HeadReach: Using Head Tracking to Increase Reachability on Mobile Touch Devices

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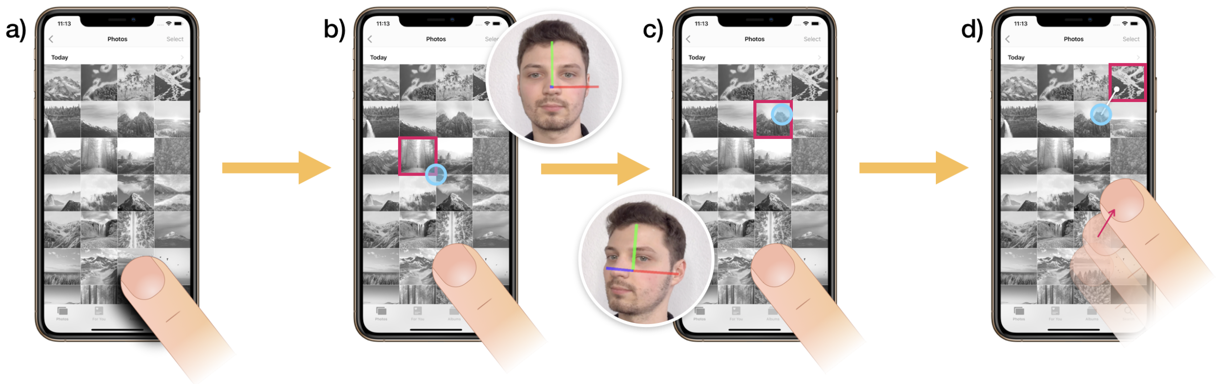

Figure 1. A user wants to select the image in the upper right corner, which is inconvenient to access without changing his device grip. The *head + touch* interaction technique enables selection by combining head and touch input: a) The technique is activated by applying a small amount of force anywhere on the screen. b) Above a certain force threshold, a virtual cursor is displayed at the center of the screen. c) The user can now control the cursor by rotating his head. d) For a more fine-grained selection, he increases the force momentarily to lock the cursor in place and then drags his finger to adjust the cursor position. Releasing his finger confirms the selection.

ABSTRACT

People often operate their smartphones with only one hand, using just their thumb for touch input. With today’s larger smartphones, this leads to a reachability issue: Users can no longer comfortably touch everywhere on the screen without changing their grip. We investigate using the head tracking in modern smartphones to address this reachability issue. We developed three interaction techniques, *pure head (PH)*, *head + touch (HT)*, and *head area + touch (HA)*, to select targets beyond the reach of one’s thumb. In two user studies, we found that selecting targets using HT and HA had higher success rates than the default direct touch (DT) while standing (by about 9%) and walking (by about 12%), while being moderately slower. HT and HA were also faster than one of the best techniques, BezelCursor (BC) (by about 20% while standing and 6% while walking), while having the same success rate.

Author Keywords

Head tracking, touch input, reachability, head selection, walking, user study

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CCS Concepts

•**Human-centered computing** → **Touch screens;** *User studies;*

INTRODUCTION

Over the last twelve years, smartphone screens have almost doubled in size, from 3.5” in Apple’s first generation iPhone in 2007 to up to 6.7” in the Samsung Galaxy S10 in 2019. While larger screens allow for displaying more content, users often interact with their smartphones using just one hand [3, 27], using only the thumb for input [23]. This introduces reachability issues: As the average size of smartphones approaches 5.5”[1], users cannot reach all parts of the screen comfortably anymore without having to re-grasp the device [8].

Several techniques have been proposed to address this problem: BezelCursor [34], ForceRay [8], and MagStick [46] create a cursor that is activated via touch to select targets beyond the reach of the user’s thumb. Other techniques, such as Sliding Screen [28] and TiltReduction [5], introduce modes that shift or scale down the interface to the lower part of the screen such that the content is brought within reach. While these approaches address the problem of reachability, they require explicit mode switching or reducing the screen real estate.

New technological developments offer the potential to create new interaction techniques that address the aforementioned

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[1] https://techcrunch.com/2017/05/31/phables-are-the-phuture/ *(sic)*

issues; of particular interest for this work will be the recently introduced capability of smartphones to track the user's head and eyes [24]. Early explorations of these head and gaze tracking features built into smartphones have begun to uncover this potential, creating interactions such as browsing through photo albums using gaze tracking [59] or unlocking the phone using eye gestures [25, 26]. Using the head as input has the benefits that users can reach the entire screen by just rotating their head, and that it does not occlude content on the screen.

In this paper, we explore how head tracking can be used to address the reachability problem on smartphones. We designed interaction techniques that use head tracking to select objects on a smartphone touchscreen in three different ways, which are also the conditions of our evaluation: *pure head, head + touch,* and *head area + touch.* In the *pure* condition, we use only the head for target selection. *Head + touch* combines head tracking and touch, by letting the user adjust the head selection with a brief touch gesture. *Head area + touch* selects a quadrant of the screen via head tracking, after which the target is selected via indirect touch.

We compare these conditions with each other and two baseline conditions, *direct touch* and *BezelCursor.* Since our head tracking techniques are designed especially for one-handed smartphone use, we chose to evaluate the five conditions with participants ($n = 15$) standing rather than sitting, since in practice, single-handed smartphone use is more likely while standing than sitting. Our results show that *head + touch* and *head area + touch* selection while standing are only 5% and 7% slower than direct touch respectively, but have a 9% resp. 8% higher success rate. For added realism and ecological validity of our findings, we also investigated the viability of all five techniques while walking [53] with ten additional participants. Here, both *head + touch* and *head area + touch* selection are 24% and 25% slower than direct touch, but have a significant higher success rate (97% and 94% vs. 82%). We discuss our findings and the usefulness of the various techniques in different application contexts, and provide recommendations for the development of mobile input techniques on larger mobile devices that rely on one-handed interaction.

