during movement may be compromised. LoPresti et al. [17] showed that Fitts' law holds for neck movements by people with motor impairments, although explicit formulations using Equation 1 were not reported. Gump et al. [9] argued that Fitts' law did *not* hold for people with Cerebral Palsy, although they noted that their data contained problematically high error rates, possibly from oculomotor problems. More recently, Smits-Engelsman et al. [25] showed that children with Cerebral Palsy do, in fact, adhere to Fitts' law. Our current study contributes to this discussion by offering further evidence in favor of the suitability of Fitts' law to model motor-impaired target acquisition for both area pointing and goal crossing.

Accot and Zhai [2] also showed that Fitts' law holds for multiple types of stylus crossing. Their results indicate that crossing was better than pointing for *ID*s less than about 4 bits, but worse than pointing for *ID*s greater than this. Thus, for large or proximate targets, crossing can be an advantage, even for able-bodied users. However, despite this prior work on goal crossing, the technique has never been explored as an alternative to area pointing for people with motor impairments.

Goal crossing has been used in a few instances in actual applications. *CrossY* [3] is a pen-based drawing application intended for able-bodied users that employs crossing as its fundamental target acquisition scheme. *Trackball EdgeWrite* [29,30] is a desktop text entry method for use by people with motor impairments that uses goal crossing to interpret trackball movements and turn them into characters or words.

Other techniques have sought to improve pointing performance by innovatively increasing target size, decreasing target distance, or both. Examples are *area cursors* and *sticky icons* [31], which respectively use an enlarged cursor and gain-diminished targets to improve mousing performance in older adults. An extension of the area cursor idea is the *Bubble Cursor* [8], which dynamically resizes itself to remain as large as possible based on the locations of nearby targets. An extension to the sticky icon is *semantic pointing* [4], which adjusts target sizes in motor space without adjusting them visually to make them easier to acquire. A similar idea was that of *haptic targets*, which Hwang et al. [10] investigated for people with motor impairments. They found that haptic feedback in the form of gravity wells was most beneficial for those subjects with the most severe motor limitations, even in the presence of distractor targets.

Although certain design considerations have to be addressed in any mouse-based (i.e., persistent cursor) goal crossing interface, applications like CrossY [3] and Trackball EdgeWrite [29,30] indicate the utility of crossing in real applications. Crossing also exists on the web (e.g., DontClick.It [6]). An obvious challenge in mouse-based crossing, which does not appear in pen-based crossing, is "the occlusion problem," in which one crossing goal obscures another. We offer potential solutions to this problem in the future work section of this paper. However, before designers expend considerable effort to solve the practical challenges raised by mouse-based goal crossing, it is essential that we first understand the human performance characteristics of goal crossing for people with motor impairments. We provide such an understanding through an experiment, described below.

3. EXPERIMENT

In order to compare goal crossing to area pointing for people with motor impairments, we conducted a formal experiment involving 16 subjects, 8 of whom had motor impairments. Subjects used an optical mouse, an optical trackball, or both according to their preferences. Speeds, error rates, and various path analysis measures [20] were computed. Also, Fitts' law [5] was used to model performance and to measure throughput, allowing us to equitably compare goal crossing to area pointing.

3.1 Method

3.1.1 Subjects

Sixteen subjects volunteered for the study. Eight were able-bodied (AB) and 8 were motor-impaired (MI). Half of the AB group were female. Average age was 30.3 (*SD*=8.2). In the MI group, 3/8 were female. Average age was 42.8 (22.0). Of these 8 MI subjects, 4 used only mice, 2 used only trackballs (Figure 3), and 2 used both. Table 1 shows detailed information for the MI group.

Subject	*Sex*	*Age*	*Wheelchair*	*Device*	*Health Condition*
MI1	m	50	no	mouse	Periph. Neuropathy
MI2	f	55	no	mouse	Parkinson's
MI3	f	21	yes	both	Cerebral Palsy
MI4	m	19	yes	trackball	Spinal Cord Injury
MI5	f	41	no	mouse	Spine Degeneration
MI6	m	23	yes	both	Cerebral Palsy
MI7	m	84	no	mouse	Periph. Neuropathy
MI8	m	49	yes	trackball	Spinal Cord Injury

Table 1. Detailed information on subjects with motor impairments.

Figure 3. MI4 used a trackball with the backs of his fingers.

3.1.2 Apparatus

Our experiment was conducted on a 19" LCD flat screen display set to 1280×1024 resolution. The mouse was a *Logitech Click!* optical mouse. The trackball was a *Kensington Expert Mouse Pro*. We had subjects use these devices instead of their personal devices to ensure consistency in deriving our Fitts' law models. The mouse speed was set to 6/10 on the Windows control panel.

The software test bed was an application we wrote in C# which ran full-screen (Figure 4). The software presented crossing and pointing trials, and wrote XML log files containing all trial data, including full cursor movement paths with 10^{-4}-second time-stamps. The system timer resolution was guaranteed to be no worse than 10 ms. A separate Java application parsed these logs and computed a variety of measures for each trial, which were then analyzed using the JMP 6.0 statistics package.

