TractorBeam Selection Aids: Improving Target Acquisition for Pointing Input on Tabletop Displays

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ABSTRACT

This paper presents a comparison of several selection aids for TractorBeam input on tabletop displays. TractorBeam is a hybrid point-touch interaction technique for tabletop displays. Our previous research with the technique showed that while pointing input was preferred (over touch) by users of tabletop displays, it was slower than touch input for small distant targets, faster for large targets, and comparable in other cases. Drawing from previous work on improving target acquisition for various types of displays, we developed and tested three selection aids for improving selection of small distant tabletop targets: expanding the cursor, expanding the target, and snapping to the target. Our experiments revealed that all three aids resulted in faster selection times than no selection aid at all, with snapping to the target being the fastest. Additionally, participants liked snapping to the target better than the other selection aids and found it to be the most effective for selecting targets in our study.

Author Keywords

Input and interaction technologies, tabletop displays, quantitative empirical methods, user studies, pen-based UIs.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces - evaluation/methodology, input devices and strategies, interaction styles.

INTRODUCTION

Tabletop displays have emerged in the past 10 years as an area of interest in HCI research. As this research continues, it is important to develop effective interaction techniques for these types of displays.

The majority of previous tabletop display research has not concentrated on specific interaction techniques, although a few researchers have developed specialized tabletop input devices and techniques [1, 3, 9, 10, 12]

In our previous work, we developed TractorBeam, a technique which seamlessly combines remote pointing and touch – both using a stylus – on tabletop displays. Results from our work demonstrate that remote pointing is faster than touch input for large targets, and was preferred over touch and also employed more often when users were given a choice. However, for small distant targets pointing was slower than touch. In remote pointing, small movements made with the hand are amplified on the screen. This amplification increases as distance to the target increases, so even though users must reach further to touch small distant targets than point to them, it is easier to make an accurate selection using touch.

Due to the amplification of small movements for distant targets, we felt that augmenting the technique with a selection aid might improve acquisition of these small, distant targets. Past research into improving target acquisition has focused primarily on traditional desktop displays. Researchers have explored methods such as expanding targets [7], area cursors [6], object pointing [5], and semantic pointing [2].

Drawing from this previous research, we developed and tested three selection aids to augment our TractorBeam technique, in order to improve acquisition of small distant targets on the table:

1. expanding the cursor (expand-cursor)
2. expanding the target (expand-target)
3. snapping to the target (snap-to-target)

All three selection aids, along with a fourth control condition, were evaluated for speed and accuracy, with snap-to-target emerging as the best option; It was the fastest, and also the most preferred by participants. The snap-augmented TractorBeam presents an ideal solution to the problem of reaching small distant targets encountered in our previous work.

RELATED WORK

TractorBeam Technique

We previously investigated interaction techniques for tabletop displays, showing that remote pointing is faster than direct touch for large targets (at any distance), slower for small distant and medium-distance targets, and comparable in all other cases [1]. Based on these results we developed the TractorBeam interaction technique, a hybrid point-touch input technique that allows users to seamlessly reach distant objects on tabletop displays.

The technique works as follows:

Using a stylus, the user points at the tabletop display. A cursor appears on the display to show the current trajectory of the stylus (Figure 1). The user moves the stylus around until the cursor is on the desired item. To select the item, the user clicks the button located on the top of the stylus.

Despite the slower times for small, distant targets, users of the TractorBeam expressed a preference for the pointing interaction technique over touch for distant targets because it required them to do less standing and reaching. Although users were willing to accept this speed-comfort tradeoff, we felt that it may be possible to make the technique even better through some sort of selection aid in order to improve movement times.

Other Tabletop Interaction Techniques

While previous tabletop research has used a wide variety of inputs, few researchers have specifically investigated interaction techniques for tabletop displays.

Exceptions to this include Wu and Balakrishnan [12], who developed a suite of hand and finger gestures for multi-touch tabletop displays. Also, tangentially to tabletop research, Rekimoto and Saitoh's hyperdragging (dragging an item off of one display and onto another with a mouse) and pick-and-drop (picking an item up from one display and dropping it on another with a stylus) techniques allow users to move files between a tabletop and other computing devices, including distant displays such as large wall screens [9].

Improving Target Acquisition

Several researchers have proposed solutions to improve target acquisition time on traditional desktop computer monitors with mouse input. In attempting to improve target acquisition on tabletop displays, knowledge of these existing desktop techniques may provide some insight.

Expanding the target

Dynamically sized widgets which change size as a cursor approaches them (expanding targets), such as those used in the OSX operating system [8], are becoming more common in current user interfaces. McGuffin and Balakrishnan [7] investigated the effectiveness of expanding targets by comparing them to statically sized targets in a Fitts task.

