EyePACT: Eye-Based Parallax Correction on Touch-Enabled Interactive Displays

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The parallax effect describes the displacement between the perceived and detected touch locations on a touch-enabled surface. Parallax is a key usability challenge for interactive displays, particularly for those that require thick layers of glass between the screen and the touch surface to protect them from vandalism. To address this challenge, we present EyePACT, a method that compensates for input error caused by parallax on public displays. Our method uses a display-mounted depth camera to detect the user's 3D eye position in front of the display and the detected touch location to predict the perceived touch location on the surface. We evaluate our method in two user studies in terms of parallax correction performance as well as multi-user support. Our evaluations demonstrate that EyePACT (1) significantly improves accuracy even with varying gap distances between the touch surface and the display, (2) adapts to different levels of parallax by resulting in significantly larger corrections with larger gap distances, and (3) maintains a significantly large distance between two users' fingers when interacting with the same object. These findings are promising for the development of future parallax-free interactive displays.

CCS Concepts: • **Human-centered computing → User interface design**; **User centered design**;

Additional Key Words and Phrases: Public Displays; Parallax; Touch screens; Gaze

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1 INTRODUCTION

Interactive displays are becoming ubiquitous and are increasingly deployed in public areas, such as universities, train stations, airports, or shopping malls. While advances in sensing technology enable new types of interaction, such as with mid-air gestures [29] or gaze [20], touch remains among the most commonly employed modalities [4]. In the early days of touch screens, infrared sensors were mounted above the screen surface to detect where the user's finger was touching. Hence, a relatively large distance existed between the touch screen and the display

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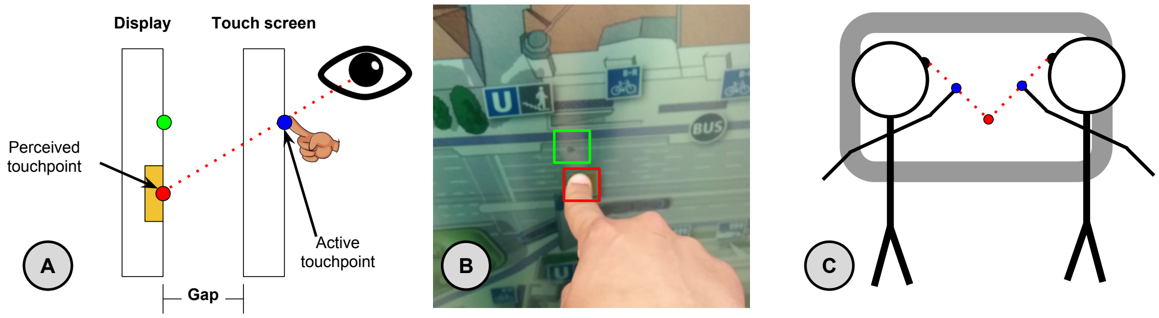


Fig. 1. The parallax effect commonly occurs on public displays where a protective glass layer separates the display and the touch screen (A) and results in the system recognizing a touch location (marked in green) that deviates from the intended one (red). To compensate for this error, EyePACT determines the expected touch location based on the position of the user's eyes and the touch point on the screen (blue) to trigger it at the perceived location (red).

that led to the so-called parallax effect [34], i.e., a difference between the perceived location at a particular UI element and users' actual touch location (see Figure 1A). This difference becomes larger as the angle between the display and the user's eyes increases (e.g., when looking at far corners of the display). The parallax effect can trigger unwanted input actions that can negatively impact usability and user experience [31].

Advances in capacitive touch screens have resulted in the screens becoming more compact, thereby reducing the parallax effect. However, the effect has become prominent again with the widespread use of public displays (see Figure 2). The reason is that on one hand, manufacturers typically protect displays against vandalism by using thick layers of glass. On the other hand, displays are often deployed behind shop windows and touch input is enabled through a transparent foil attached to the window. This increases the distance between touch screen and display and, in turn, introduces parallax (cf. Figure 1B).

Compensating for the error caused by the parallax effect is important because it makes interaction cumbersome and time-consuming which can, in turn, lead to users abandoning the displays [13, 44]. The negative impact on user experience is particularly prominent in interfaces that require several accurately located touch events, where an inaccurate touch event could result in unintended input [31]. Examples of such interfaces include interactive maps (see Figure 1B), on-screen keyboards used to provide text input or passwords (see Figure 2), calendars for choosing departure dates, etc. These interfaces would benefit from parallax correction to overcome inaccurate selections which impacts the user experience. Although a common approach is to use larger buttons aimed at covering the active and perceived touch areas, the use of larger buttons may not be feasible in the aforementioned applications. On the other hand, software-based solutions, such as training and using offset regression models like the one we discuss in Section 5, would not compensate for parallax accurately without knowledge of the user's height and position, as well as the number of users. Note that public displays often expect multiple users interacting simultaneously [11, 19, 29]

In this work we propose EyePACT, a simple, yet effective, method to overcome the parallax effect. The technique corrects for the parallax offset by estimating a gaze vector that intersects the user's touch point, hence estimating where on the screen the user *intended* to touch. Our approach relies on a depth camera, hence EyePACT is unlikely to require a significant cost, particularly since an increasing number of displays has integrated cameras to measure audience attention [2, 35], for security purposes (e.g., ATMs), and for interaction [29]. While similar ideas have been described in some patents [3, 5, 6, 18, 40], eye-based parallax compensation has never been evaluated and it therefore remains unclear how well such compensation can work and how well it is perceived by users. This work makes the following contributions: (1) We introduce the concept and implementation of

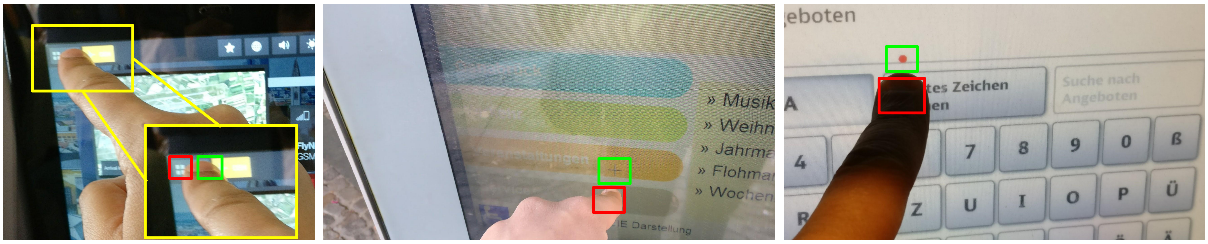


Fig. 2. The parallax effect has recently become prominent again with the widespread use of public displays that are augmented with thick layers of glass to protect against vandalism. The figure shows multiple cases where the parallax effect is prominent on real-world deployments. The red area is the touched area from the user's perspective, while the green one is the area the system mistakenly activated due to parallax.

