TractorBeam: Seamless integration of local and remote pointing for tabletop displays

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ABSTRACT

This paper presents a novel interaction technique for tabletop computer displays. When using a direct input device such as a stylus, reaching objects on the far side of a table is difficult. While remote pointing has been investigated for large wall displays, there has been no similar research into reaching distant objects on tabletop displays. Augmenting a stylus to allow remote pointing may facilitate this process. Results from our work demonstrate that remote pointing is faster than touch input for large targets, slower for small distant targets, and comparable in all other cases. In addition, when given a choice, people utilized the pointing interaction technique more often than direct touch. Based on these results we developed the TractorBeam, a hybrid point-touch input technique that allows users to seamlessly reach distant objects on tabletop displays.

Author Keywords

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

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces - Evaluation/methodology, Input devices and strategies, Interaction styles.

INTRODUCTION

While tabletop display research has become more prevalent in recent years, there is still no widely accepted standard input device for these displays. Researchers have used a wide array of interaction techniques, including fingers (touch sensitive displays) [6, 10, 20, 28], styli [10, 28], mice [11, 23], trackballs [7], and tangible input [14, 17, 19, 25, 26]. For certain activities on a tabletop display, direct interaction with the display can provide benefits [9]. However, users cannot easily interact with objects on the far side of the table using a direct input method without standing up and reaching, or walking around the display to bring the object within reach. It is important to provide users with an input technique that will allow them to seamlessly interact with far objects on tabletop displays without severely hindering interaction with close objects.

Remote pointing devices such as laser pointers have been proposed as input solutions for large wall displays with varying degrees of success [13, 15, 16]. While they allow input from various distances, they are problematic in terms of accuracy and speed. Given that the distances users typically need to reach on a tabletop display are much smaller, and the fact that people typically sit at a tabletop display with their arm supported, it is possible that a laser pointer style of interaction would perform better on a tabletop display than a wall display.

Table users are unique in that they find themselves close to some parts of the display, but distant from others. The horizontal orientation of the tabletop also means that the "up-down" movement (shown to be problematic on a wall display) is very different on a tabletop display. A user may steady their arm by resting it on the table. Additionally, the hand/arm movement required to move the cursor is not linear – rather, it becomes smaller the closer the cursor gets to the far edge of the display.

While an indirect input device, such as a mouse, may be faster and more accurate for target acquisition, it is important to consider the types of activities that will be undertaken on the tabletop display. If direct input is used for some of the activities on a tabletop display, utilizing a separate device or technique to retrieve distant objects will be problematic because of the overhead involved in switching devices and the need to adjust (both physically and mentally) to a shift in input mode. It is well established in HCI literature that minimizing reliance on modes is beneficial for reducing cognitive load and errors [24].

We conducted a user study to compare three interaction techniques for selecting objects on a tabletop display:

1. direct touch with a stylus (touch)
2. pointing with a stylus, arm kept stationary (point)
3. reaching and pointing with a stylus (reach-and-point)

All three interaction techniques were evaluated for speed and accuracy. In addition, data were gathered related to users' preferences and their choice of technique for various combinations of target size and location.

The results of our user study, along with previous research, informed the design of the TractorBeam—a hybrid point-touch interaction technique. It allows users to cast an invisible beam from the end of a stylus to select objects on a tabletop display. The TractorBeam is well suited for tabletop displays because it allows users to interact directly with nearby objects using a stylus as they normally would on a flat display (direct touch), while also aiding them in reaching distant objects by providing a laser-style pointer.

This paper first reviews related work in the area and then describes our experimental methodology to compare the effectiveness of the three proposed interaction techniques for tabletop displays. We next present the results and describe the TractorBeam interaction technique. Following this, we describe an exploratory user study that we conducted to gain insight into usage of the TractorBeam. Finally, we present our conclusions and future work.

RELATED WORK

Remote pointing on large wall displays

Remote interaction with large wall displays has been investigated in a number of studies [13, 15, 16]. Several researchers have proposed laser pointer interaction as a possible solution [15, 16], while others have examined solutions involving gyroscopic mice [13] or PDAs [15]. In most cases, these remote pointing solutions performed poorly, with slow acquisition times and large error rates. For pointing tasks on large wall displays, laser pointers were worse than both mice [15, 16] and direct touch [15] in terms of throughput and speed, and users found them difficult to operate [15]. In addition, using standard laser pointers required input to be tracked using a camera. This caused significant delays between the time a user pointed to a location and when the action was processed by the computer, resulting in delayed feedback. As conceded by Myers et al., "interaction techniques using laser pointers tend to be imprecise, error prone, and slow" [15].

Reaching distant objects on large displays

Baudisch et al. [2] developed the drag-and-pop and drag-and-pick interaction techniques for reaching display items that are far away or otherwise out of the reach of the user. In drag-and-pop, as the user drags an icon across the display, potentially related target icons are stretched towards the icon being dragged. Drag-and-pick extends this idea by popping all (related and unrelated) icons located in the direction of the drag motion, and then allowing the user to pick the desired icon. A user study revealed that users were able to locate icons 3.7 times faster when using the drag-and-pop technique [2]; however, this technique requires the system to "know" which icons are related to the one the user is dragging. Drag-and-pick removes this problem by bringing all icons towards the cursor, but may result in the user having a large number of icons to pick from.