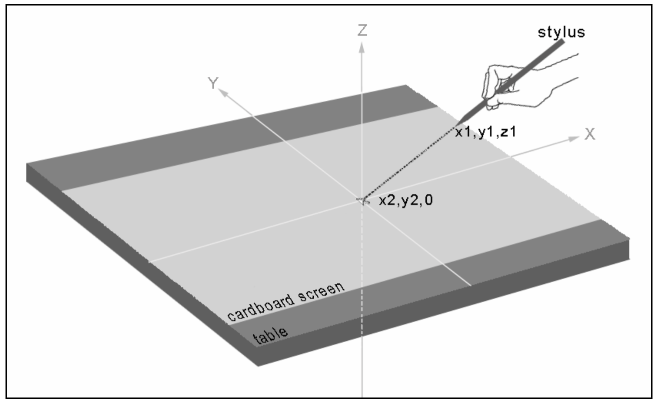

Figure 1: TractorBeam interaction technique

They found that task performance was governed by the expanded target size, rather than the initial target size, even when they were already 90% of the way to the target before the expansion happened. This means that it is not necessary to expand a target until the cursor has traveled 90% of the distance to that target, since the same benefits will be achieved by expanding the target at that distance as at further distances.

Zhai et al. [13] further investigated expanding targets to determine whether McGuffin's results held when users did not know whether or not a target would expand. They ran trials in which targets would randomly shrink, expand, or remain unchanged, and found that target expansion improved pointing performance even when the user was not able to predict the expansion beforehand.

Enlarging the cursor

Kabbash and Buxton investigated the use of an "area cursor" in a Fitts' task and showed that, when using an area cursor to select a point, the action could be modeled with Fitts' law by making W the width of the cursor, rather than the target [6]. The authors tested both a single point cursor moving between two large target areas, and a single large area cursor moving between two small target points. They found that the area cursor performed better than a single-point cursor in the task [6].

Although an area cursor could provide faster selection, it might be difficult for users to complete finer-grain actions with an area cursor, such as selecting one item from a group of small targets placed close together. To prevent such problems, a mode switch would likely be required to turn the area cursor on and off.

Object and semantic pointing

Guiard et al. introduced the idea of object pointing, where the cursor moves between valid targets and never travels in empty space between targets, as a means for improving target acquisition [5]. While object pointing outperforms regular pointing in Fitts' tasks, it may not be appropriate for interactions that require manipulations other than simple selection. For object pointing to work effectively, users would be required to change modes whenever they wanted to make selections, and out of it when they did not.

Another related target acquisition solution is semantic pointing, in which targets "expand" in motor space (but not in visual space) according to their importance [2]. For example, as a user moves across a button they will move more slowly than when they move across a blank space because the button is expanded in motor space. Although this technique may be effective with a mouse or another relative input device, is not appropriate for direct input because direct input requires constant mapping of the cursor with the input device.

TRACTORBEAM SELECTION AIDS

Our previous work revealed that acquisition of small, distant targets was difficult with the TractorBeam. Thus, we designed three possible selection aids to solve this problem: expanding the cursor (expand-cursor), expanding the target (expand-target), and snapping to the target (snap-to-target).

Expanding the Cursor

With this selection aid, users make selections using a "selection halo" area which surrounds the cursor, rather than having to use a single cursor point for selection. This is similar to the area cursor used by Kabbash and Buxton [6], which was shown to improve acquisition of small targets. Whenever the cursor travels at least 90% of the distance to a target, a 30mm halo appears under the cursor and immediately expands to 60mm (Figure 2). The halo shrinks and disappears whenever the cursor moves outside of the 90% range. In order to make these changes appear more seamless, both the expansion and shrink are animated. In order to select a target, the selection halo must only overlap the target, not encompass it.

Expanding the Target

Similar to the expanding targets studied by McGuffin and Balakrishan [7], our expanding-target selection aid expands targets from their original size whenever the cursor is within 90% of the total distance traveled to the target (Figure 3). Targets shrink whenever the cursor moves outside of the 90% range. In order to make these changes appear more seamless, both the expansion and shrink are animated. In our study, targets were originally 30mm, 40mm, or 50mm in width, and expanded to a final size of 60mm.

Snapping to the Target

With this selection aid, the cursor "snaps" to the center of the target whenever it comes within 90% of the total distance to the target (Figure 4). It remains in this snapped position unless the "real" cursor position moves outside of this 90% range.

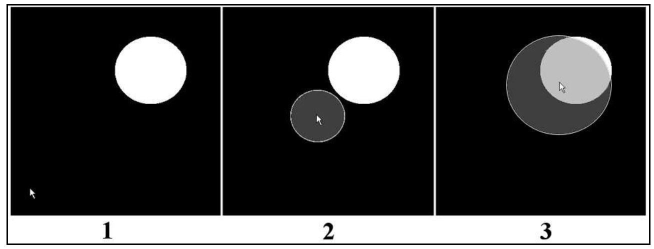

Figure 2: Expand-cursor: (1) Cursor begins to approach target; (2) Cursor reaches 90% threshold and selection halo appears and begins animated expansion; (3) Selection halo continues animated expansion until it has reached full size

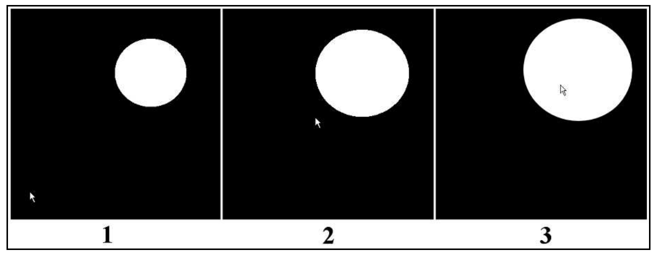

Figure 3: Expand-target (1) Cursor begins to approach target; (2) Cursor reaches 90% threshold and target begins animated expansion; (3) Target continues animated expansion until it has reached full size

