Enhanced Area Cursors: Reducing Fine Pointing Demands for People with Motor Impairments

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ABSTRACT

Computer users with motor impairments face major challenges with conventional mouse pointing. These challenges are mostly due to fine pointing corrections at the final stages of target acquisition. To reduce the need for correction-phase pointing and to lessen the effects of small target size on acquisition difficulty, we introduce four enhanced area cursors, two of which rely on magnification and two of which use goal crossing. In a study with motor-impaired and able-bodied users, we compared the new designs to the point and Bubble cursors, the latter of which had not been evaluated for users with motor impairments. Two enhanced area cursors, the *Visual-Motor-Magnifier* and *Click-and-Cross*, were the most successful new designs for users with motor impairments, reducing selection time for small targets by 19%, corrective submovements by 45%, and error rate by up to 82% compared to the point cursor. Although the Bubble cursor also improved performance, participants with motor impairments unanimously preferred the enhanced area cursors.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces—*Input devices and strategies*. K4.2. Computers and society: Social issues—*assistive technologies for persons with disabilities*.

General terms: Design, Human Factors

Keywords: Accessibility, area cursors, goal crossing, motor space, visual space, magnification, Bubble cursor.

INTRODUCTION

Computer users with motor impairments, such as low strength, intention tremor, poor coordination, and rapid fatigue, face major challenges with conventional mouse pointing. While pointing consists of both a ballistic phase and a corrective phase [24], the corrective phase can be particularly problematic for people with motor impairments where precision control is crucial [10,16,33]. As a result, small targets are especially difficult for users with motor impairments to acquire [6,32], and yet many such users still prefer to use commodity pointing devices for their availability, low cost, and lack of stigma [6,11]. Unfortunately, many small targets exist in current desktop user interfaces: for example, links on a webpage may be only 8 pixels in height, while resizing borders on windows are much smaller (*e.g.*, 4 pixels in Windows XP, and 1 pixel in Microsoft Outlook Notes). Other problems involving small targets include slipping off targets, unintended clicks, and the effort and time required to physically perform a click [18,19,29,31].

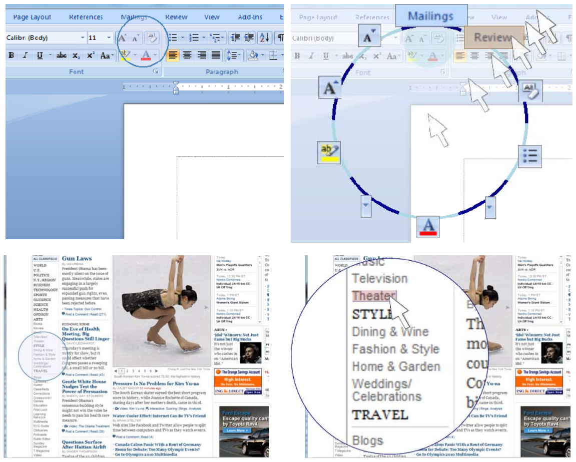

Figure 1. Two enhanced area cursors. Click-and-Cross: an area cursor (top-left) transforms covered targets into crossing arcs (top-right). Visual-Motor-Magnifier: an area cursor (bottom-left) expands visual and motor space for point-and-click selection (bottom-right).

To reduce the need for fine pointing, we introduce *enhanced area cursors* (Figure 1). Unlike traditional area cursors [17,36], enhanced area cursors are specifically designed to work with small, dense targets, which is precisely where existing area cursors break down. Our techniques are based on the following design goals: (1) to reduce the need for corrective-phase pointing, (2) to lessen the effects of small targets on acquisition difficulty, and (3) to reduce the need for accurate, steady clicking, all without requiring specialized hardware. We present and evaluate two enhanced area cursors that use *goal crossing* instead of clicking (*Cross-and-Cross* and *Click-and-Cross*) and two cursors that provide *magnification* to ease selection (*Motor-Magnifier* and *Visual-Motor-Magnifier*).

Although several techniques have been previously introduced to support target selection for users with motor impairments [15,30,34,35,36], many of these techniques degrade in small, dense target layouts—precisely those

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situations where target selection assistance is most needed. The original area cursor [17], for example, has been shown to be beneficial for older adults [36], but degenerates to a point cursor when it is over more than one target. The Bubble cursor [12], an area cursor that dynamically resizes, has also been shown to improve pen-based target acquisition for older adults [25], but degrades similarly with closely-packed targets. The "sticky targets" approach manipulates mouse gain to increase target size in motor space [5,36], but distracter targets can impede performance and are difficult to avoid, especially in the types of small dense target situations we address here.

In a controlled laboratory study with 12 motor-impaired and 12 able-bodied users, we compared the four enhanced area cursors to a traditional point cursor and the Bubble cursor [12], which is the fastest cursor in the literature. (The Bubble cursor has not been previously evaluated for users with motor impairments.) Results for the motor-impaired group show that, unlike the point and Bubble cursors, selection speed with the enhanced area cursors does not degrade when target size and spacing between targets decreases. Two of our new designs, along with the Bubble cursor, also significantly reduce fine pointing correction as measured by overall submovements. Moreover, the enhanced area cursors and the Bubble cursor reduce errors by up to 82% over the point cursor.

The main contribution of this paper is the introduction and evaluation of four enhanced area cursors that demonstrate the effectiveness of using goal crossing and magnification to decrease target acquisition time and reduce errors for users with motor impairments. Our designs include the first general-purpose goal crossing cursors designed for the desktop (rather than pen-based devices [1,3]). We also contribute the first evaluation of a cursor that uses both visual- and motor-space magnification for users with motor impairments, as well as the first study of the Bubble cursor for this group of users. Our findings show that the enhanced area cursors provide significant target-acquisition benefits for people with motor impairments, empowering them to utilize everyday input devices.