EyePACT, a simple yet effective approach for compensating for parallax. (2) We report on our findings of an accuracy evaluation of EyePACT, which show that EyePACT brings the touch points significantly closer to the target even with varying degrees of parallax. (3) We demonstrate the effectiveness of EyePACT in allowing multiple users to interact on parallax-enabled displays without overlapping fingers.

2 BACKGROUND AND RELATED WORK

Our work builds on three strands of prior research, namely (1) parallax in HCI research, (2) parallax on touch-based public displays, and (3) eye detection on public displays.

2.1 Parallax in HCI research

While we focus on one way the parallax effect could occur, there are many conditions that could lead to a similar effect. As the distance between a touch surface and a display increases, so does the discrepancy between what each of the eyes sees. This is often referred to as binocular parallax [25]. Previous work showed that when pointing at 3D stereoscopic objects, users touch between their dominant and non-dominant eye position with a bias towards the dominant eye position [39]. Addressing binocular parallax is out of the scope of this work. (1) In our work, we focus on the parallax effect on public displays, where an increase in the distance between the touch surface and the display is rarely more than 7 cm [14, 15, 30, 49]. On the other hand, binocular parallax occurs at larger distances (e.g., 30 cm between the touchscreen and the UI element [25]). (2) Employing gaze or mid-air gestures would be more suitable for contexts where the public display is physically unreachable or too far away from the user [4, 20]. And (3), our participants did not report experiencing binocular parallax in our setup.

In contrast, motion parallax refers to the depth cues that humans perceive while moving; as we move or as objects move around us, we perceive closer objects to be moving faster than farther ones. Humans use this cue (i.e., the perceived speed of objects) to estimate how far the objects are compared to each other [32]. Parallax is often exploited for simulating depth perception by using so-called parallax barriers [23], which enables stereoscopic rendering by limiting the observer's point of view [41]. The idea is to use two stacked screens, with the front one showing an array of pinholes. By doing so, the setup exploits binocular and motion parallax cues to present the user with the illusion of depth.

2.2 Parallax in Public Displays

In contrast to the aforementioned types of parallax, we focus on the parallax error induced by large distances between the touchscreen and the display, which results in a displacement between the perceived and detected touch point on a touch-enabled public display. This was previously referred to as "parallax error" [28] or "visual parallax" [24]. Parallax was a major issue in touch-based interaction in the early days of touchscreens [34]. The problem was significantly reduced with the advancements in Gorilla Glass and thin touchscreens. However public displays (see Figure 1B) are still affected by parallax due to the use of vandalism proof glass which increases the distance between the touch layer and the screen [14, 15, 30, 49].

A common approach used frequently for ATMs is to use larger buttons aimed to cover the active and perceived touch areas. Another approach is to incline the display to reduce the angle relative to the user's view and hence reduce the parallax effect. Forcing designers to use bigger buttons is not an optimal solution and might not be feasible in interfaces where there is multitude of accurately located touch events (e.g., interactive map, month calendar, or on-screen keyboard). While inclining the display is not always feasible, in particular with large displays. Previous patents discussed solutions [3, 5, 6, 18, 40]. These methods utilize a front facing camera of a mobile device to estimate the viewing vector. However, it is not clear how well these methods perform and how they are perceived by users. Moreover, the use case covered by these patents involve a single user interacting with a touchscreen of a mobile device. In contrast, we study parallax correction on public displays for single and multiple users. Migge et al. presented a parallax-correction approach that relied on a Wiimote's tracking IR-markers that are attached to the user's head [28]. On the other hand, our approach does not augment the user but relies only on a remote camera, which is readily integrated into existing public displays.

2.3 Eye and Attention Detection on Public Displays

To detect the user's eye position in front of a public display, it is essential to first detect the user's face. Several approaches have been proposed for face detection, examples are the active shape model (ASM) [10], the active appearance model (AAM) [9], the gradient-based approach [38] and the Viola-Jones detection framework [43]. After detecting the user's face, face landmarks are determined. These landmarks include features of the user's eyes (e.g., eye corners, pupils, etc..). In our work, we use an optimized version of the AAM algorithm that incorporates depth-based face segmentation by using an RGBD camera (kinect) [36].

There is an increasing interest in the detection of eyes in the vicinity and attention to public displays [2, 35, 37]. Determining where on the screen the user is looking requires estimating a gaze vector. A time-consuming and tedious calibration process preceding the actual interaction is required to obtain highly accurate gaze estimates [27]. Therefore, recent work either proposed to blend calibration into the application (e.g., as users read text [21]), or to use gaze interaction techniques that do not require accurate gaze estimates and are therefore calibration-free [42, 47].

In summary, while highly accurate gaze estimates would enable perfect parallax correction, current state-of-the-art techniques either require calibration or estimate an inaccurate gaze vector. Instead, our approach does not require an accurate gaze estimate but uses the position of the eyes in 3D space in front of the display to generate a vector that intersects the user's touch point and the display. The intersection is deemed to be the point the user is trying to touch.

3 EYEPACT– CONCEPT AND IMPLEMENTATION

To study the parallax effect, it was necessary to build an apparatus where the distance between the display and the touch screen is adjustable, hence recreating and controlling the parallax effect (see Figure 3). To do that, we laminated a touch foil[1] on a 110 cm × 60 cm × 8 mm Plexi glass. Figure 3 shows how we fixed the laminated touch foil to the display while keeping the distance between them adjustable. In particular, we fixed four metal rods into the stand of a 42 inch display (1366 × 768 pixels). We then used four 3D-printed holders to hold the display to the rods. The gap distance can be adjusted by sliding the rods and holders.