3.1.3 Procedure

All able-bodied subjects performed crossing and pointing using the mouse and trackball. The order of devices was randomized, as was the order of techniques within each device. This was also true for MI3 and MI6, who used both mice and trackballs. For the other motor-impaired subjects, the order of techniques was randomized within their single device. A main effect of *Method Order* on movement time was not significant ($F_{3,33}$=0.96, n.s.), indicating adequate counterbalancing of devices and techniques.

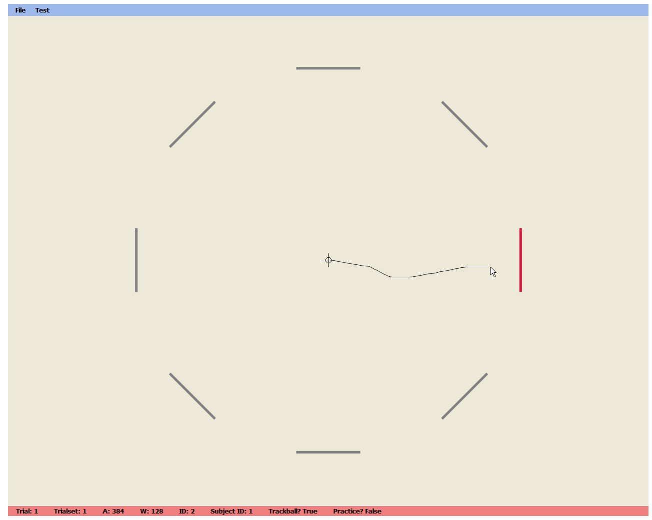

Figure 4. The 1280×1024 test application showing 8 crossing targets. The target right of center is active (red). Others are disabled (gray). The mouse has moved from the center towards the target as shown by the illustrated path. No path was drawn during actual trials. These targets are *A*=384, *W*=128 pixels. For pointing trials, the goals would be replaced by circles of diameter *W*=128.

For a given combination of device and technique, the test software randomly presented 5 practice trial-sets followed by 15 testing trial-sets covering all amplitude (*A*) × width (*W*) target combinations in random order. One trial-set consisted of 8 targets arranged in 45° increments around a center position (Figure 4), similar to the setup used by Hwang et al. [11]. A single trial consisted of the acquisition of one target. A trial did not end until the mouse stopped moving after the target was acquired. At that time, a rapid "3-2-1" countdown flashed in the center of the screen and the mouse was automatically returned to the center in preparation for the next trial. We chose to have subjects successfully acquire each target rather than end a trial after the first hit or miss in order to log multiple misses and the total time to acquisition. Once all 8 targets had been acquired, a new trial-set of 8 targets was presented. After all 15 testing trial-sets had been completed for each relevant device and technique, the experiment was over. At the end, a short questionnaire was administered. The test took 25-45 minutes.

For area pointing trials, a "miss" was defined as a click that occurred outside the active circular target (Figure 5a). For goal crossing trials, a miss was when the mouse passed over the *infinite* goal line beyond either end of the finite goal segment (Figure 5b). When a miss occurred in either technique, a "bonk" sound was played. After missing, subjects still worked to acquire the target as in [2]. Goal lines had to be crossed from within the circle outward; crossing them from outside-in was permitted but had no effect.

In keeping with Fitts' law, subjects were instructed to strive for about 1 miss in every 3 trial-sets (24 trials), which would result in an approximate 4% error rate. It should be noted that in a real user

Figure 5. (a) A miss in area pointing. **(b)** A miss in goal crossing.

interface, clicking outside an area target or passing beyond either end of a goal line is not necessarily damaging. However, in using a strict definition of misses, our error results can be viewed as an upper bound or worst case.

3.1.4 Design and Analysis

The experiment was a mixed between- and within-subjects factorial design with the following factors and levels:

- Impairment {able-bodied, motor-impaired}
- Device {mouse, trackball}
- Technique {pointing, crossing}
- Index of Difficulty (*ID*) {1.00 to 4.64 bits}
    - Amplitude (*A*) {128, 256, 384 pixels}
    - Width (*W*) {16, 32, 64, 96, 128 pixels}
- Trial-set {1..15}
- Trial {1..8}
- Subject {1..16}

Impairment is a between-subjects factor, while *Device*, *Technique*, and *ID* are within-subjects factors. Note that we do not treat *Amplitude* (*A*) and *Width* (*W*) as separate factors, since these cannot be regarded as independent. Instead, *ID* is used as a continuous factor ranging from 1.00 to 4.64 bits.

Subjects completed a total of 780 trial-sets for 6240 total trials. Of these, able-bodied subjects completed 3840 trials, while motor-impaired subjects completed 2400 trials. Our dependent measures were subjects' averages over each level of *ID* within each combination of *Device* and *Technique*, resulting in 572 individual measures over which our statistical analyses were performed.