The main contributions of this paper are the design and the evaluation of *head + touch* and *head area + touch* selection, two new input techniques that address the issue of reachability in one-handed smartphone use by combining head tracking and touch input, with promising performance.

RELATED WORK

Since we use head tracking to improve reachability on smartphone touchscreens, we discuss related work in reachability and highlight previous work in head tracking to provide some background for our implementation.

Reachability Techniques

The simplest way to solve the reachability problem is to constrain input GUI elements of a smartphone to the region within comfortable reach of the user's thumb. To define this region, Bergstrom et al. [1] developed a model that predicts which areas the user's thumb can reach. However, this approach limits the space in which interactive objects can be placed to the lower corner of the screen, ignoring the remaining space.

Chang et al. [4] developed a design space to provide a structured overview of techniques that address the reachability issue on the entire screen. In this design space, they categorize these techniques by the mechanism of how a target is selected: by applying a *screen transform*, by providing a *proxy region*, or by using a *cursor* to select the target. We follow this taxonomy in our following discussion.

Screen Transformation Techniques

Examples for screen transformation techniques can be found in the user interfaces of Apple's and Samsung's recent smartphones. On an Apple iPhone, swiping down across the bottom edge of the screen slides the screen downwards such that the upper targets can be reached by the user's thumb. However, this still leaves targets on the far side opposite the thumb unreachable and context information is lost. On many Android devices, such as Samsung and Asus smartphones, triple-tapping the home button scales down the entire screen to the lower corner of the screen near the thumb. This brings all targets into reach, but impedes readability and targeting because of reduced content size.

In HCI research, several projects have proposed alternative screen transformation techniques to address the reachability problem: Similarly to Android devices, TiltReduction [4] scales down the interface when the user tilts the device. Sliding Screen [28] and TiltSlide [4] move the screen diagonally closer to the thumb by a swiping gesture or by tilting the device, respectively. Tsai et al. [51] developed a technique in which the user can define how far the screen should move towards the thumb by performing a swipe gesture from the screen edge. Le et al. [33] presented a similar concept that lets users slide their index finger across a touchpad at the back of the device to trigger the transformation. The system from Löchtefeld et al. [37] can detect which hand unlocked the device to shift the UI towards that hand. Eardley et al. [13, 14] used tilting the device to shift the keyboard towards the users thumb.

All these interaction techniques, however, are either hiding parts of the digital content, concealing context information, or scale down the interface, making objects difficult to read and select, or need additional hardware, or use tilting, which makes reading content on the screen at an angle difficult and is prone to overshooting [47].

Proxy Region Techniques

In ThumbSpace [22, 23] the user creates a pop-up view around her thumb's touch location that represents the entire screen. This lets users reach all objects on the screen, but makes them very small and difficult to hit. TapTap [46] uses a similar concept but only shows a part of the screen in the pop-up view. A related technique by Löchtefeld et al. [36] uses the index finger on the back of the device to reach upper targets. Hasan et al. [19] developed an approach that uses the mid-air space above the touchscreen as proxy region, and Yoo et al. [57] showed that these proxy regions can extend the thumb's reach by 15%, but they require additional sensing hardware.

Cursor Techniques

Cursor techniques provide a digital cursor that allow users to reach targets outside of their thumb's reach. Bezel Cursor [35] lets users drag an accelerated cursor and uses a swiping from the bezel of the device as activation gesture. Similar interaction techniques are used by ExtendedThumb [31] and TiltCursor [4], which are activated via double tapping and tilting the device, respectively. A different technique is offered by ForceRay, a previous system from our lab [8], that lets users aim at an out-of-reach target by applying a force touch at a comfortable thumb location, casting a virtual ray towards the target. Force input alone has the caveat though that using it with an absolute mapping while walking is imprecise and difficult [53].

An additional issue that occurs when the user tries to reach a target on touch devices is occlusion, which is addressed by a variety of cursor selection techniques. MagStick [46] and Extendible Cursor [28] address this by steering the cursor in the opposite direction of the thumb movement, while 2D-Dragger [49] lets users step through objects with small dragging operations. BezelSpace [58] lets users reach targets at the screen's edge using a cursor controlled by small thumb movements, and CornerSpace [58] places a remote cursor at the corners of the screen to access them quickly. Another way of avoiding occlusion is proposed by Dual-Surface Input [55] by using an additional touchpad at the back of the device to select targets out of reach of the thumb. While many of these techniques are successful in addressing some of the problems such as occlusion and offer viable alternatives for cursor selection, they introduce drawbacks such as a decreased success rate, discomfort for the thumb, or fatigue. We seek to explore if head input can address the reachability problem while avoiding some of these issues, also in combination with other techniques.

Head Input on Mobile Devices

Head movement as an input technique is often used for users with limited arm mobility [10, 39], to move a cursor on a desktop computer [18, 44], as gesture-based input [21, 42, 43, 50, 60], or while using head-mounted displays [15, 54, 56].

Crossan et al. [11] showed that head tilting can be used to control a 1D-cursor on a smartphone while walking. They found that absolute cursor control compared to velocity cursor control was faster and more accurate when stationary but significantly poorer when users where moving. Head input can even be used for gestures, as Williamson et al. [52] pointed out that head gestures have a similar accuracy to wrist and device tilting gestures. They also found that users felt uncomfortable with head gestures during conversations with other people. Recent smartphones, such as the iPhone X or the Samsung Galaxy S8, use a similar approach to extract the user's facial and eye features and brought head and gaze tracking capabilities to off-the-shelf consumer devices [24]. In this paper, we will explore if these new capabilities can be used to address the reachability problem on modern smartphones.