[1] http://www.visualplanet.biz/touchfoil/

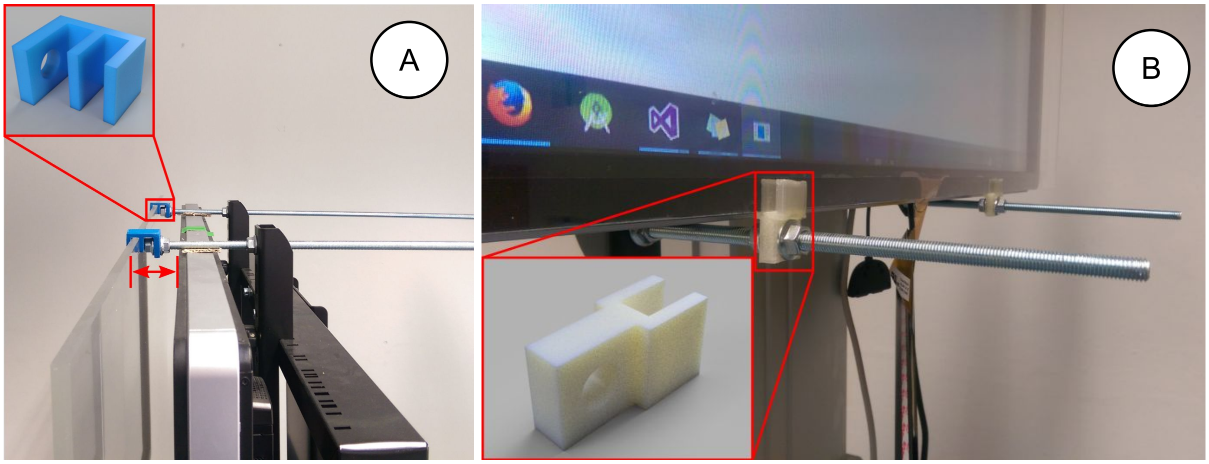


Fig. 3. The touchscreen was mounted parallel to the display using rods that are fixed to a 42-inch display stand. We used 3D-printed holders to hold the touchscreen to the rods. The upper rods (A) are adjustable by unloosing the nuts holding them to the stand, while lower ones (B) can be adjusted by unloosing the nuts holding them to the rods.

Our approach does not utilize accurate gaze point estimation and hence does not require calibration. Instead, a depth camera locates the user's eyes in the 3D space in front of the display. To do this, we mounted a Kinect 360 on a tripod positioned behind the display. We continuously track the user's pupils by employing the approach by Smolyanskiy et al., which augments the Active Appearance Model (AAM) algorithm by using depth-based face segmentation detected by an RGBD camera (kinect) [36].

Whenever a touch is detected on the touchscreen ($Active_{2D}$), the point is converted from a 2D point on the touchscreen surface to a 3D point in the 3D space in front of the display ($Active_{3D}$). Afterwards, a 3D ray is extended from the middle of both eyes and intersecting point $Active_{3D}$ to eventually intersect the display at point $Perceived_{3D}$. $Perceived_{3D}$ is then converted from a 3D point to a 2D point ($Perceived_{2D}$) on the display's surface. The system blocks the original touch event that is orthogonal to $Active_{2D}$ (green dot in Figure 1A), and triggers a touch event at $Perceived_{2D}$ instead (red dot in Figure 1A). Visual feedback appears where $Perceived_{2D}$ is triggered.

When correcting parallax for multiple users (Figure 1C), the system has to determine which user performed the action to estimate the perceived point from his/her perspective. A straightforward approach might seem to correct for the user closest to the target. This approach would fail if, for example, a user extends his/her arm to touch a point that is closer to another user.

Instead, EyePACT determines which pair of eyes to correct for depending on the closest arm to the display at the time of the touch event. This is done by utilizing skeletal tracking [48], which provides the position of users' joints in the 3D space in front of the display. The positions of the hand, wrist and elbow joints are then used to determine which user is closest to the touchscreen at the time of the touch action. Once the user is determined, EyePACT corrects for parallax from that user's perspective.

4 STUDY1: ACCURACY EVALUATION

To evaluate EyePACT's parallax correction accuracy we asked participants to touch the center of crosshairs with different levels of parallax, target states, and user positions (Figures 4A and 4B).

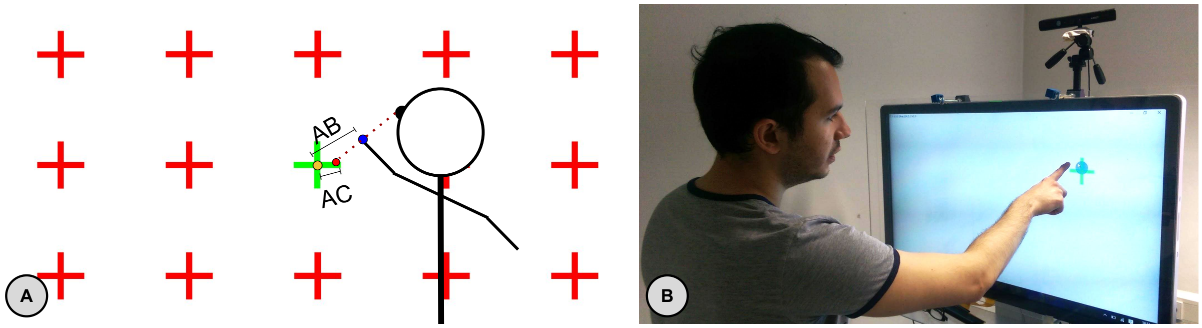


Fig. 4. In the accuracy evaluation study, participants were asked to touch the center of multiple crosshairs. (A) In the stationary target condition, one out of 15 equally distributed crosshairs was highlighted at a time. Participants had to aim at touching the center of the highlighted one (yellow dot) twice before another untouched crosshair was highlighted. The blue dot is the uncorrected touch point ($Active_{2D}$), while the red dot is the corrected touch point inferred by our system ($Perceived_{2D}$). (B) In the moving target condition, participants had to touch a moving crosshair, that bounced against edges, twice before it reappeared at a different starting position. We found that EyePACT results in significantly shorter distances to the target (Line AC) compared to the uncorrected distances (Line AB).

4.1 Design

We experimentally manipulated several independent variables that could impact the performance of EyePACT:

(1) The user's state: the participant could be stationary (standing 50 cm away from the display center) or move freely.
(2) The target's state: the target could be (T1) stationary or (T2) moving (Figures 4A and 4B respectively).
(3) The gap distance: the distance between the touch screen and the display could be (G1) short, (G2) medium, or (G3) long (4 cm, 5.4 cm and 6.8 cm respectively).

