Goal Crossing with Mice and Trackballs for People with Motor Impairments: Performance, Submovements, and Design Directions

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Prior research shows that people with motor impairments face considerable challenges when using conventional mice and trackballs. One challenge is positioning the mouse cursor within confined target areas; another is executing a precise click without slipping. These problems can make mouse pointing in graphical user interfaces very difficult for some people. This article explores goal crossing as an alternative strategy for more accessible target acquisition. In goal crossing, targets are boundaries that are simply crossed by the mouse cursor. Thus, goal crossing avoids the two aforementioned problems. To date, however, researchers have not examined the feasibility of goal crossing for people with motor difficulties. We therefore present a study comparing area pointing and goal crossing. Our performance results indicate that although Fitts' throughput for able-bodied users is higher for area pointing than for goal crossing (4.72 vs. 3.61 bits/s), the opposite is true for users with motor impairments (2.34 vs. 2.88 bits/s). However, error rates are higher for goal crossing than for area pointing under a strict definition of crossing errors (6.23% vs. 1.94%). We also present path analyses and an examination of submovement velocity, acceleration, and jerk (the change in acceleration over time). These results show marked differences between crossing and pointing and almost categorically favor crossing. An important finding is that crossing reduces jerk for both participant groups, indicating more fluid, stable motion. To help realize the potential of goal crossing for computer access, we offer design concepts for crossing widgets that address the occlusion problem, which occurs when one crossing goal obscures another in persistent mouse-cursor interfaces. This work provides the motivation and initial steps for further exploration of goal crossing on the desktop, and may help researchers and designers to radically reshape user interfaces to provide accessible goal crossing, thereby lowering barriers to access.

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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, checkboxes, radio buttons, menus, scrollbars, and text fields, 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 click is necessary to acquire the targets. This target acquisition process, called "area pointing,"[1] occurs countless times in the course of regular computer use. Accordingly, where it is difficult or impossible, it can pose a serious barrier to computer and information access for some people.

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 clicking it—can be distinctly troublesome. Hwang et al. [2004] showed that motor-impaired users often pass over or slip out of their target as they try to position their cursor inside it (Figure 1(a)). Trewin and Pain [1999] reported that 15 of 20 participants 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. [2006] considered this enough of a problem to address it later in their *Steady Clicks* system.) Trewin and Pain hastened to point out that although many of their participants had tried mouse alternatives, participants 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 [Phillips and Zhao 1993; Riemer-Reiss and Wacker 2000; Koester 2003]. 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.

Other work has shown similar difficulties with area pointing for the elderly [Smith et al. 1999] and for children [Hourcade et al. 2004]. Indeed, the same problems of positioning the cursor within a confined area and executing a click

[1]"Area pointing" may be variously called "mouse pointing" or "pointing-and-clicking"; we prefer "area pointing" for its symmetry to "goal crossing," the focus of this article. Area pointing should not be confused with area cursors [Worden et al. 1997], which are enlarged cursors with hotspots greater than one pixel. In this article, we deal only with conventional cursors pointing to targets of finite area.

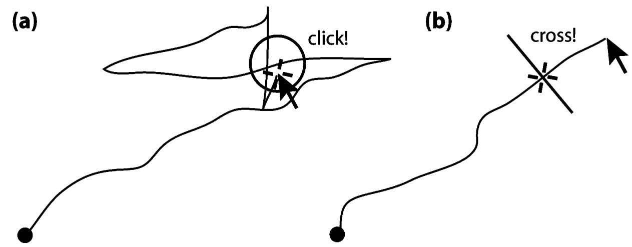

Fig. 1. **(a)** Users with motor impairments often have difficulty acquiring area targets, as shown in this figure adapted from a prior study [Hwang et al. 2004]. **(b)** In goal crossing, the need for acquiring a confined area and clicking is removed. Instead, goals must only be crossed.

without slipping have been observed for these groups. Thus, the current work may have implications beyond motor-impaired individuals to these other people as well.

This article 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 1(b)). As a result, goal crossing may be a promising foundational alternative to area pointing for people with motor impairments.

This article first reports on a recent study we published at ACM ASSETS 2007 [Wobbrock and Gajos 2007] comparing goal crossing to area pointing with mice and trackballs involving 16 people, 8 of whom have motor impairments. Our results indicate 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 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.

Here we extend our study to examine goal crossing submovement profiles of velocity, acceleration, and jerk[2] in an effort to discern *why* goal crossing may be a promising alternative to area pointing for people with motor impairments. Key findings are that participants seem to produce lesser force when goal crossing, make smoother movements, and are considerably more accurate during the course of movement.

These findings provide an empirical foundation upon which to base the pursuit of accessible goal crossing user interfaces for desktop applications. Clearly, many practical design challenges await such efforts. We therefore also present initial design concepts for "crossing widgets" that may spur new research into developing accessible crossing-based user interfaces. This work indicates that pursuing such designs may be worthwhile.

[2]*Jerk* is the change in acceleration over time, the third derivative of position. Lesser jerk is indicative of smoother movement. Beyond jerk are further derivatives, but these are difficult to interpret. They are *snap*, *crackle*, and *pop*, the fourth, fifth, and sixth derivatives of position.

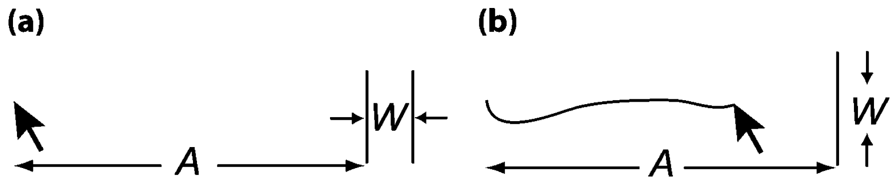

Fig. 2. **(a)** In a classic Fitts' law task, the constraint imposed by W is collinear to the movement axis. **(b)** In goal crossing, the constraint is orthogonal to the movement axis [Accot and Zhai 1997; 2002].

2. RELATED WORK

To date, goal crossing has been modeled and studied only for able-bodied users. In developing the Steering law, Accot and Zhai [1997] first proposed goal crossing and showed that it followed Fitts' law [Fitts 1954], given here as MacKenzie's popular Shannon formulation [MacKenzie 1992]:

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

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 2(a)). Note that the size constraint W in a crossing task is orthogonal, rather than collinear, to the movement axis (Figure 2(b)). 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 $bits/s$. This quantity provides a way to compare crossing and pointing results. It also supports comparisons with prior experiments, since throughput is independent of the particular experimental task used.

Rapid aimed movements of the kind assumed by Fitts' law are called "closed loop" because the participant 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 participant'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. [2000] showed that Fitts' law holds for neck movements by people with motor impairments, although explicit formulations using Eq. (1) were not reported. Gump et al. [2002] found that Fitts' law did *not* hold for people with Cerebral Palsy (CP), although they noted their data contained problematically high error rates, possibly from oculomotor problems. Bravo et al. [1990; 1993] had mixed results, showing only two of six participants with CP could be modeled by Fitts' law; the other four participants had severe spasticity and range limitations. Rao et al. [2000] tested participants with CP using displacement and isometric joysticks, finding that Fitts' law provided reasonably good fits for all but the most severely impaired participants. Flowers [1976] also used a joystick, showing that ballistic movements by people with Parkinsonian tremor differ from those of able-bodied users more so than movements by people with intention tremor, suggesting Fitts' law might not hold for those with Parkinson's disease but would for those with intention tremor. Recently, Smits-Engelsman et al. [2007] showed that children with CP do, in fact, adhere to Fitts' law. Thus, research results are somewhat mixed, although severity of impairment seems to be an important factor. The 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 [2002] 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 computer applications. *CrossY* is a pen-based drawing application intended for able-bodied users that employs crossing as its fundamental target acquisition scheme [Apitz and Guimbretière 2004]. *Trackball EdgeWrite* 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 [Wobbrock and Myers 2006a; 2006b]. Crossing also exists on the Web, for example, in the *DontClick.It* interaction design project [Frank 2005].

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 [Worden et al. 1997], which respectively use an enlarged cursor and gain-diminished targets to improve mouse performance in older adults. An extension of the area cursor is the Bubble Cursor [Grossman and Balakrishnan 2005], which dynamically resizes itself to remain as large as possible based on the locations of nearby targets. An extension of sticky icons is semantic pointing [Blanch et al. 2004], 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. [2003] investigated for people with motor impairments. They found that haptic feedback in the form of gravity wells was most beneficial for those participants with the most severe motor limitations, even in the presence of distractor targets.

To date, crossing has mainly been explored for able-bodied users of pen-based interfaces. An obvious challenge in mouse-based goal crossing, which does not appear in pen-based crossing, is the *occlusion problem*, in which one crossing goal obscures another. This is because unlike in pen-based interfaces, the mouse cursor cannot fly in, cross, and fly out. Although the mouse button can be held down while crossing to distinguish an intentional cross from an unintentional one, this is probably not an accessible design. We therefore offer potential design solutions to this problem near the end of this article. 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 participants, 8 of whom had motor impairments. Participants used an optical mouse, an optical trackball, or both according to their preferences. Speeds, error rates, path analysis measures, and submovement profiles were computed. Also, Fitts' law was used to model performance and to measure throughput. Trial-level results are presented in this section, while path analyses and submovement results are reported in the section that follows (Section 4).

3.1 Method

This section describes the experimental method employed in our evaluation of area pointing and goal crossing for people with and without motor impairments.

3.1.1 *Participants.* Sixteen participants volunteered for the study. Eight were able-bodied (AB) and 8 were motor-impaired (MI). Half of the AB group was female. Average age was 30.3 (*SD* = 8.2). In the MI group, 3/8 was female. Average age was 42.8 (22.0). Of these 8 MI subjects, 4 used mice as their input device of choice, 2 used trackballs (Figure 3), and 2 used both. In our study, the MI participants used the devices according to their own preferences. Table I shows detailed information for the MI group.

3.1.2 *Apparatus.* Our experiment was conducted on a 19-inch 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 participants use these devices instead of their personal devices to ensure consistency. The mouse speed was set to 6/10 on the Windows mouse 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 7 statistics package.

3.1.3 *Procedure.* All able-bodied participants performed goal crossing and area 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 (see Table I). For the other motor-impaired participants, the order of techniques was randomized within

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

Table I. Information about 8 Participants with Motor Impairments

Participant Information for the MI Group					
Subject	**Sex**	**Age**	**Wheelchair**	**Device**	**Health Condition**
MI1	m	50	no	mouse	Peripheral 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	Peripheral Neuropathy
MI8	m	49	yes	trackball	Spinal Cord Injury

their chosen 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.