HEAD REACHING TECHNIQUES

We designed head tracking techniques for reaching far away objects on a smartphone in three different setups: *pure head tracking*, *head + touch*, and *head area + touch*. As our goal is to identify reliable and stable interaction techniques, we intentionally decided to employ head tracking exclusively instead of gaze tracking. Mobile gaze tracking technology has improved significantly, and especially recently, a plethora of contributions has highlighted its potential for use in mobile settings [24, 25, 26]. However, there are several caveats and disadvantages that significantly constrain the real-world applicability of gaze tracking in such scenarios. Gaze tracking in mobile scenarios utilizes mostly head-mounted eye tracking hardware [12, 16, 20], but we are interested in exploring interaction with the mobile device only, and use its native sensing technology. While eye tracking has recently become available on mobile devices, such as the iPhone X or Samsung Galaxy S8, applications of eye tracking for target selection experience severe limitations outside controlled lab settings [32]. Even small body movements such as head re-positioning interfere with eye tracking, rendering its results unstable and unreliable as soon as the head is not in a fixed position anymore [32]. More active movement such as walking further complicates eye tracking as gaze and foot are connected [40]. The problem of the impact of walking on eye and head tracking has been the subject of investigation for several decades, and early studies already proved that especially during walking, eye tracking becomes increasingly unreliable [41]. Additionally, Kyto et al. [30] showed that head-based selections are slower than gaze-based selection but easy to control and have a higher success rate, and Gizatdinova et al. [17] highlighted that this is especially true for small targets. For these reasons we chose to rely on head tracking rather than eye tracking.

To track the user's head and face, we used an iPhone Xs Max and Apples' ARKit Framework that extracts facial features from a depth map calculated using a projected infrared dot pattern[2]. These facial features include the position of the user's nose, mouth, and eyes. The ARKit framework provides a 3D position and direction vector for the head relative to the front-facing camera of the smartphone. Knowing the position of that camera and the position and direction of the head, we calculate the position on the screen that the head is facing. Below, we detail the specific implementation of the interaction techniques for our three different variants.

Pure Head (PH) Selection

Our first interaction technique uses head tracking only for target selection. To activate this technique, the user touches somewhere on the screen and applies a light amount of force to enter the head tracking mode. This temporary *quasi-mode* [45] via force allows the system to differentiate between normal touch events and our interaction technique, making it more applicable in real-world scenarios. Force as a quasi-mode is an established technique on mobile devices [8, 9, 46].

While users interact with a smartphone, their head is typically facing their phone. However, in a preliminary study we found that the head is actually typically directed at a point 20–30cm above the screen, with users looking downwards with their eyes. For this reason, we assume that at the moment a user enters the head tracking mode she is looking at the screen,

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[2] https://support.apple.com/en-us/HT208108

and we display a virtual cursor at its center. Then the user's *relative* head movements move the cursor. For example, to select a target in the top right hand corner, she slightly rotates her head in this direction. As soon as the cursor is above a target, it is highlighted to indicate the current selection. Once she releases her thumb from the screen, the currently selected target is confirmed, completing the interaction.

To improve the success rate of this selection, we used a similar transfer function approach as described by Kjeldsen [29]. He used a sigmoid transfer function for the user's head movement in a multi-screen desktop environment to allow users to perform a fast, yet accurate cursor movement. Since a smartphone screen provides much less screen real-estate than a multi-screen desktop environment, it is even easier to reach items at the edge of the screen. However, we need a more precise control for the middle area of the screen.

The position the user faces on the device is inferred from the head's Euler angles α and distance to the device, which is obtained from the positional vector v. The vector v goes from the center of the screen to the center between the user's eyes, right at the root of the nose bone. We transfer head rotations to positions in a resolution-independent coordinate system ranging from -0.5 to $+0.5$, i.e., the origin is located at the screen's center. Prior to scaling, the measured point u on a screen with the physical size s is calculated as follows:

$u_x = \frac{|v| \times tan(a_y)}{s_x}$, y-axis calculated analogously.

We then scale the point u with the following sigmoid function, where o is the point that was measured at the time when the user initiated the head control:

$r_x = -1.4 \times (\frac{1}{1+e^{7(u_x - o_x)}} - 0.5)$, y-axis calculated analogously.

In preliminary studies we explored multiple transfer functions and scale factors and discovered this function to be the most effective one. At a head-to-phone distance of 20 cm (a typical value we measured), users have to move their head by 9.6° horizontally and 19.9° vertically to select targets in the corners of the smartphone.

Head + Touch (HT) Selection

The head + touch (HT) selection technique combines head tracking and touch input by allowing to adjust the head-selected target with a brief touch gesture. This interaction technique is an extension of the pure head technique, as the user activates and selects targets the same way. To improve the accuracy of the selection, the user can increase the force of the thumb press momentarily to lock the head cursor, switching into an adjustment mode. In this mode, a small indicator at the center of the head cursor appears, and dragging the thumb will draw a line in the direction of the movement (see Figure 2). Releasing the touch entirely confirms the selection, just as in the pure head tracking interaction.