Interacting on tabletop displays

Past research on tabletop displays has used of a variety of input technologies including touch [6, 10, 20, 28], styli [10, 28], mice [11, 23], trackballs [7], and tangible input [14, 17, 19, 25, 26]. While most of this previous work has not evaluated specific input techniques, a few researchers have developed and tested specialized input techniques for tabletop displays. Wu and Balakrishnan developed and evaluated a suite of hand and finger gestures for multi-touch tabletop displays [29]. Rekimoto and Saitoh explored two techniques – hyperdragging and pick-and-drop – to allow users to move files between a tabletop and other computing devices, including distant displays such as large wall screens [21].

Reaching distant objects in VR environments

Two main techniques have been identified for selection and manipulation of objects in Virtual Reality (VR) environments (which often involve distant objects): arm extension (Go-Go Gadget)[18] and ray casting [4]. The Go-Go Gadget technique allows users to stretch a virtual 3D arm to reach beyond their immediate surroundings in order to grab and manipulate objects [18]. The arm acts as a normal human's arm would until the user reaches outside of a predefined "local area", at which point the arm stretches at an increasing rate until the user reaches the desired object. The ray casting technique allows users to casts a virtual ray, pointing it at whatever object they wish to select [4]. The ray casting technique is more accurate than the Go-Go Gadget technique; however, manipulative abilities are limited by the single degree of freedom [4].

STUDY ONE: EXPERIMENTAL DESIGN

We conducted a study to compare the speed and accuracy of selecting a target by touching it (touch) versus pointing to it (point, reach-and-point).

Participants

Twelve participants, seven male and five female, took part in our study. All participants were university students and were right handed. All provided informed consent.

Hardware

The hardware setup included a top-projected tabletop display, consisting of a ceiling-mounted projector, mirror, desktop PC, and wooden table. The PC was connected to the projector and its output was projected onto the mirror, which reflected the image onto the table (Figure 1). The projected display area was 1200 x 900 mm, and was inset 200 mm from the user's side of the table (Figure 2). A cardboard screen attached to the tabletop provided a white projection surface.

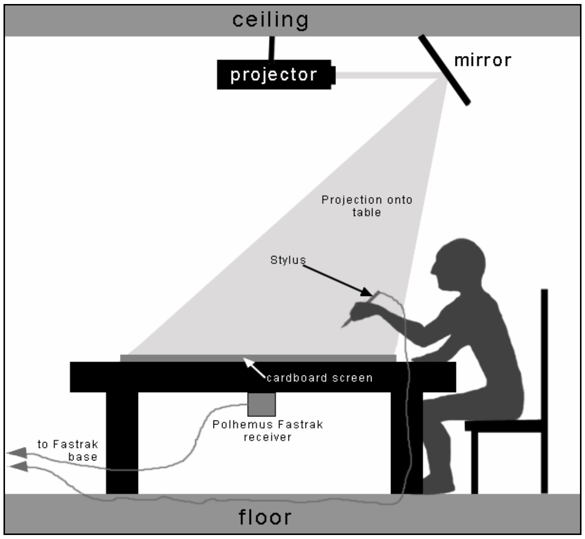

Figure 1: Top-projected tabletop hardware configuration.

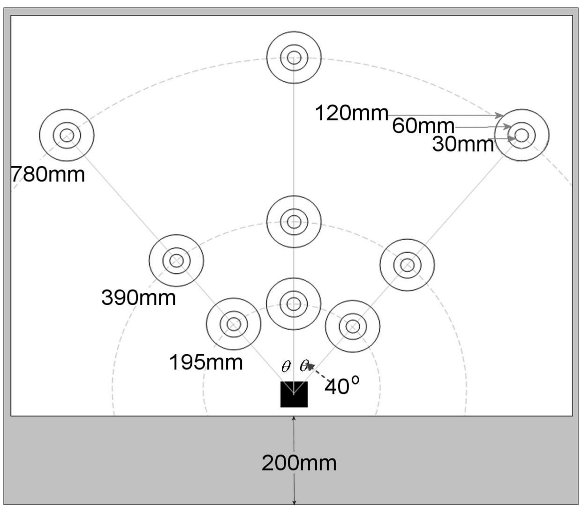

Figure 2: 2D software setup. The black square is the starting point and the circles represent the targets. Targets were three different widths (30mm, 60mm, or 120mm), on three different angles (40 degrees left, midline, and 40 degrees right), and had three different amplitudes (195mm, 390mm, and 780mm).

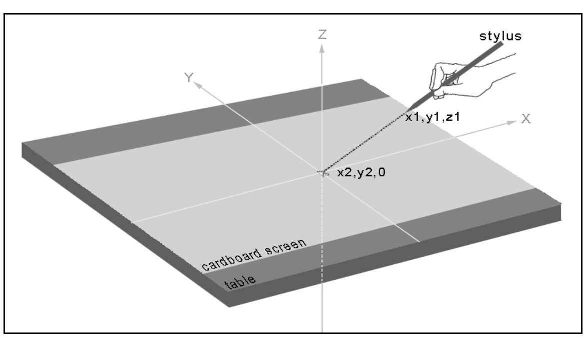

Figure 3: Pointing interaction technique. The position and orientation of the stylus (x1, y1, z1, azimuth, and elevation) was used to project the endpoint onto the table surface (x2, y2, 0).