RELATED WORK

In addition to area cursors and sticky icons [5,17,36], a number of target acquisition techniques have been proposed for users with motor impairments. Gravity wells, for example, provide force feedback when the user is directly over the target, but the presence of distracter targets negatively impacts performance [15]. A technique impervious to the number of targets is the Angle Mouse [34], which monitors the deviation of angles sampled during movement and lowers mouse gain when it detects high deviation. The Angle Mouse improved Fitts' law throughput but not overall speed over the point cursor and sticky icons for people with motor impairments. Another technique is *Steady Clicks*, which reduces slipping errors by briefly freezing the mouse at the mouse-down location but does not directly improve target acquisition time [30].

Another approach to improving target acquisition for users with motor impairments is *goal crossing*, where the user selects a target by crossing over it rather than clicking [35]. Crossing has been used for pen-based interaction for able-bodied users [1,3] and is similar to making selections on marking menus [20]. With the mouse, crossing has been shown to improve Fitts' throughput and to reduce corrective-stage pointing motion for users with motor impairments [35]. Despite this potential, crossing in a complex interface with desktop mouse input is difficult due to the *occlusion problem*: unlike the pen, the mouse cursor frequently crosses over unwanted targets as the user moves towards a goal, so the single cross used in previous work [1,3,35] is not feasible on the desktop.

In comparison to techniques that increase motor space, the combination of visual *and* motor magnification has received less attention for users with motor impairments. Zooming (increasing motor and visual space) has been used to improve selection speed and accuracy with eye trackers [4]. In a technique similar to our Visual-Motor-Magnifier, an area cursor with magnification has been proposed to reduce target ambiguity [22]; however, no evaluation was reported. Purely *visual* magnification lenses for low vision users have been around for years, but they only change visual space and do not aid motor movement.

Motor and visual magnification have been explored to a greater degree for able-bodied users. Expanding targets that increase in size when the mouse approaches can only magnify in visual (and not motor) space when targets are closely packed [23]. Fisheye views also increase only visual space and can make it more difficult to point [13]. In contrast, Pointing Lenses magnify visual and motor space to improve pen-based selection of small targets [27], but require fine motor control to activate (*e.g.*, using various degrees of pen pressure) and may be difficult for users with motor impairments. The combination of visual and motor magnification can also improve mouse selection of small one-dimensional targets [7] and has been used for selecting small targets on a touch screen [2]. Although these findings are not directly applicable to users with motor impairments, we build upon them where possible in our designs.

FOUR ENHANCED AREA CURSORS

In creating our four enhanced area cursors, we sought to limit corrective-stage motion by retaining the benefit of an area cursor's size during the initial ballistic phase of pointing. Enhanced area cursors are also designed to reduce the need for accurate, steady clicking, and to avoid degradation in the case of small, dense targets (unlike Bubble and point cursors, Figure 2).

The four new cursor designs were informed by iterative testing with one user with cerebral palsy over six sessions of 1 hour each. The designs also reflect refinements that were made after two pilot sessions of the experiment involving people with cerebral palsy and muscular dystrophy. All of the final enhanced area cursor designs convert a single pointing task into two steps: *activation* and

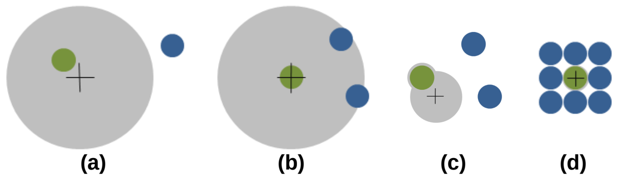


Figure 2. (a) Area cursor over single target. **(b)** area cursor over multiple targets (degenerates to point cursor). **(c)** Bubble cursor resized based on surrounding targets. **(d)** Bubble cursor over grid of targets (degenerates to point cursor).

selection, as described below. This division of labor is necessary to disambiguate intentional from unintentional crosses in a desktop mousing environment. Although dragging across goals with the mouse button could work, it would be a poor design choice for people with motor impairments, for whom dragging is difficult if not impossible, especially with trackballs.

Two Crossing Cursors

Our crossing cursors transform 2D point-and-click targets into crossing goals to ease selection for users with motor impairments. The *Click-and-Cross* cursor and the *Cross-and-Cross* cursor are shown in Figures 3 and 4. To our knowledge, these designs are the first *mouse-based* crossing techniques for general target acquisition.

Activation

The user activates each crossing cursor as follows:

Click-and-Cross cursor (Figure 3). The user moves a circular area cursor over the desired target and clicks to activate. Note that although clicking is used here, the use of a large area cursor minimizes the need for fine motor control in proportion to the cursor's size, which can be adjusted via the mouse wheel.

Cross-and-Cross cursor (Figure 4). This cursor eliminates the need for clicking. Here, the user controls a regular point cursor embedded inside a larger circle (the area cursor). When the embedded pointer reaches the edge of the circle, it pushes the circle in its direction of movement. This behavior is similar to that of tracking menus [9]. The circle also rotates smoothly so that a red *trigger arc* is always opposite the direction of motion. To activate, the user reverses direction through the circle, crosses over the red trigger arc, and comes to a stop for 300 ms (a value determined in piloting). Crossing the trigger arc does not cause the area cursor to move, but instead activates it.

Selection

Upon activation, the crossing cursors behave identically. A large circle of crossing targets (arcs) appears at or as close as possible to the area cursor location, overlaying the original target space. Crossing arcs are alternately colored to distinguish their extents. Each target that was under the area cursor is assigned a crossing arc segment. To aid visual mapping, *proxy* targets quickly animate from the original target location to the corresponding crossing arc. The proxies also increase in size compared to the original targets if space is available.

A regular point cursor then appears at the center of the crossing arcs. To select a target, the user crosses the pointer over the corresponding arc and comes to a stop for at least 300 ms. The crossing movement does not need to be precise: once an arc is crossed, a selection is confirmed by stopping *anywhere* outside the circle of crossing arcs. This behavior promotes a natural "follow through" from the crossing motion. Note that the proxy targets serve as labels for their corresponding arcs; in other words, the mouse does not need to cross directly through the proxy target as long as it crosses over the proxy's arc segment (*e.g.*, as in Figures 3b and 4b).