Head Area + Touch (HA) Selection

In the head area + touch selection technique, the screen is divided into four quadrants that can be selected using head movement. Since the lower right area is in reach of the user's thumb, the selected targets in this area use normal direct touch. We call this area the touch input area. To select a target further away, i.e., outside the touch input area, the user activates the head tracking selection mode by applying a small amount of force, as in the HT technique. Instead of a cursor as in the HT technique, the system shows a frame around a selected quadrant (see Figure 2), and the user can select one of the three other areas by rotating their head into the desired direction. Similar to the previous technique, the area can be locked by applying a stronger force with the thumb momentarily. Now, the touch point from the touch input area is mapped to the selected area using absolute mapping. This mapping is indicated by a virtual cursor representing the thumb's touch location inside the selected area. By moving the thumb, the user can control the position of the cursor inside the selected area, and finalize their selection by releasing the touch.

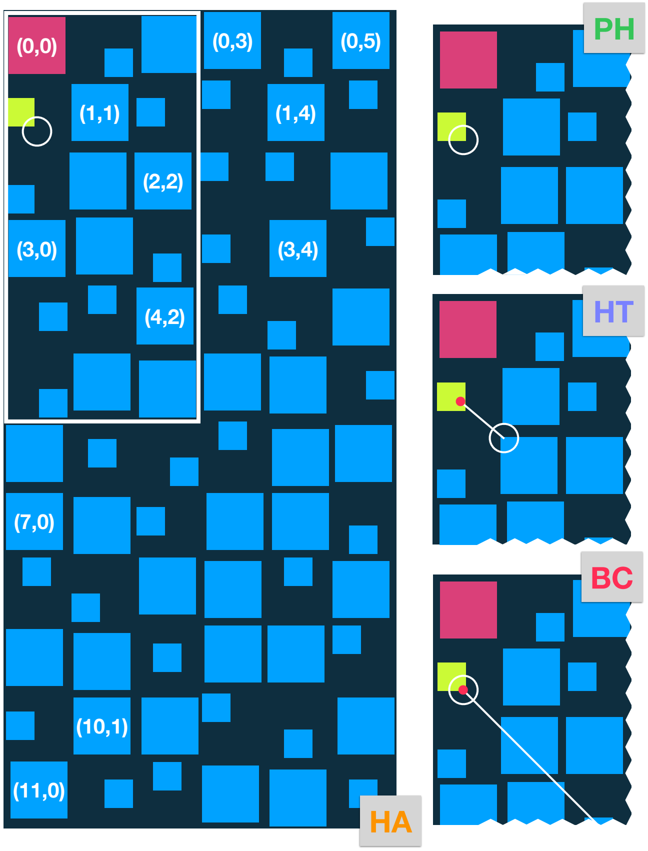

Figure 2. The targets were arranged in a 6 x 12 grid, as labeled by the coordinates (not in the actual trial). In each trial the users were asked to select the red target, in this example showing the large target SIZE. The four screens show the details of our visualization in different conditions. HA: The user just moved her head in the direction of the upper left area and moved her thumb such that the green target is selected. HT: The user has increased the force of the thumb to lock the virtual cursor and is currently dragging the thumb upwards to the left. PH: The user has activated the head tracking technique and rotated her head such that the green target is currently selected. BC: The user is selecting the green target with BezelCursor.

We divided the screen into four areas for two reasons: First, to select an area using head movement, a slight head rotation into the general direction is sufficient, resulting in faster head

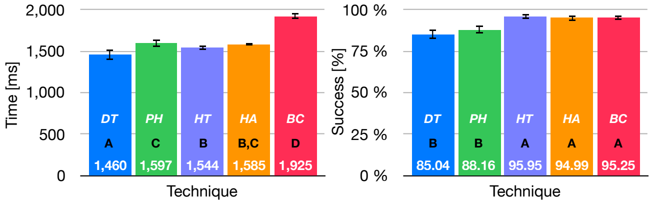

Figure 3. Study 1 (standing): *Time* [ms] (left) and *Success* [%] (right) by TECHNIQUE. For each variable, pairs of levels that do not share a letter are significantly different (*Time*: all $p < .001$, *Success*: all $p < .05$). Whiskers denote 95% CI.

area selection. Second, the touch input area is small enough to be reached comfortably by the thumb.

STUDY 1: STANDING

To understand how our different reaching techniques compare to each other and established methods, we conducted a user study with 15 participants (23–69 years, $M = 37.66$ $SD = 13.94$; 6 female; 9 male; all right handed; thumb length: $M = 73.56$ mm $SD = 7.3$ mm). They were all smartphone users (screen size: $M = 5.3"$, $SD = .68"$). We compared our three techniques (PH, HT, HA) to BezelCursor (BC) [35] and Direct Touch (DT) input as baseline. We chose to use BezelCursor as an additional baseline method, since it was shown to be a very accurate and fast reaching technique [7, 35]. We asked users to select the targets with their thumb on a smartphone using each of these techniques while standing and holding the device in their right hand in portrait orientation.

Apparatus and Techniques

As described above, we used an iPhone Xs Max to present the task to our users and to capture data. The iPhone screen measured 896×414 pt (149×69 mm).

To active all three head and reaching techniques, as described above, we set the force activation threshold to 1.33 units (about 0.7 newton), which is significantly higher than a normal touch on iOS devices [8]. To lock the cursor or the area in HT and HA we used the maximum force value (about 4 newton) that the iPhone can detect.