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 and provided our software with information about the current position of the stylus in relation to the display.

Task

A multi-directional task (2D Fitts discrete task) was used to evaluate selection tasks in three conditions: *touch*, *point*, and *reach-and-point*.

In the touch condition, participants selected objects by touching the stylus to an item on the table. In the point condition, users selected objects by pointing at them with a stylus (using it like a laser pointer, with a cursor appearing on the table). Participants were required to keep their upper arm stationary on the table and refrain from reaching towards the targets while pointing. In the reach-and-point condition, users selected objects by pointing at them (similar to the point condition) but were encouraged to reach out over the display to reduce the distance between the stylus and the target.

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 2). Target circles were presented with one of three widths (30mm, 60mm, 120mm), at one of three angles (40 degrees left, midline, 40 degrees right), and at one of three amplitudes (195mm, 390mm, 780mm).

A Java application was developed to implement the selection interactions required for each of the three conditions. Positional information (x, y, z, azimuth, and elevation) was received from the stylus and projection of the endpoint of the stylus onto the table was calculated (Figure 3: x2,y2).

The Polhemus stylus was used for all conditions, including touch, and visual feedback was provided via a cursor on the display. In all three conditions, selection was indicated by a cursor dwell time of at least 300 milliseconds inside a target.

Each individual trial began when a user selected the home square, and ended when they selected the target circle. Between the user's selection of the square and the appearance of the target circle, there was a random-length pause of between 500 and 1500 ms. Software logged when a target appeared, when a user moved off the home square, and when a target circle was selected. Movement time was calculated as the difference between the time a user moved off the home square and the time they selected the target.

Procedure

A within subjects design was utilized with each participant using all three interaction techniques. 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 three conditions. Participants sat at the tabletop display and were asked to remain seated for the duration of the session, unless it was necessary to briefly stand in order to reach distant targets.

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 10 minutes to complete each interaction technique (including answering the questionnaire), for a combined session total of approximately 30 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 input technique they had just used. Once all three conditions were finished, users were given a final questionnaire asking them to rank the three techniques in terms of satisfaction and perceived effectiveness.

Hypotheses

Given previous findings in pointing research using Fitts' Law, we expected that there would be effects of target width, target angle, and target amplitude on movement time. Previous experimentation with laser pointers on large wall displays has shown that laser pointers are slower than mice [15, 16] and touching with a finger [15]. In addition, participants experienced a great deal of difficulty related to accuracy resulting from hand jitter. Since the jitter of a pointer is amplified with distance, we expected that pointing on a tabletop display could yield better results than pointing on a wall display given the shorter distance to the target. Because users were required to lift their bodies off their chair to touch distant targets, we expected that it would take longer to touch distant targets using the stylus than pointing with it. Although a user could move much faster with a pointer, it would likely take them longer to home in on the target due to the amplification of their movements. For this reason we expected that it would be faster to point to large targets than to touch them with a stylus. For the same reason we also expected that it would take longer to point to small targets than to touch them with a stylus. To summarize, our hypotheses were:

1. Fitts' Law would be upheld using all three interaction techniques. Also, it would be faster to point along the midline and towards the right, than towards the left.
2. Pointing would be faster than touching for distant targets, but not different for close targets.
3. Pointing to small targets would be slower than touching.

Data analyses

Computer logs were used to determine the following dependent measures: movement time (MT), error rate, and entry rate (the number of times a user entered the target before making a selection). Movement time data were calculated from when the cursor exited the home square until the user selected the target. This method of computing movement time does not include reaction time. We chose to measure movement time in this manner since the large tabletop display did not fit within the users' field of view and locating a target required a visual scan (which would be impacted by different angles, widths and amplitudes). As this was not a focus of our study, it was important that the time required to scan the display did not influence the time taken to actually perform the movement. In addition, the 300 ms dwell time (required to determine a selection) was not included in the movement time measure.

Participants were required to select the target before moving on to the next trial, so there were no missed targets (errors from endpoints outside the target circle). Errors occurred in one of two ways: either the cursor left the home square before the target appeared (anticipatory error); or the participant did not complete the trial within a reasonable amount of time (timeout error). Timeout errors occurred when subjects could not home in on the target or dwelled outside the target for 4 seconds. We removed 69 (1.4% of total trials) anticipatory errors and 24 (0.5% of total trials) timeout errors from the analysis.

Outliers were removed for each participant by calculating each individual's mean movement time for all trials, and removing any individual times that were more than three standard deviations from this mean.

Welford's extension to Fitts' Law [27] was used to recognize the potential separable effects of width and amplitude: $MT = a + b_1 \log_2 A - b_2 \log_2 W$

In this model, $b_1 \log_2 A$ may correspond to the initial impulse towards the target, while $b_2 \log_2 W$ may correspond to the feedback based final adjustment.

Participants may have entered the target circle more than once as a result of overshooting, especially for smaller targets. We logged each time a user entered the target to get an indication of the degree of overshooting (entry rate).