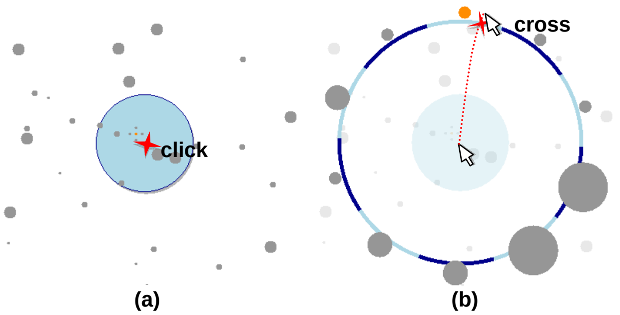


Figure 3. The Click-and-Cross cursor. **(a)** Clicking activates the cursor and transforms covered targets into crossing arcs. **(b)** Crossing an arc selects a target.

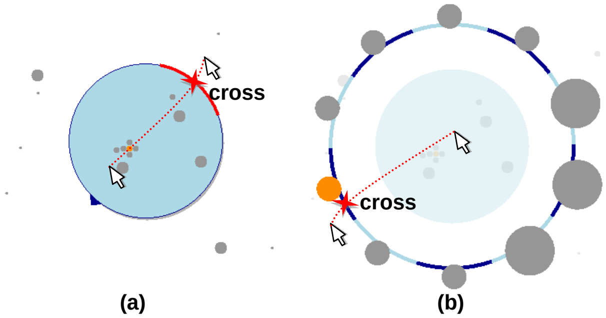


Figure 4. The Cross-and-Cross cursor. **(a)** Crossing the red trigger arc activates the cursor and transforms targets into crossing arcs. **(b)** Crossing an arc segment selects that target.

Advanced design elements allow the user to recover from incorrect actions. If the cursor is activated in the wrong location (*i.e.*, not over the intended target), a click within the circular layout cancels the selection (the only time a click is needed for Cross-and-Cross). If the user accidentally crosses the wrong arc, smoothly returning the mouse to the inside of the circle without stopping for 300 ms prevents a selection. Similarly, if the user accidentally crosses the trigger arc in the Cross-and-Cross cursor, smoothly returning the mouse pointer to within the area cursor without stopping for 300 ms prevents activation.

Crossing Arc Placement Algorithm

Predictable arc placement is critical for the success of the crossing cursors. Clearly, when a target is close to the edge of the area cursor, its crossing arc should also be placed at that location. However, arc placement becomes complex when some targets are boxed in by other targets (*e.g.*, where should the targets in the middle be placed?) or targets are skewed to one side of the area cursor (*e.g.*, which targets get priority for arcs on that side?).

The arc placement algorithm assigns targets as follows. The centroid is first calculated and all targets under the cursor are sorted around it by angle. Where two or more targets have the same angle, the target *farthest* from the center of the area cursor is ordered first. Targets are assigned to arc segments in that order. We explored calculating target angles from the center of the cursor instead of the centroid of targets, but chose the centroid because it accounted for off-center clusters of targets and allowed for more predictable arc placement across activations, thereby reducing dependency on the cursor location.

The circumference of the circle containing the crossing arcs is divided equally for all active targets, so for n targets, each arc spans 360 / n degrees. Thus, with more targets, the angle span assigned to each arc decreases. As a countermeasure, we increase the radius of the circle if space is available, so arc length remains constant at 100 pixels, an adjustable setting.

Area Cursor Size

Following the design of the Bubble cursor, which adapts its size based on the proximity of targets, all of the enhanced area cursors cover only a maximum number of targets and reduce their size as necessary. For the crossing cursors, the default setting is to contain 10 targets or a radius of 100 pixels, whichever is less. During iterative design, we also allowed users to resize the area cursor with the mouse scroll wheel (this feature was disabled for the study). If the user activates any of the enhanced area cursors when only one target is covered, that target is selected without having to complete the crossing-based selection stage; this situation did not occur during the study.

Two Magnification Cursors

We designed two magnification cursors: the *Motor-Magnifier* provides only motor magnification, while the *Visual-Motor-Magnifier* increases both visual and motor space (Figures 5 and 6). As with the crossing cursors, the magnification cursors provide activation and selection phases, and resize to cover a maximum number of targets.

Activation and Selection

To activate either magnification cursor, the user moves an area cursor over the desired target and clicks once (the same as Click-and-Cross activation). Upon activation, the cursors enter a *selection* phase.


(a) (b)

Figure 5. Motor-Magnifier: **(a)** before activation and **(b)** selection using inset Bubble cursor.

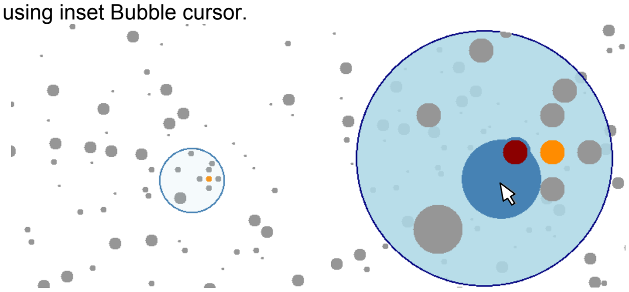

(a) (b)

Figure 6. Visual-Motor-Magnifier set to 4x magnification: **(a)** before activation and **(b)** selection with inset Bubble cursor.

Motor-Magnifier (Figure 5). When the user activates the Motor-Magnifier, the mouse gain drops, magnifying the motor space by a default factor of four. A pointer appears and the user controls an inset Bubble cursor within the magnified space, selecting a target by pointing and clicking. No visual magnification occurs and the target locations do not change.