For a given combination of device and technique, the test software randomly presented five practice trial-sets followed by 15 testing trial-sets covering all amplitude (A) $\times$ width (W) target combinations in random order. One trial-set consisted of eight targets arranged in 45° increments around a center position (Figure 4), similar to the setup used in prior work [Hwang et al. 2004]. 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 to begin the next trial. We chose to have participants successfully acquire each target rather than end a trial

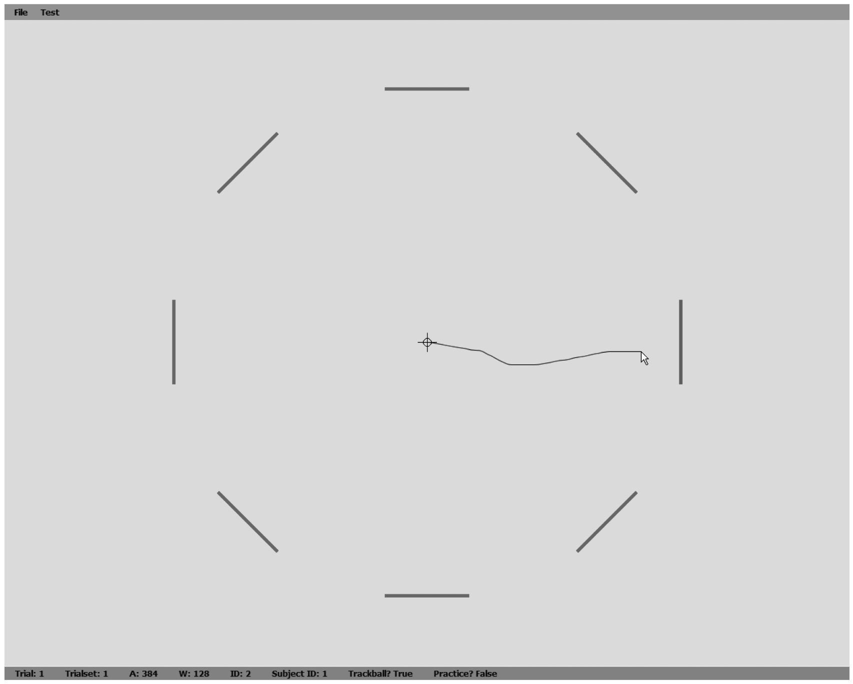

Fig. 4. The 1280×1024 full screen test application showing 1 trial-set comprising 8 crossing targets. The target right of center is active and appeared red to participants. The other targets are disabled and appeared gray. The mouse has moved from the center towards the target as shown by the illustrated path. (No path was actually drawn during testing.) These targets are $A = 384$, $W = 128$ pixels. For pointing trials, the goals would be replaced by circles of diameter $W = 128$.

after the *first* hit or miss in order to log repeated misses and the *total* time to acquisition. Once all eight 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 per participant.

For area pointing trials, a "miss" was defined as a click that occurred outside the active circular target (Figure 5(a)). For goal crossing trials, a miss was when the mouse passed over an *infinitely extended* goal line beyond either end of a finite goal segment (Figure 5(b)). When a miss occurred in either technique, a "bonk" sound was played. After missing, participants still worked to acquire the target as in prior work [Accot and Zhai 2002]. Goal lines had to be crossed from within the circle outward; crossing them from outside-in was permitted but had no effect. Only one target goal was active at any one time.

In keeping with Fitts' law, participants were instructed to strive for about one miss in every three trial-sets (24 trials), which would result in an approximate 4% error rate [MacKenzie 1992]. It should be noted that in a real user interface, clicking outside an area target or passing beyond either end of a crossing goal would not necessarily be damaging. However, in using a strict

Fig. 5. **(a)** A miss for area pointing trials. **(b)** A miss for goal crossing trials. Although these misses are well defined for each technique, they are inevitably "apples and oranges," since the fundamental nature of target acquisition differs considerably in each case.

definition of misses, our error results can be viewed as a kind of 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}
—*Participant* {1..16}

Impairment is a between-subjects factor, while *Device*, *Technique*, and ID are within-subjects factors. We did not treat *Amplitude* (A) and *Width* (W) as separate factors, since Fitts' law [Fitts 1954] clearly shows that these factors are not independent. Instead, $ID = \log_2(A/W + 1)$ was used as a continuous factor ranging from 1.00 to 4.64 bits.

All participants together completed a total of 780 trial-sets each containing 8 trials for 6240 total trials. Of these, able-bodied participants completed 3840 trials, while motor-impaired participants completed 2400 trials. Our dependent measures were participants' 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 [Littell et al. 1996; Schuster and von Eye 2001]. *Impairment*, *Device*, *Technique*, and ID were modeled as fixed effects, and *Participant* was modeled correctly as a random effect [Littell et al. 1996; Frederick 1999; Schuster and von Eye 2001]. Mixed-effects models properly handle the imbalance in our data due to not all participants in the MI group using both devices. Mixed-effects models also account for correlated measurements within participants [Schuster and von Eye 2001]. However, they retain large denominator degrees of freedom (dfs), which can be fractional for unbalanced

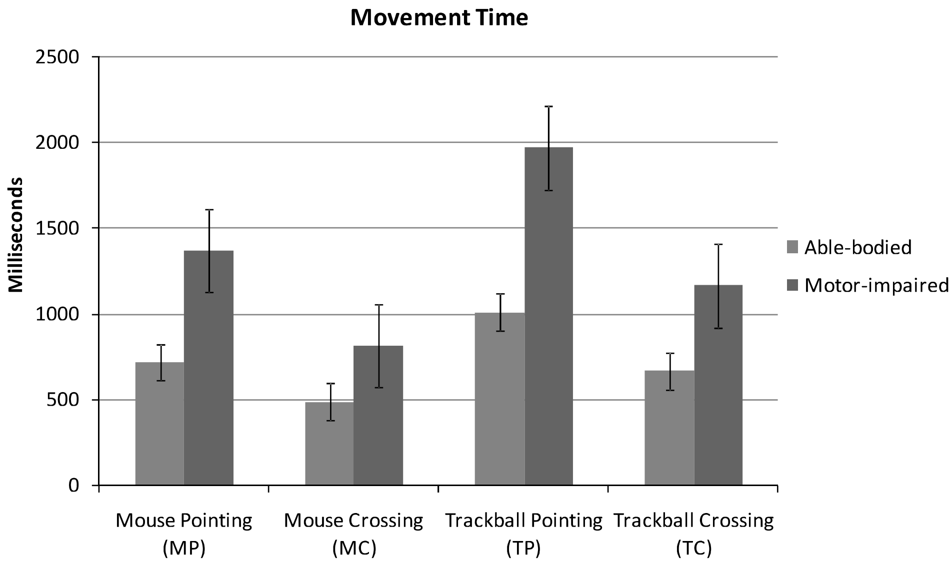

Fig. 6. Movement times in milliseconds. Error bars represent ±1 standard error (SE).

data.[3] These larger *df*s do not make detection of significance easier due to the use of wider confidence intervals [Frederick 1999]. Our model contained interactions up to the third degree. The model fit our movement time data well with R^2 = 904 for N = 572. In our results, we omit reporting the effects of ID since these effects are expected (i.e., harder trials were indeed significantly slower and more error prone than easier trials).

3.2 Results for Overall Performance

In this section, we present overall performance results for movement times, error rates, Fitts' law throughputs, and subjective impressions. Fine-grain results in the form of path and submovement analyses are left for Section 4.

3.2.1 *Movement Times and Error Rates.* Movement time (*MT*) is the time it takes to acquire a target. As is common [Accot and Zhai 2002], we exclude trials with misses, choosing to revisit this choice below. There were 95/3840 misses for AB subjects (2.47%), and 160/2400 misses for MI subjects (6.67%). In all, 255/6240 trials were excluded (4.09%), which is near the 4% error rate prescribed by Fitts' law [MacKenzie 1992]. Figure 6 shows average *MT*.

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 participant group

[3]For a short readable explanation of fractional degrees of freedom, see http://www.mrc-cbu.cam.ac.uk/Statistics/faq/satterthwaite.shtml. Accessed February 21, 2008.

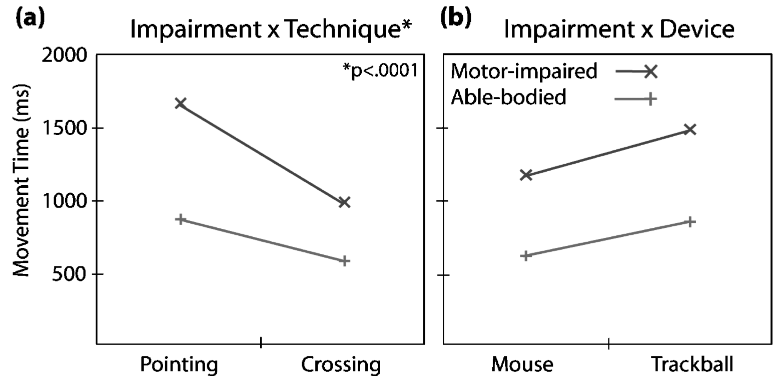

Fig. 7. **(a)** Crossing improves target acquisition time more for MI participants than for AB participants. **(b)** The trackball was slower than the mouse for both participant groups about equally.

differently (Figure 7(a)). Crossing reduced *MT* more for MI participants than it did for AB participants. 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 participants (Figure 7(b)).

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 the MI group, who benefited more from crossing with a trackball than did AB participants.

Error rates (%) were calculated as the percentage of trials with misses (see Figure 5). Figure 8 shows average error rates.

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 participant 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 (see 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 ($\chi^2_{(1,N=572)} = 2.40, p = .12$, both) (Figure 9).

We have thus far examined movement time (*MT*) excluding errors and errors themselves, finding crossing to be significantly faster than pointing, especially for the MI group, but more error prone. We now examine movement time with errors *included* (Figure 10). A question is whether or not the inclusion of trials with errors changes the movement time analysis, since misses and recovering from misses takes time. Thus, this measure indicates the *total* time

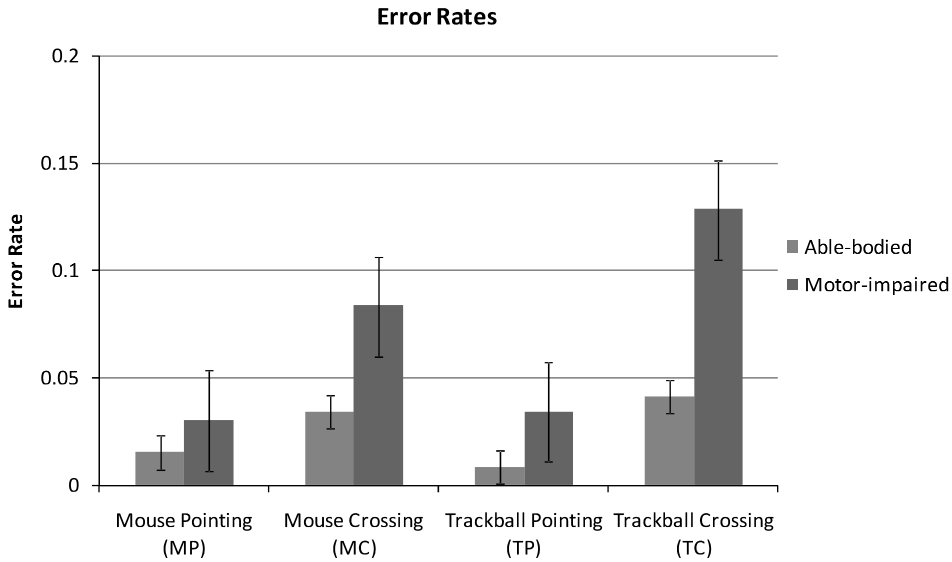

Fig. 8. Error rates indicating trials with misses. Error bars represent ±1 SE.