The experiment was designed as a repeated measures study, where all participants performed all conditions. To make sure participants are not influenced by the predefined *stationary user* position, all participants started with the *moving user* condition. To minimize learning effects, we alternated the order at which participants performed the conditions of the target state. For example, the first participant started with the stationary target condition, while the second user started with the moving one. The same was done for the third variable.

In the stationary target condition, a random crosshair out of 15 equally distributed ones was highlighted at a time. Participants had to touch the center of the highlighted one (yellow dot in Figure 4A) twice before another untouched crosshair was highlighted. In the moving target condition, participants had to touch a moving crosshair twice before it reappeared at a different starting position. Each participant touched 15 moving crosshairs twice. All crosshairs moved at a constant speed, but in different directions with different starting positions.

We covered three gap distances to experiment with different levels of parallax. The manufacturer's recommendation is to use a distance of 4.0 cm between the display and the touch screen to overcome the electrical noise caused by the display, which could interfere with the capacitive touch sensors. We used this as our minimum distance in addition to two larger distances: 5.4 cm and 6.8 cm. These values were determined by adding the recommended air-gap distance and the typical thicknesses of current vandalism-resistant glass. For example, at the time of submission of this paper, companies manufacture security glass that range in thickness from 6.5 mm to 25 mm [14], and from 11.5 mm to 39 mm [30].

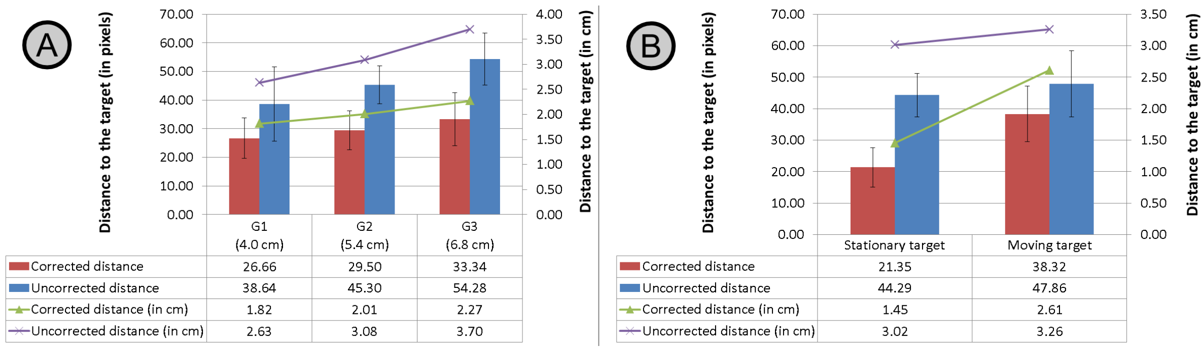


Fig. 5. Figure A shows that: (1) The uncorrected distance (blue) increases depending on the gap distance. This indicates that parallax was successfully created in our setup. (2) The corrected distance to the target (red) is always shorter than the uncorrected one. This means that EyePACT significantly improves accuracy for all gaps. (3) The portion of the uncorrected distance that is decreased (i.e., difference between the red and blue bars) becomes larger as the gap distance increases. This means that EyePACT's correction adapts to the size of the gaps. Figure B shows that although EyePACT reduces the distance to both moving and stationary targets significantly, the improvement is significantly higher with stationary targets than with moving ones.

4.2 Participants

We recruited 18 participants (5 females) with ages between 21 and 36 ($M = 25.2$, $SD = 4.4$) through mailing lists and social network groups. The height of the participants ranged from 172 cm to 189 cm ($M = 178.3$, $SD = 5.1$). They were compensated with online shop vouchers or participation points.

4.3 Procedure

The experimenter explained the study. Each participant performed 3 blocks with each block covering one of the three gap distances and 4 conditions (2 user states × 2 target states), amounting to 12 conditions × 15 targets × 2 touches = 360 touches. The study was concluded with a questionnaire and a semi-structured interview.

4.4 Results

At every touch event, we logged the uncorrected touch point, the corrected touch point, and the center of the target, which correspond to the blue dot, red dot, and yellow region/dot in Figures 1A and 4A respectively. We logged 7406 touch points – slightly more than what we expected, because participants sometimes performed more than two touches when uncertain if they hit the target. This mostly happened for moving targets. To address this we measured the average Euclidean distance between the points and the target for each condition. We compared the Euclidean distance between the uncorrected touch point and the target (Line AB in Figure 4A) and between touch point corrected by EyePACT and the target (Line AC in Figure 4A). Before analyzing the data, we excluded 122 out of 7406 measurements as outliers ($> \mu + 2.5 \times StandardDeviation$).

For analysis we used repeated measures ANOVA to test for significance in case of parametric data. Post-hoc pair-wise comparisons were done using t-tests. For non-parametric data (e.g., not normalized), we used Friedman's test for significance, and Wilcoxon signed-rank tests with for pair-wise comparisons. In all cases, the p-value was corrected using Bonferroni correction to counteract the multiple comparisons problem.

Effect of Gap Distance on Accuracy. A significant main effect was found for the gap distance on the distance to the target $F_{2,34} = 22.28$, $p < 0.001$. Post-hoc analysis revealed significant differences between all pairs ($p < 0.05$). This means that our setup successfully recreated a parallax effect that significantly affects accuracy.

Effect of EyePACT Correction on Accuracy. A significant main effect was found for EyePACT correction on distance to target $F_{1,17} = 87.06$, $p < 0.001$. Post-hoc analysis showed a significant difference ($p < 0.001$) between corrected distance ($M = 29.84$, $SD = 13.15$) and uncorrected distance ($M = 46.07$, $SD = 15.08$). This means that EyePACT results in a significantly shorter distance to the target.

Effect of EyePACT Correction on Accuracy With Respect to the Gap Distances. To study the effect of the gap distance further, we ran paired-samples t-tests and found that the corrected distance to the target is significantly shorter compared to the uncorrected one in all gap distances: G1 $t(17) = -6.059, p < 0.001$, G2 $t(17) = -8.154, p < 0.001$ and G3 $t(17) = -8.89, p < 0.001$.