Visual-Motor-Magnifier (Figure 6). On activation, the area cursor and all targets beneath it increase in size, animating larger until they reach a preset magnification factor (by default four). As with the Motor-Magnifier, the user controls a Bubble cursor within the magnified space and selects a target with a single click. Importantly, the mouse gain does not change with respect to the unmagnified display, so *both* motor and visual space are magnified.

Abandoned Designs

We informally tested several other designs. Two designs that we felt held the most promise based on our design rationale, but which ultimately did not perform well, were the *Ballistic Square* and the *Scanning Area Cursor*. We briefly describe these designs.

Ballistic Square

The Ballistic Square (Figure 7a) allows selection through ballistic mouse movements only. To activate, the user moves a square area cursor over the target they wish to select and clicks. Four quadrants appear and the user progressively shrinks the square by making gross ballistic movements toward the quadrant in which their target resides. That quadrant then subdivides and the process continues recursively until only a single target is left below the cursor. Although this design fully eliminates the need for fine pointing, we found that it was slow, requiring too much movement and attention at each step.

Scanning Area Cursor

The Scanning Area cursor (Figure 7b) is a circular area cursor activated by a single click. Upon activation, the cursor iterates through all targets it covers, highlighting each one in turn; the user clicks to select the highlighted target. Targets are clustered into rows and scanning order proceeds from left to right, then top to bottom. The scan

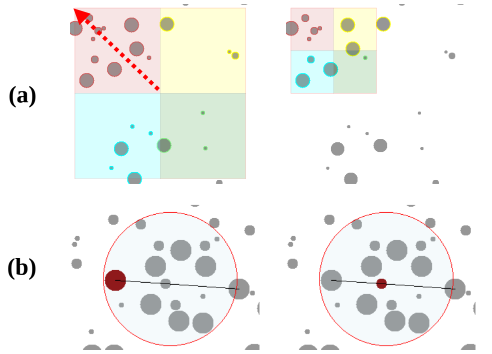


Figure 7. Abandoned designs. **(a)** Ballistic Square, showing recursive subdivision of the area cursor. **(b)** Scanning Area Cursor showing scan movement from left to right.

				Self-Reported Impairments											
ID	Age	Device	Health Condition	Fa	Co	St	Mo	Gr	Ho	Tr	Sp	Se	Dir	Dist	Other Impairments
1	58	Mouse	Parkinson’s				■	■	■	■			■		
2	53	Mouse	Multiple sclerosis	■	■	■		■		■		■			Pain
3	34	Mouse	Friedreich's ataxia		■		■	■	■	■	■	■	■	■	
4	24	Mouse	Fibrodysplasia ossificans progressiva												Limited range of motion
5	58	Trackball	Parkinson’s	■	■	■	■	■	■	■			■	■	
6	26	Mouse	Cerebal palsy		■				■		■				
7	56	Mouse	Tetraplegia				■	■	■						
8	22	Mouse	Muscular dystrophy	■		■	■	■	■						
9	31	Mouse	Cerebral palsy											■	
10	57	Mouse	De Quervain's tenosynovitis		■	■	■	■	■						
11	32	Mouse	Cerebal palsy, fibro-myalgia, chronic fatigue	■	■	■	■	■	■				■	■	
12	49	Mouse	Spinal cord injury (5/6 incomplete)	■	■	■		■	■			■	■		

Legend: Fa=rapid fatigue, Co=poor coordination, St=low strength, Mo=slow movements, Gr=difficulty gripping, Ho=difficulty holding, Tr=tremor, Sp=spasm, Se=Lack of sensation, Dir=difficulty controlling direction, Dist=difficulty controlling distance

Table 1. Details for the impaired group, including age, device used during the study, health condition, and self-reported motor impairments.

position and direction can be adjusted by the user with ballistic mouse movements in any cardinal direction. For example, a movement to the left reverses a rightward horizontal scan direction, while up and down movements shift to a row above or below. While the scan speed could be adjusted to the skill of the user, reaction time for most users was too slow for the scanner to be competitive with the point cursor. However, this technique may be more promising for scenarios where jitter greatly prohibits making fine corrections, such as input from eye-trackers.

EXPERIMENT METHOD

The main goal of this study is to evaluate whether our enhanced area cursor designs improve performance and reduce corrective submovements among motor impaired users compared to point and Bubble cursors, particularly with small, closely-packed targets. Although our focus is on users with motor impairments, we include an analysis of able-bodied participants for baseline comparison.

Participants

Twelve participants with motor impairments (4 males) and twelve able-bodied participants (12 males) were recruited. All were regular computer users. For a detailed breakdown of the impaired group, see Table 1. The able-bodied participants were between the ages of 18–31 (M=22.0). Participants were reimbursed $40 (impaired group) or $12 (able-bodied group, where sessions were shorter).

Apparatus

The experiment software was coded in C# .NET 2.0. Sessions were run using an 18” LCD monitor (1280×1024 resolution) connected to one of three comparable laptops running Windows 7. The system recorded all mouse movement with millisecond timestamps. Windows’ mouse acceleration was turned off to eliminate multiple sources of mouse gain change. Participants had the option of using a mouse or trackball; all able-bodied participants chose the mouse, while Table 1 shows the impaired group’s choices.

Procedure

Sessions lasted 90-120 minutes for the impaired group and 45 minutes for the able-bodied group. We began each cursor type with a ~5 minute introduction, demonstrating how the cursor worked and asking the participant to repeat our actions. An open learning phase then allowed participants to familiarize themselves with the cursor and to ask clarifying questions. The learning phase ended once the participant had completed at least 10 unassisted trials in a row, which took approximately 2-7 minutes depending on a user’s ability. A test block of 36 trials was then presented and participants were asked to complete the trials as quickly and accurately as possible. For each trial, the participant had to correctly select an orange target among a set of gray distracter targets. At the completion of each cursor type, a Likert scale questionnaire was issued. Finally, overall preference data was collected.