Movement time and entry rate 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 movement time and mean entry rate data. All main effects and interactions were tested at α=.05. We also performed multiple regressions on means for MT (averaged across all subjects) using ID, or A and W as predictors, separately for each technique. Questionnaire data were analyzed using non-parametric statistics.

STUDY ONE: RESULTS AND DISCUSSION

Movement time data for the midline, separated by interaction technique, amplitude, and width are presented in Table 1. Entry rates (the number of times the cursor entered the target prior to selecting it) separated by interaction technique, amplitude, and width are shown in Table 2. Note that an entry rate of 1.0 would signify that participants never overshot the target.

Hypothesis 1a: Fitts' Law would be upheld using all three interaction techniques.

Regression analysis

Research has shown that movement times for similar indices of difficulty will differ for varying combinations of target amplitude and width [12], and that target amplitude and width are better predictors of movement time than ID alone [8]. Using a multiple linear regression, our data was fit across subjects for MT using ID, or A and W as predictors for each interaction technique (Table 3).

Consistent with previous work, Welford's two-part model provided a better fit than ID alone. Note that for touch on the midline, Fitts' Law only accounted for 67% of the variance, while the two-part model accounted for 97%, a great improvement. The two-part model revealed that for similar IDs, movement times were more sensitive to changes in target amplitude than target width when touching. This is shown by the magnitude of the constant term preceding the $\log_2 A$ and $\log_2 W$ terms. For pointing, the relative contribution of target width was much higher.

The separable effects of amplitude and width are clearly seen for touching. Because participants were required to lift completely off their chair to reach the distant targets, we thought that MT for these targets would be disproportionately slower than MT for targets within reach. Plotting both the predicted MT from a model of close and middle targets and the actual MT as evidenced in the data reveals this to be the case. Figure 4 shows that for close and middle target distances, the predicted and actual MTs are similar. For the distant target, actual MT is larger than predicted MT for all three target widths. For pointing, the difference between predicted and actual MT is particularly large for small, distant targets.

Hypothesis 1b: It would be faster to point along the midline and towards the right, than towards the left.

Movement time

Repeated measures ANOVAs were performed on the movement time data for the 3 (interaction technique) by 3 (target angle) design. Consistent with our hypothesis, there was a main effect for angle ($F_{2,22}$ =15.74, p=.000, $\eta 2$=.59), but no main effect for interaction technique ($F_{2,22}$=1.55, p=.240, $\eta 2$=.12). Pairwise comparisons revealed that movement times were significantly faster for targets on the right than targets on the midline ($F_{1,11}$=12.66, p=.004, $\eta 2$=.54) or on the left ($F_{1,11}$=24.64, p=.000, $\eta 2$=.69). This is consistent with our hypothesis.

Amp (mm)	Width (mm)	Touch Mean (SE)	Point Mean (SE)	Reach-and-point Mean (SE)
195	30	438 (36)	513 (35)	543 (44)
	60	341 (27)	310 (22)	311 (23)
	120	296 (25)	176 (15)	179 (17)
390	30	582 (52)	711 (44)	827 (56)
	60	573 (65)	557 (33)	561 (35)
	120	463 (37)	376 (26)	404 (29)
780	30	1027 (68)	1480 (98)	1433 (68)
	60	975 (98)	938 (63)	1038 (68)
	120	829 (76)	682 (46)	770 (58)

Table 1: Mean movement time (MT) for each technique, separated by amplitude and width.

Amp (mm)	Width (mm)	Touch Mean (SE)	Point Mean (SE)	Reach-and-point Mean (SE)
195	30	1.08 (0.04)	1.56 (0.06)	1.55 (0.06)
	60	1.03 (0.01)	1.29 (0.05)	1.34 (0.05)
	120	1.01 (0.01)	1.28 (0.03)	1.26 (0.03)
390	30	1.06 (0.03)	1.52 (0.08)	1.82 (0.12)
	60	1.03 (0.01)	1.56 (0.09)	1.42 (0.07)
	120	1.00 (0.00)	1.26 (0.05)	1.31 (0.07)
780	30	1.12 (0.03)	3.43 (0.23)	3.14 (0.20)
	60	1.07 (0.04)	2.18 (0.15)	2.37 (0.15)
	120	1.02 (0.01)	1.65 (0.12)	1.63 (0.05)

Table 2: Mean entry rate for each technique, separated by amplitude and width.

	Regression	R^2
Touch	MT (ms) = -90 + 199 ID	.67
	MT (ms) = -1801 + 330 $\log_2 A$ - 67 $\log_2 W$	.97
Point	MT (ms) = -433 + 290 ID	.88
	MT (ms) = -738 + 331 $\log_2 A$ - 249 $\log_2 W$	.90
Reach-and-point	MT (ms) = -512 + 326 ID	.91
	MT (ms) = -895 + 375 $\log_2 A$ - 278 $\log_2 W$	.93

Table 3: Linear regressions for prediction of movement time separated by angle. Fitts' model uses ID, while Welford's model separates A and W.