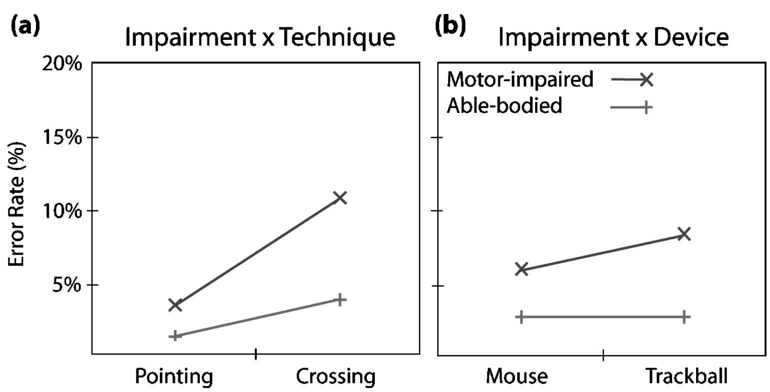

Fig. 9. **(a)** Pointing and crossing error rates for both groups of participants. **(b)** Mouse and trackball error rates for both groups of participants. Recall that errors were misses as defined in Figure 5 and were thus conceptually quite different for the two techniques.

to acquire targets, even in the presence of misses. We call this movement time with errors, or MT_ε.

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.), as both participant groups were similarly slower with the trackball than with the mouse. However, unlike for MT, there was no significant effect of *Impairment*Device*Technique*

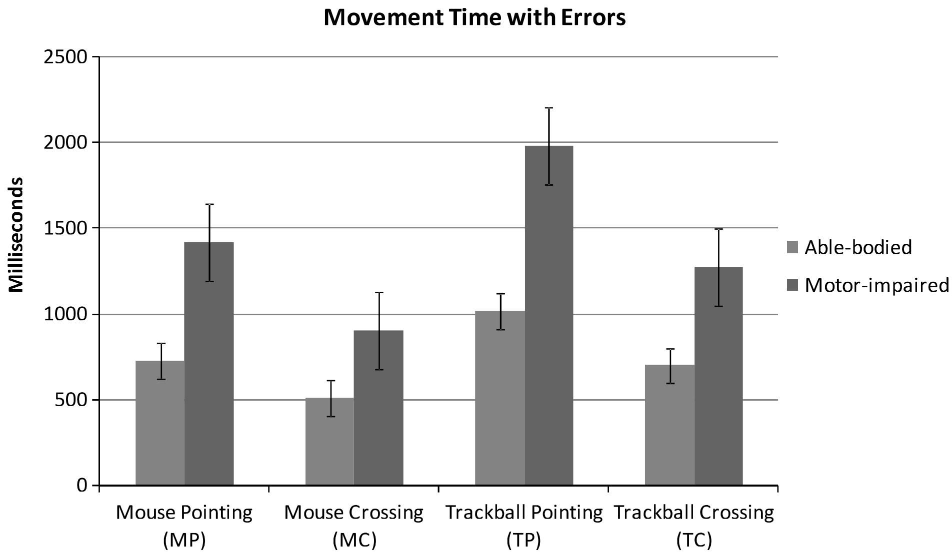

Fig. 10. Movement times with error trials included in milliseconds. Even with the higher rate of errors for crossing trials, goal crossing is still faster than area pointing. Error bars represent ±1 SE.

on MT_ε ($F_{1,542.7}$ = 1.86, n.s.), indicating that although crossing was faster than pointing more for the trackball than for the mouse, this was the case for both participant groups about evenly. The important point from these analyses of MT_ε is that crossing misses were not so time consuming so 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 Throughputs.* Fitts' law (Eq. (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*), which refers to the throughput of performance. As noted in related work (Section 2), there has been some disagreement as to whether people with motor impairments adhere to Fitts' law. Our data show that Fitts' law does apply to area pointing and goal crossing for all our participants with good results ($R^2 > .90$).

Current methods for using Fitts' law enforce a *post hoc* error rate of 4% by using effective target width (W_e) [MacKenzie 1992; MacKenzie and Soukoreff 2003; Soukoreff and MacKenzie 2004]. However, such models depend on having a large number of trials for each target in order to approximate a normal distribution of endpoint selections. Because motor-impaired participants cannot endure long experiments with myriad trials, our data were not sufficiently numerous to delineate such distributions, and we found traditional W_e models to be very poor. Therefore, we utilized the traditional method of excluding error trials [MacKenzie and Soukoreff 2003] and used the nominal width (W)

Table II. Fitts' Law Models for Each Participant Group of the Form $MT = a + b \cdot ID$. IP is Throughput. For Each Model, $N = 11$ and $p < .0001$

Able-bodied Participants				
Device and 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 Participants				
Device and 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

to compute ID. We found these models to fit our data well. Using traditional models also supports comparisons to prior goal crossing studies in which such models were used [Accot and Zhai 1997; 2002]. The downside of using traditional models is that throughput can be overestimated, as it refers to only those trials without misses. However, our analysis in the last section showed that excluding trials with misses does not substantially alter our movement time results. In addition, our throughput values for AB participants using the mouse and trackball are similar to results from prior studies [MacKenzie et al. 1991]. Our Fitts' law models are shown in Table II.

These models show good fits as judged by R^2 values greater than 0.90 for pointing and crossing with both able-bodied and motor-impaired participants. An important observation is that within each device, the AB group had lower throughput (*IP*) for crossing than for pointing, but the MI group had *higher* throughput for crossing than for pointing. See Figure 11 for depictions of Fitts' law models and Figure 12 for error rates by ID.

3.2.3 *Subjective Responses.* As a whole, participants did not indicate a significant preference for area pointing or goal crossing. However, the two participant 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 (Figure 13(a)). Participants' 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 (Figure 13(b)). 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 (Figure 13(c)). These ratings mirror the direction of throughput results in Table II. Finally, participants overall felt that crossing was less accurate than pointing (3.3 vs. 4.0, $F_{1,30.4} = 11.74$, $p < .01$), which reflects actual performance.

Thus far, we have seen that overall performance results and subjective responses support goal crossing as a possible alternative to area pointing for

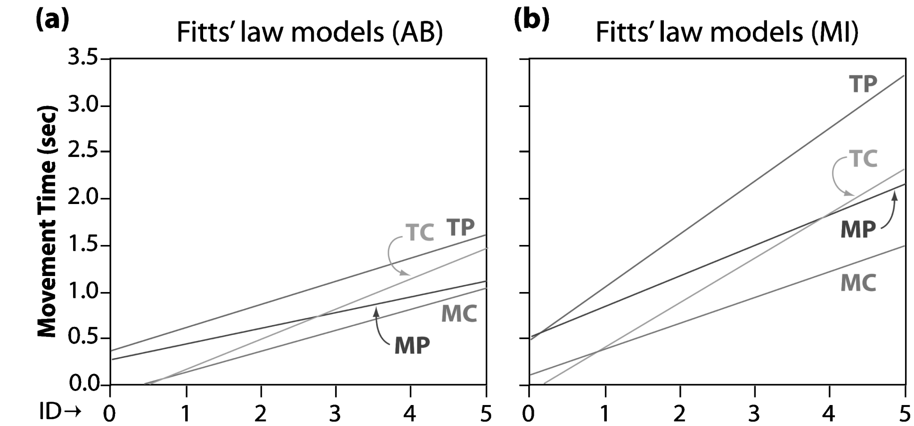

Fig. 11. Fitts' law models movement time ($y = MT$) by index of difficulty ($x = ID$). **(a)** For able-bodied participants, although crossing was faster than pointing over the tested IDs, pointing had higher throughputs (IP) as shown by the shallower slopes of the TP and MP lines relative to TC and MC, respectively. **(b)** Participants with motor impairments were also faster with crossing than pointing over the tested IDs, and crossing exhibited slightly better throughputs as well. See Table II for exact values and expansions for the abbreviations.

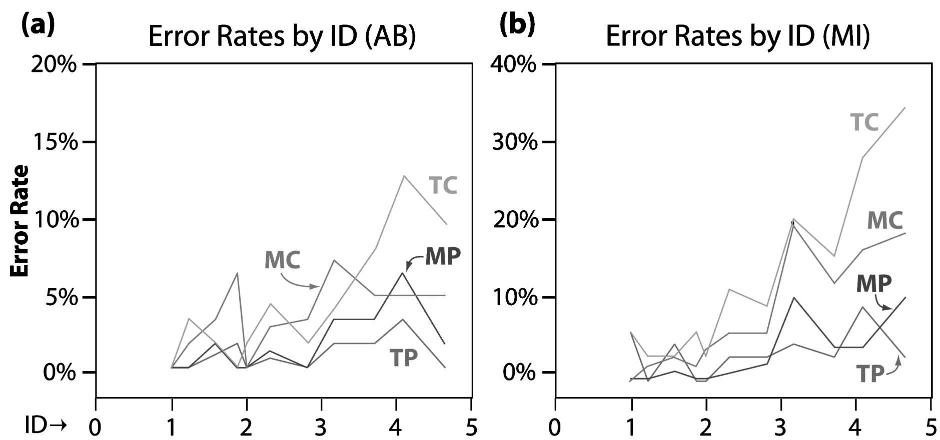

Fig. 12. Error rates (y) by index of difficulty ($x = ID$) for **(a)** able-bodied participants and **(b)** participants with motor impairments. Recall that error rates are defined as the percentage of trials that contained one or more misses as illustrated in Figure 5.

people with motor impairments. To get a better understanding of participants' motor behavior in goal crossing trials, we examined what happens *during* movement. These results are presented in the following section.

4. PATH ANALYSES AND SUBMOVEMENTS

In Section 3, we discovered *that* goal crossing is a promising alternative to area pointing for some people with motor impairments, but we did not discover *why*

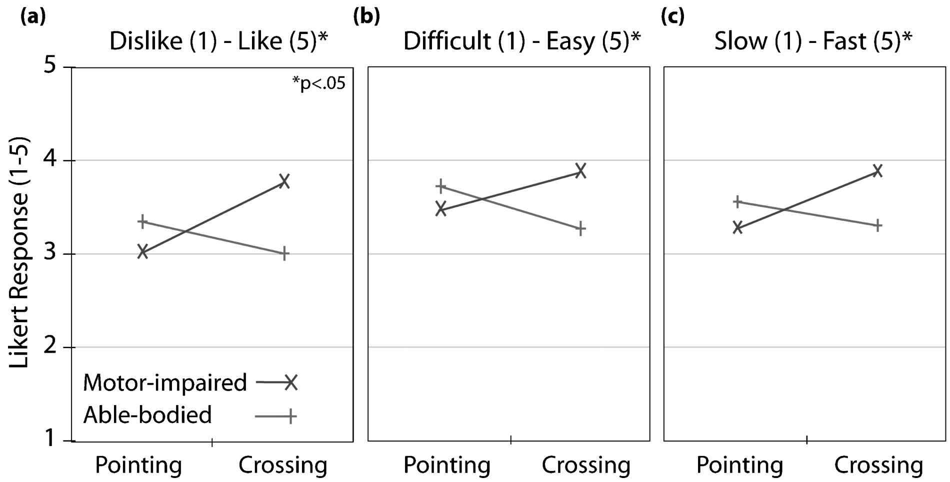

Fig. 13. Likert scale responses for subjective measures. Higher is better. The able-bodied participants and the motor-impaired participants felt oppositely about area pointing and goal crossing with respect to these scales for **(a)** liking, **(b)** ease of use, and **(c)** perceived speed.

this might be the case. Indeed, overall trial-level results such as speed, errors, or Fitts' throughput do not convey the underlying motor behavior responsible for performance differences [Mithal and Douglas 1996; MacKenzie et al. 2001; Hwang et al. 2004]. To gain better insight into the underlying differences in movements among the techniques, we performed path analysis measures and examined submovement profiles. Although an exhaustive treatment of submovements is beyond the current scope, our analysis is sufficient to highlight key differences between participant groups, devices, and most importantly, target acquisition techniques.