Experiment Design

The study was a 6×3×3×2 within-subjects factorial design. Factors and levels were:

- **Cursor Type:** Point, Bubble, Visual-Motor-Magnifier, Motor-Magnifier, Click-and-Cross, Cross-and-Cross.
- **Target Size (width):** 4, 8, and 16 pixels (respectively: about the width of a window border, a common text link height, and a standard toolbar icon size).
- **Target Spacing:** no spacing around the target, half-target width spacing, full-target width spacing.
- **Target Clutter:** 250 and 1000 distracters (relatively sparse *vs.* cluttered). These distracters were not placed immediately around the target.

Since novel target acquisition techniques often degrade with increased target density (*e.g.*, [12,15]), we varied density along two dimensions: *spacing* and *clutter* (Figure 8). While these concepts are related, spacing directly quantifies how closely packed distracter targets are around the target to be selected, whereas clutter represents the total number of distracter targets present on the entire screen. These dimensions have been used in several previous target acquisition studies (*e.g.*, [12,25]), and are relevant to real user interfaces, where targets often appear in clusters but the clusters do not cover the entire screen. Spacing conditions were achieved by placing four distracter targets of equal size around the goal target (Figure 8a-c; the approach used in the evaluation of the Bubble cursor [12]).

All area cursors, including Bubble, had a maximum radius of 100 pixels (a maximum is recommended for Bubble [12]). The enhanced area cursors resized dynamically to cover no more than 10 targets at once. For the Visual-

(a) No spacing **(b)** Half-target spacing **(c)** Full-target spacing

(d) Low clutter **(e)** High clutter

Figure 8. Cropped screenshots of spacing and clutter levels.

Motor-Magnifier, magnification was set to a factor of four. This magnification factor has been shown to improve performance of small target acquisition for able-bodied users [7,27], and offered a noticeable benefit in piloting whilze allowing the magnified cursor to fit easily on the screen. For the Motor-Magnifier, the mouse gain dropped to 30%, similar to the gain drop used for sticky icons [36]; this value was the closest possible match to the Visual-Motor-Magnifier available through the Windows API.

Presentation order for Cursor Type was counterbalanced using a balanced Latin square. Participants were randomly assigned to presentation orders such that each of the six presentation orders were used an equal number of times. Target Size, Spacing, and Clutter conditions (18 combinations) were blocked by Cursor Type and presented randomly for each participant. Each participant performed 216 trials (two trials per combination of levels).

Distracter target sizes were chosen randomly from the Target Size set. To reduce the impact of any individual target layout on performance, the goal target and distracter target locations were randomized per trial.

Measures

Acquisition time was measured as mean trial duration, calculated as the elapsed time from the end of the previous trial to selection of the correct target. Error rate was the percentage of trials in which at least one selection of a distracter target or whitespace occurred. We also collected exhaustive logs of mouse movements across trials, which enabled us to perform submovement analyses similar to those conducted for the Angle Mouse [34]. This analysis temporally resampled movement at 100 hertz and smoothed velocity profiles with a 1D Gaussian kernel filter (σ parameter=5). Submovements were counted in the smoothed profile as local maxima. Visual inspection of velocity graphs blind to condition confirmed that this approach matched our intuition. Finally, Likert scale ratings were based on the NASA TLX workload index [26] and included mental demand, physical demand, temporal demand, performance, effort, and frustration.

Analysis

As is customary, analyses of the time and submovement data were done on logarithmically transformed data to correct for violations of normality. We analyzed speed and submovement data using a mixed-effects model analysis of variance with repeated measures: Cursor type, Size, Spacing, and Clutter were modeled as fixed effects, while Participant was modeled as a random effect because the levels of this factor were drawn randomly from a larger population. Although such analyses retain larger denominator degrees of freedom, detecting significance is no easier because wider confidence intervals are used [21,28]. We used non-parametric Friedman tests and Wilcoxon tests for pairwise comparisons on error rate data. The same non-parametric tests were also used for Likert scale data. All post-hoc pairwise comparisons used a Bonferroni adjustment. Data from the impaired and able-bodied groups were analyzed as separate experiments due to the extreme variability present in the impaired group, which would have violated an assumption of ANOVA.

RESULTS

We focus on the impaired group and only highlight able-bodied results for comparison and at the end of the section. All pairwise comparisons mentioned are significant at $p<.05$ unless otherwise noted. Due to space constraints, we only report main and interaction effects with Cursor Type. We also use the following abbreviations: CLC (Click-and-Cross), CRC (Cross-and-Cross), VMM (Visual-Motor-Magnifier), and MM (Motor-Magnifier).

Acquisition Time

A significant main effect of Cursor Type on trial time was found ($F_{5,1177}=124.11$, $p<.001$), in addition to several interaction effects that we report in more detail below. Time measures include the 300 ms delays required for the crossing cursors. Average target acquisition times were 6.7 seconds for CRC, 5.3 seconds for Point, 5.1 seconds for MM, 4.3 seconds for CLC, 4.2 seconds for VMM, and 4.1 seconds for Bubble (see Figure 9).

Unlike Point and Bubble, most of the enhanced area cursors did not degrade with small, closely packed targets. We found a significant 3-way interaction between Cursor

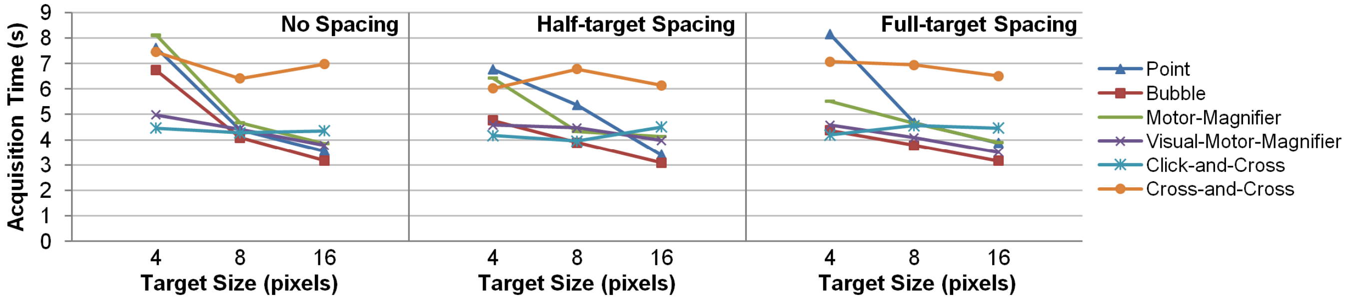


Figure 9. Acquisition time across Spacing and Size for the impaired group shows more degradation for Point and Bubble cursors than most enhanced area cursors at small target sizes, especially for no spacing. (N=12)