Our data were analyzed using a mixed-effects model analysis of variance with repeated measures [16,24]. *Impairment*, *Device*, *Technique*, and *ID* were modeled as fixed effects, and *Subject* was modeled as a random effect [7,16,24]. Mixed-effects models properly handle the imbalance in our data due to subjects in the MI group not all using both devices. Mixed-effects models also account for correlated measurements within subjects [24]. However, they retain large denominator degrees of freedom (DFs), which can be fractional for unbalanced data.[1] These larger DFs do not make detection of significance easier due to the use of wider confidence intervals [7]. Our model contained interactions up to the third degree. The model fit our movement time data well with R^2=.904 (n=572). In our results, we omit reporting the effects of *ID* since such results are expected (i.e., harder trials were indeed significantly slower and more error prone than easier trials).

[1] For a short readable explanation of fractional degrees of freedom, see http://www.mrc-cbu.cam.ac.uk/Statistics/faq/satterthwaite.shtml.

3.2 Results

3.2.1 Movement Times and Error Rates

Movement time (MT) is the time it takes to acquire a target. As is common [2], we exclude trials with misses (we revisit this choice below). There were 95/3840 such trials for AB subjects (2.47%), and 160/2400 such trials for MI subjects (6.67%). In all, 255/6240 trials were excluded (4.09%), which is close to the 4% error rate prescribed by Fitts' law [19]. Table 2 shows average MT.

Device, Technique	*AB Movement Time*		*MI Movement Time*	
Mouse Pointing (MP)	716.14	(232.71)	1367.23	(541.13)
Mouse Crossing (MC)	486.24	(281.10)	813.35	(370.67)
Trackball Pointing (TP)	1007.85	(332.16)	1967.52	(828.27)
Trackball Crossing (TC)	666.92	(440.14)	1162.54	(705.04)

Table 2. Movement times and standard deviations (ms).

Impairment ($F_{1,13.7}$=28.34, p<.001), *Device* ($F_{1,554.8}$=148.00, p<.0001), and *Technique* ($F_{1,542.7}$=834.23, p<.0001) all had a significant effect on MT. An *Impairment*Technique* interaction was also significant ($F_{1,542.7}$=139.13, p<.0001), indicating that *Technique* affected each subject group differently (Figure 6a). Crossing reduced MT more for MI subjects than it did for AB subjects. Conversely, no significant *Impairment*Device* interaction was found ($F_{1,554.8}$=2.90, n.s.), indicating that the trackball's slowdown relative to the mouse was similar for all subjects (Figure 6b).

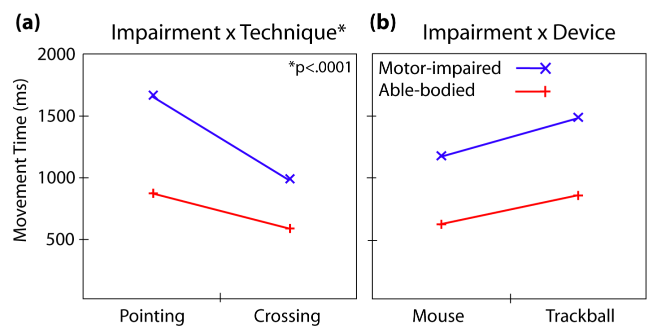

Figure 6. (a) Crossing improves acquisition times. **(b)** The mouse is faster than the trackball.

There was also a significant *Device*Technique* interaction ($F_{1,542.7}$=29.38, p<.0001) because crossing was faster than pointing more for the trackball than for the mouse. A significant *Impairment*Device*Technique* interaction ($F_{1,542.7}$=4.40, p<.05) indicates that this was especially true for MI subjects, who benefited more from crossing with a trackball than did AB subjects.

Error rates (%) were calculated as the percentage of trials with misses (Figure 5). Table 3 shows average error rates.

Device, Technique	*AB Error Rate*		*MI Error Rate*	
Mouse Pointing (MP)	1.52%	(3.65)	3.00%	(6.86)
Mouse Crossing (MC)	3.43	(5.67)	8.33	(10.59)
Trackball Pointing (TP)	0.83	(2.83)	3.41	(6.93)
Trackball Crossing (TC)	4.14	(6.30)	12.83	(16.84)

Table 3. Error rates (%) and standard deviations for both groups.

As is often the case with error data, ours is highly skewed towards 0%, even under customary transformations, since most trials contained no errors for both subject groups. This prohibited the use of analyses of variance due to violations of normality. Therefore, we used nominal logistic regression to compare the proportion of results in which an error occurred to the proportion of those in which no errors occurred. The overall model was significant ($\chi^2_{(28,N=572)}$=168.27, p<.0001), justifying an examination of effects. However, among our factors of interest, only *Technique* was significant ($\chi^2_{(1,N=572)}$=53.17, p<.0001), indicating that pointing was more accurate than crossing (1.94% *vs*. 6.23%) under our strict definition of crossing errors (Figure 5b). With respect to *Impairment*, although able-bodied users were more accurate on average, this factor was not significant due to high variance. *Impairment*Technique* and *Impairment*Device* were both only marginal ($\chi^2_{(1,N=572)}$=2.40, p=.12) (Figure 7).