We calculated the difference between the corrected and uncorrected distances (*Diff*) which is represented by the green bar in Figure 5A. We also found that *Diff* is significantly different depending on the gap distance $\chi^2(2) = 20.333, p < 0.001$. Post-hoc analysis with Wilcoxon signed-rank tests with Bonferroni correction showed significant differences between all pairs ($p \leq 0.01$). The largest correction was apparent in $Diff_{G3}$ ($M = 20.94$, $SD = 9.99$), followed by $Diff_{G2}$ ($M = 15.81$, $SD = 8.22$) then $Diff_{G1}$ ($M = 11.97$, $SD = 8.38$). This implies that EyePACT adapts to different levels of parallax, resulting in larger corrections when the parallax effect is higher.

The results are visualized in Figure 5A, and summarized in its caption.

Effect of Target State on Accuracy. A significant main effect was found for target state on distance to the target $F_{1,17} = 51.2$, $p < 0.001$. Post-hoc analysis revealed that the distance in case of stationary targets ($M = 32.82$, $SD = 16.73$) is significantly shorter ($p < 0.001$) than in the case of moving targets ($M = 43.09$, $SD = 14.14$). This motivated us to further investigate how well EyePACT performs with respect to the target state.

Running paired-samples t-tests, we found significant differences between the corrected distance ($M = 21.35$, $SD = 8.92$) and the uncorrected distance ($M = 44.29$, $SD = 14.74$) in the case of a stationary target $t(17) = -13.084, p < 0.001$, and also between the corrected distance ($M = 38.32$, $SD = 11.07$) and the uncorrected distance ($M = 47.86$, $SD = 15.1$) in the case of a moving target $t(17) = -4.416, p < 0.001$. This means that EyePACT significantly reduces the distance to stationary and moving targets. However the improvement is significantly higher in case of a stationary target. Results are visualized in Figure 5B and summarized in its caption.

Effect of User's Height on Accuracy. Compared to short users, taller ones are expected to experience a stronger parallax effect due to the steeper angle to the target. Indeed, we found a strong positive correlation between the participant's height and the distance between the uncorrected point and the center of the target $|r| = 0.535$ ($p < 0.05$) – data was shown to be linear according to a Shapiro-Wilk's test ($p > 0.05$). On the other hand, we did not find any indicators that the height of the user, or distance between the eyes and the screen, influences or correlates with the accuracy of EyePACT. A Pearson's product-moment correlation was run and showed a small correlation ($|r| = 0.105$), that was not statistically significant ($p > 0.05$), between the participant's height and the distance between the corrected touchpoint and target.

On the other hand, a repeated measures ANOVA showed significant main effect of the position of the target's row on the accuracy of EyePACT $F_{2,34} = 10.7$, $p < 0.001$. Pairwise comparisons using Bonferroni correction showed that only the accuracy at the topmost row ($M = 18.8$, $SD = 4.5$) and at the lowermost row ($M = 24.9$, $SD = 9.9$) are significantly different ($p < 0.005$). This implies that EyePACT's accuracy drops as the target's position is towards the bottom of the display. This is because the parallax grows further as the target is farther away from the user (see Figure 6).

In summary, we neither found an influence of height on EyePACT's accuracy, nor a relationship between height and our method's accuracy. However, not finding significant differences does not mean that there is none. In fact, the significant effect of the position of the target on accuracy means that the distance between the user's eyes and the target has an influence. Hence whether the user's height influences EyePACT's accuracy remains an open question for future research. This can be investigated by a large scale study with balanced heights, and performing statistical power analysis to estimate the probability of accepting the null hypothesis (i.e., that the user's height has no influence on accuracy) [12].

4.5 Observations and Feedback

When asked about the accuracy of the system on a 5-point scale (1=very imprecise; 5=very precise), responses ranged from 2 to 5 and were more inclined towards high precision ($M = 3.28$, $SD = 0.83$). Almost all participants indicated to find it easier to select stationary targets, which is reflected in the quantitative analysis. P9 mentioned that touching the moving crosshair became easier over time. P3 and P4 noted that they found the system to be highly accurate. P3 was surprised the system worked despite the touch screen being far from the display. P11 and P18 remarked that they perceived no difference in accuracy between the smallest and medium gap distances. This is in-line with our findings which show that EyePACT corrections are equally good for different gap distances (see Figure 5A).

Additionally we asked participants if they attempted to compensate for the parallax effect themselves. While some needed an explanation of what parallax is, some others indicated that although they did at the beginning, they quickly realized that the system responds more intuitively if they touch where they see the target. On a 5-point scale (1=very rarely; 5=very often), responses varied from 1 to 4 and indicate that participants rarely corrected for parallax ($M = 2.56$, $SD = 1.04$).

Although participants were explicitly asked to move freely in the *moving user* conditions, participants often remained in the center. Some highlighted that they were too lazy to move and targets were easily reachable from the center. Others did not think that they would perform better by moving. While P12 said he would avoid walking while looking at the screen lest he trips or steps on someone's feet. This explains the lack of significant effects of user state on the distance to the target.

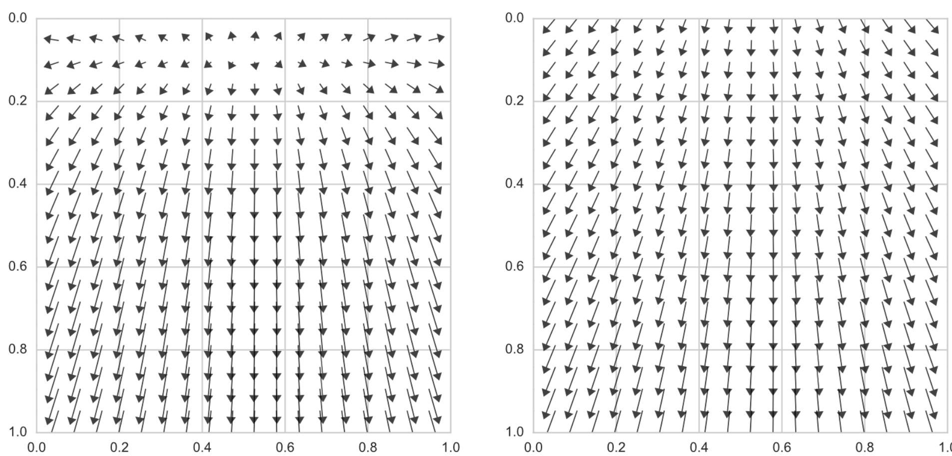


Fig. 6. Offset regression models for stationary (left) and moving targets (right). Arrows point from touch to target locations, revealing 2D offset patterns across the screen.