We also compared our techniques to **Direct Touch (DT)** and **BezelCursor (BC)**. We choose BC as baseline condition as Corsten at al. [8] showed in a similar study setup that BC is faster and has a higher success rate than most other reaching techniques such as MagStick [46] or Samsung's edge-triggered ThumbSpace. In a pre-study, we also tested our earlier ForceRay [8] technique, but found out that selecting a specific force value while walking is very difficult due to the hand and arm movement. BezelCursor was implemented as described by Li et al. [35] and also included the additional details described by Corsten et al. [8]. It is triggered by a swiping gesture from the edge of the smartphone. After detecting the gesture, a line that expands linearly by a factor of three in the direction of the thumb is displayed. Similar to DynaSpot [6], the end of the line has a circular area cursor that expands exponentially up to 7.3 mm depending on the speed of the swipe movement. If the speed drops below 2 $\frac{mm}{s}$ the area shrinks co-exponentially. When a target is below the cursor, it is highlighted. When multiple targets intersect with the area cursor, the target with the smallest distance from its center to the cursor location is chosen. Lifting off the thumb selects the target.

	DT			PH			HT			HA			BC		
	M	CI		*M*	CI		*M*	CI		*M*	CI		*M*	CI	
Border	1,536	±50	B,C	1,554	±44	B,C	1,581	±30	C,D	1,584	±25	C,D	1,937	±43	E
Center	1,384	±41	A	1,640	±44	D	1,507	±30	B	1,586	±33	C,D	1,913	±44	E

Figure 4. Study 1: *Time* [ms] by TECHNIQUE × TARGET. Pairs of levels that do not share a letter are significantly different (*Time*: all $p < .001$). CI denotes 95% CI.

Task and Targets

Participants were asked to select a target as quickly as possible using each of the five techniques. At the beginning of each trial one target was highlighted in green and the current selected target was marked in red, as shown in Fig. 2. To confirm the selection of a target, the participants had to release the thumb from the touch screen. After a target was selected, the next trial was automatically shown after a delay of 500 ms. The targets were arranged in a 6×12 grid (Fig. 2) across an area of 414×864 pt; each cell measured 69×72 pt. We excluded the top 32 pt due to the camera notch of the iPhone. To avoid a regular looking grid, each target was shifted within its cell [22].

Variables

The **Independent Variables** were TECHNIQUE (PH, HT, HA, BC, and DT), TARGET, and SIZE. Our twelve targets (Fig. 2) were split into two groups: targets (0,0), (0,3), (0,5), (3,0), (8,0), and (11,0) located at the border of the screen, while the remaining six targets were more towards the center of the screen. The SIZE represented typical iOS widget sizes, i.e., the height of a button (30 pt; 4.8×4.8 mm) and an app icon (60 pt; 9.6×9.6 mm).

Each participant was asked to perform 5 TECHNIQUE × 12 targets × 2 SIZE × 2 repetitions = 240 trials. TECHNIQUE was counter-balanced using a Latin Square and the order of the targets were randomized. We also randomized the SIZE but, similar to our ForceRay study [8], we ensured that each participant started half of each TECHNIQUE with small targets and the other half with large targets. Before the participants started with a new TECHNIQUE, they where given two minutes to perform trials to familiarize themselves with the new technique. After these test trials they selected two times twelve targets, followed by the remaining SIZE for the current TECHNIQUE, again starting with the test trials. After both sizes for a TECHNIQUE was completed a new TECHNIQUE was presented. Overall, the participant took approximately 35 minutes to complete the study.

Dependent Variables were trial completion *Time* [ms], and user's *Success* [0,1], i.e., whether they selected the correct target or not. We measured the *Time* from the moment a new target was displayed until the user released the finger from the touch screen to confirmed the selection. After the participants finished a technique, they were asked how much they agreed that the technique was easy to use, how fatiguing the technique was, how stable they could hold the device, and how comfortable the head movement was for the three

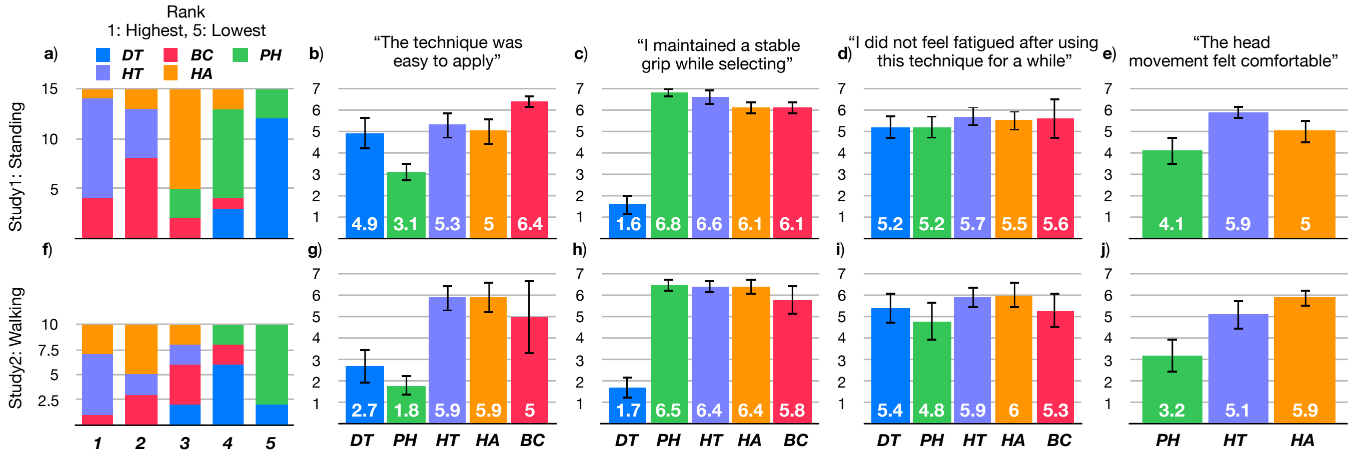

Figure 5. The graphs show the results of questionnaires for the standing (top) and walking (bottom) conditions. Graphs a) and f) show users' ranking of techniques (1: most preferred; 5: least preferred). The other graphs show how much the participants agree with the statement above on a 7-point likert scale (1: totally disagree, 7: totally agree). The CI denotes the 95% CIs.

head techniques on a 7-point Likert scale (7 = totally agree). At the of the study, the participants were asked to rank all techniques by preference from highest (1) to lowest (5). We choose these measurements instead of a Fitts' Law approach to allow a comparison of the results to other reaching methods such as ForceRay [8] or MagStick [46]. In addition, HA and HT consist of two different, partially overlapping Fitts' Law tasks. Modeling these as such would have required a different methodological approach.