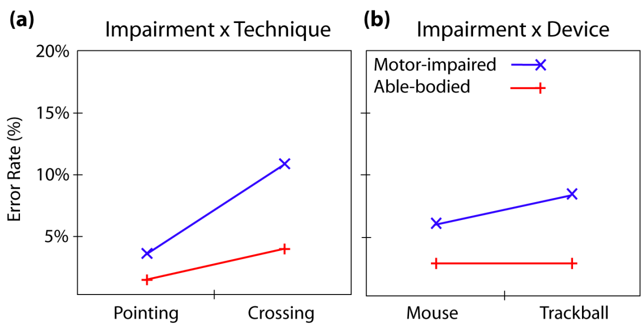

Figure 7. (a) Average pointing and crossing error rates for both subject groups. **(b)** Average mouse and trackball error rates for both subject groups.

We have thus far separately examined MT (excluding errors) and errors, finding crossing to be significantly faster than pointing, especially for the MI group, but more error prone for both groups. We now examine movement time with errors *included* (Table 4). This measure indicates the total time to acquire targets, even in the presence of misses. We call this MT with errors (MT_ε).

Device, Technique	*AB MT_ε (w/errors)*		*MI MT_ε (w/errors)*	
Mouse Pointing (MP)	725.54	(241.55)	1416.71	(614.30)
Mouse Crossing (MC)	508.77	(291.67)	903.42	(451.48)
Trackball Pointing (TP)	1014.19	(335.93)	1979.88	(827.86)
Trackball Crossing (TC)	696.53	(454.31)	1272.13	(726.57)

Table 4. MT with errors (MT_ε) and standard deviations (ms).

As there had been for MT, there were significant effects of *Impairment* ($F_{1,13.7}$=28.17, p<.001), *Device* ($F_{1,555.9}$=133.50, p<.0001), *Technique* ($F_{1,542.7}$=655.71, p<.0001), *Impairment*Technique* ($F_{1,542.7}$=100.31, p<.0001), and *Device*Technique* ($F_{1,542.7}$=18.56, p<.0001) on MT_ε. Again, there was no effect of *Impairment*Device* ($F_{1,555.9}$=1.64, n.s.). However, unlike for MT, there was no significant effect of *Impairment*Device*Technique* on MT_ε ($F_{1,542.7}$=1.86, n.s.), indicating that although crossing was faster than pointing for the trackball more than for the mouse, this was the case for both subject groups about evenly.

The important point from these analyses of MT_ε is that crossing errors were not so time consuming as to negate the overall speed advantages of crossing over pointing.

Although MT, errors, and MT_ε give us some indication of how goal crossing compares to area pointing, we can take a step further to obtain a task-independent measure using Fitts' law.

3.2.2 Fitts' Law and Throughput

Fitts' law (Equation 1) allows us to model MT as a function of task difficulty (*ID*). This allows us to derive a task-independent index of performance (*IP*). As noted in related work, there has been some disagreement as to whether people with motor impairments adhere to Fitts' law. Our data show that Fitts' law applies to area pointing and goal crossing for all our subjects.

Current methods for using Fitts' law enforce a *post hoc* error rate of 4% by using effective target width (W_e) [19,21]. However, such models depend on a large number of trials on each target to approximate a normal distribution. Because motor-impaired subjects cannot endure long experiments with myriad trials, our data were not sufficiently numerous to delineate such distributions, and we found the W_e models to be very poor. Therefore, we utilized the traditional method of excluding error trials [21] and used the nominal width (*W*) to compute *ID*. We found these traditional models to fit our data very well. Using traditional models also supports comparisons to prior goal crossing studies in which nominal models were also used [1,2]. Our Fitts' law models are shown in Table 5.

Able-bodied Subjects (AB)				
Device, Technique	*a* (ms)	*b* (ms/bit)	R^2	*IP* (bits/s)
Mouse Pointing (MP)	270.05	172.85	.993	5.79
Mouse Crossing (MC)	-105.47	229.12	.996	4.36
Trackball Pointing (TP)	362.53	249.83	.982	4.00
Trackball Crossing (TC)	-178.23	327.18	.995	3.06
Motor-impaired Subjects (MI)				
Device, Technique	*a* (ms)	*b* (ms/bit)	R^2	*IP* (bits/s)
Mouse Pointing (MP)	520.71	326.16	.969	3.07
Mouse Crossing (MC)	102.85	274.69	.987	3.64
Trackball Pointing (TP)	494.28	567.74	.961	1.76
Trackball Crossing (TC)	-91.22	476.83	.913	2.10

Table 5. Fitts' law models for each subject group of the form MT=a+b×ID. IP is throughput. For each model, n=11 and p<.0001.

These models show good fits as judged by R^2 values for pointing and crossing with both able-bodied and motor-impaired subjects. A crucial observation is that AB subjects had lower throughput (*IP*) for crossing than for pointing, but MI subjects had *higher* throughput for crossing than for pointing. See Figure 8 for depictions of Fitts' law MT models and error rates by *ID*.

3.2.3 Path Analysis Measures

Thus far we have considered aggregate measures over the path of movement. However, we can gain insight into what happens *during* movement by using path analyses developed by MacKenzie et al. [20] and extended by Keates et al. [13] (Table 6). Although space precludes a full treatment of submovement analyses [11,14,28], we briefly discuss these path analyses to highlight differences between goal crossing and area pointing. We leave a thorough submovement analysis to future work.

