The Angle Mouse: Target-Agnostic Dynamic Gain Adjustment Based on Angular Deviation

Jacob O. Wobbrock
The Information School
DUB Group
University of Washington
Seattle, WA 98195 USA
wobbrock@u.washington.edu

James Fogarty, Shih-Yen (Sean) Liu, Shunichi Kimuro, Susumu Harada
Computer Science & Engineering
DUB Group
University of Washington
Seattle, WA 98195 USA
{jfogarty, sysliu, kimuro, harada}@cs.washington.edu

ABSTRACT

We present a novel method of dynamic C-D gain adaptation that improves target acquisition for users with motor impairments. Our method, called the *Angle Mouse*, adjusts the mouse C-D gain based on the deviation of angles sampled during movement. When angular deviation is low, the gain is kept high. When angular deviation is high, the gain is dropped, making the target bigger in motor-space. A key feature of the Angle Mouse is that, unlike most pointing facilitation techniques, it is *target-agnostic*, requiring no knowledge of target locations or dimensions. This means that the problem of distractor targets is avoided because adaptation is based solely on the user's behavior. In a study of 16 people, 8 of which had motor impairments, we found that the Angle Mouse improved motor-impaired pointing throughput by 10.3% over the Windows default mouse and 11.0% over sticky icons. For able-bodied users, there was no significant difference among the three techniques, as Angle Mouse throughput was within 1.2% of the default. Thus, the Angle Mouse improved pointing performance for users with motor impairments while remaining unobtrusive for able-bodied users.

Author Keywords: Mouse pointing, pointing facilitation, pointing techniques, control-display gain, dynamic gain adjustment, target acquisition, cursor control.

ACM Classification Keywords: 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*.

INTRODUCTION

Pointing facilitation techniques promise to improve the efficiency of one of the most common actions users take with desktop computer systems: acquiring targets with the mouse cursor. This action, although seemingly incidental in isolation, becomes important when repeated hundreds or thousands of times. Therefore, small improvements in pointing speed or accuracy may culminate in large overall efficiency gains when using graphical user interfaces [2].

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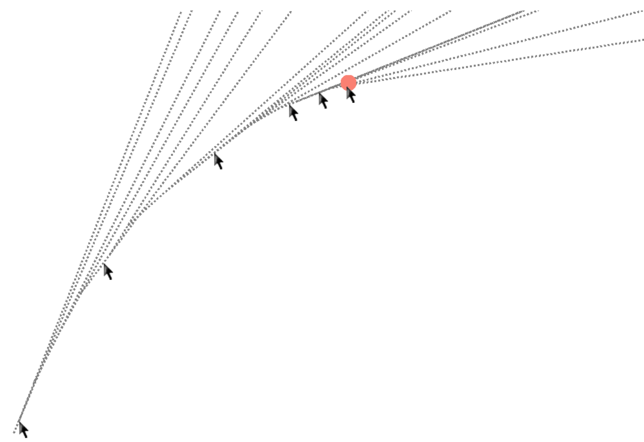

Figure 1. Mouse path showing 16 angle samples and their spread (i.e., deviation) during movement. The central idea of the *Angle Mouse* is to dynamically adjust C-D gain in response to this spread.

One may reasonably wonder why we do not see more pointing facilitation techniques in practice. The answer may be that most techniques are inherently *target-aware* [2], meaning they require the mouse cursor to know about, and respond to, the locations and dimensions of on-screen targets. Examples are gravity wells [16], force fields [1], sticky icons [36], semantic pointing [5], area cursors [19], bubble cursors [13], bubble targets [7], and object pointing [14]. Target-aware techniques may even require the ability to alter the targets themselves, for example, by enlarging them [27] or bringing them closer to the mouse cursor [3].

In contrast, few techniques are *target-agnostic*, meaning that the mouse cursor can remain ignorant of all on-screen targets, and targets themselves are not directly manipulated. Conventional pointer acceleration [6] is by far the most common target-agnostic technique, one found in all modern commercial systems. Other target-agnostic techniques are much more specialized, such as for multiple monitors [4] or for use with eye-pointing [37]. In general, target-agnostic techniques represent a tiny minority of pointing facilitation techniques.

However, at least two challenges threaten the success of target-aware techniques. The first is pragmatic: at any given time, possibly myriad targets exist on the screen, and all must be made known to the mouse cursor. Whenever a window is closed, a menu opened, or an application launched, the set of on-screen targets changes, and the cursor must be made aware of this. The second problem is more fundamental: at any given time, a user means to acquire one target, but $N-1$ "distractor" targets exist, representing obstacles [1,16]. This problem becomes pathological in dense target layouts. Consider, for example, a document full of text. What, exactly, is the set of targets? Each character? word? paragraph? the margins? Or take a calendar program, where clicking anywhere on unscheduled space allows one to create a new appointment, making *all* timeslots potential targets and therefore distractors. Target-agnostic techniques do not suffer from either of these problems, but they are limited as a result of being blind to the very targets they seek to acquire.

Although successful pointing facilitation techniques benefit any computer user, these techniques may be most beneficial to users who have difficulty pointing with the mouse. Such users may include people with motor impairments [17], young children [15], or elderly users [31]. Apart from the exceptions noted in our review of related work, few research efforts have attempted to invent pointing facilitation techniques for people in these groups.

In the case of users with motor impairments, such techniques may be particularly beneficial. Specialized assistive technologies may be used by people with *severe* disabilities, but many people with limited use of their hands still prefer mice, trackballs, and touchpads [11]. In fact, some studies show that under 60% of people who indicate a need for adaptations actually use them [9]. But mouse pointing presents numerous difficulties for people with motor control problems [17,33]. Thus, it is important to improve the effectiveness of ordinary commodity devices for individuals with motor impairments [12,35].