Results

In this study we are most interested in the participants' performance depending on the TECHNIQUE used, therefore, we will focus our analysis on this main effect and related interaction effects. We conducted a repeated-measures ANOVA on the log-transformed *Time* data and calculated the effect size using the partial eta squared measurement. For the dichotomous *Success* data, we ran McNemar and Cochran's Q tests and used the approach from Berry et al. [2] to determine the effect size. Likert scale data was compared using Friedman tests and we used Kendall's Concordance Coefficient W for calulating the effect size. The pairwise comparisons for the Likert scale data used the Bonferroni correction.

TECHNIQUE had a significant main effect on ***Time*** ($F_{4,3560} = 217.74$, $p < .001$, $\eta_p^2 = .196$). Tukey HSD post hoc pairwise comparisons were all significant ($p < .001$) except between PH and HA (Fig. 3, left). Not surprisingly, participants were fastest with DT (1,460 ms) followed by HT (1,544 ms). HA (1,585 ms) and PH (1,597 ms) were the third fastest techniques, followed by BC (1,925 ms). The results are also shown in Figure 3. SIZE of the targets had a significant main effect on ***Time*** ($F_{1,3560} = 67{,}14$, $p < .001$. $\eta_p^2 = .018$). The Student's t post hoc pairwise comparisons revealed that the large targets (1,551 ms) were selected significantly faster than the small targets (1,647 ms). The TARGET position had a significant main effect on ***Time*** ($F_{1,3560} = 15.26$, $p = < .001$, $\eta_p^2 = .004$). The Student's t post hoc pairwise comparisons revealed that the targets at the border (1,621 ms) were selected slower than the other targets (1,575 ms); however, with an almost unnoticeable effect size. There was also a TECHNIQUE × TARGET interaction effect on ***Time*** ($F_{4,3560} = 13.67$, $p < .001$, $\eta_p^2 = .015$). The HSD post hoc pairwise comparisons are shown in Figure 4.

TECHNIQUE had a significant main effect on ***Success*** ($Q(4) = 95.56$, $p < .001$, $\mathscr{R} = .025$, Fig. 3, right). Post hoc tests revealed that *Success* for BC, HA and HT were significantly higher compared to DT and PH. The target SIZE had a significant main effect on ***Success*** ($Q(1) = 13.68$, $p = < .001$, $\mathscr{R} = .862$). Post hoc tests revealed that the *Success* rate for larger targets is 3.51% higher than for smaller targets. There was also a TECHNIQUE × SIZE interaction effect on ***Success*** ($Q(9) = 163.02$, $p = < .001$, $\mathscr{R} = .063$). The Post hoc pairwise comparisons showed that the SUCCESS rate for small targets using DT was significantly lower (75.43%) than all other conditions. The SUCCESS rates for PH for small (89.50%) and large targets (87.30%) were also significantly lower than the other conditions. All other conditions, except DT on large target (94%), were not significantly different. Furthermore, there was a TECHNIQUE × TARGET interaction effect on ***Success*** ($Q(9) = 131.62$, $p = < .001$, $\mathscr{R} = .028$). The Post hoc pairwise comparisons revealed that the SUCCESS rate for DT on targets at the border of the screen (80.11%) was significantly lower than all the other conditions. The SUCCESS rate for PH on non-border targets (85.3%) was significantly higher then DT on border TARGETS, but significantly lower than all the other conditions.

Figure 5 (top part) shows the mean and 95% CI for the questionnaire data. TECHNIQUE had a significant effect on participants' ***ranking*** ($\chi^2(4) = 41.21$, $p < .001$, W = .804). The post hoc pairwise comparisons show that participants significantly preferred HT, BC and HA over PH. DT was rated significantly lower than all the other technique. TECHNIQUE had also a significant effect on the ***ease of use*** ($\chi^2(4) = 40.16$, $p < .001$, W = .586). Users found BC similarly easy to use to DT and HT but significantly easier to use than HA. PH was significantly more difficult to use than the other techniques. The

TECHNIQUE had also a significant effect on the ***grip stability*** ($\chi^2(4) = 45.22$, $p < .001$, W = .754). The participants found that they did have a more unstable grip using DT than the other techniques. The TECHNIQUE had no significant effect on the participants perceived ***fatigue*** but on how comfortable the ***head movement*** was rated ($\chi^2(4) = 45.22$, $p < .001$, W = .866).

STUDY 2: WALKING

In the first study we evaluated our reaching interaction technique while participants were standing. However, users often interact with handheld devices while they are walking; therefore our next study explored how these techniques performed in that situation. We conducted our user study with 10 participants (19–69 years, $M = 36.50$ $SD = 13.54$; 4 female; 6 male; all right handed; thumb length: $M = 70.21$ mm $SD = 7.5$ mm). None of these participants participated in the first study. They were all smartphone users (screen size: $M = 5.1$", $SD =$ .45"). The study was conducted in the same way as the first study and we used the same study setup, device, dependent and independent variables. The only difference was that the user had to walk. Similar to the setup from Crossan et al. [11], the users were asked to walk around a set of obstacles (in our case small tables) in a 4 by 4 meter rectangle, as shown in Figure 6.