5 TOUCH OFFSET REGRESSION ANALYSIS

Beyond overall accuracy, it is also insightful to evaluate the *offset patterns* underlying the observed touch interactions. Related work analyzed such patterns on mobile devices with regression models [7, 8, 45, 46]. We also trained linear offset models (see [7, 8]) on the data of the accuracy study to analyze offset patterns.

Figure 6 visualizes models for stationary and moving targets: Users had large vertical offsets, which grow with the target location towards the bottom of the screen. Smaller horizontal offsets grow towards the left/right screen edges. This is explained by geometry – parallax grows the further users have to look down and to the side. Thus, these patterns visually explain why knowing the eye position relative to the display is highly valuable information for correcting parallax.

Since offset models map touches to targets, they can also be applied for parallax correction. We used leave-one-user-out cross-validation to train and test the models. ANOVA showed that the factor *model* (with levels: no model, hardware, software, both) has a significant effect on touch offsets (corrected by Greenhouse-Geisser: $F_{1.92,32.64} = 175.54$, $p < 0.001$; moving: $F_{1.71,29.04} = 51.29$, $p < 0.001$). Post-hoc tests revealed that both hardware and software approach significantly reduce offsets, and that combining their predictions significantly reduces offsets further. This results in a total improvement in offset RMSE of 56.6% (over the baseline) for fixed crosshairs and 29.7% for moving crosshairs.

Note, however, that the software approach requires (1) training data for the models, (2) might not work for users with heights different from those the data was trained with, and (3) cannot distinguish multiple users.

6 STUDY2: SUPPORTING MULTIPLE USERS

In a following step, we investigated how well EyePACT corrects parallax for multiple users and in turn allowing them to interact with the same on-screen object. We invited participants in pairs to participate in a collaborative multiplayer game where balloons would appear at the bottom and float to the top (Figure 7). The task was to collaboratively pop the balloons by (1) one player touching the balloon to *stop* it and (2) the second player touching it to *pop* it.

6.1 Design

This study was designed as a repeated measures experiment where all participants went through all conditions. We studied the effect of two independent variables:

(1) Target size: we experimented with small, medium and large balloons with diameters 30, 60 and 90 pixels (2.15°, 4.29°, 6.44° of visual angle respectively).
(2) Gap distance: similar to the accuracy study, we experimented with 4 cm, 5.4 cm and 6.8 cm gap distances.

The order of conditions was counterbalanced using a Latin-square. Participants swapped roles, that is, if participant A *stopped* a balloon, and participant B *popped* it, the following time a balloon appeared participant B *stopped* it, while participant A *popped* it. Each pair popped 8 balloons per condition.

6.2 Participants

We invited 20 participants (10 pairs, 19-55 years, ($M = 25.7$, $SD = 7.77$)), 160 to 191 cm tall ($M = 177.3$, $SD = 8.7$). Participants were recruited using mailing lists and social networks. They were compensated with online shop vouchers or participation points.

6.3 Procedure

Participants filled in consent forms and were explained the study. Pairs were then asked to take positions (Figure 7), which they maintained till the end of the study. Each pair performed 3 blocks with each block covering one of the three gap distances and 3 conditions. This means each pair performed 3 gap distances × 3 target sizes × 8 balloons = 72 balloon bursts.

6.4 Results

At each *stop* and *pop* action, we logged the uncorrected and corrected touch points. This allowed us to measure:

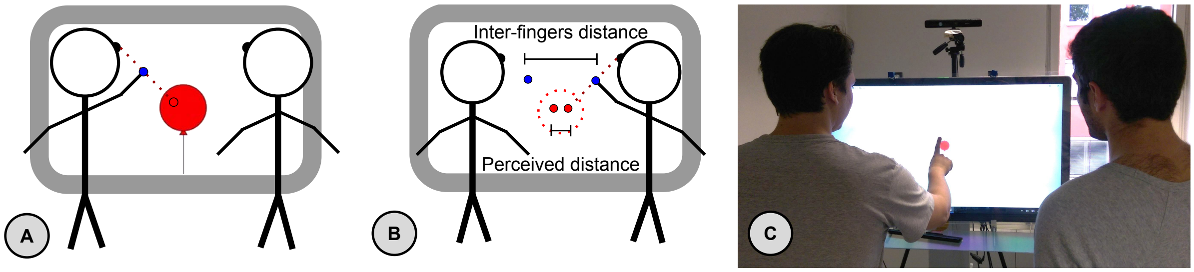


Fig. 7. We invited pairs of participants to the multiuser study to play a multiplayer game where players collaboratively stop and pop balloons that are floating to the top of the screen. In Figure (A) the participant on the left touches the balloon to stop it, which allows the second participant (B) to pop it by touching it another time. We measured the distance between the two uncorrected points (inter-fingers distance) and between the two corrected points (perceived distance). Figure (C) demonstrates the successful parallax correction by EyePACT; although the participant is not touching the red balloon from the camera's perspective, EyePACT is accurately correcting the touch point for the left participant based on his eyes' position, allowing him to successfully touch the balloon's center from his perspective.

- The *inter-fingers distance*: the distance between the two uncorrected points.
- The *perceived distance*: the distance between the two corrected points.

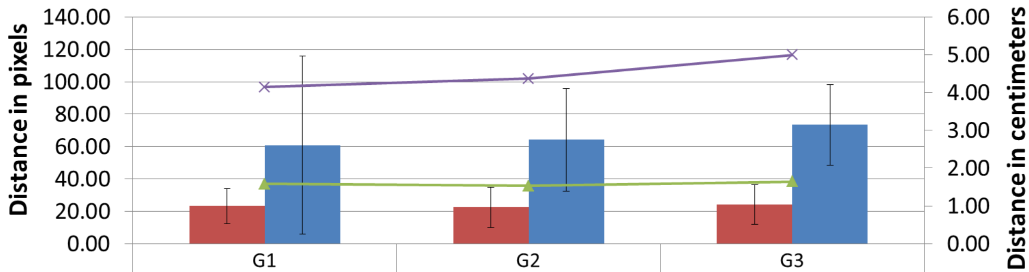
We investigated how the conditions influence these two distances and the difference between them (see Figure 7B).

Effect of Parallax Correction. A repeated measures ANOVA showed significant main effect of EyePACT correction on the distance between the two points $F_{1,9} = 56.61, p < 0.001$. Post-hoc analysis using Bonferroni correction showed that the *perceived distance* ($M = 23.26$, $SD = 13.07$) is significantly shorter than the *inter-fingers distance* ($M = 58.12$, $SD = 23.83$). This means that EyePACT brings the two touch points significantly closer to each other when multiple participants touch the same object.