In light of these considerations, we present the *Angle Mouse* (Figure 1), a target-agnostic pointing facilitation technique that improves target acquisition performance for people with motor impairments. The Angle Mouse observes the "spread of angles" created during a pointing movement. When this spread is narrow (Figure 2a), the control-display (C-D) gain is maintained. When the spread widens (Figure 2b), as often occurs when a user makes submovement corrections [17], the gain is dropped (Figure 3), effectively making the target larger in motor-space [5].[1] Conveniently, because this scheme relies only on cursor behavior, the Angle Mouse avoids the problem of distractor targets and is equally suited for pointing to any pixel as any other.

[1] Dropping the gain means that moving the physical mouse a given distance on the desk will result in a proportionally smaller cursor movement on the screen.

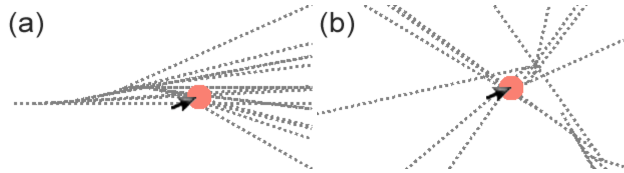

Figure 2. (a) Coherent movement produces low angular deviation (σ_θ), 13.7° in this example, and retains most of the maximum gain (89%). **(b)** Divergent movement produces high angular deviation (94.8°) and keeps less of the maximum gain (21%).

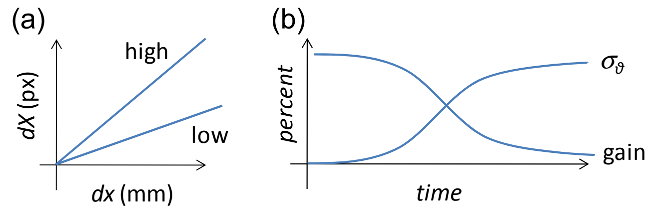

Figure 3. (a) High and low constant gain. The gains are the slopes of the lines as *dX*/*dx* in pixels/mm. **(b)** Conceptual relationship between angular deviation (σ_θ) and C-D gain.

We wanted to see if the Angle Mouse could improve the pointing performance of motor-impaired computer users without hampering the performance of able-bodied users. In a formal pointing experiment based on ISO 9241-9 [8], we found that this was the case. Motor-impaired performance with the Angle Mouse improved throughput by 10.3% compared to the Windows default mouse and 11.0% compared to sticky icons [36], while able-bodied throughput was not significantly different among the three techniques. For able-bodied users, the Angle Mouse was within 1.4% of the throughput of the default mouse on average, indicating little effect of our technique. This indicates that the Angle Mouse is a potentially viable real-world technology that may benefit some users while remaining unobtrusive for others.

RELATED WORK

Numerous pointing facilitation techniques have been studied, many of which are mentioned in this paper's introduction. Due to space limitations, all of these cannot be discussed; readers are directed to prior surveys [2].

Aside from pointer acceleration [6,24] and manual gain control [18,30], most facilitation techniques that manipulate C-D gain are target-aware. These include sticky icons [36], also formalized as semantic pointing [5], and gravity wells [16], which can be used to increase gain when moving into targets and reduce gain when moving away [21]. Others have performed gain adaptation only along one axis of movement to reduce the problem of distractor targets [7]. Studies of these techniques [26] show that subtle gain changes are more acceptable to users and can still provide a performance benefit.

A few research projects have studied pointing facilitation techniques for people with motor impairments. Some examine physical force-feedback using haptic devices [16,23], finding these aid motor-impaired performance. Koester et al. [22] devised a system for automatically recommending a C-D gain setting based on a user's performance over a set of pointing trials, but found the recommended gain was not significantly better than the Windows default. Gajos et al. [12] showed performance benefits not by altering the gain, but by customizing the entire user interface. Wobbrock and Gajos [35] investigated motor-impaired goal crossing as an alternative to pointing, finding crossing was better for motor-impaired users.

ANGLE MOUSE THEORY

This section explains the Angle Mouse in detail, including the mathematics for calculating angular deviation and for mapping it to C-D gain.

Basic Design

The Angle Mouse relies on a queue of sampled angles that are taken during movement. In our implementation, upon the arrival of each mouse point, we test whether it is at least ΔD pixels from the previously sampled mouse point. If so, we find the angle between the two points and store it as θ_i in our queue of n angles. We found $\Delta D = 8$ pixels and $n = 16$ angles worked well in practice.

The most basic Angle Mouse design uses a scheme that adjusts the C-D gain based on unweighted angular deviation (σ_θ). *Angular deviation* reflects the spread of angles and is defined with Eq. 1:

$$\sigma_\theta = \sqrt{\frac{\sum_{i=1}^{n} \Delta\theta_i^2}{n-1}}, \quad (1)$$

where n angles are currently queued and

$$\Delta\theta_i = \left\|\theta_i - \bar{\theta}\right\|_\theta. \quad (2)$$

In Eq. 2, the notation $\|\varphi_i - \varphi_j\|_\theta$ means the "angular distance between φ_i and φ_j." We define *angular distance* as the nonnegative acute angle formed between two angles, with range [0°…180°]. Some examples are $\|359° - 1°\|_\theta = 2°$ and $\|1° - 270°\|_\theta = 91°$ (Figure 4).

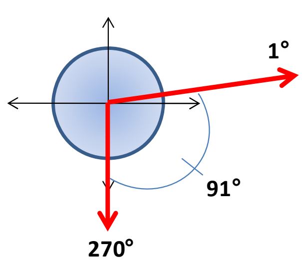

Figure 4. The angular distance between 1° and 270° is 91°.