Results

In this study we used the same statistical methods as in the first study. TECHNIQUE had a significant main effect on ***Time*** ($F_{4,2336} = 152.03$, $p < .001$, $\eta_p^2 = .206$). Tukey HSD post hoc pairwise comparisons were all significant ($p < .001$) except between PH and HA (Fig. 7, left). Also in walking, users were fastest with DT (1,344 ms) followed by HT (1,772 ms), HA (1,806 ms), and by BC (1,931 ms); PH (2,203 ms) was the slowest. The results are also shown in Figure 7 (right). SIZE of the targets had a significant main effect on ***Time*** ($F_{1,2336} =$ 11,82, $p = .006$, $\eta_p^2 = .335$). Similiar to the first study, the Student's t post hoc pairwise comparisons revealed that the large targets (1,651 ms) were faster selected than the small targets (1,724 ms). The TARGET position had a significant main effect on ***Time*** ($F_{1,2336} = 11.48$, $p < .001$, $\eta_p^2 = .329$). In contrast to the first study, the Student's t post hoc pairwise comparisons revealed that the targets at the border (1,724 ms) were selected faster than the other targets (1,651 ms). There was also a TECHNIQUE × SIZE interaction effect ($F_{4,2336} =$ 5.08, $p = .008$, $\eta_p^2 = .335$) and a TECHNIQUE × TARGET interaction effect on ***Time*** ($F_{4,2336} = 54.51$, $p < .001$, $\eta_p^2 =$ .085). The HSD post hoc pairwise comparisons for both effects are shown in Figure 8.

For the dependent variable ***Success*** we found the following effects: TECHNIQUE had a significant main effect on ***Success*** ($Q(4) = 380.019$, $p < .001$,). The results of the hoc pairwise comparisons are shown in Fig. 7 (right). The target SIZE had also a significant main effect on ***Success*** ($Q(1) = 14.290$, $p < .001$, $\mathscr{R} = .162$). Larger targets (87%) had significantly higher success rate than smaller targets (82%). The TARGET position had a significant main effect on ***Success*** ($Q(1) =$ 7.197, $p < .001$, $\mathscr{R} = .003$). Targets at the border (86%) had a significantly higher success rate than targets in the middle of the screen (83%). There was also a TECHNIQUE × SIZE interaction effect on ***Success*** ($Q(4) = 439.440$, $p < .001$, $\mathscr{R} =$ .003). The post hoc pairwise comparisons show that selecting targets (small and large) with PH has the lowest success rate and the selecting small targets with DT has a significantly higher success rate then PH but a significantly lower success rate then all other conditions. The TECHNIQUE × TARGET position interaction effect had also a significant effect on the ***Success*** ($Q(4) = 497.896$, $p <.001$, $\mathscr{R} = .034$). Here the post hoc comparisons show again that selecting targets with PH has the lowest success rate and that selecting not-border targets with DT has a significantly higher success rate then border targets.

Figure 6. To evaluate the technique in the walking condition, participants were asked to walk around tables on an eight-shaped path.

Similar to study 1, the TECHNIQUE had a significant effect on users' ***ranking*** ($\chi^2(4) = 30.001$, $p <.001$, W = .750). Users preferred HT, BC, and HA over DT followed by PH as the least preferred technique. TECHNIQUE had also a significant effect on the ***ease of use*** ($\chi^2(4) = 36.237$, $p <.001$, W = .906). Users found HT and HA significantly easier to use than DT and PH. There was no difference between BC and the other techniques. The TECHNIQUE had also a significant effect on the ***grip stability*** ($\chi^2(4) = 27.739$, $p <.001$, W = .693). Similar to the first study, the users found that they had a much more unstable grip using DT than the other techniques. It had also a significant effect on the ***head movement*** ($\chi^2(2) = 12.684$, $p <.001$, W = .357). User agreed significantly more that the head movement while using HA was more comfortable than while using PH. In contrast to the first study, the TECHNIQUE had no significant effect on the users' perceived ***fatigue*** ($\chi^2(4) =$ 9.560, $p = .049$, W = .239). Figure 5 (lower part) shows the mean and 95% CI for the questionnaire data. However, due to the Bonferroni correction the pairwise comparisons did not reveal any significant differences between the condition.

DISCUSSION

The results of our evaluation led us to important insights of how head tracking can be used. Our goal was to address the problem of reachability on smartphones specifically, but we believe our findings can also more generally inform the design of interaction techniques that aim to leverage head tracking.

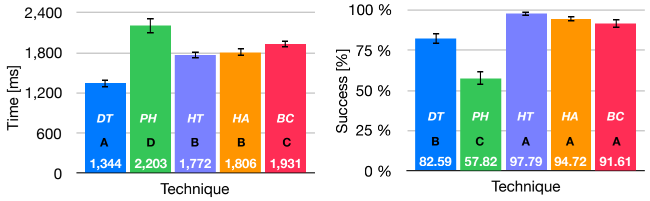

Figure 7. Study 2 (walking): *Time* [ms] (left) and *Success* [%] (right) by TECHNIQUE. For each variable, pairs of levels that do not share a letter are significantly different (*Time*: all $p < .001$, *Success*: all $p < .05$). Whiskers denote 95% CI.