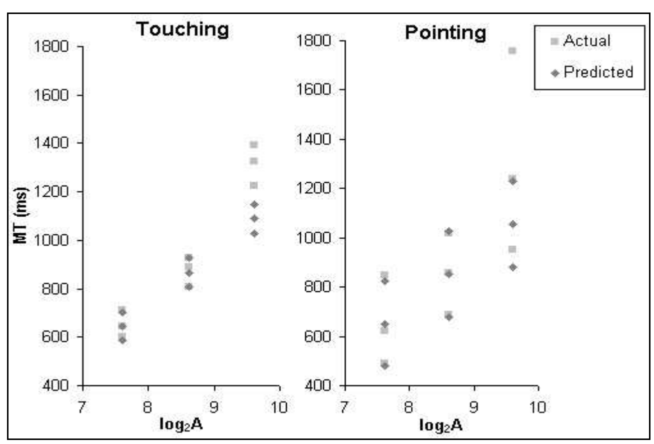

Figure 4: Predicted and actual MTs based on models of close and mid targets. For each $\log_2 A$ the three vertical symbols represent small, medium, and large target widths (top to bottom).

Hypothesis 2: Pointing would be faster for distant targets but not different for close targets.

Movement time

Repeated measures ANOVAs were performed on the movement time data for the 3 (interaction technique) by 3 (target amplitude) by 3 (target width) design. A significant 3-way interaction between width, amplitude, and interaction technique was found ($F_{8,88}$=8.0, p=.000, η^2=.42). Since our hypothesis stated that MTs between the techniques would differ as a function of target amplitude, we separated this interaction by target amplitude. Figure 5 shows this 3-way interaction.

For distant targets there was a significant interaction effect of width by interaction technique ($F_{4,44}$=21.2, p=.000, η^2=.66). To further explore this interaction effect we separated by target width and performed ANOVAs on movement time data for the 3 (interaction technique) design. This analysis revealed that the first part of our hypothesis was validated for large targets but not for medium or small targets. For large distant targets, we found a main effect of interaction technique ($F_{2,22}$=4.6, p=.021, η^2=.30) and pairwise comparisons revealed that the point technique was significantly faster than both the touch and reach-and-point techniques, ($F_{1,11}$=5.4, p=.040, η^2=.33 and $F_{1,11}$=5.6, p=.038, η^2=.34 respectively) while no significant different was found between touch and reach-and-point ($F_{1,11}$=2.8, p=.123, η^2=.20).

For medium-sized distant targets there was no significant difference between interaction techniques ($F_{2,22}$=1.9, p=.173, η^2=.15).

For small distant targets, a main effect of interaction technique was found ($F_{2,22}$=13.8, p=.000, η^2=.56), and pairwise comparisons revealed that touch was significantly faster than both point and reach-and-point ($F_{1,11}$=12.7, p=.004, η^2=.54 and $F_{1,11}$=36.35, p=.000, η^2=.77 respectively), and no significant difference between point and reach-and-point ($F_{1,11}$=.001, p=.972, η^2=.000).

For close targets there was also a significant interaction effect of width by interaction technique ($F_{4,44}$=9.5, p=.000, η^2=.47). To further explore this interaction effect we separated by target width and performed ANOVAs on movement time data for close targets in the 3 interaction technique design. We found that the second part of our hypothesis was validated for small and medium targets but not for large targets. For small and medium targets there was no significant difference between the three techniques ($F_{2,22}$=1.98, p=.163, η^2=.15 and $F_{2,22}$=1.15, p=.334, η^2=.10 respectively). For large targets there was a main effect of interaction technique ($F_{2,22}$=28.7, p=.000, η^2=.72) and pairwise comparisons revealed both the point and reach-and-point techniques were significantly faster than the touch technique ($F_{1,11}$=28.2, p=.000, η^2=.72 and $F_{1,11}$=37.0, p=.000, η^2=.77 respectively), while there was no significant difference between point and reach-and-point ($F_{1,11}$=.088, p=.773, η^2=.008).

For small targets at medium distances there was a main effect of interaction technique ($F_{2,22}$=17.3, p=.000, η^2=.61) and pairwise comparisons revealed that touch was significantly faster than both point and reach-and-point ($F_{1,11}$=6.9, p=.023, η^2=.39 and $F_{1,11}$=38.9, p=.000, η^2=.78, respectively), while point was significantly faster than reach-and-point ($F_{1,11}$=10.3, p=.008, η^2=.48).

For small targets at close distances no significant difference was found between the three interaction techniques ($F_{2,22}$=1.98, p=.163, η^2=.15).

Entry Rate

Homing in on small targets with a pointer style interaction can be difficult. In general, when pointing, users overshoot the target then make compensatory movements. This overshoot can happen more than once, which may indicate that a target is difficult to acquire. We expected that pointing to small targets would yield higher entry rates than touching (and would subsequently cause MTs to be slower).