Effect of Gap Distance. After excluding 7 outliers ($> \mu + 3 \times StandardDeviation$), a repeated measures ANOVA showed significant main effect of the gap size on the *inter-fingers distance* $F_{2,18} = 11.2944, p < 0.005$. Post-hoc analysis using Bonferroni correction showed that there is a significant difference ($p < 0.005$) between the shortest ($M = 45.2$, $SD = 14.86$) and the largest gap distance ($M = 72.3$, $SD = 23.62$). The other pairs were not significantly different.Yet, Figure 8 suggests that the larger the gap distance, the larger the *inter-fingers* distance. From this we conclude that the larger the parallax, the farther users' fingers will be when touching the screen while looking at the same object.

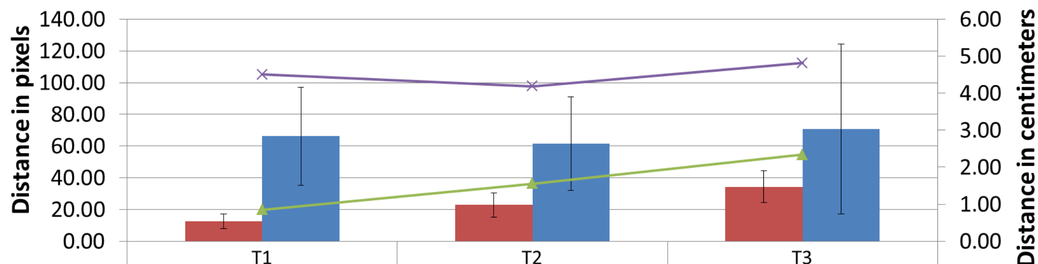
On the other hand, no significant main effects were found for the gap distance on the *perceived distance* ($p > 0.05$). This means that there is no evidence that the gap distance influences the distance between the corrected points. Figure 8 shows that the distance between the two touch points corrected by EyePACT is almost the same across the different gap distances. This suggests that EyePACT corrects equally well for multiple users at different levels of parallax.

Effect of Target Size on Perceived and Inter-fingers distances. A repeated measures ANOVA showed significant main effect of target size on the perceived distance $F_{2,18} = 106.32, p < 0.001$. Post-hoc analysis using Bonferroni correction revealed significant differences between all pairs ($p < 0.001$), indicating that the distance was shortest for small targets ($M = 12.56$, $SD = 4.67$), followed by medium targets ($M = 22.86$, $SD = 7.53$), and longest for large targets ($M = 34.38$, $SD = 9.95$). This is expected as both corrected touch points need to be closer to each other to fit in smaller targets. We found no significant effect of target size on distance between the two uncorrected points (inter-fingers distance). This means there is no evidence that the target size influences the distance between the fingers.



	G1 (4.0 cm)	G2 (5.4 cm)	G3 (6.8 cm)
Distance between the two corrected points (in pixels)	23.19	22.48	24.11
Distance between the two uncorrected points (in pixels)	60.87	64.12	73.39
Distance between the two corrected points (in cm)	1.58	1.53	1.64
Distance between the two uncorrected points (in cm)	4.14	4.37	5.00

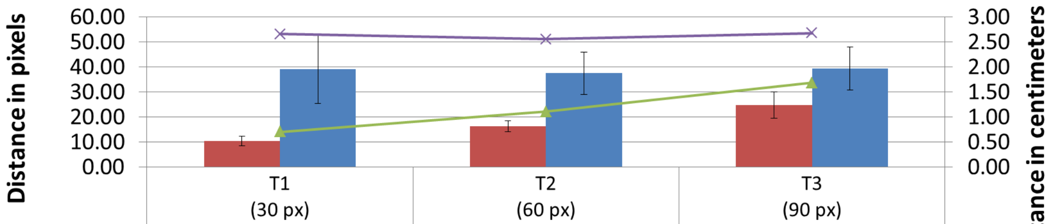
Fig. 8. The figure shows that as the gap between the touch screen and the display increases, so does the distance between the users fingers when they both touch the same object (inter-fingers distance). The figure also shows that despite the increasing gap distance, which in turn results in a stronger parallax effect, the distance between the two corrected touch points (perceived distance) does not vary a lot.



	T1 (30 px)	T2 (60 px)	T3 (90 px)
Distance between the two corrected points (in pixels)	12.55	22.86	34.38
Distance between the two uncorrected points (in pixels)	66.15	61.50	70.73
Distance between the two uncorrected points (in cm)	0.85	1.56	2.34
Distance between the two corrected points (in cm)	4.50	4.19	4.82

Fig. 9. The figure shows the effect of the target's size on the distance between the two corrected points (perceived distance), and the distance between the two uncorrected points (inter-fingers distance). As expected, the smaller the target, the smaller is the distance between the two corrected points within the target. The figure also suggests that the Inter-fingers distances are random and are not influenced by the target's size. The value between brackets denotes the distance in centimeters.

Effect of Target Size on the Distance to Target Center. Although the main aim of the second study was to evaluate EyePACT in case of multiple users, it was also possible to study the influence of the target size on EyePACT's accuracy for each individual user, since the task involved touching balloons of different sizes. We did not find any



	T1 (30 px)	T2 (60 px)	T3 (90 px)
Distance between the two corrected points (in pixels)	10.24	16.18	24.65
Distance between the two uncorrected points (in pixels)	39.00	37.48	39.30
Distance between the two corrected points (in cm)	0.70	1.10	1.68
Distance between the two uncorrected points (in cm)	2.66	2.55	2.68

Fig. 10. The figure shows that the distance between the uncorrected touchpoint and the target center remained almost unchanged, while the distance between the corrected touchpoint and the target center is significantly shorter when touching smaller targets. This means that EyePACT adapts to smaller targets without requiring users to be more precise.

significant effect of target size on the distance between the target center and the uncorrected touchpoint ($p > 0.05$). On the other hand, a repeated measures ANOVA with Greenhouse-Geisser correction revealed a significant main effect of target size on distance between the target center and the corrected touchpoint $F_{1.2,10.9} = 39.97$, $p < 0.001$. Pairwise comparisons with Bonferroni correction showed significant differences between all pairs. The distance between the corrected touchpoint and the small target ($M = 10.16$, $SD = 4.63$) was the shortest, followed by that between the corrected touchpoint and the medium target ($M = 15.45$, $SD = 8.34$), and finally that between the corrected touchpoint and the large target ($M = 24.13$, $SD = 14.07$).