4.1 Movement Filtering

Performing detailed measures of mouse cursor movement using raw mouse movement data is problematic for many reasons. The raw movements are effectively aliased in both time and space due to the limited sampling from the input hardware and software. The result is that numerous "peaks and jaggies" pervade movement plots based on raw cursor movements. As a result, it is useful to smooth the movement using established techniques [Kaiser and Reed 1977]. These techniques do not alter the fundamental shapes of movements; they simply remove unwanted noise from the data and reduce the chances of obtaining results influenced by spurious points.

Specifically, we resampled the mouse cursor traces at 100 Hz, then applied an NER 30 Hz low-pass filter [Kaiser and Reed 1977]. Next we used a differentiating filter (NERD) to compute the velocity, acceleration, and jerk. Finally, we pass position, velocity, acceleration, and jerk through the NER filter again at 7 Hz. Essentially, this is the same process used in prior work [Jagacinski et al. 1980; Meyer et al. 1988; Walker et al. 1993].

Table III. Path Analysis Measures and Standard Deviations for Each Participant 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)

	AB Participants				**MI Participants**			
	MP	**MC**	**TP**	**TC**	**MP**	**MC**	**TP**	**TC**
Target re-entry (TRE)	0.07 (.11)	n/a	0.11 (.14)	n/a	0.24 (.33)	n/a	0.38 (.33)	n/a
Task axis crossings (TAC)	0.81 (.46)	0.91 (.49)	1.10 (.61)	1.20 (.71)	1.25 (.77)	1.02 (.57)	1.79 (1.14)	1.60 (.98)
Movement direction changes (MDC)	4.13 (1.47)	2.77 (1.63)	5.24 (2.54)	4.82 (3.50)	8.45 (3.52)	4.61 (2.48)	11.51 (6.12)	8.93 (5.76)
Orthogonal direction changes (ODC)	2.88 (1.53)	0.41 (.46)	3.55 (2.54)	1.43 (2.01)	6.74 (3.50)	1.44 (1.55)	8.92 (5.12)	4.74 (4.20)
Movement variability (MV)	14.88 (10.02)	10.24 (4.59)	12.13 (6.41)	8.50 (2.35)	18.36 (11.05)	15.09 (7.02)	16.90 (6.31)	14.04 (4.93)
Movement error (ME)	18.55 (9.00)	11.65 (5.15)	16.76 (7.35)	10.35 (3.61)	20.02 (9.07)	17.10 (8.59)	19.95 (6.29)	15.23 (4.60)
Movement offset (MO)	-1.16 (7.53)	0.69 (5.77)	0.38 (9.48)	0.11 (4.59)	3.13 (10.28)	0.38 (7.69)	2.83 (7.76)	-1.81 (6.79)
Path distance (PD)	290.51 (125.87)	271.52 (104.03)	281.94 (117.15)	272.17 (101.75)	335.97 (142.38)	292.23 (108.05)	367.54 (138.21)	306.20 (128.36)

4.2 Path Analysis Measures

MacKenzie et al. [2001] developed various accuracy measures for cursor movement based on the path taken by the cursor relative to the ideal task axis, which is a straight line from the start position to the target center. These measures involve counting various quantities: target re-entries (*TRE*), task axis crossings (*TAC*), movement direction changes parallel to the task axis (*MDC*), and orthogonal direction changes perpendicular to the task axis (*ODC*). They also involve pixel-distance measures: movement variability (*MV*), or "wiggliness," movement error (*ME*), the absolute distance from the task axis, and movement offset (*MO*), a signed direction-sensitive distance from the task axis. Graphical illustrations can be found in the original work [MacKenzie et al. 2001]. We also add a measure for the overall path distance (*PD*). These data are shown in Table III. They are extracted from successful trials up to the acquisition of the target.[4]

As one might expect, nearly all measures indicate a significant difference due to *Impairment* ($p < .05$) in favor of the AB group. The only exception to this is movement offset (*MO*), a signed measure of deviation from the task axis, which was not significant ($F_{1,12.1} = 0.59$, n.s.).

Our chief interest is in how goal crossing compares to area pointing for each of the participant groups. *TAC* measures how often the task axis was crossed.

[4]An earlier version of these results [Wobbrock and Gajos 2007] did not perform the smoothing steps prior to conducting the path analysis measures or performed the measures only up until the target was acquired. As a result, we feel the results here are more reliable.

An omnibus test indicates that *Technique* was not significant for *TAC* ($F_{1,543.1}$ = 1.78, n.s.). However, a significant *Impairment*Technique* interaction indicates that each participant group performed differently ($F_{1,543.1}$ = 15.78, $p < .0001$). Contrasts show that the AB group had significantly fewer task axis crossings for pointing than for crossing ($F_{1,543.1}$ = 4.63, $p < .05$), but the MI group was opposite, with significantly fewer *TAC*s for crossing than for pointing ($F_{1,543.1}$ = 11.27, $p < .001$). Thus, we see an advantage in crossing for the MI group that does not emerge for the AB group.

Movement direction changes (*MDC*) measure directional changes parallel to the task axis. *Technique* had a significant effect on *MDC* overall ($F_{1,542.8}$ = 186.96, $p < .0001$), as crossing had fewer directional changes than pointing for both participant groups. In addition, there was a significant *Impairment*Technique* interaction ($F_{1,542.8}$ = 59.68, $p < .0001$), as crossing was more effective at reducing *MDC* for participants with motor impairments than it was for able-bodied participants.

Orthogonal direction changes (*ODC*) count the changes in direction that are perpendicular to the task axis. As for *MDC*, we see a significant effect of *Technique* on *ODC* ($F_{1,542.5}$ = 600.06, $p < .0001$), as both participant groups had fewer *ODC*s with crossing than with pointing. Again, there was a significant *Impairment*Technique* interaction ($F_{1,542.5}$ = 72.54, $p < .0001$), as crossing lowered *ODC*s more for the MI group than for the AB group.

Pixel-level measurements also show an advantage for crossing over pointing for both participant groups. Movement variability (*MV*) is a measure of how wiggly a movement is. Our data show that crossing was substantially less wiggly than pointing, as indicated by a significant effect of *Technique* ($F_{1,542.1}$ = 45.79, $p < .0001$). The effect was similar for both participant groups, so there was no significant *Impairment*Technique* interaction ($F_{1,542.1}$ = 1.02, n.s.).

Movement error (*ME*) is a measure of absolute distance away from the task axis. Like *MV*, it also was significantly less in favor of crossing ($F_{1,541.8}$ = 86.76, $p < .0001$). Interestingly, crossing lowered *ME* for the AB group relative to pointing *more* than it did for the MI group, as indicated by a significant *Impairment*Technique* interaction ($F_{1,541.8}$ = 6.31, $p < .05$).

Movement offset (*MO*) is similar to *ME* but is a signed (directional) measure of distance from the task axis. Yet again, there is a significant advantage for crossing over pointing ($F_{1,541.1}$ = 5.14, $p < .05$). There is also a significant *Impairment*Technique* interaction ($F_{1,541.1}$ = 12.31, $p < .001$). Contrasts show that crossing had significantly lower *MO* than pointing for the MI group ($F_{1,541.1}$ = 13.34, $p < .001$), but there was no detectable difference for the AB group ($F_{1,541.1}$ = 1.03, n.s.).

Finally, path distance traveled (*PD*) gives a sense of how much cursor movement is occurring. (It is obviously positively correlated with many of the other measures such as *MDC* and *MV*.) Crossing had significantly less overall cursor travel distance than pointing ($F_{1,541.5}$ = 18.04, $p < .0001$). The reduction in distance due to crossing was different for each participant group ($F_{1,541.5}$ = 5.87, $p < .05$). Participants with motor impairments moved much less with crossing than with pointing ($F_{1,541.5}$ = 17.80, $p < .0001$). Able-bodied participants did not exhibit this result ($F_{1,541.5}$ = 2.22, n.s.).

Out of all of the path analysis measures, the only one for which pointing was better than crossing was for task axis crossings (*TAC*) for the able-bodied participants. All other results were either in favor of crossing over pointing, or non-significant. Thus, crossing consistently showed itself to be better than pointing for participants with motor impairments. It seems that the movement created when crossing is more accurate than pointing in a variety of ways.

4.3 Submovement Profiles

We now examine our movement data at an even finer level by looking at submovement profiles for velocity, acceleration, and jerk. These profiles previously have been called the "microstructures of movement" [Jagacinski et al. 1980; Mithal and Douglas 1996], and can give us further insight into *why* crossing seems a promising alternative to pointing for improved computer access.

4.3.1 *Submovement Parsing.* Submovements were parsed from the movement logs in a fashion similar to prior work [Meyer et al. 1988; Hwang 2002; Keates et al. 2002]. Specifically, a new submovement was said to start when the raw speed[5] fell below 0.05 pixels/ms and then rose to above 0.5 pixels/ms. These criteria were based on a prior scheme developed for people with motor impairments [Keates et al. 2002]. We explored other levels for these values, but found that these criteria matched intuition when manually inspecting a sample of submovement graphs. All of our submovement calculations are from the start of the movement until the moment at which the target is acquired. Figure 14 shows the number of submovements made in each condition.

The number of submovements made was significantly affected by *Impairment* ($F_{1,12.3}$ = 7.07, $p < .05$), *Device* ($F_{1,349.7}$ = 88.16, $p < .0001$), and their interaction ($F_{1,349.7}$ = 9.39, $p < .01$). Somewhat surprising was that *Technique* did not significantly affect the number of submovements made ($F_{1,541.2}$ = 2.61, p = .11), although the marginal result suggests that crossing may produce fewer. In sum, able-bodied participants made fewer submovements than motor-impaired participants, and the mouse made fewer submovements than the trackball.

4.3.2 *Velocity Profiles.* Results for average velocity are exactly proportional to the movement time (*MT*) results shown in Figure 6. Thus, we forego reproducing them here. More interestingly, velocity profiles allow us to examine the average *maximum* velocities for each participant group, device, and technique (Figure 15). These peaks give an empirical upper bound on the velocity profiles.

Perhaps not surprisingly, *Impairment* had a significant effect on maximum velocity ($F_{1,13.3}$ = 6.78, $p < .05$), with able-bodied participants having higher speeds than participants with motor impairments. *Device* was not significant ($F_{1,392.6}$ = 0.47, n.s.), but *Technique* was ($F_{1,542.4}$ = 53.56, $p < .0001$), indicating

[5]We used the raw speed when calculating submovements because the movement filtering described above retains frequency trends but loses instantaneous frequency magnitudes, especially for short "bursty" peaks.