Type, Size and Spacing (Figure 9, $F_{20,1177}$=1.68, p<.05), and highlight the interesting significant pairwise comparisons. Overall, trial duration did *not* increase for VMM, CRC, and CLC as targets got smaller and more closely spaced (with only one exception: VMM was slower at 4 px and no spacing than 16 px and full spacing). In contrast, Point took longer as size decreased, and Bubble took longer as size *and* spacing decreased (4 px size and no spacing was slower than all other Bubble conditions).

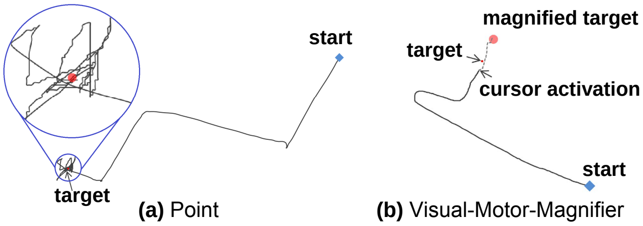
VMM, CLC, and Bubble were fastest for small targets. There was a significant interaction of Cursor Type and Size on trial time ($F_{10,1177}$=21.96, p<.001). At the smallest size, pairwise comparisons showed that VMM, CLC, and Bubble were faster than the other three cursors. This advantage decreased as target size increased, and by the largest target size, Point and Bubble were fastest and no different from each other.

Most of the enhanced area cursors were not negatively affected by decreased spacing. A significant interaction of Cursor Type and Spacing on trial time was found ($F_{10,1177}$=2.42, p<.01). As expected, pairwise comparisons showed Bubble was slower with no spacing than in the other two spacing conditions. MM also did not fare well as spacing decreased, as it was slower with no spacing than full-target spacing. The other enhanced area cursors did not exhibit this degradation in performance.

Crossing cursors were negatively impacted by increased clutter. A significant interaction of Cursor Type and Clutter on trial time was found ($F_{5,1177}$=5.54, p<.001). Pairwise comparisons showed the crossing cursors were faster with low clutter than with high clutter (CLC: 4.1s *vs.* 4.6s; CRC: 6.2s *vs.* 7.3s), likely due to the smaller angle available for each crossing arc as more targets are added. (Recall that *Clutter* refers to the total number of targets, whereas *Spacing* refers to the area only around the intended target.)

Submovements

Submovement analysis examines the degree of fine pointing correction by segmenting overall movement from a trial into a series of smaller movements based on maxima in a smoothed velocity profile. Changes in mouse speed and direction, for example, will begin new submovement segments. Figure 10 shows representative movement paths taken by a participant in the impaired group: the fine-correction submovements that enhanced area cursors are designed to avoid are evident for the Point cursor, whereas the VMM cursor appears to require fewer submovements.



(a) Point **(b)** Visual-Motor-Magnifier

Figure 10. Sample cursor paths showing reduction of fine pointing correction for P3 (smallest target size, no spacing, high clutter). The red point indicates the target location.

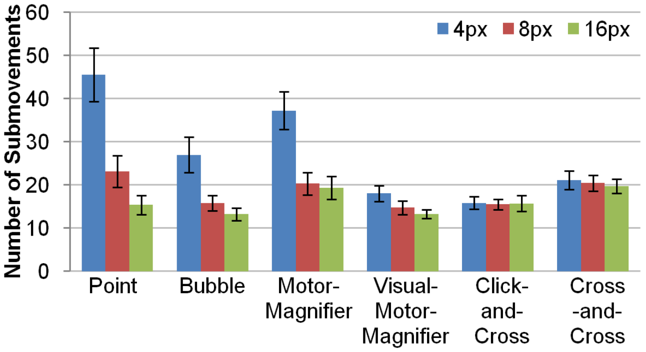


Figure 11. Number of submovements by Cursor Type and Size shows Point had a high number of submovements, especially for smaller sizes. Error bars represent ±1 standard error. (N=12)

Average submovement counts per trial were 28.0 for Point, 25.6 for MM, 20.5 for CRC, 18.7 for Bubble, 15.7 for CLC, and 15.4 for VMM (see Figure 11).

CLC, VMM, and Bubble all reduced submovements compared to Point. There was a main effect of Cursor Type on the number of submovements ($F_{5,1177}$=23.32, p<.001). Pairwise comparisons showed that the cursors fell into two different groups: CLC, VMM and Bubble had significantly fewer submovements than the other three cursors, which, in turn, were not found to be different from each other.

Submovement reduction was greatest at the smallest target size. There was an interaction effect of Cursor Type and Size ($F_{10,1177}$=14.80, p<.001). Pairwise comparisons showed the advantage of the enhanced area cursors was greatest at the smallest size. At this size, in addition to the overall trends already seen, CLC resulted in fewer submovements than Bubble, and CRC reduced submovements compared to Point. Again, MM did not fare as well as the other enhanced area cursors and was no different from Point.

Following the speed results, Bubble was negatively affected by Spacing, and CLC was negatively affected by Clutter. There were interaction effects of Cursor Type with Spacing ($F_{10,1177}$=2.34, p=.010), and Cursor Type with Clutter ($F_{5,1177}$=3.27, p=.006). Pairwise comparisons showed that, as expected, Bubble degraded when there was no spacing. Following the speed results, there was also an increased number of submovements for CLC as clutter increased.