This means that although the distance between the uncorrected touchpoint and the target center remained almost unchanged (see Figure 10), the distance between the corrected touchpoint and the target center adapted based on the target size. This provides evidence for an additional usability advantage made available by EyePACT. That is, although smaller targets typically require more precise pointing by users, EyePACT users do not need to be more precise in order to touch smaller targets. Figure 10 illustrates this advantage: our participants did not need to be more precise when touching smaller targets compared to larger ones (blue bars); EyePACT made their touchpoints more precise and corrected them to trigger on the targets (red bars).

7 DISCUSSION

Our findings from the first study show that EyePACT (1) brings the touch point significantly closer to the target for all gap distances, (2) results in significantly higher accuracy for stationary targets, (3) adapts to parallax by resulting in significantly larger corrections when the gap distance is increased. The second study shows that EyePACT (1) maintains a significantly large distance between two users' fingers when interacting with the same object, and (2) is flexible with regard to targets of different sizes.

Technical Realization. While we are starting to see a rising adoption of interaction via mid-air gestures and gaze, touch remains the most prominent interaction technique for public displays [11]. Many of these displays have readily integrated cameras. For example, ATM machines are often equipped with cameras for security reasons. This makes the adoption of EyePACT straightforward; our approach only requires detection of the user's eyes. We use a depth camera for multi-user scenarios to identify which arm is closest to the display at the time of interaction. Although achieving the same with high accuracy using an RGB camera would result in higher processing demand, which could in turn result in a delay in the system's response, advances in hardware and processing power make the use of an RGB camera for the same purpose also feasible in the near future.

Eliminating the Error Completely. Although EyePACT significantly improves touch accuracy based on the user's eye position, it does not completely eliminate the error caused by parallax. This is due to several reasons. One reason is that even with perfect eye tracking, knowing the exact pixel the user is focused on is almost impossible; users can move attention within the fovea, which is around 2 degrees of visual angle, without moving their eyes [27]. Another reason is that the user's touch tends to be biased towards the dominant eye [39]. An interesting direction for future work is to estimate the user's dominant eye based on these biases and adapt the parallax correction accordingly.

Manual Parallax Correction and Showing Visual Feedback. In general, users do not expect parallax correction. This was observed in our studies where several users upon the first touch overcompensated since they expected a parallax effect. In the two studies visual feedback was provided. Hence, participants quickly understood where the touch point was registered and stopped compensating. From this we learn that upon deployment in a public space, visual feedback is crucial in order not to confuse users. Furthermore, future versions of EyePACT can detect such over compensations and use them as a form of calibration to improve the correction.

Other Application Opportunities. In this work we focused on addressing the problem of the displacement between the perceived and detected touch points on a public display. However, this is not the only issue resulting from the large distance between the touch surface and the display. For example, binocular parallax occurs when the distance between the touchscreen and UI elements is very large (e.g., 30 cm [25]). While this is not a realistic setting for public displays that are in the scope of this work, and binocular parallax was not reported by our participants, EyePACT can be optimized to address binocular parallax as well. In particular, previous work showed that when pointing at 3D stereoscopic objects, users touch between their dominant and non-dominant eye position with a bias towards the dominant eye position [39]. Valkov et al. developed guidelines to address this issue for interacting with 3D stereoscopic objects, extrapolating their 3D solution to the 2D case could be a direction for future work to optimize EyePACT for contexts where this issue occurs (e.g., transparent displays [25, 26]).

Reaching Farther Objects. While the parallax effect comes with its shortcomings, it could also offer opportunities that can improve the user experience. For example, by intentionally introducing a large gap between the touch surface and the display, the angle between the user's gaze vector and the touch surface plane becomes wider. This can, in turn, reduce the user's effort to reach out to distant objects since the user does not have to be in a position that is orthogonal to the object (see Figures 1A, 1C, and Figure 7). A typical problem with touch screens is the reachability of distant content [16, 17]. This problem is amplified as large displays become more common [1, 22, 33], which results in hardly reachable on-screen objects. The use of EyePACT with a large gap can also allow users to interact with a larger portion of the display while being stationary. Nevertheless, interacting with far-away objects is likely to cause binocular parallax. Furthermore, a large gap can result in making it difficult for the user to focus on his/her fingers and the displayed object at the same time. An interesting direction for future work is to investigate starting at which gap distances focusing becomes uncomfortable for the user.

7.1 Limitations and Future Work

In our experiments, the speed and direction of the moving target was randomly decided at the beginning of each trial. Future work could investigate the impact of speed and direction of moving targets on the accuracy of EyePACT. Furthermore, as indicated in section 4.4, we plan to conduct a large scale study in which we balance the height of participants to better understand the impact of the user's height on the parallax error and correct it accordingly. Finally, an interesting direction for future work is to study how knowledge about the user's dominant eye and dominant hand can help in improving the accuracy of EyePACT. In the future we plan to further extend EyePACT to address different types of parallax (e.g., Binocular parallax). Furthermore, EyePACT can be exploited to support interaction by, for example, allowing users to reach farther objects, addressing binocular parallax, and allowing novel collaborative multi-user interactions by eliminating finger interferences.

8 CONCLUSION

In this work we presented EyePACT, a low-computation yet effective approach for overcoming parallax on public displays. First, we discussed why parallax is an issue on public displays nowadays and the need for research in this space. Second, we described a prototype with which we created and controlled the parallax effect. Third, we desribed the implementation of EyePACT. Forth, we demonstrated EyePACT's accuracy in a first user study to show that it (1) significantly improves accuracy in the presence of parallax, (2) adapts to different levels of parallax, (3) improves accuracy for both stationary and moving targets, but the improvement is more significant for stationary ones, and (4) although future work is needed to determine if it is not affected by the user's height, we did not find any significant effects in our study. Fifth, we described a software-based regression model that was trained using the data from the first study, and described why it is not sufficient in the case of users with different heights and in multiuser scenarios. Finally, in a second user study we showed that EyePACT (1) significantly improves accuracy for multiple users and also adapts to different levels of parallax, (2) enables multiple users to interact with the same objects while keeping their fingers far apart, (3) does not require users to be more precise when touching smaller targets. In addition we utilized this method to enable novel ways of interaction that are otherwise infeasible.

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