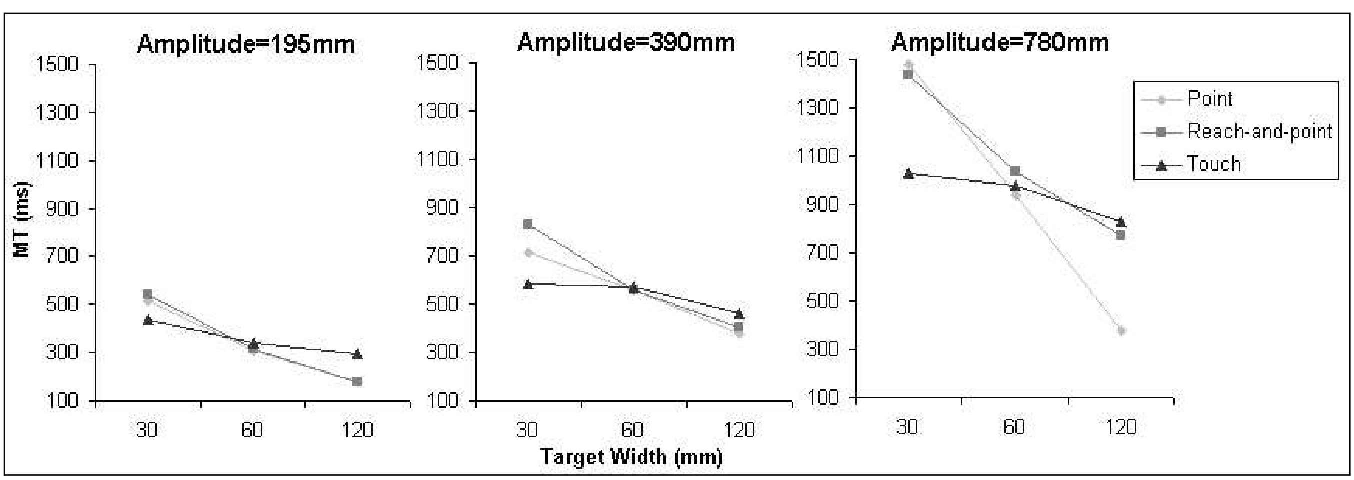

Figure 5: Significant 3-way interaction between width, amplitude, and technique. Note that touching is faster than pointing for small distant targets, and slower for large close targets.

ANOVAs were performed on the entry rate data for the smallest target width for the 2 (interaction technique) by 3 (target angle) by 3 (amplitude) design. This revealed a significant interaction effect between amplitude and interaction technique ($F_{2,22}$=114.25, p<.000, η^2=.91). Exploring this interaction effect further, we separated on interaction technique and ANOVAs were performed on the 3 (target angle) by 3 (amplitude) design.

We found that amplitude had a significant effect on the entry rate for the point interaction technique ($F_{2,22}$=93.8, p=.000, η^2=.90). Pairwise comparisons revealed a significantly higher entry rate at the distant amplitude than at either the close or medium amplitudes ($F_{1,11}$=95.16, p=.000, η^2=.90, and $F_{1,11}$=109.06, p=.000, η^2=.91, respectively).

For the touch interaction technique no significant difference was found for amplitude ($F_{2,22}$=1.36, p=.275, η^2=.11) but a significant main effect was found for angle ($F_{2,22}$=3.77, p=.039, η^2=.26). Pairwise comparisons revealed a significantly higher entry rate at the left and right angles than on the midline ($F_{1,11}$=7.65, p=.018, η^2=.41, and $F_{1,11}$=5.21, p=.043, η^2=.32, respectively).

Further analyses

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 interaction techniques, results from these questionnaires were analyzed using a Friedman test. The means are summarized in Table 4. Participants felt that touching the table required significantly more physical effort than pointing or reaching and pointing (χ^2=7.2, p=.027), however, they experienced less wrist fatigue when touching the table than when pointing or reaching and pointing (χ^2=9.4, p=.009).

At the end of the experiment we asked the participants to rate the three interaction techniques according to how effective they were and how much they liked each technique. There were no significant differences between the three conditions for either variable.

Participant feedback provided additional evidence that it was more difficult to point to small, far targets. One participant commented that "significant effort was required on my part to select small objects that were further away" while another noted "I often over-shot the target and it required more movement in my arm to select."

Participants' questionnaire comments also displayed concern about the fatigue caused by reaching for distant targets in the touch condition:

> "My knees hurt from reaching and standing."
>
> "When the target was close [touching] was fine … But when I had to actually get up from my seat to reach the target it was AWFUL!"

	Touching Mean(SD)	Pointing Mean(SD)	Reaching Mean(SD)
Mental Effort	2.7 (1.0)	2.3 (1.0)	2.9 (1.0)
Physical Effort*	4.8 (0.5)	3.7 (1.2)	3.8 (1.3)
Perceived Accuracy	4.5 (0.7)	4.1 (0.9)	3.9 (0.9)
Perceived Speed	4.0 (0.9)	4.0 (0.7)	3.8 (0.9)
Wrist Fatigue*	2.7 (0.9)	3.2 (1.3)	3.7 (1.0)
Arm Fatigue	3.7 (1.2)	3.7 (1.0)	3.5 (1.4)
Shoulder Fatigue	3.7 (1.6)	3.5 (0.7)	3.1 (1.4)
Neck Fatigue	2.8 (1.4)	2.8 (1.2)	2.4 (1.2)
Comfort	2.8 (1.3)	3.3 (0.9)	3.3 (1.3)
Ease of Use	3.8 (1.2)	4.3 (0.5)	3.8 (1.0)

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

Furthermore, some participants noted the tradeoff between speed and comfort, stating their preference for the pointing technique for far targets even though it was slower:

> "I don't think I was as accurate but I liked it better because I didn't have to keep standing and sitting over and over."