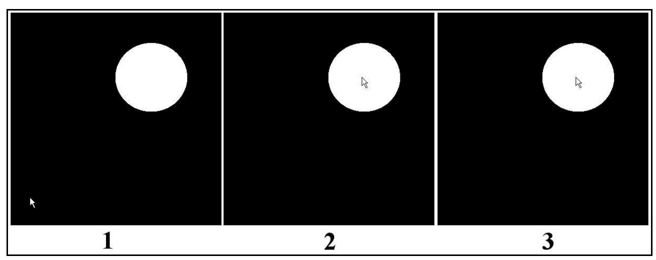

Figure 4: Snap-to-target: (1) Cursor begins to approach target; (2) Cursor reaches 90% threshold and immediately snaps to centre of target; (3) Cursor remains snapped to target centre until pointer moves outside of 90% range

EXPERIMENTAL DESIGN

Participants

Twenty-four participants, 18 male and 6 female, took part in our study. All participants were university students, staff, or faculty, and were right handed. None had participated in the previous TractorBeam user studies. All provided informed consent, and were compensated $10 for their participation in the study.

Hardware Setup

The hardware setup included a top-projected tabletop display consisting of a ceiling-mounted projector, mirror, desktop PC, wooden table, and white cardboard "screen" (Figure 5). The PC was connected to the projector and its output was projected onto the mirror, which reflected the image onto the table. The cardboard screen was used to provide a clearer projection surface than the table alone.

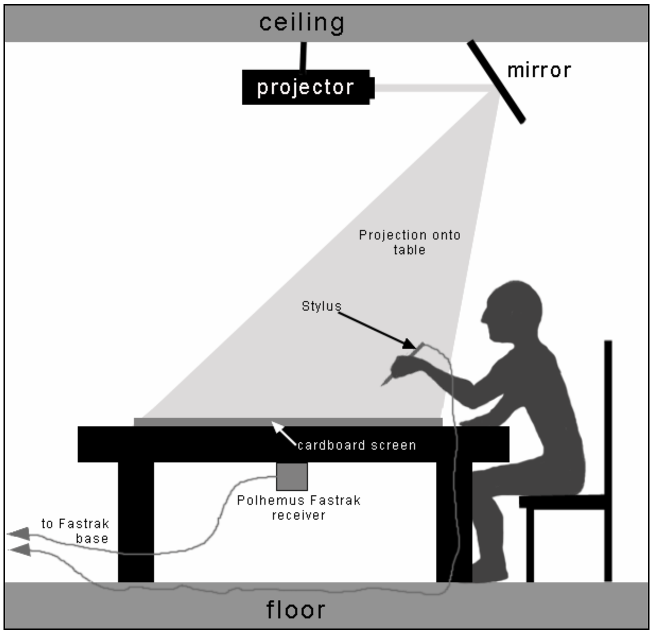

Figure 5: TractorBeam hardware configuration

Input for the tabletop display was received via a corded stylus and receiver attached to a Polhemus Fastrak® (a "six degrees of freedom" 3D tracking system). The Fastrak® receiver was secured to the centre of the underside of the table.

Using information from the stylus and receiver, the Fastrak® base provided continuous information about the position of the stylus in 3D space to our software through a serial port connection on the PC. Our software then used this information to calculate the spot on the table to which the pen was pointing, and draw the cursor at that location.

Task

A multi-directional task (2D Fitts discrete task) was used to evaluate selection tasks in four conditions: control, expand-cursor, expand-target, and snap-to-target. A Java application was developed to implement the selection aids required for each of the four conditions on our tabletop display.

Participants used the TractorBeam interaction technique throughout the experiment, but used each of the four types of selection aids in four separate conditions. In all conditions, participants selected targets on the table by pointing to them or touching them with the stylus to position the cursor on the target, and clicking the stylus button to indicate the selection.

We had previously used dwell times to indicate target selection with the TractorBeam [1]. The stylus button click technique used in the present experiment introduces a small problem: the physical act of clicking the button caused the TractorBeam stylus to shift slightly, potentially displacing the cursor from the intended target. To compensate for this problem, our software tracked the length of time between the cursor exiting the target and the button being pressed. If the cursor was outside of the target when the button was pressed, but the time since it had exited the target was under a pre-determined threshold, we counted the click as a successful target selection. We tested several button-press threshold times in a small pilot study and found 100ms to be a suitable length of time to provide adequate compensation. Thus, if the button was pressed within 100ms after the cursor exited a target, it was counted as a successful target acquisition.

It has been shown that, with expanding targets, the expanded target width dictates the difficulty of the task even if the target does not expand until the cursor has already traveled 90% of the distance from the start position to the target [7]. As such, we designed all three of our selection aids to only take effect after the cursor had traveled 90% of the distance to the target. By limiting the distance in such a way, we hoped to minimize interference between multiple targets which are close to each other, and make the interaction technique scalable for closer targets – both of which we plan to explore in future work. In this study, however, it was not an issue since only one target was visible at a time, and all targets were distant.

In each condition, participants were presented with a series of trials that required them to first select a home square (located in the bottom centre of the display area) and subsequently select a target circle (Figure 6). Target circles were presented with one of three widths (30mm, 40mm, 50mm), at one of three angles (40 degrees left, midline, 40 degrees right), and at one of three amplitudes (520mm, 650mm, 780mm).