In general, angular distance can be computed numerically for all $-\infty < \varphi_i, \varphi_j < +\infty$ as

$$\left\|\varphi_i - \varphi_j\right\|_\theta = \left|(|180 - \varphi_i + \varphi_j| \bmod 360) - 180\right|. \quad (3)$$

In Eq. 2, $\bar{\theta}$ is the *angular mean*, and intuitively represents the angle geometrically most central to all others. Mathematically, of course, we cannot simply average angle values: the angular mean of 359° and 1° is 0°, not (359° + 1°) / 2 = 180° (Figure 5).

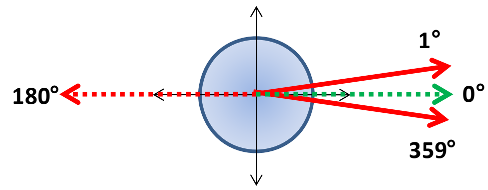

Figure 5. A proper angular mean calculation for 1° and 359° is 0°.

Using unit vectors representing each of our queued angles θ_i, we compute the angular mean as

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right), \quad (4)$$

where $(\bar{x}, \bar{y})$ is the mean unit vector. Of course, to convert any one of our angles θ_i to a unit vector (x_i, y_i), we use

$$(x_i, y_i) = (\cos\theta_i, \sin\theta_i). \quad (5)$$

At this point, we have successfully computed the angular deviation (σ_θ) using the angular mean ($\bar{\theta}$). Now we must map σ_θ to a gain G:

$$G = G_{\min} + \left(1 - \frac{\sigma_\theta}{\sigma_{\theta_{\max}}}\right)(G_{\max} - G_{\min}), \quad (6)$$

where $G_{\min}$ and $G_{\max}$ are the minimum and maximum gains in our desired range, and $\sigma_{\theta_{\max}}$ is the maximum angular deviation, which we empirically determined to be about 120° for our queue of $n = 16$ angles.

The mouse configuration on Windows XP/Vista uses an abstraction for the gain setting, where integers 1 to 20 can be set that correspond to positions on the mouse control panel slider. The Windows default slider value is 10. For our experiment, we chose ($G_{\min}$,$G_{\max}$) to be (2,11) on this scale. The mappings of these slider values to actual C-D gain values will be discussed in our experiment below.

Although our definition and use of angular deviation is novel, a similar notion was raised by Hwang et al. [16], who defined *angular distribution* as the histogram of angles formed with the task axis over the course of a movement. Keates et al. [20] defined essentially the same thing as a cursor's *curvature distribution*. Neither concept was used in the creation of a new pointing facilitation technique.

Weighted Angles

During testing and development, we found that the unweighted treatment of angles left something to be desired. Every new angle "mattered" the same as every old angle, and this meant that restoring coherence after high deviation was met with some lag. The angle queue could be shortened to reduce this lag, but then fewer angles were "remembered," which resulted in insufficient gain reduction during the final phase of target acquisition.

To address this problem, we explored the use of *weighted* angle queues, which allowed emphasis to be placed on more recent angles while retaining the original queue length. Eqs. 7-10 compute weighted versions of angular deviation ($w\sigma_\theta$) and angular mean ($w\bar{\theta}$) to replace Eqs. 1, 2, 4 and 6. For readability, we omit the usual summation bounds $i = 1$ to n:

$$w\sigma_\theta = \sqrt{\frac{\sum w_i}{\left(\sum w_i\right)^2 - \sum w_i^2}\left(\sum w_i \cdot \Delta\theta_i^2\right)}, \tag{7}$$

$$\Delta\theta_i = \left\|\theta_i - w\bar{\theta}\right\|_\theta, \tag{8}$$

$$w\bar{\theta} = \tan^{-1}\left(\frac{\frac{1}{\sum w_i}\sum w_i \sin\theta_i}{\frac{1}{\sum w_i}\sum w_i \cos\theta_i}\right), \tag{9}$$

$$G = G_{\min} + \left(1 - \frac{w\sigma_\theta}{\sigma_{\theta_{\max}}}\right)\left(G_{\max} - G_{\min}\right), \tag{10}$$

where w_i is the i^{th} weight from a weighting function. Note that Eq. 9 just combines Eqs. 4 and 5 and applies weights.

Using weighted angles, we can place more emphasis on recent angles with the rationale that they are more indicative of what the user is trying to do than older angles. We explored various weighting functions, a few of which are shown in Figure 6. We tested these in pilot studies with able-bodied and motor-impaired participants. The best results were with the *Gaussian*, *linear*, and *constant* functions. Interestingly, however, these functions performed best during *different* phases of target acquisition. For example, Gaussian weights were best while traveling to a target, but constant weights were best when making final-stage corrections. This led us to *dynamic weighting*.

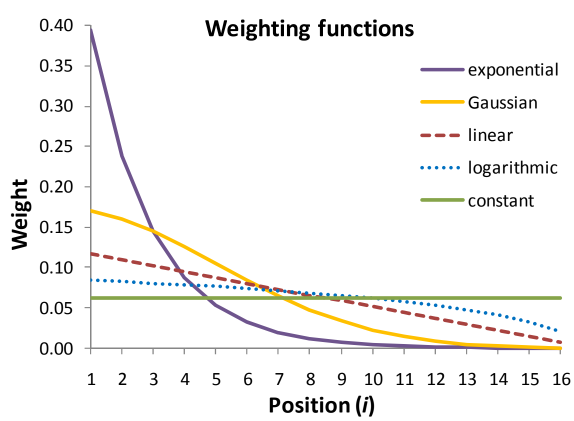

Figure 6. Five weighting functions normalized to sum to 1.0 over our queue of $n = 16$ angles. Many other functions were explored, including the reverse of these.