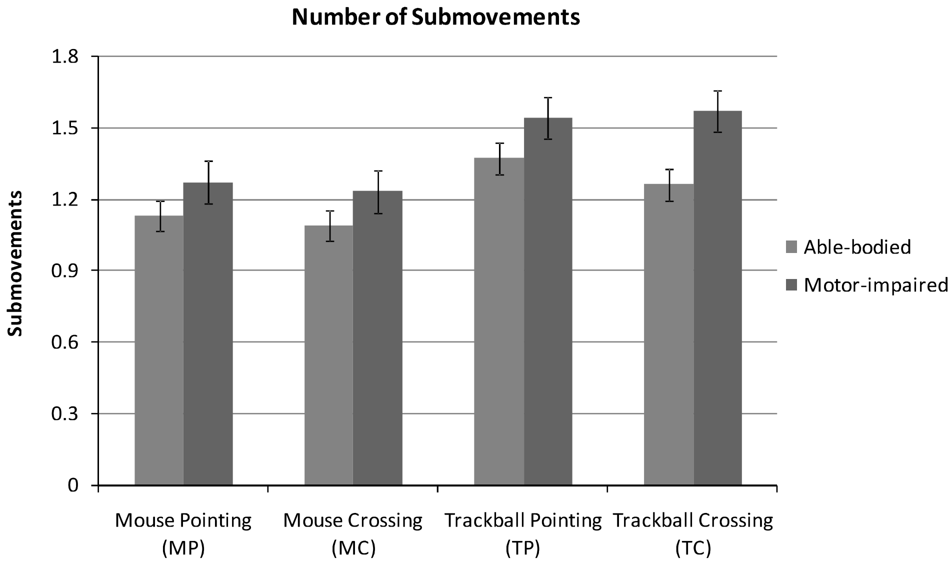

Fig. 14. Average number of submovements for each participant group, device, and technique. Error bars represent ±1 SE.

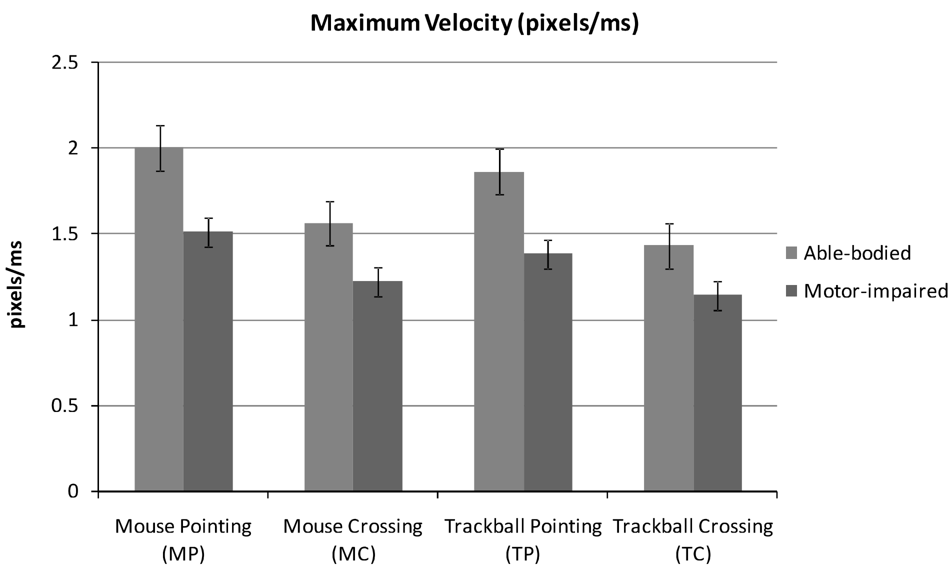

Fig. 15. Average maximum velocities in pixels/ms. Error bars represent ±1 SE.

that pointing had higher maximum speeds than crossing. This is interesting because crossing was significantly *faster* overall for both user groups (see Figure 6). Thus, higher maximum speeds for pointing did not translate into faster overall trial times. This is at least in part due to the additional time it takes to click when pointing.

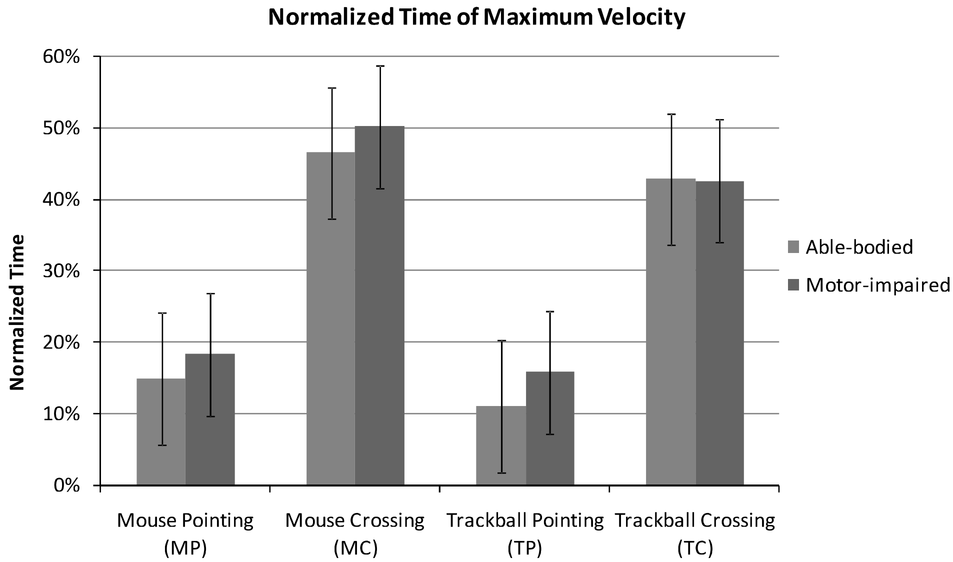

Fig. 16. Normalized time (%) of maximum velocity. Error bars represent ±1 SE.

We see further differences when we examine the times at which maximum velocities occurred. Figure 16 shows the average normalized time at which the maximum velocity occurred. This is the percentage of the way through the movement at which the top velocity was reached. Zero percent (0%) is the start of the movement, while 100% is the moment at which the target was acquired.

Impairment did not have a significant effect on the normalized time of maximum velocity ($F_{1,13.2}$ = 0.98, n.s.), suggesting that the phenomena is fundamental to pointing and crossing irrespective of the participant groups. Both *Device* ($F_{1,421.3} = 38.83$, $p < .0001$) and *Technique* ($F_{1,542.3} = 1398.82$, $p < .0001$) were significant. The maximum velocity came significantly earlier in the movements for the trackball than for the mouse, but the biggest difference was due to crossing versus pointing. As Figure 16 shows, the maximum velocity in pointing movements comes very early in the overall movement profile—usually before 20% of the movement time has elapsed. This is consistent with prior work showing large initial ballistic submovements at the start of pointing trials followed by submovement corrections [Meyer et al. 1988; Walker et al. 1993; Mithal and Douglas 1996]. However, for goal crossing, both participant groups reached their maximum velocity much later in the movement, about 45% of the way through. Our anecdotal observations concur with these numbers, as we regularly saw participants from both groups move their cursors steadily towards the crossing goals, then slow down slightly while positioning themselves in preparation for crossing the target in a smooth rapid fashion.

We can plot velocity over time to get a sense for how the speed of a movement unfolds. Figure 17 shows velocity profiles from prototypical trials for pointing and crossing. Many of the findings mentioned in this section are evident in these trials.

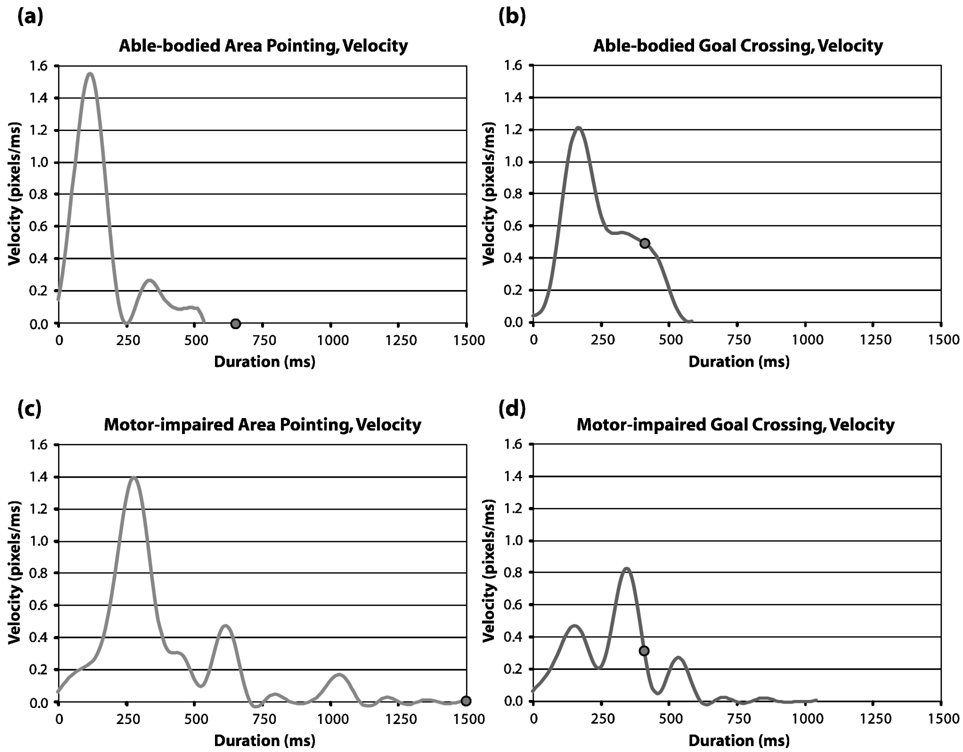

Fig. 17. Velocity profiles over time using the mouse for **(a,b)** able-bodied participants and **(c,d)** motor-impaired participants. The dot represents the click or crossing event. The graphs on the left are for area pointing. The graphs on the right are for goal crossing.

4.3.3 *Acceleration Profiles.* We briefly examine maximum acceleration, the time at which maximum acceleration occurred, and the number of zero-crossings, which mark where acceleration turned from positive to negative and vice-versa—that is, how many acceleration/deceleration changes occurred.

Figure 18 shows the maximum acceleration in pixels/ms^2 for each participant group, device, and technique. Maximum acceleration is of particular interest, since it corresponds to maximum exerted force during movement [Walker et al. 1997].

Impairment was significant ($F_{1,13.8}$ = 13.70, $p < .01$), with able-bodied participants having higher peak accelerations than participants with motor impairments. Of particular interest is *Technique*, which was highly significant due to the higher maximum acceleration for pointing than for crossing ($F_{1,543.0}$ = 73.10, $p < .0001$). Each participant group exhibited this differently, as shown by a significant *Impairment*Technique* interaction ($F_{1,543.0}$ = 11.46, $p < .001$). Able-bodied participants had comparatively higher acceleration with pointing than crossing relative to participants with motor impairments, but motor impaired participants still exhibited significantly lower acceleration for crossing than for pointing ($F_{1,543.0}$ = 10.67, $p < .01$). Somewhat surprisingly, neither *Device* ($F_{1,387.9}$ = 0.35, n.s.) nor *Impairment*Device* ($F_{1,387.9}$ = 0.82, n.s.)