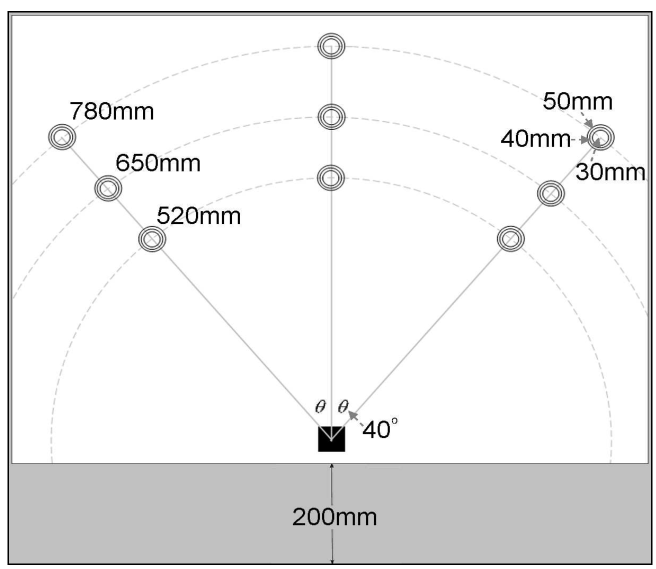

Figure 6: 2D task setup. The black square is the starting point and the circles represent the targets. Targets were three different widths (30mm, 40mm, or 50mm), on three different angles (40 degrees left, midline, and 40 degrees right), and had three different amplitudes (520mm, 650mm, and 780mm).

Participants in our previous research were slower with pointing than touching for small, distant targets. Therefore, for this study we chose widths which ranged from slightly smaller than the “medium” sizes in our first study to exactly the “small” sizes used in our first study and amplitudes which ranged from just above the “medium” amplitude in our first study to exactly the “far” amplitude in our first study.

Each individual trial began when a user selected the home square, and ended when they selected the target circle. Selection was defined by a stylus button click in the target circle. Between the users’ selection of the home square and the appearance of the target circle, there was a random-length pause of between 500 and 1500 ms.,

Participants were asked to keep the cursor on the home square until the target appeared. Software logged when a target appeared, when a user moved off the home square, and when a user selected the target circle. As in our earlier studies, movement time was calculated as the difference between the time a user moved off the home square and the time they selected the target. One target was visible at a time, and all targets were distant.

Procedure

A within subjects design was utilized with each participant using all three selection aids and a control condition. To minimize any order effects, condition order was counterbalanced.

After completing a background questionnaire, participants were asked to perform a series of trials using the experimental task software in each of the four conditions.

Participants sat at the tabletop display and were asked to remain seated for the duration of the session.

For every condition, each participant first completed a warm-up session which required them to select 10 random targets. They then completed exactly five trials of each unique combination of amplitude, width, and angle, for a total of 135 trials. The ordering of the trials was randomized for each participant. On average, participants took 12 minutes to complete each interaction technique (including answering the questionnaire), for a combined session total of approximately 48 minutes for all three interaction techniques.

Following each condition, users completed a post-task questionnaire to gather data on their comfort and perceived performance with the selection aid they had just used. This questionnaire was based on the device assessment questionnaire from the ISO 9241, Part 9 standard [4], which outlines requirements for non-keyboard computer input devices. Once all four conditions were finished, users were given a final questionnaire asking them to rate the selection aids in terms of satisfaction and perceived effectiveness.

Hypotheses

Our previous research showed that users had difficulty using the TractorBeam to home in on small, distant targets. We expected that each of our three selection aids, when compared to using the TractorBeam with no selection aid (control condition), would perform better. We also expected that there would be significant differences between the three selection aids.

To summarize, our hypotheses were:

1. The control condition would be slower than the other selection aid conditions.
2. There would be a difference between the three selection aid conditions.

Data Analyses

Computer logs were used to determine the dependent measures of movement time (MT) and error rate. We did not include reaction time in the movement time, due to the fact that the large tabletop display didn’t fit in a user’s field of view and some time may have been spent visually finding each target. Instead, MT data were calculated from when the cursor exited the home square until the user selected the target.

Errors occurred if the cursor was not on the target when the stylus button was clicked. We removed 1960 (14.7% of total trials) selection errors from the MT analysis. The high number of errors reflects the fact that all of the targets in our study were small and fairly distant from the participants. Has a wider range of target sizes and distances been used, we would have expected a lower error rate.

Movement time data for the five repeated trials at each unique combination of target variables were averaged. Repeated Measures Analysis of Variance (ANOVAs) were performed on the mean MT and entry rate data. All main effects and interactions were tested at α=.05. Questionnaire data were analyzed using non-parametric statistics.

RESULTS

Movement time and error data for all conditions are presented in Table 1. For the error rates, totals for each condition are given along with the percentage of total trials constituted by those errors.

Condition	**Movement Time** *Mean (SE)*	**Error Rate** *Total (%)*
Control	1544 (19.5)	586 (18.1%)
Expand-cursor	1326 (20.5)	313 (9.7%)
Expand-target	1370 (16.3)	429 (13.2%)
Snap-to-target	1060 (15.6)	582 (17.9%)

Table 1: Mean MT and error rate for each condition.