Dynamic Weighting

The idea behind dynamic weighting is to actually have the weights change during motion based on how coherent or divergent the movement is, i.e., based on the instantaneous weighted angular deviation ($w\sigma_\theta$). Thus, $w\sigma_\theta$ not only affects the gain G according to Eq. 10, but it also affects the weights w_i. The rationale is that during coherent movement (Figure 2a), newer angles are representative and the gain can be kept high during long traversals; but during divergent corrective movements (Figure 2b), to keep the gain low, older deviate movements must still "matter," and newer angles should matter less in proportion—thus, a constant or quasi-constant weighting function is best. We can achieve this result by parameterizing a Gaussian weighting function so that it is peaked during long traversals but nearly flat during corrective movements.

Conveniently, a Gaussian distribution $g(i)$ yielding weight w_i is made sharper or flatter according to its standard deviation (σ_g).[2] Reducing σ_g results in more peaked curves.

$$g(i) = \frac{1}{\sigma_g\sqrt{2\pi}} e^{\frac{-i^2}{2\sigma_g^2}}. \tag{11}$$

So with the arrival of each new angle θ_i, we recompute our weighted angular deviation ($w\sigma_\theta$), map that to the Gaussian standard deviation (σ_g), and then recalculate our weights using Eq. 11. The mapping of $w\sigma_\theta$ to σ_g is simply

$$\sigma_g = \sigma_{g_{\min}} + \left(\frac{w\sigma_\theta}{\sigma_{\theta_{\max}}}\right)\left(\sigma_{g_{\max}} - \sigma_{g_{\min}}\right). \tag{12}$$

As in Eqs. 6 and 10, $\sigma_{\theta\max}$ is 120°. For ($\sigma_{g\min}$,$\sigma_{g\max}$) we use (5,15) as the range of Gaussian standard deviations. Figure 7 shows this range of curves, from peaked to almost flat. Thus, in dynamic weighting, a greater spread of angles during movement lowers gain and (mostly) equalizes the amount each angle contributes to the spread calculation. A lesser spread of angles increases gain, and places more emphasis on newer angles and more quickly ignores older ones.

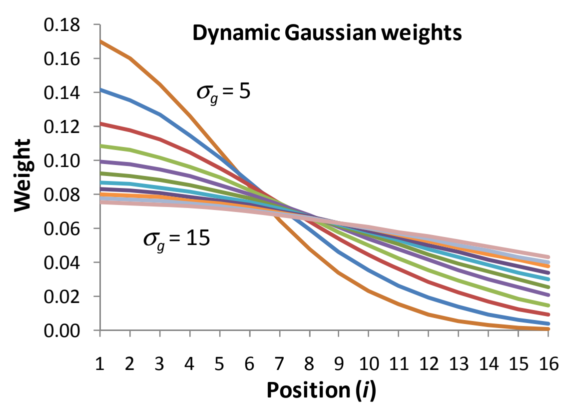

Figure 7. The range of Gaussian weighting curves used in the Angle Mouse. The curves have standard deviation (σ_g) ranging from 5 (most peaked) to 15 (most flat). The former is used when angular deviation ($w\sigma_\theta$) is low; the latter when it is high.

[2] The standard deviation of a Gaussian distribution (σ_g) and the angular deviation during movement ($w\sigma_\theta$) should not be confused.

Pilot testing indicated that the dynamic Gaussian design was most successful among weighting schemes. Now we turn to an experiment in which the Angle Mouse was compared to the Windows default mouse and sticky icons for people with and without motor impairments.

EXPERIMENT METHOD

To examine how the Angle Mouse compared to the Windows default mouse and sticky icons [36], we conducted a formal experiment with motor-impaired and able-bodied users. An established approach was used based on the ISO 9241-9 standard for pointing evaluation [8,32].

Participants

Sixteen participants took part in the study, 8 of whom had motor impairments (Table 1). The average age of the motor-impaired users was 41.1 (*SD*=14.9). For able-bodied users, it was 31.4 (*SD*=7.3). Each group comprised 5 females and 3 males. All participants indicated they were daily computer users and users of mice. One participant, P6, had severe cerebral palsy and was too impaired to readily acquire targets in our study.

Participant	Sex	Age	Wheelchair?	Health Condition
P1	m	51	no	neuropathy
P2	m	52	no	multiple sclerosis
P3	f	20	yes	muscular dystrophy
P4	f	30	yes	cerebral palsy and fibromyalgia
P5	f	57	no	Parkinson's disease
P7	f	28	yes	Friedreich's ataxia
P8	m	58	no	ALS
P9	f	33	yes	Friedreich's ataxia

Table 1. Information on participants with motor impairments.

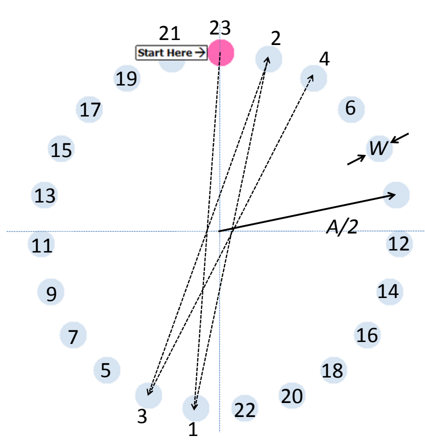

Figure 8. The ISO 9241-9 target arrangement with 23 targets in a given *A*×*W* condition. Our analysis omits the first 3 targets as practice. Arrows and labels are shown here for illustration only.

Apparatus

To facilitate this study, we constructed a testbed application that implemented the two-dimensional circular ISO 9241-9 pointing task [8,32] (Figure 8). The testbed ran full-screen on a 1680×1050 22" flat panel monitor driven by a Lenovo T61 running Windows Vista SP1 at 2.20 GHz with 2.0 GB RAM. Our testbed administered pointing trials and recorded mouse cursor activity with millisecond precision. The mouse device was a Logitech *Click!* connected over USB.