TRACTORBEAM INTERACTION TECHNIQUE

Our study showed that direct touch and pointing both have speed advantages in certain situations. Additionally, participant feedback suggested that users would accept the tradeoff between technique and speed for distant targets, if it allowed them to select objects without moving from their seats. Keeping this in mind, we have designed an interaction technique that combines close touch and distant pointing, allowing users to interact with nearby parts of the display more naturally with a stylus, and use the pointing functionality when they need to select an item that is beyond their reach.

One of the main benefits of the TractorBeam interaction technique is that it allows users to interact with both close and distant items on a tabletop display without having to switch modes or devices. To interact with a close object, the user simply touches the stylus to the table, as one would normally use a stylus with a flat display. To interact with a distant object, the user simply points the stylus towards their desired target, casting a virtual beam which positions the cursor where the user is pointing.

Previous research into pointing on large displays primarily used camera-tracked laser pointers for input [15, 16]. This resulted in significant lag time as the camera processed what the laser was doing. To avoid this problem, we use a "six degrees of freedom" tracking system (Polhemus Fastrak) to achieve the TractorBeam's pointing functionality, so the input does not have the lag problems associated with camera-tracked laser pointers. However, the tracking system we used was a wired system and therefore the styli used for the TractorBeam are tethered, so do not provide the same freedom of movement as a laser pointer.

When pointing from a distance, it may be harder for a user to control the cursor. However, Scott et al. noted that users primarily select distant objects in order to bring them closer, and typically perform more complicated interactions such as manipulation once the items are close [22]. By allowing users to touch locally and point remotely, the TractorBeam provides the means for direct manipulation of close objects, and quick selection of distant objects. The modelessness of our technique further facilitates the process described by Scott et al., allowing users to switch seamlessly from selecting to moving to manipulating.

As described in our first experimental design, the TractorBeam software uses positional information provided by a Polhemus Fastrak to calculate the projected endpoint of a Polhemus stylus. As a result, the software is able to position the cursor to where the stylus is pointing on the table. The software includes a TractorBeamMouse class that generates standard Java mouse events. A TractorBeamMouse can be added to any Java application to allow input via our new technique.

STUDY TWO: EXPERIMENTAL DESIGN

We ran a follow-up study on our TractorBeam interaction technique to determine which input techniques users would choose for selecting various size objects at various locations on the tabletop display.

Task

A simple pointing task was used to observe participants' use of the TractorBeam technique to select targets on a tabletop display. Participants were instructed to use their preferred combination of touch, point, and reach-and-point to make selections.

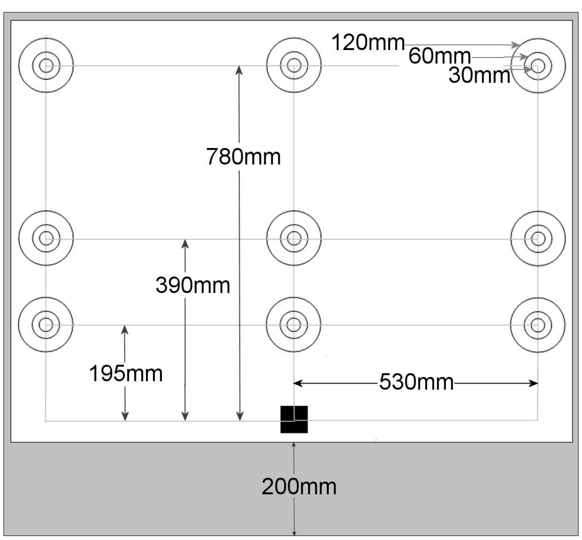

Figure 6: The black square is the starting point and the circles represent the targets. Targets were of three widths (30mm, 60mm, or 120mm), and appeared at nine table locations.

A second Java application was developed, similar to the one used in our first study, and was run on the same tabletop display. It presented a series of selection trials in which target circles appeared in one of 9 locations on the display (Figure 6). As with the first study, targets were one of 3 widths (30mm, 60mm, 120mm).

Participants

Six participants, two male and four female, took part in this study. All had participated in our previous user study and were familiar with the tabletop display and the three different input techniques.

PROCEDURE

Each participant completed exactly five trials of every possible combination of location and width, for a total of 135 trials. The ordering of the trials was randomized.

The focus for this study was on choice of technique, rather than target acquisition time. As such, we used a coding sheet to record which input technique (touch, point, reach-and-point) participants used to select each target.

Hypotheses

The results from our first study revealed that for distant targets, pointing was faster for large targets and touching was faster for small targets. However, our participants expressed appreciation for the point and reach-and-point techniques because they required less physical effort. Based on this, we hypothesized that:

1. For distant targets, users would use the point or reach-and-point techniques.
2. For close targets users would use the touch technique.