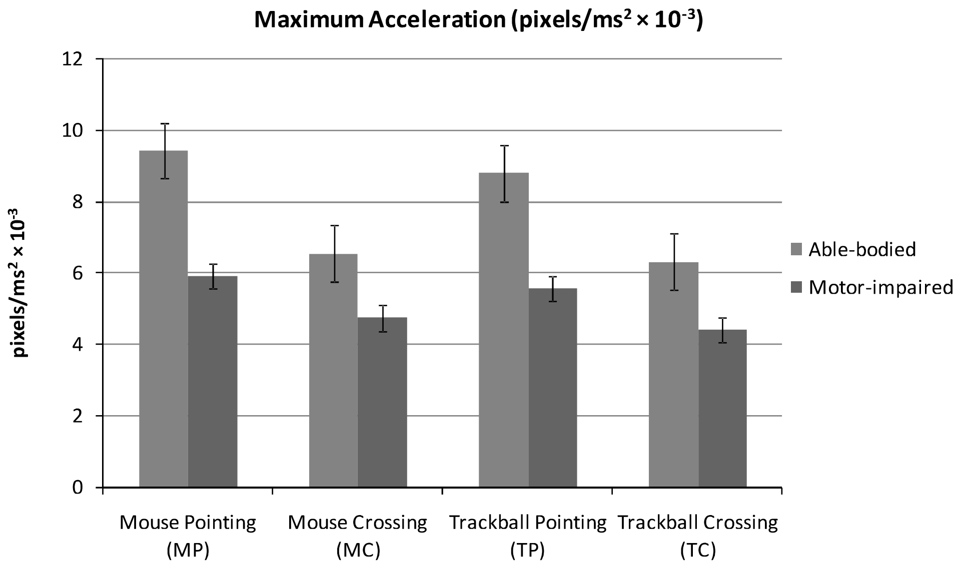

Fig. 18. Average maximum acceleration in pixels/ms^2. Error bars represent ± 1 SE. Scientific notation is used for readability (e.g., 8.00 = 8.00e-3 =.008).

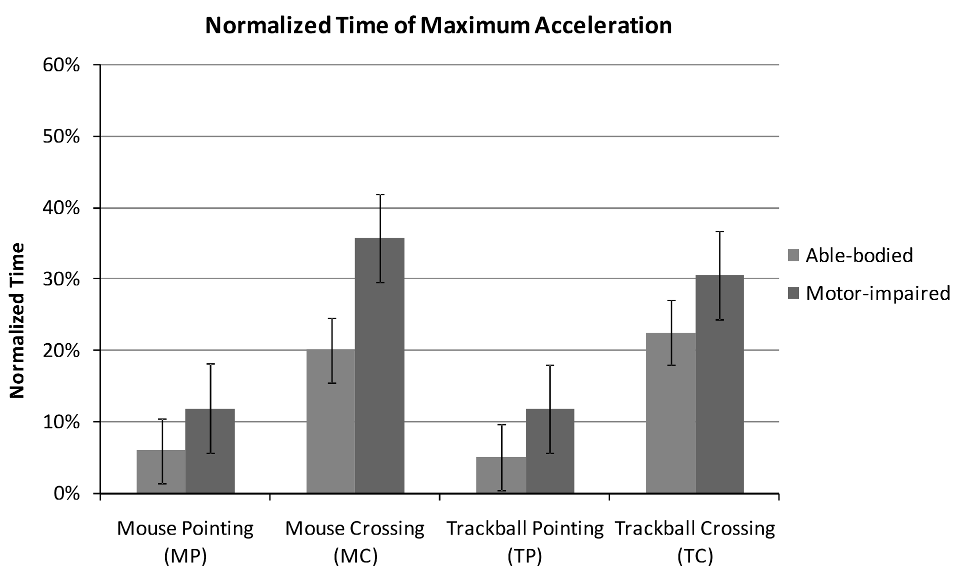

Fig. 19. Normalized time (%) of maximum acceleration. Error bars represent ± 1 SE.

were significant, indicating that within each participant group, differences in the maximum accelerations for mice and trackballs were about proportional.

As we did with velocity, we can examine *when* in the profile acceleration reached its maximum. Figure 19 shows the normalized time of the maximum acceleration. As in Figure 16, zero percent (0%) indicates the start of

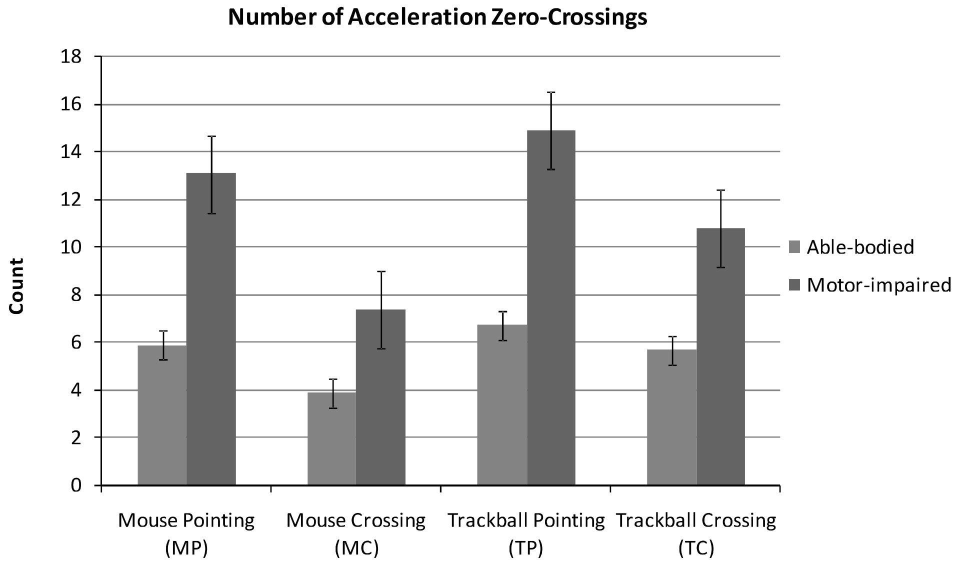

Fig. 20. Number of times the acceleration profile crosses the *x*-axis, on average, indicating a change from acceleration to deceleration. Error bars represent ± 1 SE.

movement, while 100% indicates the moment that the target is acquired. Note how early in pointing trials maximum acceleration is reached (about 5–10%), while maximum acceleration in crossing trials is not reached until much later (about 20–35%).

Impairment was significant ($F_{1,13.5} = 5.62$, $p < .05$), with able-bodied participants reaching maximum acceleration earlier than participants with motor impairments. *Device* was also significant ($F_{1,460.1} = 7.72$, $p < .01$), with trackballs peaking earlier than mice. The biggest difference is for *Technique* ($F_{1,542.6} = 539.52$, $p < .0001$), which indicates that pointing peaked in acceleration much sooner than crossing. Significant *Impairment*Device* ($F_{1,460.1} = 12.33$, $p < .001$), *Impairment*Technique* ($F_{1,542.6} = 12.21$, $p < .001$), and *Impairment*Device*Technique* ($F_{1,542.6} = 7.22$, $p < .01$) interactions were also present. Thus, acceleration was affected by all three major factors in this study.

A final item to consider for acceleration is the number of zero-crossings. A zero-crossing occurs when acceleration changes from positive to negative or vice-versa. In the ideal case, there would be only one zero-crossing as the participant speeds up toward the target, slows at the approach, and arrives perfectly on the mark. Thus, we can ask whether crossing contains fewer zero-crossings than pointing, especially for the MI group, and regard this as a measure of "smoothness." Acceleration zero-crossings also can be thought of as peaks occurring in velocity profiles. Although these peaks do not necessarily constitute submovements in their own right, they do convey the smoothness of motion. Figure 20 shows the average number of acceleration zero-crossings for the factors of interest.

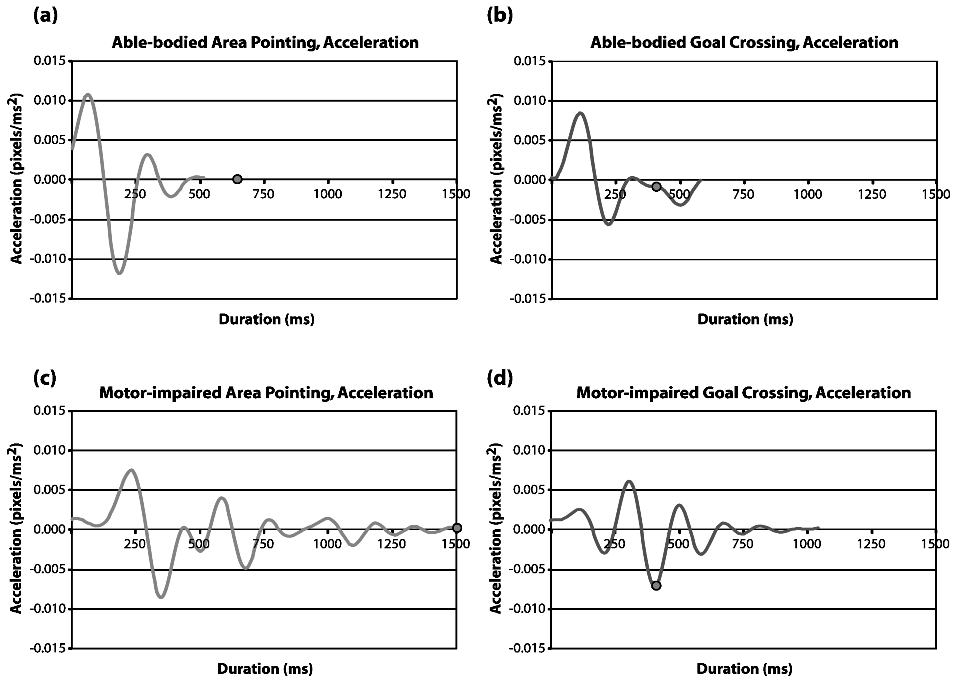

Fig. 21. Acceleration profiles over time using the mouse for **(a,b)** able-bodied participants and **(c,d)** motor-impaired participants. The dot represents the click or crossing event. The graphs on the left are for area pointing. The graphs on the right are for goal crossing. These profiles are for the same movements used in Figure 17.

From Figure 20 we can see that goal crossing is "smoother" than mouse pointing; that is, it results in fewer acceleration/deceleration changes within each device for each participant group. A significant effect of *Technique* confirms this ($F_{1,542.9}$ = 293.39, p< .0001). *Impairment* was also significant ($F_{1,13.8}$ = 35.91, p< .0001), as able-bodied participants had fewer zero-crossings than motor-impaired participants. *Device* was also significant ($F_{1,540.5}$ = 39.89, p < .0001), as the mouse had fewer zero-crossings than the trackball. There was a significant *Impairment**Technique* interaction ($F_{1,524.9}$ =81.81, p <.0001), as motor-impaired participants had comparatively fewer zero-crossings with crossing than with pointing relative to able-bodied participants. These results help explain why goal crossing was found to be beneficial for people with motor impairments in our overall performance results.

Figure 21 shows the acceleration plots for the same typical trials as shown in Figure 17. Many of the findings just mentioned can be seen by comparing the graphs.