As mentioned above, Windows XP/Vista platforms expose an integer from 1-20 to set the C-D gain; 10 is the default. However, this integer is not the C-D gain itself. Although some on-line documentation[3] discusses pointer ballistics in Windows, it does not contain sufficient information to establish the slider-to-gain mapping. We therefore carefully measured the mapping for our experiment directly (Figure 9). For convenience, however, our subsequent discussion will refer to Window's 1-20 abstraction.

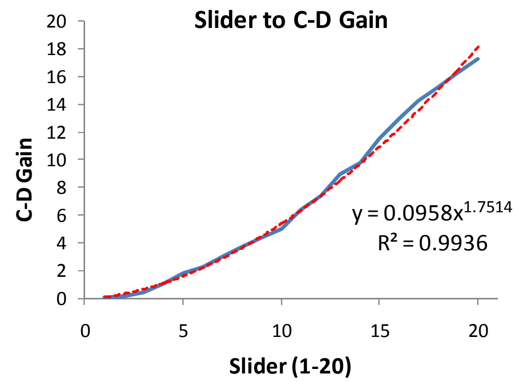

Figure 9. The Windows slider-to-gain mapping for our apparatus.

Because the Windows default operates at a slider value of 10 (gain of 5.0), we set the slider value of sticky icons to also be 10 outside targets and 3 (gain of 0.5) inside targets, a similar ratio to prior work [36]. To ensure the Angle Mouse was operating in the same range, we set its (G_{min}, G_{max}) slider values to be (2, 11); see Eq. 10. This range's extremes are rarely reached, so (3, 10) was the effective slider value range. Thus, at its slowest, the Angle Mouse was about equal to sticky icons inside a target, and at its fastest, it was about equal to the default and sticky icons cursors outside targets.

We disabled pointer acceleration [6] for this study, as prior studies have done [5,26,36], to avoid confounding multiple sources of gain change. The utilized slider range was about 3-10 (0.5-5.0 gain), and quantization was not an issue.

Procedure

Participants were presented with a randomized series of target rings (Figure 8) with different amplitudes (*A*) and target widths (*W*). Each ring had 23 targets, the first three of which were practice unbeknownst to the participant, who was told to acquire targets at a pace that would miss about 1 per ring (5%), which is suitable for the application of Fitts' law [32]. Participants were not told which mouse type they were using. All *A*×*W* conditions were run with each mouse type before a new mouse type was loaded. Of course, participants were encouraged to manipulate the mouse in their natural fashion (Figure 10).

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[3] http://www.microsoft.com/whdc/device/input/pointer-bal.mspx

Figure 10. P3 using two hands to control the mouse.

Design and Analysis

The study was a 3×3×2 within-subjects design for the motor-impaired group and a 3×3×3 within-subjects design for the able-bodied group. It comprised the following factors and levels:

- *Mouse Type* {Angle Mouse, default, sticky icons}
- *Amplitude* (*A*) {448, 576, 704 pixels}
- *Width* (*W*) {8, 16, 32 pixels}

To save time, $W = 8$ was not administered to participants with motor impairments. The Fitts' index of difficulty range was therefore 3.91-5.49 for motor-impaired participants and 3.91-6.48 for able-bodied participants. With 3 mouse types in 6 $A \times W$ conditions and 20 test trials per condition, motor-impaired participants each performed 360 trials, or 2880 for 8 people. Able-bodied participants performed 3×9×20 = 540 test trials, or 4320 for 8 people. In all, the study had 7200 test trials.

The primary independent variable was *Mouse Type*. The main effects of amplitude (*A*) and width (*W*) were predictable and uninteresting. Participants with and without motor impairments were analyzed separately, as the effects of motor impairments were not the focus of this study. Continuous measures were analyzed with repeated measures ANOVA, while event-count measures were analyzed with nonparametric Friedman tests.

RESULTS

In this section, we present the results of the experiment for both motor-impaired and able-bodied participants.

Movement Time

Average movement times for each *Mouse Type* are shown in Table 2. There was no significant effect of *Mouse Type* ($F_{2,14}$=1.11, *ns*), but *Mouse Type* did have a significant interaction with *A* ($F_{4,28}$=3.43, p<.05) and a marginal interaction with *W* ($F_{2,14}$=3.52, p=.06). The Angle Mouse was fastest for short and medium trials, while sticky icons was fastest for the longest trials. The Angle Mouse and sticky icons were about equal for medium-sized targets, but Angle Mouse was fastest for large targets.

For able-bodied users, *Mouse Type* did not exert a significant effect ($F_{2,14}$=0.14, *ns*), but it did interact significantly with *A* ($F_{4,28}$=3.34, p<.05). Sticky icons were slower for short and medium trials, but fastest for long trials.

Motor-impaired group

Mouse Type	*MT (ms)*	*Errors (%)*	*SD (px)*	*TP (bits/s)*
Angle Mouse	2014	5.95^{d}	7.35^{s*}	$3.03^{d,s}$
default	2195	7.30	6.99^{s}	2.75
sticky icons	2041	5.85^{d*}	8.23	2.73

Able-bodied group

Mouse Type	*MT (ms)*	*Errors (%)*	*SD (px)*	*TP (bits/s)*
Angle Mouse	1155	9.95	5.64^{s}	4.26^{s*}
default	1146	10.59	5.50^{s}	4.31
sticky icons	1165	10.76	6.70	4.00

^{d}Better than the Windows default mouse (p<.05).
^{s}Better than sticky icons (p<.05).
*Marginal result (p<.10).

Table 2. Averages for movement time (*MT*), error rate (%), endpoint standard deviation (*SD*), and Fitts' throughput (*TP*). For all measures except *TP*, lower is better.