Hypothesis 1: The control condition would be slower than the other conditions.

ANOVAs were performed on the movement time data for the 4 condition design. As expected, there was a main effect for condition ($F_{3,69}$=14.7, p=.000, η^2=.39). Pairwise comparisons revealed our hypothesis was validated, with the control condition being significantly slower than expand-cursor ($F_{1,23}$=8.6, p=.008, η^2=.27), expand-target ($F_{1,23}$=5.7, p=.026, η^2=.20), and snap-to-target ($F_{1,23}$=51.5, p=.000, η^2=.69) conditions.

Hypothesis 2: There would be a difference between the three selection aid conditions.

We removed the control condition from the analysis and ANOVAs were performed on the movement time data for the 3 condition design. There was a main effect for condition ($F_{2,46}$=9.7, p=.000, η^2=.30), which validated our hypothesis.

Pairwise comparisons revealed that the snap-to-target condition was significantly faster than both the expand-cursor ($F_{1,23}$=9.4, p=.006, η^2=.29) and expand-target ($F_{1,23}$=20.9, p=.000, η^2=.48) conditions. However, there was no significant difference between the expand-cursor and expand-target conditions ($F_{1,21}$=0.4, p=.556, η^2=.02).

Further analyses on movement time

ANOVAs performed on the movement time data for the 4 (condition) by 3 (target amplitude) by 3 (target width) design revealed significant two-way interaction effects of condition by angle ($F_{6,114}$=5.2, p=.000, η^2=.21), condition by amplitude ($F_{6,114}$=11.2, p=.000, η^2=.04), and condition by width ($F_{6,114}$=11.2, p=.000, η^2=.37), and a significant three way interaction effect of condition by angle by amplitude ($F_{12,228}$=2.1, p=.017, η^2=.10). Graphs of movement times for each condition, separated by amplitude and width are presented in Figure 7.

In order to further explore the interaction effects involving condition, ANOVAs were performed on the movement time data for each condition individually, with a 3 (target angle) by 3 (target amplitude) by 3 (target width) design for each.

For the control condition, there were significant main effects of angle ($F_{2,42}$=5.6, p=.007, η^2=.21), amplitude ($F_{2,42}$=67.9, p=.000, η^2=.76), and width ($F_{2,42}$=68.6, p=.000, η^2=.77). On average, movement times increased as amplitude increased, and also as width decreased. Pairwise comparisons of angle revealed that it was significantly faster to point to the right than along the midline ($F_{1,21}$=12.0, p=.002, η^2=.36) or to the left ($F_{1,21}$=6.9, p=.016, η^2=.25).

The expand-cursor condition also had significant main effects of angle ($F_{2,46}$=9.7, p=.000, η^2=.30), amplitude ($F_{2,46}$=36.5, p=.000, η^2=.61), and width ($F_{2,46}$=13.1, p=.000, η^2=.36). On average, movement times increased as amplitude increased, and also as width decreased. Pairwise comparisons of angle revealed significantly faster movement times on the right angle than on the left ($F_{1,21}$=24.1, p=.000, η^2=.51), but no significant difference between midline and right ($F_{1,21}$=.088, p=.770, η^2=.004).

ANOVAs performed on the expand target condition revealed a single significant main effect of amplitude ($F_{2,42}$=44.5, p=.000, η^2=.68). As expected, movement times increased as amplitude increased. There were no significant effects of angle ($F_{2,42}$=1.8, p=.172), η^2=.08) or width ($F_{2,42}$=1.8, p=.171, η^2=.08), which is consistent with previous work on expanding targets [7].

The snap-to-target condition exhibited a significant interaction effect of angle by amplitude ($F_{4,92}$=3.6, p=.009, η^2=.13). In order to further explore this interaction effect, ANOVAs were performed on the snap-to-target movement time data for each angle individually.