Data analyses

A coding sheet was used to record the interaction technique that participants chose to use for each trial. A researcher recorded the technique used for each individual trial. We classified touch as any selection where the stylus touched the table, point as any selection where the user's arm remained stationary, and reach-and-point as any selection where the user's arm moved forwards or sideways to get closer to a target prior to pointing. The counts were totaled for each user and percentages calculated for each size and table location. Friedman tests were then used to evaluate the counts for each of the hypotheses.

STUDY TWO: RESULTS AND DISCUSSION

The counts and percentages for the number of times participants chose to use each interaction technique were recorded. For each table location there are a total of 90 trials (5 trials x 3 sizes x 6 participants). Figure 7 presents a visual representation of the data, showing use percentages for each of the three interaction techniques.

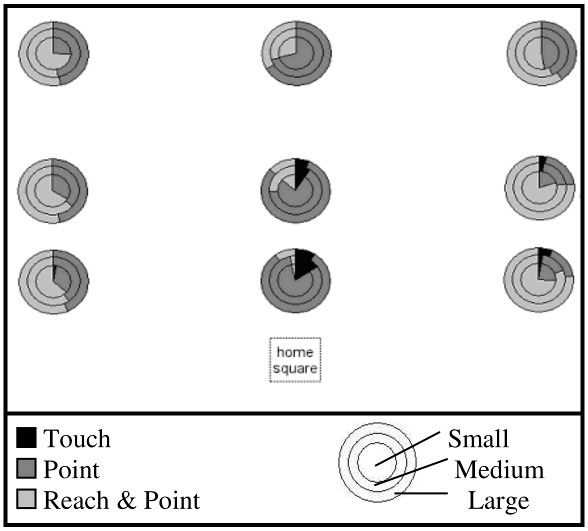

Figure 7: Percentages by size and target location. Nested pie charts represent amounts different techniques were used.

Hypothesis 1: For distant targets, users will choose to use the point or reach-and-point techniques.

Interaction technique counts

For far targets, no participant ever used the touch interaction technique. Results from a Friedman two-way ANOVA revealed that the first hypothesis was validated in that users **always** chose to use the point or reach-and-point techniques for far targets ($\chi^2_{2,N=6}$=8.087, p=.018). On average, the point technique was used 51% of the time and the reach-and-point technique was used 49% of the time.

Hypothesis 2: For close targets users will choose to touch targets directly with the stylus.

Interaction technique counts

For close targets, only one participant used the touch interaction technique (and they used it a total of 18 times out of 45 trials). The remaining five participants **never** used the touch interaction technique. For these five participants, the results from a Friedman two-way ANOVA revealed that hypothesis two was not validated in that the users always chose to point or reach-and-point to close targets ($\chi^2_{2,N=5}$=6.421, p=.040). These five participants used the point technique 54% of the time and used the reach-and-point technique 46% of the time. The one participant who did use the touch interaction technique utilized it 40% of the time, utilized the point technique 4% of the time and utilized the reach-and-point technique 56% of the time.

Further analyses

Interaction technique counts

Further analyses of the interaction technique choice revealed that users' choice of whether to point or reach-and-point was dependent more on the angle of the target than the amplitude of the target. For both the point and the reach-and-point technique, the results from a Friedman two-way ANOVA revealed a significant difference between the interaction technique usage for the left, centre, and right targets (point: χ^2(2, N=6)=8.32, p=.016 and reach: χ^2(2, N=6)=7.90, p=.019) while no difference was found based on target amplitude. Users tended to use the point technique more for centre targets and used the reach-and-point technique more for targets on the left and right hand side of the table.

CONCLUSIONS

Summary of results

Although previous research has found that remote pointing is a poor input technique for large wall displays, our studies found it to be a highly effective technique for tabletop computer displays. It is appropriate for reaching distant objects, and would be effective for users who want to select distant items to move them closer into their personal space for manipulation. The TractorBeam capitalizes on the benefits offered by both pointing and touch, allowing the user to use both techniques seamlessly and without the need to switch between different modes.

When selecting an interaction technique, user comfort must also be considered. The results from our second user study clearly indicated that users preferred to use a pointing interaction style to select distant objects. Thus, although our first experiment revealed that touching was faster for small, far targets, the touch input technique was fatiguing, and not preferred by users (and never utilized for far targets in our second study).

Future work

The Fitts' Law evaluation on the results of our first study raised interesting questions about the use of pointing on tabletop displays. Pointing was slower than touching for small, distant targets. Since a pointer can travel faster than a user's arm, we speculate that the extra movement time is contained within the percent time after peak velocity, or the home-in phase of the movement. Collecting positional data at a high frequency would enable further investigation of this result.

We also plan to further evaluate our TractorBeam technique using a suite of tasks such as tunneling [1] docking [3], and tracing [5]. This will provide a better overall indicator of the TractorBeam's performance on the tabletop. In addition, we would like to test the use of the TractorBeam in ecologically valid tasks using robust applications. Since pointing to small, distant targets was slow and users overshot the target several times before successful selection, we would also like to consider methods of improving a user's ability to select these targets.

Finally, we would like to examine the impact of multiple TractorBeams on co-located collaboration around a tabletop display. We are interested in how this interaction technique affects task work, and whether teamwork will be affected. For example, we think that the TractorBeam might aid in the awareness of other people's activities over traditional indirect methods of input such as mice.

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