Errors

Average error rates are shown in Table 2. For motor-impaired users, a Friedman test gives a marginal result for *Mouse Type* ($\chi^2_{(2,N=48)}$=5.69, p=.06). Pairwise comparisons indicate that the Angle Mouse made fewer errors per condition than the default mouse ($\chi^2_{(1,N=48)}$=4.00, p<.05). Sticky icons was marginally more accurate than the default mouse ($\chi^2_{(1,N=48)}$=3.57, p=.06).

For able-bodied users, *Mouse Type* did not exert a significant effect on errors ($\chi^2_{(2,N=72)}$=0.44, *ns*), and no pairwise comparisons were significant.

Throughput

Although movement times and error rates are useful, they conflate task differences with any performance differences that may exist. Fitts' law [10] provides a measure of *throughput* that combines speed and accuracy in a single measure independent of task parameters, removing task variability to isolate performance differences. We followed the latest academic recommendations in applying Fitts' law [32], including the use of effective index of difficulty (ID_e), amplitude (A_e), and width (W_e); removal of outliers but not errors; and calculating throughput as ($ID_e / \overline{MT}$), not as the inverse of the regression slope ($1/b$). The fit of the corrected Fitts' law models for motor-impaired performance was r=0.77. For able-bodied users, it was better, at r=0.91.

Throughput is influenced by the spread of hits as $W_e = 4.133 \times SD$. The *SD* for our two-dimensional task is the bivariate deviation from the normalized centroid point for each $A \times W$ condition [8]. We recognize that larger spreads may be caused by features of the interaction technique, not just by user performance. For example, in preventing the cursor from easily moving to the target center, sticky icons may have higher endpoint deviation because endpoints tend to fall at target edges. That said, our trials are normalized by approach angle, so there is no reason that a tight clustering of endpoints cannot occur at the target's edge using the sticky icons technique. (Recall that endpoint distances from the target center are irrelevant.)

Throughput averages are shown in Table 2. *Mouse Type* had a significant effect on throughput for participants with motor impairments ($F_{2,14}$=4.16, p<.05). The Angle Mouse performed about 10.3% better than the default mouse ($F_{1,14}$=6.89, p<.05), and 11.0% better than sticky icons ($F_{1,14}$=5.52, p<.05). The latter two were not significantly different ($F_{1,14}$=0.01, *ns*). No interactions were significant, but *Mouse Type*×*W* was marginal ($F_{2,14}$=3.45, p=.06)—sticky icons had higher throughput than the default mouse for medium targets, but vice versa for large targets. The Angle Mouse was highest for both.

For able-bodied users, *Mouse Type* did not have a significant effect on throughput ($F_{2,14}$=2.53, *ns*). The Angle Mouse and default mouse performed within about 1.2%, while sticky icons was about 7% worse. Looking closer, *Mouse Type* interacted significantly with both *A* ($F_{4,28}$=2.77, p<.05) and *W* ($F_{4,28}$=5.58, p<.01). The Angle Mouse performed best for the middle amplitude, but all three mice performed similarly for the longest amplitude. Also, all three mice performed similarly for small and medium targets, but sticky icons was worse for the largest ones. This is probably because other targets in the ring were larger also, becoming distractors, or because large sticky targets were easy to enter, but therefore hard to exit.

Target Entries and Target Overshoots

Beyond errors, we can also count target entries and target overshoots. An ideal trial has only one target entry and zero target overshoots. With overshoots, a target entry is not required; it is enough to pass by the target but remain outside it (Figure 11).

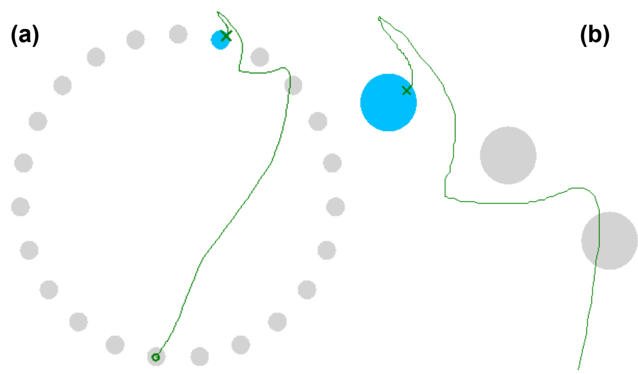

Figure 11. (a) Trial path and **(b)** close-up from our testbed software. This trial by P7 shows one target entry and one target overshoot.

For the motor-impaired group, *Mouse Type* was significant for number of target entries per trial ($\chi^2_{(2,N=48)}$=67.99, p<.0001). Sticky icons had the least at 1.01, followed by the Angle Mouse at 1.27, and the default mouse at 1.39. Sticky icons had significantly less than the other two (p<.01).

Mouse Type also had a significant effect on target overshoots per trial ($\chi^2_{(2,N=48)}$=8.09, p<.02), with sticky icons having the least at 0.44, the Angle Mouse coming next at 0.51, and the default mouse having the most at 0.53. Again, sticky icons had significantly less than the other two (p<.05).

For the able-bodied group, the same ordering occurred for target entries ($\chi^2_{(2,N=72)}$=91.84, p<.0001), with sticky icons lowest at 0.92, the Angle Mouse next at 1.15, and the default mouse highest at 1.20. Sticky icons was significantly less than the other two (p<.0001).

There was no significant effect of *Mouse Type* on overshoots for able-bodied users ($\chi^2_{(2,N=72)}$=3.40, *ns*). The default mouse and sticky icons had 0.36 overshoots per trial, while the Angle Mouse had 0.42. No pairwise comparisons were significant.

Control-Display Gain Adjustment

Our testbed logged C-D gain over the course of each movement. In the case of the default mouse, the gain slider value remained constant at 10. This is also the case for sticky icons, unless the cursor was within a target, in which case the slider value dropped to 3. For participants with motor impairments using sticky icons, the average gain slider value was 8.99, and at the moment of clicking, it was 3.06. For the Angle Mouse, it was 9.59, and at the moment of clicking, it was 7.52. Thus, the same general gain values were being used by these techniques, but in response to different things.