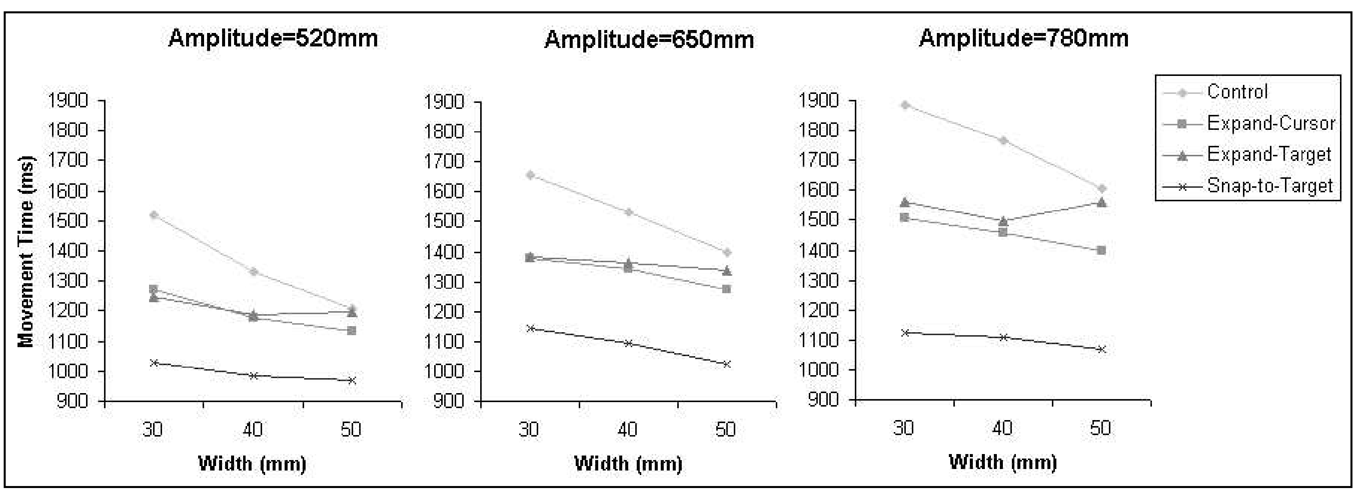

Figure 7: Mean movement times for each condition, separated by amplitude and width.

For the left angle, there were significant main effects of both amplitude ($F_{2,46}$=10.2, p=.000, η^2=.31) and width ($F_{2,46}$=6.0, p=.005, η^2=.21) with movement times increasing at larger amplitudes and smaller widths. For the midline and right angles there was only a significant main effect of amplitude ($F_{2,46}$=5.6, p=.007, η^2=.20 and $F_{2,46}$=11,8, p=.000, η^2=.34, respectively) with movement times increasing at larger amplitudes.

Error Rates

We were also interested in whether or not there was a significant difference in the number of errors in the various conditions. ANOVAs were performed on the error rate data for the 4 condition design. There was a main effect for condition ($F_{3,69}$=7.2, p=.000, η^2=.24). Pairwise comparisons revealed that the control condition had significantly more errors than both expand-cursor ($F_{1,23}$=34.5, p=.000, η^2=.60) and expand-target ($F_{1,23}$=6.2, p=.021, η^2=.21, but that there was no significant difference with snap-to-target ($F_{1,23}$=.003, p=.956, η^2=.000).

Mean error rates for each condition, separate by amplitude and width, are displayed in Figure 8. Note that a value of zero would indicate that no errors occurred for that target.

The snap-to-target condition had significantly more errors than the expand-cursor ($F_{1,23}$=20.0, p=.000, η^2=.47) condition, but not the expand-target condition ($F_{1,23}$=3.2, p=.088, η^2=.12). There was no significant difference in errors between the expand-cursor and expand-target conditions ($F_{1,23}$=2.0, p=.170, η^2=.08).

Further analyses on error rates

ANOVAs performed on the error rate data for the 4 (condition) by 3 (target angle) by 3 (target amplitude) by 3 (target width) design revealed significant two-way interaction effects of condition by amplitude ($F_{6,138}$=3.8, p=.001, η^2=.143), and condition by width ($F_{6,138}$=4.1, p=.001, η^2=.15) and a significant 3-way interaction effect of angle by amplitude by width ($F_{8,184}$=2.2, p=.026, η^2=.09).

In order to further explore the interaction effects involving condition, ANOVAs were performed on the error rate data for each condition individually, with a 3 (target angle) by 3 (target amplitude) by 3 (target width) design for each.

For the control condition, there were significant main effects of angle ($F_{2,46}$=7.9, p=.001, η^2=.26), amplitude ($F_{2,46}$=29.1, p=.000, η^2=.56), and width ($F_{2,46}$=12.8, p=.000, η^2=.36), with errors, on average, increasing as amplitude increased and also as width decreased. For angle, the number of errors decreased moving from left to right, with the right angle having significantly fewer errors than both the midline ($F_{1,23}$=17.9, p=.000, η^2=.44) and the left ($F_{1,23}$=7.7, p=.011, η^2=.25).

The expand-cursor condition also had significant main effects of angle ($F_{2,46}$=9.4, p=.000, η^2=.29), amplitude ($F_{2,46}$=33.2, p=.000, η^2=.59), and width ($F_{2,46}$=3.4, p=.041, η^2=.13), with errors increasing at larger amplitudes and smaller widths. And again, the right angle had significantly fewer errors than midline ($F_{1,23}$=11.5, p=.003, η^2=.33) or left ($F_{1,23}$=17.9, p=.000, η^2=.44)

ANOVAs performed on the expand-target condition revealed significant main effects of angle ($F_{2,46}$=3.4, p=.041, η^2=.13) and amplitude ($F_{2,46}$=13.9, p=.000, η^2=.38), but not width ($F_{2,46}$=.34, p=.715, η^2=.014). As expected, error rates increased as amplitude increased, and again the right angle had the fewest errors.

A significant interaction effect of angle by amplitude ($F_{4,92}$=2.9, p=.026, η^2=.11) was found for the snap-to-target condition. In order to further explore this interaction effect, ANOVAs were performed on the snap-to-target error rate data for each angle individually. For the left and midline angles there were no significant main effects.