Error Rate

Average error rates were 14.3% for Point, 6.0% for Bubble, 5.6% for MM, 4.2% for CLC, 3.2% for CRC, and 2.5% for VMM (Figure 12). Non-parametric tests were used on this data, with Bonferroni adjustments for significance testing. Unadjusted p-values are reported for consistency. These tests lack power relative to their parametric counterparts; only significant results are reported.

Both crossing cursors and VMM reduced errors compared to Point, especially with small targets. Overall, Cursor Type had a significant effect on error rate ($\chi^2_{(5,N=12)}$=27.96, p<.001) and pairwise comparisons showed CRC, CLC, and VMM reduced errors compared to Point. On examining how the cursors compared as Size changed, we found that the differences were largely a result of the smaller target

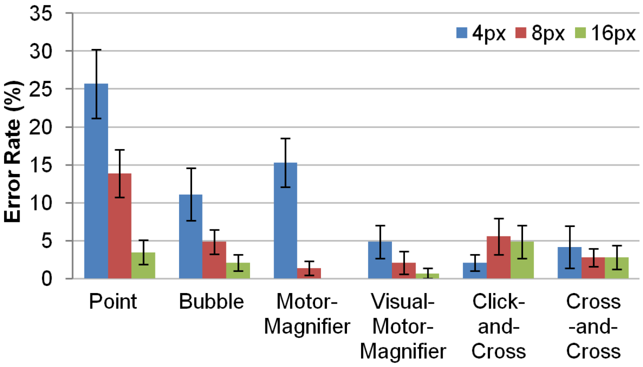


Figure 12. Mean error rates by Cursor Type and Size show higher rates for Point, especially with small targets. Error bars represent ±1 standard error. (N=12)

sizes: there was a significant effect of Cursor Type at the 4 px size ($\chi^2_{(5,N=12)}=31.17$, $p<.001$) and the 8 px size ($\chi^2_{(5,N=12)}=16.73$, $p<.05$), but not the 16 px size.

Unclear whether Spacing affects error rates with different cursors. There was a significant effect of Cursor Type within both half- and full-target spacing ($\chi^2_{(5,N=12)}=32.31$, $p<.001$; $\chi^2_{(5,N=12)}=25.70$, $p<.001$), but no pairwise comparisons were significant.

Subjective Measures

Preference and Qualitative Findings

We asked participants to rate their most and least favorite cursors. Seven of 12 impaired participants preferred VMM, while 3 chose CRC and 2 chose CLC. Interestingly, the Bubble cursor was not preferred by *any* of the impaired participants. However, the advantage of the inset Bubble cursor used in the magnifier designs did not go unnoticed. For example, P3 liked VMM because, "It reminds me of the [visual-only] magnifier on my computer but this is better. I like this because it selects the target that you're closest to and I really like that." Participants also recognized the crossing cursors were agnostic to target size: for example, P4 said of CLC that, "The size of the target doesn't matter."

In terms of *least* preferred, most participants chose Point (9 of 12 responses), while MM, CRC, and CLC each received one response. When asked to explain their preferences, several participants commented on the difficulty of clicking on small targets in Point. For example, P8 said of Point, "It is just more difficult to do. With the other ones you don't have to be right on." Similarly, P6 commented, "You had to use more energy to click on them."

Workload Measures

Perceived workload measures are shown in Figure 13. We found Cursor Type significantly impacted all dimensions of workload (physical: $\chi^2_{(5,N=12)}=20.33$, $p<.01$; temporal: $\chi^2_{(5,N=12)}=15.29$, $p<.01$; mental: $\chi^2_{(5,N=12)}=29.15$, $p<.001$; effort: $\chi^2_{(5,N=12)}=27.37$, $p<.001$; frustration: $\chi^2_{(5,N=12)}=21.56$, $p<.001$; performance: $\chi^2_{(5,N=12)}=13.77$, $p<.05$).

VMM, MM and Bubble reduced some perceived workload measures compared to Point. Pairwise comparisons showed VMM was less mentally demanding, effortful, and frustrating than Point. Although, the impaired group had not indicated an overall preference for Bubble, Bubble also reduced mental demand and frustration compared to Point. MM was perceived as reducing effort, despite its relatively poor speed outcomes.

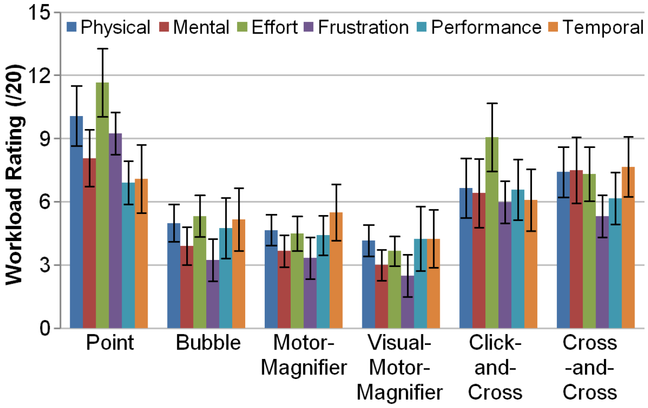


Figure 13. Perceived workload ratings show the magnification and Bubble cursors resulted in relatively low workload (lower ratings are better). Error bars represent ±1 standard error. (N=12)

Highlights from the Able-Bodied Results

Unsurprisingly, the able-bodied group was faster and made fewer errors and submovements than the impaired group: on average across all conditions, able-bodied users took less than half the time of impaired users (2.2s *vs.* 5.0s per selection) and had far lower error rates (2.3% *vs.* 6.0%). Pairwise comparisons following a main effect of Cursor Type on acquisition time ($F_{5,1177}=443.26$, $p<.001$) showed that all of the enhanced area cursors were slower than Bubble and Point. Moreover, the enhanced area cursors actually increased submovements compared to Point and Bubble. This finding was based on pairwise comparisons following a main effect of Cursor Type on number of submovements ($F_{5,1177}=224.17$, $p<.001$). Given low error rates (2.3%) and high variation (SD=11.5%), it is unclear whether the enhanced area cursors improved accuracy.