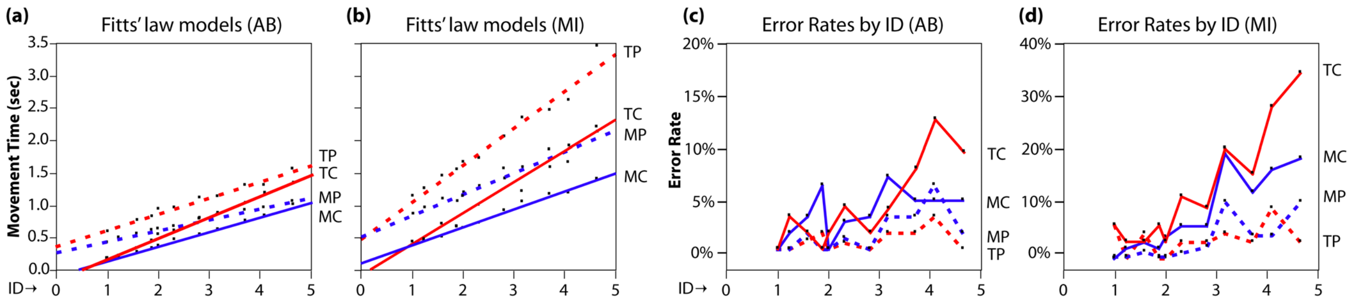

Figure 8. Fitts' law MT (sec) by ID for **(a)** the AB group and **(b)** the MI group using the results in Table 5. (The y-axes for these graphs are the same.) Error rates generally increase across ID for **(c)** the AB group and **(d)** the MI group. (Note the different y-axes for (c) and (d).)

	Able-bodied Subjects (AB)				Motor-impaired Subjects (MI)			
	MP	MC	TP	TC	MP	MC	TP	TC
Target re-entry (TRE)	0.08 (.11)	n/a	0.12 (.15)	n/a	0.29 (.40)	n/a	0.39 (.37)	n/a
Task axis crossing (TAC)	0.84 (.47)	1.24 (.60)	1.06 (.54)	1.56 (.76)	1.42 (.94)	1.57 (.80)	1.72 (.98)	2.23 (1.10)
Movement dir. change (MDC)	3.81 (1.31)	6.09 (3.04)	4.39 (1.87)	6.91 (3.69)	10.98 (6.58)	14.41 (7.81)	11.24 (5.24)	15.81 (6.66)
Orthogonal dir. change (ODC)	1.00 (.68)	0.49 (.41)	1.07 (.80)	0.38 (.39)	3.55 (2.58)	1.98 (1.52)	3.46 (1.84)	2.54 (1.97)
Movement variability (MV)	11.78 (8.11)	8.07 (3.87)	10.16 (5.92)	7.20 (2.37)	15.61 (9.43)	12.86 (6.05)	14.93 (5.47)	13.67 (5.27)
Movement error (ME)	15.68 (7.25)	11.02 (4.24)	15.16 (7.20)	9.83 (3.07)	18.02 (7.63)	15.59 (6.93)	18.49 (5.84)	15.80 (5.20)
Movement offset (MO)	-1.05 (6.85)	-0.29 (5.22)	0.30 (9.07)	-0.13 (4.29)	3.05 (8.98)	2.02 (6.17)	2.53 (7.46)	-1.13 (7.89)
Path distance (PD)	292 (126)	283 (104)	284 (117)	282 (104)	344 (150)	316 (120)	375 (139)	344 (137)

Table 6. Path analysis measures [20] and standard deviations for each subject group with mouse pointing (MP), mouse crossing (MC), trackball pointing (TP), and trackball crossing (TC). Units: TRE, TAC, MDC, and ODC (count/trial); MV, ME, MO, and PD (pixels/trial).

As one would expect, nearly all measures indicate a significant difference due to *Impairment* ($p<.02$) in favor of the AB group. The only exception to this is *MO*, which was not significant.

Our main interest is in how crossing compares to pointing. *TAC* measures how often the task axis was crossed. *TAC* was significantly higher for crossing than for pointing ($F_{1,542.8}$=87.73, $p<.0001$). This was also the case for *MDC*, which measures directional changes parallel to the task axis ($F_{1,542.6}$=240.93, $p<.0001$). However, an interesting finding is that *ODC*, which measures directional changes perpendicular to the task axis, was significantly *lower* for crossing ($F_{1,542.9}$=138.27, $p<.0001$). These findings held for both subject groups.

Pixel-level measurements indicate an advantage for crossing over pointing for both subject groups. *MV* is a measure of how wiggly a movement is. It was significantly less for crossing ($F_{1,542.1}$=35.84, $p<.0001$). *ME* is a measure of distance away from the task axis. It was also significantly less for crossing ($F_{1,541.9}$=58.21, $p<.0001$). *MO* is a signed directional measure of deviation from the task axis. Yet again, the result was less for crossing ($F_{1,541=14.5}$, $p<.001$). The total path distance (*PD*) was about the same with crossing and pointing for AB subjects, but for MI subjects, *PD* with crossing was significantly less than *PD* with pointing ($F_{1,542.1}$=5.32, $p<.05$).