For able-bodied participants using sticky icons, the average gain slider value was 9.09, and 3.04 when clicking. For the Angle Mouse, it was 9.75, and 8.04 when clicking.

Figure 12 shows the angular deviation and slider gain setting for the trial by P7 from Figure 11. These graphs, created automatically by our testbed, give an intuition about how the Angle Mouse is working (see also Figure 3b). As the weighted angular deviation ($w\sigma_\theta$) increases, the gain (G) proportionally decreases.

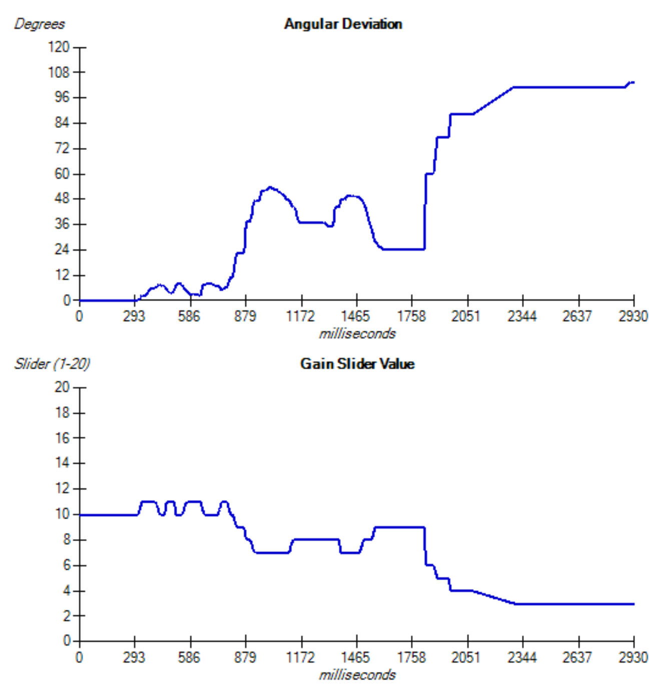

Figure 12. Angular deviation and corresponding gain slider value for the pointing movement by P7 shown in Figure 11.

Path Analyses

To identify potential causes of performance differences, MacKenzie et al. [25] defined path analysis measures. These measures capture what happens during the course of a movement and have been previously used for people with motor impairments [20]. For convenience, they are briefly described here.

- *Task axis crossings (TAC).* A count of how often the task axis from the start point to target center is crossed.
- *Movement direction changes (MDC).* A count of path direction changes parallel to the task axis.
- *Orthogonal direction changes (ODC).* A count path direction changes perpendicular to the task axis.
- *Movement variability (MV).* A continuous measure of "wiggliness" indicating the extent to which the path lies on a straight line parallel to the task axis (pixels).
- *Movement error (ME).* A continuous measure of how much the path deviates from the task axis (pixels).
- *Movement offset (MO).* A continuous signed measure of how much the path deviates from the task axis, where equal deviations to either side of the axis cancel (pixels).

Space precludes a full discussion of the outcomes for each of these measures. Table 3 gives the results.

Motor-impaired	*Angle Mouse*	*default*	*sticky icons*
*TAC**	2.14 (0.49)^d	2.50 (0.76)	2.08 (0.47)^d
*MDC**	4.53 (1.60)^d	5.08 (1.61)	4.39 (1.13)^d
ODC	1.79 (1.32)	1.83 (1.28)	1.58 (1.14)
MV	19.32 (9.60)	17.89 (7.09)	19.90 (10.74)
ME	17.58 (7.60)	16.22 (5.70)	18.22 (9.34)
MO	0.83 (4.50)	0.18 (5.28)	2.20 (5.42)
Able-bodied	*Angle Mouse*	*default*	*sticky icons*
*TAC**	1.82 (0.36)^d	2.04 (0.41)	1.78 (0.36)^d
*MDC**	3.43 (0.58)	3.53 (0.60)	3.31 (0.46)^d
ODC	0.98 (0.68)	0.99 (0.55)	0.86 (0.46)
MV	14.31 (4.76)	13.77 (3.66)	13.83 (3.71)
ME	13.78 (4.12)	12.84 (3.21)	13.31 (3.56)
MO	-0.50 (4.01)	0.50 (4.11)	0.47 (3.59)

Table 3. Path analysis measures. (*) indicates a significant main effect of *Mouse Type* (p<.05). If so, (^{d}) indicates a significant pairwise comparison with the default mouse. Lower is better.

Interestingly, for both participant groups, *TAC* and *MDC* showed the only significant effects of *Mouse Type*. For both groups, these two measures favor the Angle Mouse and sticky icons over the default mouse. On average, although count measures did not favor the default mouse, the continuous measures did but were not significantly different among the different mouse types. These outcomes are considered further in the discussion.

Submovement Profiles

For another view into the target acquisition process, we examined *submovement profiles*, plots of velocity and acceleration over time (Figure 13). Submovement analyses have been useful in distinguishing the pointing performance of elderly and young people [34], in discovering differences among devices [29], and in formulating explanatory theories of movement [28].

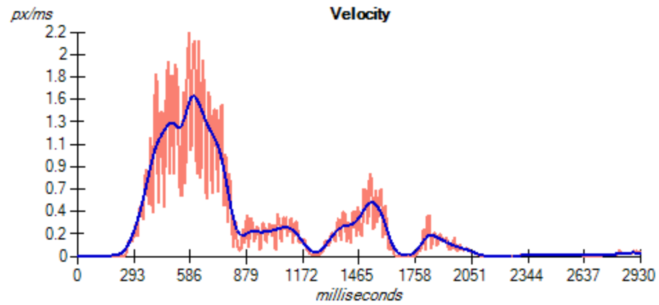

Figure 13. Velocity profile for the pointing movement by P7 shown in Figure 11. After the initial ballistic phase, multiple submovement corrections are visible.