DISCUSSION

We were most interested in whether the enhanced area cursors would help users with motor impairments to select small, densely packed targets, a situation in which existing cursors often fail. Happily, in comparison to the Bubble and point cursors, the enhanced area cursors did *not* degrade when size and spacing decreased. The Visual-Motor-Magnifier (VMM) and Click-and-Cross (CLC) cursors were the most successful new designs, reducing selection time for small targets, reducing corrective submovements, and reducing error rate by 70% and 82%, respectively, compared to the point cursor. Although accuracy is often considered secondary to speed in target acquisition research, it may be particularly important for participants with motor impairments as errors can require effortful additional steps to remedy (*e.g.*, cancelling an erroneously selected dialog). Although we required participants to correctly complete a trial before continuing to the next, thoroughly studying the real-world penalty of errors is left for future work.

There is a tradeoff, however, between task difficulty and the relative benefit of the enhanced area cursors. At the largest target size, the enhanced area cursors were slower than point-and-click. This tradeoff was reflected with able-bodied results, where the enhanced area cursors were most often slower than the point and Bubble cursors. Reducing the size of the area cursor to account for an individual's pointing abilities may address this issue. Another option is a hybrid design, where the Bubble cursor is used for large targets, but when the cursor nears small or densely-packed targets, the bubble is allowed to cover multiple targets at once, and an enhanced area cursor scheme is used.

Cross-and-Cross (CRC) was relatively slow, but for users who have particular difficulty or experience pain when clicking (*e.g.*, users with repetitive stress injury), the benefit of a *clickless* cursor may outweigh the time cost. Surprisingly, Cross-and-Cross was preferred by three of the motor-impaired participants, highlighting its potential.

Unfortunately, the Motor-Magnifier (MM) offered neither an objective nor preference benefit. More so than the Visual-Motor-Magnifier, the Motor-Magnifier appeared to be affected by the disadvantages of the inset Bubble cursor; it was slower when there was zero spacing between targets.

While the focus of our study was on enhanced area cursors, it is encouraging to find the Bubble cursor improved performance over the point cursor for users with motor impairments (and more so than for able-bodied users). This finding builds on recent work showing the Bubble cursor is useful for pen-based interaction for older adults [25]. However, we found that *all* of the participants with motor impairments preferred the enhanced area cursors to the Bubble cursor, which cannot be attributed to a novelty effect because the Bubble cursor was just as unfamiliar to our participants as were the other designs.

We recruited motor-impaired participants who *already* use the mouse, trackball, or touchpad, but our designs may also be useful for people who are currently just beyond the threshold of being able to use a commodity pointing device. For example, P12 was one of the more impaired participants in the motor-impaired group, and he chose to use a trackball for the study because the mouse was generally too difficult. At the end of the study we asked if he would try some of the tasks with the mouse, and after using Cross-and-Cross and the Visual-Motor-Magnifier he said, "believe it or not, using the mouse is a lot easier than the trackball."

Users with motor impairments exhibit substantial variability between participants and even individually from one day to the next [14]. As a consequence, the ability to make simple customizations or to toggle a technique easily (*e.g.*, using a key shortcut) is important. One feature of our designs that may address this challenge is the ability to change the size of the area cursor using the mouse scroll wheel. While we did not allow customizations in the study to minimize variability, the participant in the iterative design phase of the research used the scroll wheel to his advantage: he sometimes reduced the size of the area cursor so that he could select targets with a single click, but when the cursor covered more than one target or the targets were small, the second-stage selection would occur (*e.g.*, magnification or crossing). We also implemented other options, such as changing the magnification factor, and allowing for point-and-click, Bubble cursor, *or* dwell selection during the second stage of the magnifiers.

A limitation of our study is that we evaluated the new cursor designs only in a controlled lab setting. Since most of the enhanced area cursors dramatically change the visual layout of the interface, it is important to consider how they fare in a complex graphical user interface and more realistic context. To explore this question, we built a prototype that allowed users to interact with a replica of Microsoft Word 2007 and the New York Times web page. (Screenshots are shown in Figure 1.) While we did not formally evaluate these prototypes, we did demonstrate them for some of the participants and feedback was positive. Creating this prototype highlighted design questions that may arise in a fully functional application. For example, it may not make sense to transform targets larger than the area cursor itself (*e.g.*, the figure skater in Figure 1). An important future step will be to evaluate the cursor designs in a more ecologically valid context.

Another potential challenge with the enhanced area cursor designs is that they are *target aware*, meaning that the cursors must know the location and size of all on-screen targets. The crossing cursors require this knowledge to create visual proxies and assign crossing arc locations. In contrast, both magnifiers could be implemented by simply capturing and cropping a screenshot (with one exception, namely if the inset Bubble cursor option is used instead of a point cursor). Although target aware techniques have traditionally been difficult to deploy in the wild [34], recent advances in reverse engineering interface structure from drawn pixels [8] will make this task easier.

CONCLUSION

We have introduced enhanced area cursors, target acquisition techniques designed to reduce fine pointing correction and improve performance for users with motor impairments. We focused on designing cursors that would allow users to select small, closely packed targets more easily, which is an intensely difficult situation for people with motor impairments, and is a situation in which many target acquisition techniques fail. Our designs used *goal crossing* and *magnification*. The Visual-Motor-Magnifier and Click-and-Cross cursor were the most successful for users with motor impairments. These cursors eased selection for small, dense targets, and reduced corrective submovements and errors compared to the point cursor and Bubble cursor. The Bubble cursor was also beneficial for users with motor impairments, where it may provide an even greater advantage over the point cursor than it does for able-bodied users. This work highlights the potential for software to make commodity input devices more usable for people with motor impairments, lessening the burden of acquiring specialized high-cost hardware in favor of low-cost, readily available devices.

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