With the exception of *TAC* and *MDC*, these path accuracy results were in favor of crossing. And yet, crossing was faster overall (Table 4). Since there is no click necessary in crossing, subjects can remit click-time to a more deliberate, steady movement and remain faster overall. It is interesting that with the exception of *PD*, these results applied to both subject groups, suggesting a possible fundamental advantage of crossing.

3.2.4 *Subjective Results*

As a whole, subjects did not indicate a significant preference for area pointing or goal crossing. However, the two groups felt quite differently as indicated by a significant *Impairment***Technique* interaction ($F_{1,31.5}$=6.81, $p<.05$). On a *Dislike* (1)-*Like* (5) scale, the MI group rated crossing and pointing 3.9 and 3.1, respectively; the AB group rated them 3.0 and 3.4. Subjects' perceptions of ease show a similar interaction ($F_{1,30.1}$=4.94, $p<.05$). On a *Difficult* (1)-*Easy* (5) scale, the MI group rated crossing and pointing 4.0 and 3.6, respectively; the AB group rated them 3.3 and 3.9. The same pattern held for perception of speed ($F_{1,26.8}$=4.31, $p<.05$). On a *Slow* (1)-*Fast* (5) scale, the MI group rated crossing and pointing 4.0 and 3.4, respectively; the AB group rated them 3.4 and 3.7. These ratings mirror the direction of throughput results in Table 5. Finally, subjects overall felt that crossing was less accurate than pointing (3.3 *vs.* 4.0, $F_{1,30.4}$=11.74, $p<.01$), which reflects their actual performance. Figure 9 shows some subjective results for the two groups.

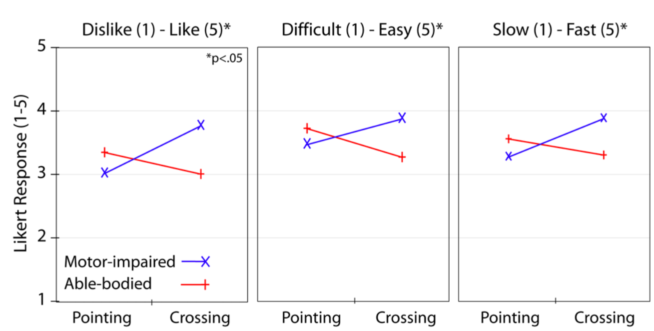

Figure 9. Preference differences between the two subject groups.

4. DISCUSSION

The most interesting finding from our study is that our MI subjects could perform goal crossing, and that they could do so faster than pointing (Table 2). The MI group also preferred goal crossing to area pointing (Figure 9a), and felt it easier to perform (Figure 9b). Further, our MI subjects were well-modeled by Fitts' law, and had higher throughput for crossing than for pointing (Table 5). Our AB subjects, on the other hand, had higher throughput for pointing, and generally preferred it. But they, too, were faster with goal crossing over the range of tested *ID*s. Had higher *ID*s been tested, AB throughput indicates that pointing would have been faster. (We omitted high *ID*s from our study because we did not know how well people in our MI group would be able to do crossing. As it was, the *W*=16 targets were difficult for our MI subjects to acquire, especially at *A*=384.)

Although our MI subjects' throughput was in favor of crossing, this finding is somewhat compromised by the higher error rate for MI crossing than for MI pointing (Table 3). As noted, our data did not permit us to normalize *W* to a 4% error rate as W_e due to high variance and not enough trials per combination of *A*-*W*. (Further analysis shows that over 45% of the MI crossing errors were for *W*=16, suggesting that larger crossing goals should be employed for motor-impaired users.) This normalization obstacle is not surprising, however, in light of the challenges of applying able-bodied models to motor-impaired subjects [12,13]. However, it should be noted that our definitions of pointing and crossing errors are unavoidably like apples and oranges. Unlike studies comparing different input devices on the same pointing tasks [18], we have semantically distinct notions of errors (Figure 5). Therefore, in light of these concerns, it is not unreasonable to use nominal *W*'s in our calculations and to report errors separately, as have prior studies of crossing and pointing [2]. Regardless, the absolute throughputs shown in Table 5 are of secondary interest to the relative performance of crossing and pointing within each subject group. Since all subjects did both crossing and pointing, we can be confident in our within-subject-group comparisons that indicate crossing's promise relative to pointing for those with motor impairments.

Path analysis measures generally favor crossing over pointing for both subject groups. Although *TAC* and *MDC* were higher for crossing, all other measures—*ODC*, *MV*, *ME*, *MO*, and *PD*—were lower for crossing. This is somewhat surprising, since crossing resulted in more misses overall. The reason may be due to differing strategies for the two techniques. We observed that when pointing, subjects "flew out" quickly from the center to their intended target with a large ballistic movement (Figure 10a). Then they corrected their position near the target, often after overshooting. However, with crossing, such a strategy is dangerous, because overshooting wide of the target results in a miss. Thus, subjects moved steadily toward their intended goal line until they felt confident they could move quickly across it (Figure 10b). Often subjects would "flick" the cursor across the goal line once they were sure they could hit it, especially with the trackball. As an initial investigation into goal crossing for motor-impaired users, this paper omits a detailed discussion of submovement analyses. However, such analyses would quantify these insights; they are now justified based on the findings from this study. We discuss this more in future work.