The right angle had a single significant main effect of amplitude ($F_{2,46}$=4.3, p=.020, η^2=.16), with the middle

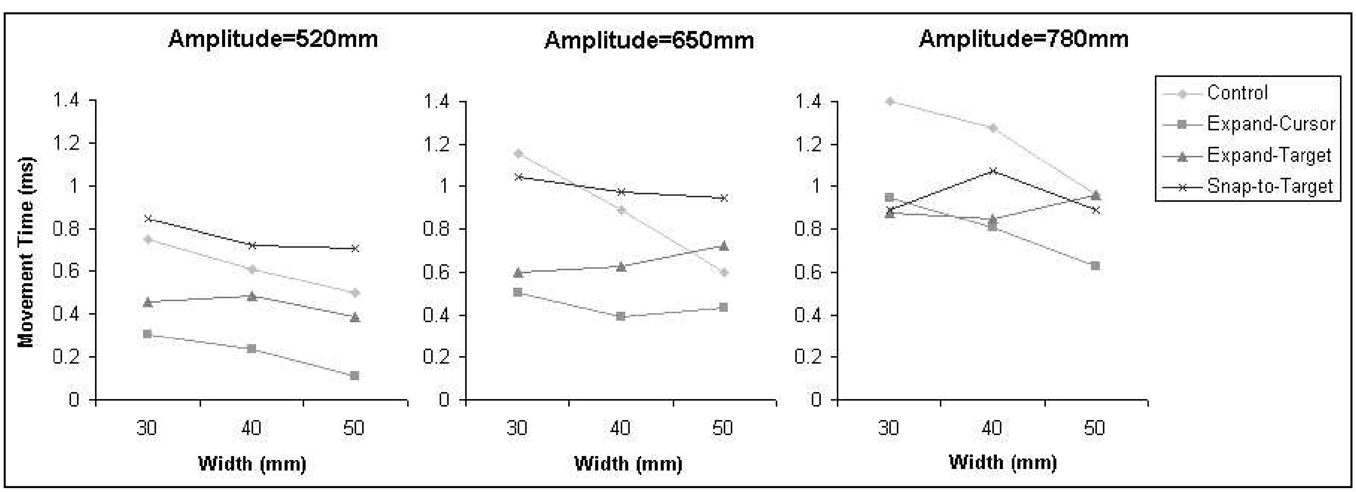

Figure 8: Mean error rates for each condition, separated by amplitude and width.

amplitude having significantly more errors than the smallest one ($F_{1,23}$=7.2, p=.013, η^2=.24), but no significant difference between the smallest and largest amplitudes ($F_{1,23}$=4.2, p=.053, η^2=.15) or the medium and largest amplitudes ($F_{1,23}$=.84, p=.370, η^2=.04).

Inverse Efficiency

Although snap-to-target was found to be the fastest selection aid in our study, it also had significantly more errors than the slower expand-cursor aid. Thus, we wanted to investigate the speed/accuracy tradeoffs of the various conditions. Townsend and Ashby [11] suggested combining movement time and error measures with the following equation for inverse efficiency (IE):

$$IE = MT/(\text{Proportion of trials correct})$$

For example, a mean movement time of 2000ms with 4 out of 5 trials successful would result in an inverse efficiency of 2500 (IE = 2000/0.8). A lower IE score corresponds to a more efficient technique.

Inverse efficiencies were calculated using the collected MT and error data. Mean inverse efficiency for each of the conditions is displayed in Table 2.

ANOVAs were performed on the IE data for the 4 condition design. There was a main effect for condition ($F_{3,69}$=5.1, p=.003, η^2=.18). Pairwise comparisons revealed that snap-to-target had significantly lower inverse efficiency than the control condition ($F_{1,23}$=18.2, p=.000, η^2=.44). However, while the mean IE for snap-to-target was also lower than that of the other selection aid conditions, it was not significantly different ($F_{1,23}$=4.0, p=.055 η^2=.15 when compared to expand-target, $F_{1,23}$=.95, p=.341, η^2=.04 compared to expand-cursor).

Questionnaire Responses

After each condition participants rated a number of factors related to effort, comfort, and effectiveness on a five-point scale. To determine differences between the conditions, results from these questionnaires were analyzed using a Friedman test. The means are summarized in Table 3.

There was a significant difference in perceived speed of the four conditions (χ^2=18.7, p=.000). Wilcoxon matched-pairs tests revealed that participants perceived that both expanding-cursor (p=.003) and snap-to-target (p=.002) were significantly faster than the control condition, and there were no significant differences between other pairs.

Condition	Inverse Efficiency (IE)
Control	2411
Expand-cursor	1606
Expand-target	2003
Snap-to-target	1446

Table 2: Mean inverse efficiency for each condition

There was also a significant difference between conditions in terms of perceived accuracy (χ^2=16.1, p=.001). Wilcoxon matched-pairs tests revealed that they found snap-to-target (p=.006) significantly faster than the control condition, but there were no significant differences between other pairs.

In terms of comfort, there was again a significant difference between conditions (χ^2=10.2, p=.017), with matched-pairs tests showing snap-to-target as significantly more comfortable than the control (p=.008) but no other significant differences between pairs. For ease of use, there was also a significant difference between conditions (χ^2=14.5, p=.002), with matched-pairs tests revealing both snap-to-target (p=.003) and expanding-cursor (p=.004) significantly easier to use than the control, and no other significant differences between pairs.

At the end of the experiment we asked the participants to rate the four conditions according to how effective they were and how much they liked each technique. To determine differences between the interaction techniques, results from these questionnaires were also analyzed using a Friedman test. The means are summarized in Table 4. There was a significant difference between the conditions in terms of both effectiveness (χ^2=22.96, p=.000) and enjoyability (χ^2=22.94, p=.000).