For participants with motor impairments, *Mouse Type* had a significant effect on submovements per trial ($\chi^2_{(2,N=48)}$=14.11, p<.001). Sticky icons had the least at 6.20, the Angle Mouse was next at 6.71, and the default mouse had the most at 6.96. All three pairwise comparisons were significant (p<.05).

For able-bodied participants, *Mouse Type* also had a significant effect on submovements per trial ($\chi^2_{(2,N=72)}$=18.86, p<.0001). Again, sticky icons had the least at 3.44, the default mouse was next at 3.64, and the Angle Mouse had the most at 3.68. Sticky icons was significantly less than the other two (p<.01).

Submovement profiles also give us peak velocity. For users with motor impairments, there was a significant effect of *Mouse Type* on peak velocity ($F_{2,14}$=12.90, p<.001). The Angle Mouse had the greatest peak velocity at 3.20 px/ms, sticky icons was next at 2.91 px/ms, and the default mouse least at 2.61 px/ms. All three pairwise comparisons were significantly different (p<.05).

By contrast, *Mouse Type* did not cause a significant difference in peak velocity among able-bodied participants ($F_{2,14}$=1.79, *ns*).

Acceleration is proportional to exerted force, which is proportional to motor noise, a cause of endpoint deviation [34]. For motor-impaired users, *Mouse Type* caused significant differences in peak acceleration ($F_{2,14}$=13.76, p<.0001), with the Angle Mouse being highest at 0.20 px/ms^2, sticky icons being next at 0.19 px/ms^2, and the default mouse being least at 0.16 px/ms^2. All three pairwise comparisons were significantly different (p<.05).

As with peak velocity, *Mouse Type* did not cause a significant difference in peak acceleration for able-bodied participants ($F_{2,14}$=2.46, *ns*).

DISCUSSION

For participants with motor impairments, the Angle Mouse had higher throughput than the default mouse and sticky icons. Movement times and error rates were similar for the Angle Mouse and sticky icons, and higher for the default mouse. But the default mouse and Angle Mouse produced less endpoint deviation than sticky icons, which resulted in sticky icons having lower throughput. This is partly due to the difficulty of getting into the center of sticky icon targets. But when the gain is dropped for the Angle Mouse during the final stages of acquisition, a similar effect is achieved: the target is made bigger in motor-space.

The Angle Mouse exhibited benefits besides throughput. Its peak velocity and peak acceleration were both higher than those of the default mouse and sticky icons. Despite this, the Angle Mouse was not significantly less accurate than sticky icons, and was significantly *more* accurate than the default mouse. Also, the Angle Mouse had significantly fewer target entries and submovements than the default mouse, indicating an easier time of getting inside the target, which, after all, is the point of the Angle Mouse design.

Note that higher peak velocity and peak acceleration do not often produce lower acquisition times; indeed, they can do just the opposite due to greater motor noise, more endpoint deviation, and the need for more submovement corrections. Interestingly, neither errors, nor peak velocity, nor peak acceleration were significantly different among able-bodied participants, nor did able-bodied participants show any significant differences in throughput, lending support to these areas as sources of benefit.

One deterrent to sticky icons performing better was distractor targets—a major problem with target-aware techniques. While we could have chosen to enable stickiness only on the active target, this would have been excessively artificial, since the problem of distractor targets is precisely the drawback of sticky icons and a key advantage of the Angle Mouse. Distractors did not seem to matter for sticky icons except when the targets were large ($W = 32$), which reduced the space between neighbors.

We note that the sticky icons technique requires a user to hit a target to obtain its benefits. Although a sticky icon may be reached at greater speeds, if it is missed, this benefit becomes a detrimental overshoot. This is not the case with the Angle Mouse, where the benefits begin whenever and wherever the user moves in a corrective fashion. Users do not have to first successfully hit the target.

FUTURE WORK

Unlike many target-aware pointing facilitation techniques, the Angle Mouse could be deployed with ease. A small software program running in the background could observe cursor movement and alter the system's gain accordingly. The program could write log files and keep a record of gain changes for later analysis of real-world pointing data.

This study focused on people with motor impairments. Future studies could examine whether the Angle Mouse improves pointing for children [15] or elderly users [31], who are both known to exhibit mousing difficulties.

Although our Angle Mouse has great promise, the space of its parameters is vast and has yet to be fully explored. A study must find the optimal angle queue length (n), minimal travel distance per sample (ΔD), the range of utilized Gaussian standard deviations ($\sigma_{g_{\min}}, \sigma_{g_{\max}}$), the range of utilized gains ($G_{\min}, G_{\max}$), and the mapping between angular deviation ($w\sigma_\theta$) and gain change (Eq. 10). Also, the effects of pointer acceleration [6] should be investigated now that the Angle Mouse has been studied in isolation.

CONCLUSION

Due to the prevalence of commodity input devices in the hands of people with motor impairments, it is necessary to improve device performance in fundamental computer tasks. Although numerous pointing facilitation techniques have been invented, most are impractical for real-world use because they must be *target-aware*. As a *target-agnostic* technique, the Angle Mouse dynamically adjusts C-D gain based only on the behavior of the user, making it practical for deployment in current desktop systems. The Angle Mouse shows higher throughput than the Windows default mouse and sticky icons, making everyday computer use more efficient for a wide range of users.

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The first author dedicates this paper to ultrasound innovator Peter M. Pawluskiewicz, whose engineer's mind adjoined a poet's heart. *Sto lat!*

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