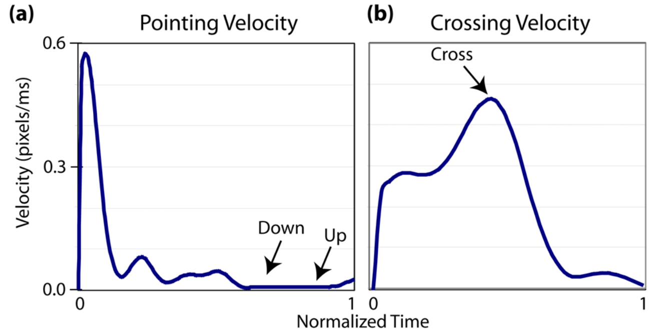

Figure 10. Velocity profiles from MI8 for two successful target acquisitions. These profiles indicate different strategies. **(a)** Pointing starts with an initial ballistic motion followed by corrections. **(b)** Crossing accelerates gradually, peaking at the point of acquisition. Both trials contained no misses or target re-entries and were for *A*=128, *W*=16.

5. FUTURE WORK

As the first to quantify performance in area pointing and goal crossing for motor-impaired users, this study perhaps raises more questions than it answers. Such questions are both fundamental and applied. Fundamental questions include seeking to assess precisely what target distances and sizes are effective for people with motor-impairments, what functional capabilities of motor-impaired users are best suited to goal crossing, and what insights can be gleaned from submovement profiles of velocity, acceleration, and jerk [11,14,28]. Applied questions include how to design accessible goal crossing interfaces, what "goal widgets" can and should be created, and how such widgets should be designed, rendered, and arranged.

An obvious challenge that must be solved in persistent cursor-based crossing interfaces is "the occlusion problem." Here we mean the problem of one goal line obscuring another as the mouse travels over the first to reach the second. Various design choices can be investigated to solve this problem. Three possibilities worth studying are: (1) using an explicit confirmation step, such as a second goal that appears at a 90° angle after a first goal has been crossed, (2) using a settable mode in which goal crossing is active, and (3) using submovement characteristics to intelligently discern whether or not any given crossing event was intended. A worthwhile next step would be to design, build, and evaluate these and other strategies in order to solve the occlusion problem.

6. CONCLUSION

We have presented a quantitative study of area pointing and goal crossing for people with and without motor impairments. Our results show that goal crossing is a feasible alternative to area pointing for people with motor impairments. In our experiment, goal crossing was faster and had higher Fitts' throughput than area pointing for our motor-impaired subjects. These subjects also liked goal crossing more than area pointing, and felt that it was easier to perform. Path analysis measures indicate that goal crossing movement is less wiggly and deviant than movement during area pointing. However, a downside of goal crossing is that it has higher error rates under a strict definition of crossing errors. In reporting these findings, this study has laid the foundation for further investigation into the creation of accessible crossing-based user interfaces.

7. ACKNOWLEDGEMENTS
The authors gratefully acknowledge the thoughts and services of the following people (in alphabetical order): Duen Horng Chau, Dan Comden, Mark Harniss, Curt Johnson, Kurt L. Johnson, Shaun Kane, I. Scott MacKenzie, Robert Milan, Brad A. Myers, Daniel S. Weld, and Shumin Zhai.

8. REFERENCES
[1] Accot, J. and Zhai, S. (1997) Beyond Fitts' law: Models for trajectory-based HCI tasks. *Proc. CHI '97*. New York: ACM Press, pp. 295-302.

[2] Accot, J. and Zhai, S. (2002) More than dotting the i's: Foundations for crossing-based interfaces. *Proc. CHI '02*. New York: ACM Press, pp. 73-80.

[3] Apitz, G. and Guimbretière, F. (2004) CrossY: A crossing-based drawing application. *Proc. UIST '04*. New York: ACM Press, pp. 3-12.

[4] Blanch, R., Guiard, Y. and Beaudouin-Lafon, M. (2004) Semantic pointing: Improving target acquisition with control-display ratio adaptation. *Proc. CHI '04*. New York: ACM Press, pp. 519-526.

[5] Fitts, P.M. (1954) The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology 47* (6), pp. 381-391.

[6] Frank, A. (2005) DontClick.It. *Diploma project in Communication Design*. University of Essen-Duisburg. Essen, Germany. Available at http://www.dontclick.it/. Accessed May 24, 2007.

[7] Frederick, B.N. (1999) Fixed-, random-, and mixed-effects ANOVA models: A user-friendly guide for increasing the generalizability of ANOVA results. In *Advances in Social Science Methodology*, B. Thompson (ed). Stamford, Connecticut: JAI Press, pp. 111-122.