	Control Mean (SD)	**Expand-Cursor** Mean (SD)	**Expand-Target** Mean (SD)	**Snap-to-Target** Mean (SD)
Mental Effort	3.21 (.93)	2.96 (.81)	3.08 (.78)	2.58 (.97)
Physical Effort	3.92 (.65)	3.58 (.72)	3.71 (.69)	3.46 (.83)
Perceived Speed*	3.21 (.93)	3.96 (.81)	3.71 (.91)	4.25 (.90)
Perceived Accuracy*	2.96 (1.16)	3.58 (1.11)	3.79 (.88)	4.04 (1.12)
Wrist Fatigue	3.50 (.98)	3.17 (.92)	3.46 (.72)	3.25 (1.03)
Arm Fatigue	2.96 (1.09)	2.75 (.90)	3.13 (1.19)	2.75 (1.03)
Shoulder Fatigue	2.71 (1.09)	2.67 (.96)	2.50 (1.02)	2.37 (.82)
Neck Fatigue	2.33 (.96)	2.54 (.98)	2.21 (.88)	2.29 (.96)
Comfort*	2.96 (.81)	3.50 (.83)	3.42 (.88)	3.67 (.82)
Ease of Use*	3.04 (.96)	3.88 (1.04)	3.46 (1.02)	3.96 (.81)

Table 3: Mean responses from condition questionnaires on a five-point scale where 1 is low and 5 is high. (* denotes p<.05)

	Control Mean (SD)	Expand-Cursor Mean (SD)	Expand-Target Mean (SD)	Snap-to-Target Mean (SD)
Effective*	2.33 (1.01)	3.71 (.859)	3.63 (.875)	4.04 (1.122)
Enjoy*	2.33 (1.129)	3.75 (.847)	3.62 (1.09)	4.00 (1.103)

Table 4: Mean responses from post-session questionnaires on a five-point scale where 1 is low and 5 is high. (* denotes p<.05)

Matched-pairs tests revealed that snap-to-target (p=.001), expand-cursor (p=.000), and expand-target (p=.001) were all perceived by users to be significantly more effective than the control condition, but there were no significant differences between other pairings. Additionally, users enjoyed using snap-to-target (p=.001), expand-cursor (p=.000), and expand-target (p=.001) significantly more than the control condition, with no significant differences between other pairings.

Participant feedback confirmed our quantitative finding of snap-to-target as an effective and enjoyable selection aid:

> "The snap helps a lot especially for small targets."

> "[I] found the snap-to-target was the easiest and fastest to use. The expand-target was also easy to use [but] not as fast as the snap-to-target."

> "I liked the fact that the snap-to-target stopped the cursor, as objects far away were harder to select because the cursor became more sensitive."

However, four participants indicated that they did not like the snap-to-target technique:

> "I found this no easier than the control."

> "Snap to target often caused me to move off the target when it snapped to it."

DISCUSSION

We hypothesized that all three of our selection aids would improve upon the original TractorBeam interaction technique used in the control condition. This hypothesis was validated, as movement times for the control condition were significantly slower than all three selection aids. We were also able to confirm our hypothesis that there would be a difference between the three selection aids, with snap-to-target being significantly faster than the other two conditions.

There were also differences in the number of errors made by participants in the different conditions. There was no significant difference between the number of errors in the control and snap-to-target conditions. So, although the snap-to-target selection aid improved on movement times it did not improve on error rates. Additionally, despite its slower movement time, the expand-cursor selection aid had significantly fewer errors than snap-to-target.

Combining the errors and movement times with an inverse efficiency calculation provided some insight into the speed/accuracy tradeoffs for our four conditions. While our fastest condition - snap-to-target – did have a significantly lower inverse efficiency than the control condition, there was no significant difference between it and the other two selection aids. This suggests that the number of errors that happen with snap-to-target may limit its efficiency to the point of it being on par with our other techniques.

Through our questionnaires, we found that users perceived snap-to-target to be significantly faster, more accurate, more comfortable, and easier to use than the control condition. They also perceived expanding-cursor as significantly faster and easier to use than the control. Additionally, all three selection aids were perceived to be more enjoyable and effective than the control condition.

Overall, snap-to-target was the only selection aid to be perceived as significantly more comfortable and accurate than the control condition. It was also had significantly lower movement times than all other conditions, and was as good as the other two selection aids in terms of inverse efficiency. While there were more errors with snap-to-target than some of the other selection aids, future work on the TractorBeam could explore optimal snap thresholds for minimizing error while maximizing movement time, eventually improving on the condition's error rate.

CONCLUSIONS & FUTURE WORK

We explored several methods for improving selection of small, distant targets with the TractorBeam. Augmenting the TractorBeam with each of these selection aids increased our technique's effectiveness for selection of distant items. Additionally, despite no significant difference in inverse efficiency scores between the three selection aids, the positive user feedback from our third study gives snap-to-target an edge over the other solutions. Snap-to-target solves the main problem encountered with the TractorBeam technique in our first study, and further increases its viability as an interaction technique for large tabletop displays.

Although the snap-to-target selection aid had excellent results in our user study, this finding was only for isolated, distant targets. We plan to further test the TractorBeam with this selection aid in less controlled tasks. In particular, we would like to test its effectiveness with groups of targets which are close together, as well as the general usability of the technique for close targets.

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Removed for blind review.

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