4.3.4 *Jerk Profiles.* Jerk measures the change in acceleration over time. It is the third derivative of position. Although jerk is somewhat hard to intuit, jerk submovement profiles correlate with how smooth a movement is. We can

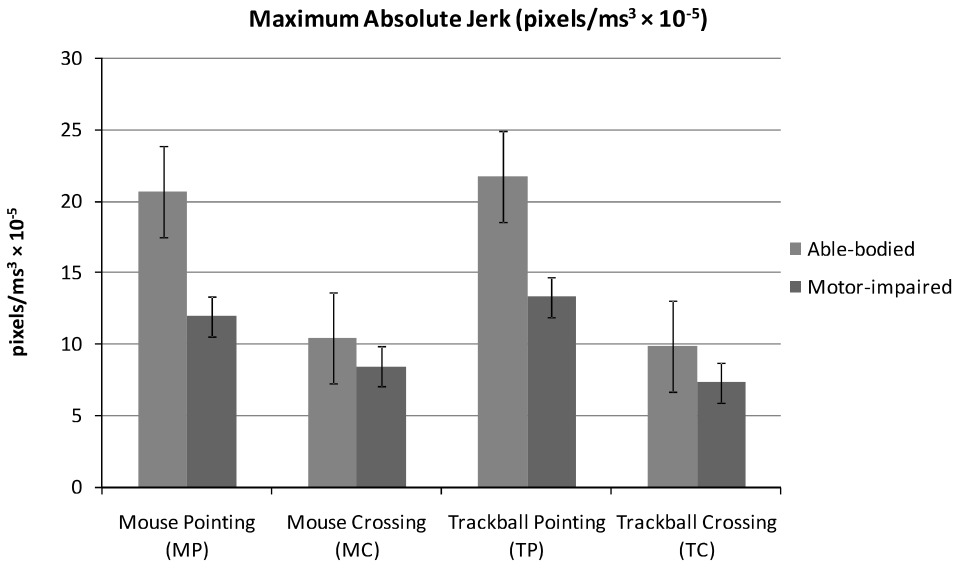

Fig. 22. Average maximum of absolute jerk in pixels/ms^3. The absolute value is used so that jerk above and below the x-axis is considered. Error bars represent ±1 SE. Scientific notation is used for readability (e.g., 20.00 = 20.00e-5 =.00020).

look at the maximum absolute jerk in the jerk profiles to get a sense of how smooth participants' movements were (Figure 22).

Motor-impaired participants had lower maximum absolute jerk than able-bodied participants ($F_{1,14.1}$ = 15.91, $p < .01$). However, the biggest difference lay in crossing versus pointing ($F_{1,543.2}$ = 232.55, $p < .0001$). As can be seen in Figure 22, crossing exhibited much lower maximum jerk than pointing. The amount to which this was the case depended significantly on the participant group ($F_{1,543.2}$ = 36.91, $p < .0001$). Although both groups exhibited lower maximum jerk for crossing than for pointing, the reduction for able-bodied participants was greater than for participants with motor impairments. Thus, by this measure, crossing seems to "smoothen" users' movements.

The maximum absolute jerk does not address the entire jerk profile. For this we look to the *minimum jerk model* [Hogan 1984; Flash and Hogan 1985], which asserts that human motion strives to minimize jerk over the course of aimed movements. Although a full examination of our data with respect to this model is beyond the current scope, we can use the model's definition of total square integrated jerk to compute the amount of jerk in entire movements. These results are shown in Figure 23.

Unlike for absolute maximum jerk, *Impairment* only marginally affected total square integrated jerk due to high variance ($F_{1,14.4}$ = 4.12, p = .06). However, the difference between crossing and pointing was again strong ($F_{1,544.6}$ = 95.70, $p < .0001$), with crossing having much less jerk overall than pointing. This again was different depending on participant group, as judged by a significant *Impairment*Technique* interaction ($F_{1,544.6}$ = 19.36, $p < .0001$). In fact,

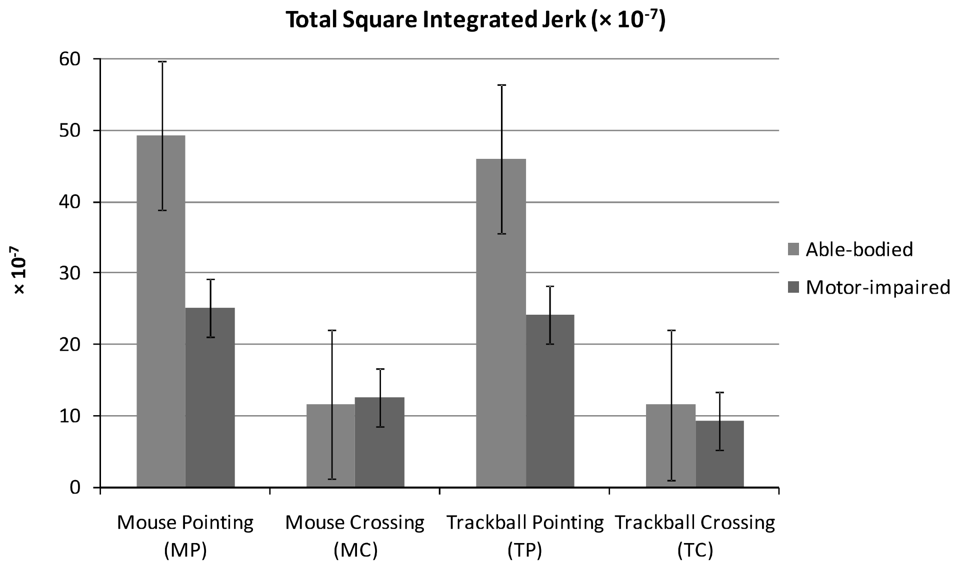

Fig. 23. Average total square integrated jerk. These measures are for comparisons only and are to be regarded as unitless. Error bars represent ±1 SE. Scientific notation is used for readability (e.g., 50.00 = 50.00e-7 =.0000050).

the jerk of both participant groups for goal crossing was not significantly different ($F_{1,20.1}$ = 0.02, n.s.). The difference was clear, however, between able-bodied pointing and motor-impaired pointing as it concerns jerk ($F_{1,20.1}$ = 12.93, $p < .01$). Put another way, in view of jerk, goal crossing makes participants from both groups appear indistinguishable, but conventional area pointing highlights their differences.

It may strike some readers as counterintuitive that for pointing, the motor-impaired participants had less overall jerk than the able-bodied participants. However, slower longer movements generally produce less jerk, and in view of our velocity and acceleration results, which were lower for motor-impaired participants than able-bodied participants, it seems that this is a probable explanation. This may be one form of compensatory movement behavior similar to that found for elderly participants [Walker et al. 1997]. We return to this issue in our discussion.

Figure 24 shows the jerk profiles for the same typical trials used in creating velocity and acceleration profiles above. The findings in this section are evident in these graphs.

5. DISCUSSION

Perhaps the most interesting finding from our study is that our participants with motor impairments could indeed perform goal crossing, and that they could do so faster than pointing (Figure 6). The MI group also preferred goal crossing to area pointing (Figure 13(a)), and felt it easier and faster to

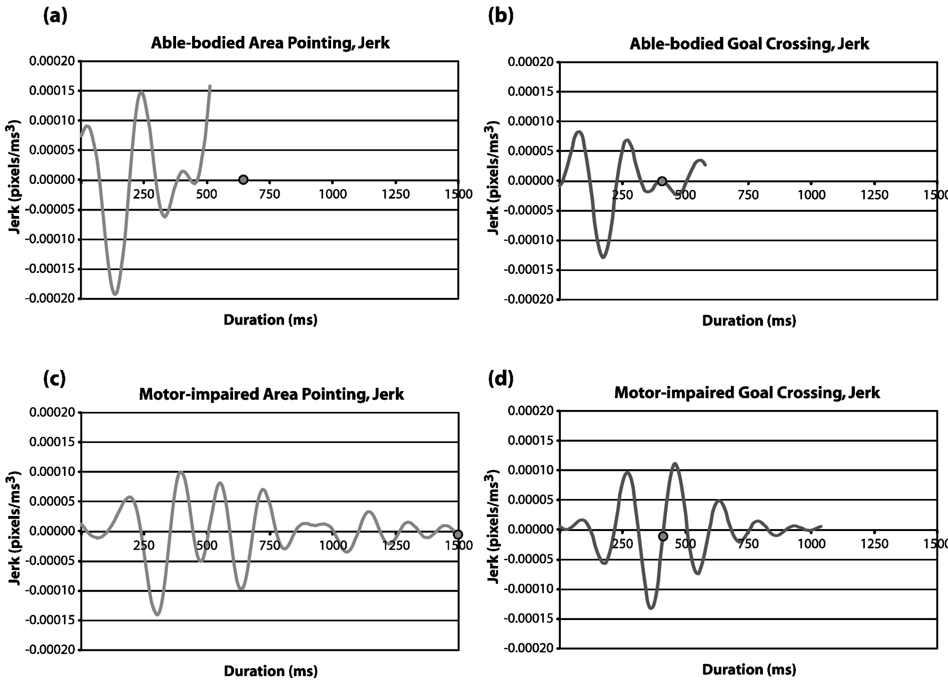

Fig. 24. Jerk profiles over time using the mouse for **(a,b)** able-bodied participants and **(c,d)** motor-impaired participants. The dot represents the click or crossing event. The graphs on the left are for area pointing. The graphs on the right are for goal crossing. These profiles are for the same movements used in Figures 17 and 21.

perform (Figures 13(b) and 13(c)). Furthermore, these participants were modeled well by Fitts' law, and had higher throughput for crossing than for pointing (Table II). Our able-bodied participants, 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 IDs. Had higher IDs been tested, AB throughput indicates that pointing would have become faster. (We omitted high IDs from our study because we did not know whether people in the MI group would be able to do crossing in the first place, let alone at high IDs. As things stood, the W = 16 targets were difficult for these users to acquire, especially at A = 384.)

Although our MI participants' throughput was in favor of goal crossing, this finding is somewhat compromised by the higher error rate for MI crossing than for MI pointing (Figure 8). As noted, our data did not permit us to normalize W to a 4% error rate using W_e due to high variance and not enough trials per $A - W$ combination. (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 participants [Keates et al. 2000; 2002]. However, it should be noted that our definitions of pointing and crossing errors are unavoidably "apples and oranges." Unlike studies comparing different input devices on the same pointing tasks [MacKenzie et al. 1991], we have semantically distinct notions of errors (Figure 5). 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 [Accot and Zhai 2002]. Regardless, the absolute throughputs shown in Table II are of secondary interest to the relative performance of crossing and pointing within each participant group. Because all participants did both crossing and pointing, we can be confident in our within-group comparisons that indicate crossing's promise relative to pointing for those with motor impairments.

Path analysis measures favor crossing over pointing for both groups of participants (Table III). Task axis crossings (*TAC*) were fewer with crossing than pointing for motor-impaired participants, even though this was flipped for able-bodied participants. Crossing had fewer directional changes of both types (*MDC* and *ODC*) than pointing for both participant groups. Movement variability (*MV*), movement error (*ME*), and movement offset (*MO*) were all in favor of crossing, particularly for the motor-impaired participants. Crossing also incurred less overall cursor travel distance (*PD*). These results are almost unequivocal in their support of goal crossing over area pointing, especially for people with motor impairments.

Submovement results also generally favor goal crossing over area pointing. Maximum velocities, accelerations, and jerks were lower for crossing than for pointing for both participant groups. In addition, the maximum velocities and accelerations were reached much earlier in pointing trials than in crossing trials. These findings suggest a qualitatively different "feel" to crossing, where smoother, less ballistic movements are made as goals are steadily approached.