[8] Grossman, T. and Balakrishnan, R. (2005) The Bubble Cursor: Enhancing target acquisition by dynamic resizing of the cursor's activation area. *Proc. CHI '05*. New York: ACM Press, pp. 281-290.

[9] Gump, A., LeGare, M. and Hunt, D.L. (2002) Application of Fitts' law to individuals with Cerebral Palsy. *Perceptual and Motor Skills 94* (3 Pt 1), pp. 883-895.

[10] Hwang, F., Keates, S., Langdon, P. and Clarkson, P.J. (2003) Multiple haptic targets for motion-impaired computer users. *Proc. CHI '03*. New York: ACM Press, pp. 41-48.

[11] Hwang, F., Keates, S., Langdon, P. and Clarkson, P.J. (2004) Mouse movements of motion-impaired users: A submovement analysis. *Proc. ASSETS '04*. New York: ACM Press, pp. 102-109.

[12] Keates, S., Clarkson, P.J. and Robinson, P. (2000) Investigating the applicability of user models for motion-impaired users. *Proc. ASSETS '00*. New York: ACM Press, pp. 129-136.

[13] Keates, S., Hwang, F., Langdon, P., Clarkson, P.J. and Robinson, P. (2002) Cursor measures for motion-impaired computer users. *Proc. ASSETS '02*. New York: ACM Press, pp. 135-142.

[14] Ketcham, C.J., Seidler, R.D., Van Gemmert, A.W.A. and Stelmach, G.E. (2002) Age-related kinematic differences as influenced by task difficulty, target size, and movement amplitude. *Journal of Gerontology: Psychological Sciences 57B* (1), pp. 54-64.

[15] Koester, H.H. (2003) Abandonment of speech recognition by new users. *Proc. RESNA '03*. Arlington, Virginia: RESNA Press.

[16] Littell, R.C., Milliken, G.A., Stroup, W.W. and Wolfinger, R.D. (1996) *SAS System for Mixed Models*. Cary, North Carolina: SAS Institute, Inc.

[17] LoPresti, E.F., Brienza, D.M., Angelo, J., Gilbertson, L. and Sakai, J. (2000) Neck range of motion and use of computer head controls. *Proc. ASSETS '00*. New York: ACM Press, pp. 121-128.

[18] MacKenzie, I.S., Sellen, A. and Buxton, W. (1991) A comparison of input devices in elemental pointing and dragging tasks. *Proc. CHI '91*. New York: ACM Press, pp. 161-166.

[19] MacKenzie, I.S. (1992) Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction 7* (1), pp. 91-139.

[20] MacKenzie, I.S., Kauppinen, T. and Silfverberg, M. (2001) Accuracy measures for evaluating computer pointing devices. *Proc. CHI '01*. New York: ACM Press, pp. 9-16.

[21] MacKenzie, I.S. and Soukoreff, R.W. (2003) Card, English, and Burr (1978) – 25 years later. *Extended Abstracts CHI '03*. New York: ACM Press, pp. 760-761.

[22] Phillips, B. and Zhao, H. (1993) Predictors of assistive technology abandonment. *Assistive Technology 5* (1), pp. 36-45.

[23] Riemer-Reiss, M.L. and Wacker, R.R. (2000) Factors associated with assistive technology discontinuance among individuals with disabilities. *Journal of Rehabilitation 66* (3), pp. 44-50.

[24] Schuster, C. and von Eye, A. (2001) The relationship of ANOVA models with random effects and repeated measurement designs. *Journal of Adolescent Research 16* (2), pp. 205-220.

[25] Smits-Engelsman, B.C.M., Rameckers, E.A.A. and Duysens, J. (2007) Children with congenital spastic hemiplegia obey Fitts' Law in a visually guided tapping task. *Experimental Brain Research 177* (4), pp. 431-439.

[26] Trewin, S. and Pain, H. (1999) Keyboard and mouse errors due to motor disabilities. *International Journal of Human-Computer Studies 50* (2), pp. 109-144.

[27] Trewin, S., Keates, S. and Moffatt, K. (2006) Developing Steady Clicks: A method of cursor assistance for people with motor impairments. *Proc. ASSETS '06*. New York: ACM Press, pp. 26-33.

[28] Walker, N., Philbin, D.A. and Fisk, A.D. (1997) Age-related differences in movement control: Adjusting submovement structure to optimize performance. *Journal of Gerontology: Psychological Sciences 52B* (1), pp. 40-52.

[29] Wobbrock, J.O. and Myers, B.A. (2006) Trackball text entry for people with motor impairments. *Proc. CHI '06*. New York: ACM Press, pp. 479-488.

[30] Wobbrock, J.O. and Myers, B.A. (2006) From letters to words: Efficient stroke-based word completion for trackball text entry. *Proc. ASSETS '06*. New York: ACM Press, pp. 2-9.

[31] Worden, A., Walker, N., Bharat, K. and Hudson, S.E. (1997) Making computers easier for older adults to use: Area cursors and sticky icons. *Proc. CHI '97*. New York: ACM Press, pp. 266-271.