	DT			PH			HT			HA			BC		
	M	**CI**		***M***	**CI**		***M***	**CI**		***M***	**CI**		***M***	**CI**	
TARGET															
Border	1,453	±50	97	1,804	±145	C	1,774	±65	C,D	1,802	±75	C,D,E	1,976	±86	E
Center	1,233	±41	47	2,604	±136	F	1,769	±75	C,D	1,810	±84	C,D	1,885	±62	E,D
SIZE															
small	1,419	±98	A	2,170	±159	E	1,885	±84	C,D	1,871	±80	C,D	1,927	±71	D,E
large	1,269	±48	A	2,237	±139	D,E	1,741	±48	B	1,741	±79	B,C	1,935	±78	D,E

Figure 8. Study 2: *Time* [ms] by TECHNIQUE × TARGET and TECHNIQUE × SIZE. Pairs of levels that do not share a letter are significantly different (*Time*: all $p < .001$). CI denotes 95% CI.

Supplementing head tracking with touch input

The results of both studies show that our HT and HA reaching techniques have a higher success rate than DT and a similar success rate as BC. Especially in the walking condition, HT and HA have a higher success rate than BC (see Figure 3) even though there is no statistical significance. This makes HT and HA particularly useful for scenarios in which an accurate selection of a target is important. Both techniques are only slightly slower than DT while standing and about 25% slower while walking, a trade-off that was partially expected as our selection technique combines two different input modalities. However, HT and HA were significantly faster than BC, and we believe that once users get more familiar with those new input techniques it would further narrow the gap to DT. These findings show that head tracking input in combination with touch offers a good trade-off between speed and accuracy. As the users can target any point in their vicinity using their heads both techniques HT and HA can also be used on larger devices such as tablets with similarly small finger movements. While using BC on large devices, on the other hand, the movements of the fingers to reach a target increase on larger devices. However, they both require the camera of the devices to track the user's head, which could lead to increased battery consumption. Furthermore, both head tracking techniques require the users to actively look at device whereas it is sufficient to glance at it while using BC.

The importance of realistic testing conditions

Our study revealed that while PH performance in the standing condition is similar to the other head tracking techniques, it becomes almost unusable in the walking condition. We believe this to be rooted in the problem that while a user is walking not only the head is moving but also the arm and thus the smartphone as well. Those results are in alignment with previous works that have identified issues with head tracking in real world scenarios [11]. Our study contributes an important data point due to the comparative study of different techniques in two different conditions, and presents solutions for this problem by supplementing head tracking with touch input. We hope this not only inspires future research to develop new interaction techniques, but also encourages to consider evaluations in more realistic scenarios, as the results of controlled lab studies might not be replicable in the real world, rendering promising interaction techniques unusable.

User preference and mitigating frustration

While our participants rated HT as the best technique, the results also see HA ranked quite high in the walking condition. This highlights that the general concept to combine coarse head selection and touch fine tuning was accepted by the users. Although in a different context, a similar insight was reported for gaze interaction by Stellmacher and Dachselt [48] where users did a coarse selection on a wall-sized display with the eye and fine tuning via touch input. The user preference here plays an important role when comparing novel approaches with established techniques: While direct touch was in general the fastest selection method it led to a high level of frustration. Not only did participants rank DT extremely low in both conditions in terms of grip stability; three participants even dropped the phone while they tried to reach a target in the upper corner of the display. Our post-study questionnaire also highlighted another issue of head tracking for input: Fatigue that is well-known from previous research [38]. However, when pairing head tracking with another technique, this effect can be mitigated as the head movement is less enunciated due to it only being used for coarse pre-selection, as highlighted in our HT and HA conditions in both studies (cf. Figure 5, d, e, i, and j).

Future Work: Comparing HT and HA Techniques

Across all conditions, we saw no significant difference between HT and HA in terms of performance, both in terms of sucess rate and time. Most of the questionnaire responses show a similar result as we saw no strong differences between the two techniques or relatively small preferences for either technique in one of the conditions (head movement comfortability, Figure 5 e and j). The most significant difference to distinguish both techniques can be found in the ranking, as most participants ranked HT as their favorite selection technique in both conditions, and HA as second (walking) or third (standing, behind BC). However, further work is required to investigate the differences between those and potential other techniques in more detail. For example, which concrete real-world use cases can best be supported by which technique? We only considered portrait view—but are there scenarios using landscape orientation, and how does head + touch perform in those situations? How do those techniques scale, e.g., on larger screens such as tablets when reachability even becomes an issue in multi touch environments when using two hands to hold a tablet while talking? Can head tracking in combination with touch input also be useful in such a scenario, and if so, how is it best implemented?

CONCLUSION

In this paper, we investigated the use of head tracking for addressing the reachability issue on handheld touchscreens. In addition to pure head tracking as a target selection input technique, we developed *head + touch*, an approach that complements head tracking with touch input for refining the target selection, and *head area + touch*, an additional technique that allows users to select a target area first via head tracking and then refine the selection within that area of the screen. We compared those three techniques to traditional direct touch input and a well-known technique that aims to address reachability, BezelCursor [34]. To ensure that our evaluation reflects a realistic use case, we conducted two user studies in different conditions: in one, participants selected targets using all five different techniques while standing, in the other while walking.

The results of our evaluation show that our combination of head tracking and touch input not only addresses the reachability problem, but also performs well in comparison to existing techniques. While we identified that pure head tracking as a selection technique encounters issues, in particular in the walking condition to the point of not being viable as an alternative, our refined techniques are viable interaction techniques. Both approaches that combine head tracking with touch input were more accurate than direct touch, although slightly slower, and faster than BezelCursor, with almost similar success rate. Our *head + touch* and *head area + touch* techniques offer a useful trade-off between success rate and speed of input for target selection tasks, and especially in real-world scenarios of one-handed smartphone operations can be an improvement over traditional touch input. We believe that this work can also inform future research into identifying ways how to leverage head tracking as a complementary input technique on touch devices, as head tracking becomes more ubiquitous in today's technology.

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