We observed participants adopting different strategies for the two techniques. When pointing, participants in both groups "flew out" quickly to their intended target with a large ballistic movement (Figures 17(a) and 17(c)). 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, participants moved steadily toward their intended goal line until they felt confident they could move across it. Often participants would "flick" the cursor across the goal line once they were sure they could hit it, especially with the trackball, which affords this kind of action.

Of particular interest is how crossing improved the performance of participants with motor impairments. Crossing enabled smoother movements, as judged by fewer acceleration/deceleration shifts (Figure 20) and lower overall jerk (Figure 23)—in fact, this was true for *both* groups of participants. Interestingly, motor-impaired participants were able to exhibit the same jerk as able-bodied participants when doing goal crossing, even though they were very different when doing area pointing.

The *optimized submovement model* says that the noise in an aimed movement is proportional to the force applied [Meyer et al. 1988]. As Walker et al. [1997] observed for elderly users, motor-impaired participants seem to compensate for greater noise in their motor system by using more submovements (Figure 14) and applying less force during movement (Figure 18). This

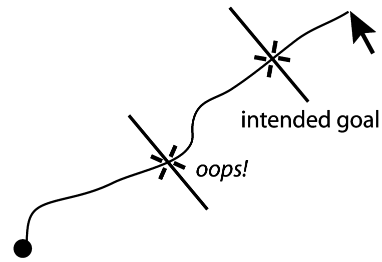

Fig. 25. The occlusion problem in mouse-based user interfaces. Unlike in pen interfaces [Apitz and Guimbretière 2004], a desktop mouse cursor cannot "fly in," cross, and then "fly out."

compensatory behavior creates smoother target acquisition movements for people with motor impairments. Such movements seem to suit goal crossing, since these movements lend themselves to a delayed peak velocity and acceleration compared to pointing.

Although rethinking user interfaces to remove the need for pointing-and-clicking may seem implausible or even unimaginable, these results give evidence for the benefits of goal crossing for motor-impaired users. Were the results more equivocal, the time and expense to "design away" pointing-and-clicking may not be justified. However, the malleability of software allows us to explore radical new target acquisition schemes with relative ease. The next section offers some initial design directions for crossing widgets with an eye towards solving a key fundamental problem related to occlusion in two-dimensions.

6. DESIGN DIRECTIONS

The empirical findings presented here suggest that goal crossing may be useful for people with motor impairments. In a way, this is not surprising in light of the problems with area pointing described in the introduction. However, the design of "crossing widgets" is rife with challenges, and workable solutions are by no means clear. This section attempts to jumpstart design efforts by describing possible crossing widgets. Ultimately, accessible crossing-based applications and even crossing-based user interface toolkits may be built, enabling a proliferation of these interfaces among the people who need them.

A key issue in mouse-cursor crossing interfaces is *the occlusion problem*. When one goal lies in front of another, how can the system know which crossing event is intentional and which is not? (Figure 25)

A quick solution to this problem is to require the mouse button to be held down for intentional crosses. However, a major motivation for this work is the difficulty people with motor impairments have when clicking and dragging [Trewin and Pain 1999]. We therefore do not consider dragging across goal lines to be a promising solution. Besides, dragging with a trackball is especially difficult [MacKenzie et al. 1991].

To date, we have devised five solution categories for addressing the occlusion problem in crossing-based interfaces. Specific ideas within these categories

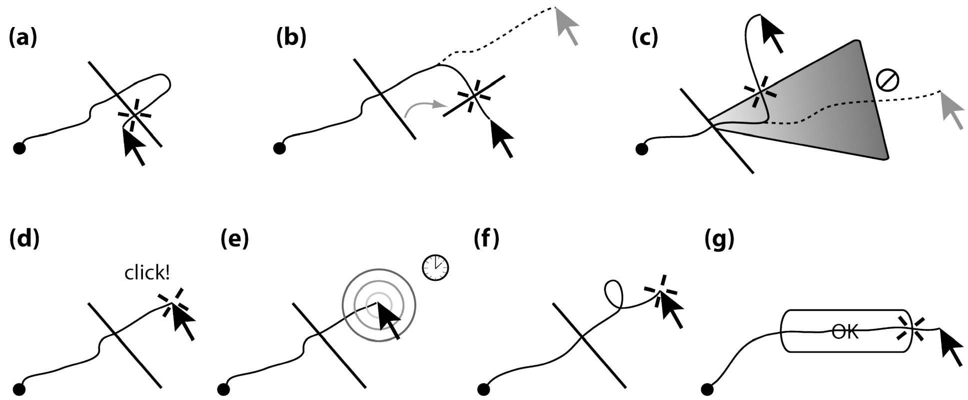

Fig. 26. Two-stage designs for confirming an intentional cross in mouse-based user interfaces: **(a)** Re-crossing a goal backwards, **(b)** crossing a secondary "swing out" goal, **(c)** exiting a rotating wedge tunnel from the side, **(d)** clicking anywhere after crossing, **(e)** pausing briefly after crossing, **(f)** making a pigtail gesture after crossing, or **(g)** steering along a crossing "button."

have yet to be tested; these categories represent initial conceptual steps. The five solution categories are:

(1) Two-stage crossing.
(2) Modal crossing.
(3) Submovement analyses.
(4) Features of the crossing event.
(5) Supplement crossing with the eyes or voice.

Each of these is briefly described in the sections that follow.

6.1 Two-Stage Crossing

The idea behind two-stage crossing is to use a second action to confirm that the most recently crossed goal was crossed intentionally. There are many possibilities for two-stage designs: crossing a second goal, clicking anywhere, pausing briefly, gesturing after a cross, or successfully steering. These ideas are depicted in Figure 26.

Certainly not all of these approaches will be accessible to people with motor impairments. As with any interaction technique, the exact details of a design make a big difference. The next step is to prototype these and other two-stage concepts and conduct usability studies of their feasibility, human performance, visual clarity, and likeability. Which designs work better in high-density situations? Which designs are most intuitive to new users? What other two-stage ideas will emerge? Talented designers can begin to think along these lines, and radically reshape user interfaces in the process.

6.2 Modal Crossing

Although it may be a tired approach, using a mode to disambiguate intentional from unintentional crosses may be a viable solution. As with any mode, the issues are how the mode will be set, how it will be perceived, and how it will be unset. We can distinguish between *active modes* and *passive modes*. An active mode requires the user to constantly maintain it, increasing the user's awareness but requiring ongoing effort. A passive mode is a toggle that can be discretely set and unset.

The idea of having the mouse button held down while crossing a goal is an example of an active mode. But as we have said, this is likely to present problems for many users with motor impairments.

Numerous possibilities exist for setting passive modes that precede an intentional cross. In fact, a mode may be set by performing any of the two-stage actions in Figures 26(d) through 26(f). In other words, a user could click anywhere, pause briefly, or perform a gesture just before crossing. Doing these actions would set a mode that indicates the next goal crossed is done so intentionally. Once the goal is crossed, the mode would unset. More simply, a passive mode could also be set by pressing a physical switch or keyboard key (e.g., the spacebar).

6.3 Submovement Analyses

Our analysis of submovement profiles in this article was chiefly concerned with developing a better understanding of pointing versus crossing, particularly regarding speed, accuracy, exerted force, and smoothness. However, it may also be possible to distinguish intentional crosses from unintentional ones based on patterns that emerge at the submovement level. For example, we discovered that maximum goal crossing velocity happened on average about 45% of the way through the movement (Figure 16), and that the crossing event usually occurred after this during a deceleration phase (Figures 17 and 21). If these observations are reliable, this type of information could be used to intelligently infer which crosses are intentional and which are not.

Another approach might be one based on machine learning, where a user intentionally and unintentionally crosses a series of goals from various start positions in a cluttered field. Submovement features could be extracted and weighted to help distinguish these crossing events. One drawback of this approach, however, would be that each user would have to train the system individually, especially in light of the high variation in function that exists among people with motor impairments [Keates et al. 2000].

6.4 Features of the Crossing Event

Perhaps solving the occlusion problem using submovement features would be unreliable, hard for the user to decipher, or introduce lag into the determination of intentional and unintentional crosses. It may be that instead, we can consider features of the crossing event itself. At least three aspects of the crossing event may be used: approach angle, speed, and acceleration. For approach angle, perhaps it is sufficient to require that intentional crosses be close to perpendicular. Crosses within $\pm 10^{\circ}$ might acquire the widget, but crosses at other angles would not. Alternatively, maybe intentional crosses must simply be above (or below) a certain speed threshold. As long as this threshold is outside the normal range of mouse speeds, casual mouse movement should not produce unwanted acquisitions. Yet another option might be to require that the acceleration of an intentional cross be above a threshold. Crossing at a steady velocity would not acquire any goals, but speeding up significantly over a goal would. These features of the crossing event itself might be easier to discern and more intuitive to the user than aspects of submovement profiles.

6.5 Supplement Crossing with the Eyes Or Voice

If we are willing to allow for additional hardware and software, we might solve the occlusion problem using either the user's eyes or voice. Previous research shows that users' gaze arrives at targets before the mouse cursor does [Jacob and Karn 2003]. This information alone could help distinguish intentional crosses from unintentional ones: any goal crossed without first being fixated upon by the eyes would simply be ignored. Similar techniques have been used in applications for able-bodied users [Jacob 1990; Zhai et al. 1999; Kumar and Winograd 2007]; perhaps the eyes would work equally well as a supplement to goal crossing user interfaces. Unfortunately, however, adding the requirement of an eye-tracker undermines the original motivation for this work, compromising our attempt to provide accessible mouse- and trackball-based user interfaces that do not require uncommon specialized technologies. Because our goal is to reduce barriers to access, one must carefully consider whether an eye-tracker (or similar add-on) is really a viable solution.

A related solution that somewhat avoids this concern is to use the human voice as a disambiguation signal. With this design, the user would simply utter a distinct consonant sound such as "ch" or "ck" after an intentional cross. A separate sound, perhaps a vowel sound (e.g., "aaah"), could undo any misrecognized crosses and the actions that followed them. Explicit word recognition should be avoided to better support users with speech impediments. These types of nonspeech sounds are similar to those found in the *Vocal Joystick* [Harada et al. 2006] and the *VoiceDraw* application [Harada et al. 1997].

The ideas in Sections 6.1–6.5 require extensive design, prototyping, and evaluation. A sound design process will involve people with motor impairments at every step, particularly through rapid iterative testing. This presents its own challenges [Coyne 2005], but is necessary for human performance designs like this to succeed.

Ultimately, crossing applications or crossing-based user interface toolkits could be built, allowing others to create software that may be more accessible to people with motor impairments. Beyond toolkits would be applications that can change themselves from pointing-based to crossing-based at the flip of a switch. Although such applications are not available today, recent work has demonstrated the feasibility of applications that tailor themselves to the functional abilities of their users [Gajos et al. 2007].

7. 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 promising 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 participants. These participants also preferred goal crossing to area pointing, and felt that it was faster and easier to perform. Path analysis measures indicate that goal crossing movement is less wiggly and more consistent 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. Submovement results indicate that goal crossing reduces the maximum force applied and the overall jerk, and increases the smoothness of motion. In reporting these findings and presenting new design ideas, this work has laid the foundation for further investigation into the creation of accessible crossing-based user interfaces for desktop computing.

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