Understanding Back-to-Front Pinching for Eyes-Free Mobile Touch Input

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ABSTRACT
Using a smartphone touchscreen to control apps mirrored to a distant display is hard, since the user cannot see where she is touching while looking at the distant screen. Tactile landmarks at the back of the phone can mitigate this problem, especially in landscape mode [3]: By moving a finger across these landmarks, the user can haptically estimate the finger position in proportion to the touchscreen. Upon pinching the thumb resting above the touchscreen towards that finger at the back, the finger position is transferred to the front and registered as a touch. However, despite proprioception, this technique leads to a shift between back and front position, denoted as *pinch error*. We investigated this error using different target locations, device thicknesses, and tilt angles to derive target sizes that can be acquired at a 96% success rate.

Author Keywords
Back-of-device; eyes-free; pinch error; proprioception

ACM Classification Keywords
H.5.2 User Interfaces: Input Devices and Strategies

INTRODUCTION
Interaction with smartphones and similar touchscreens not only depends on the user's ability to perceive visual feedback from the UI, but also on the perception of the hand relative to the touchscreen [6]. There are, however, situations in which the user is looking elsewhere, e.g., at an external display that mirrors a game or other app from the smartphone, or at the road while driving a car and trying to hit the 'answer phone call'-button. In both cases, the touchscreen then acts as an absolute input-only device. However, not looking at the touchscreen decreases input accuracy significantly [6].

HaptiCase [3] mitigated this problem using only phone protection cases with tactile landmarks at the back that correspond to the size and position of the opposed touchscreen—without modifying the app or touchscreen. By moving her fingers across the landmarks, the user can feel where a touch *would* land in relation to the touchscreen (Fig. 1, middle).

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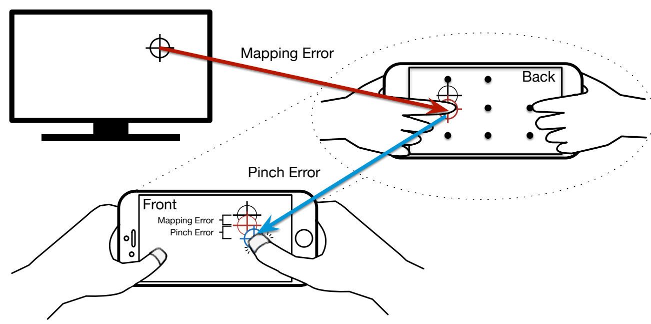

Figure 1. The two parts of error in *HaptiCase* [3]. Top → middle: Mapping a target (black) from the distant screen to in incorrect position (red) at the back of the smartphone results in a *mapping error*. Middle → bottom: Pinching from back to front (blue) results in a further *pinch error*.

Upon pinching the thumb resting above the touchscreen to a finger at the back, that position is transferred to the front and registered as a touch. This transfer works eyes-free as it is based on human proprioception.

Still, there is evidence that thumb-to-finger pinching induces an error, that we call *pinch error* (Fig. 1, middle → bottom): [3] reports that users felt an drift between their pinching fingers—the touch at the front was a little off relative to the finger's position at the back. Similarly, [15] observed a pinch offset between thumb and fingers when using a double-sided multi-touch tablet grasped from the side.

In this paper, we investigate the impact of **(i)** device thickness, **(ii)** tilt angle, and **(iii)** target location on the pinch error. To understand whether and how these factors lead to an error, we collected data from 18,000 pinches. We report recommended target sizes that can then be used, e.g., to improve success rates for pinching in techniques such as HaptiCase [3].

MAPPING ERROR AND PINCH ERROR
Using HaptiCase [3], targets on a distant display are acquired in three steps, without looking at the touchscreen. A typical usage is holding a smartphone with two hands in landscape mode while looking at a distant screen. **(1)** First, the user spots a target at the distant screen. **(2)** She then needs to map the location of the distant target to the back of the smartphone. She moves one of her fingers at the back of the phone to the location equivalent to the distant target. To ease this mapping, a tactile frame allows the user to feel the size and location of the opposing touchscreen. Additional tactile landmarks on the inside of the frame, e.g., raised dots, can provide further help, and a matching aspect ratio between the frame and

the mirrored UI further eases the mapping [6]. **(3)** Finally, since the back of the device does not register touches, the user transfers the touch position at the back to the same position at the front by thumb-to-finger pinching.

These steps provide two sources of error that reduce tapping accuracy (Fig. 1): **(i)** Despite the aid of tactile landmarks, the user may not map the location of the distant target to the back of the phone precisely, resulting in a *mapping error*. **(ii)** During pinching, thumb and finger position may not match up exactly, adding a *pinch error*, which this paper addresses.

RELATED WORK

Proprioception is the "perception of positions and movements of the body segments in relation to each other, without the aid of vision, touch, or the organs of equilibrium." [2]. Early studies of generic finger opposition tasks showed that proprioception as the only information is not sufficient for precise targeting across space, as there can be a shift of up to 8 cm [5]. Users point too far to the left when trying to match their right index finger tip to their left index finger tip from below against a horizontal surface [11]. Reversing the tasks results in a drift to the right [10, 8, 4]. [7] studied index finger to index finger matching at small distances fixed along the vertical axis. There was almost no error when the user actively repositions the target finger to which the other hand's index finger has to point to. However, for back-to-front pinching, the fingers are not fixated and can drift in both directions. Still, index to index finger matching is more precise in localizing a target in depth compared to vision, whereas vision is more precise when localizing in azimuth direction [12]. Although this sounds promising for back-to-front pinching, since it is performed in the direction of depth, the impact of this effect is unknown for thumb-to-finger pinching of the same hand.

Differences in touch accuracy between front- and back-of-device interaction for mobile devices have also been studied. [15] compared pinching gestures at the sides between back and front of a double-sided multi-touch tablet. Users stated, e.g., that the device thickness limits the gesture performance. The authors observed an offset along the horizontal axis between thumb at the front and the other fingers at the back of the device. However, the offset was not quantified, and users could watch the thumb position at the front. When either tapping at the back or at the front without pinching, gestures were performed symmetrically with both hands, but positions between back and front differed vertically [16]. [13] also identified performance differences. While touching with the index finger at the back works well, reaching with the thumb at the front is worse. For tablet-sized touchscreens, center regions at the front are slightly more difficult to reach than at the back when hands are grasping from the side [14]. Targets beyond 76 mm from the left and 66 mm from the right will not be reached easily. However, these boundaries may not hold true for devices thicker than the prototype used in [14] that exceed thumb and finger reach. HaptiCase [3] uses pinching from back to front on a smartphone to enable users to control a UI mirrored from the phone to a distant screen without looking at the fingers. This technique provides non-sensitive tactile landmarks at the back of the smartphone that the user senses with her fingers to estimate the location of her finger in relation to the touchscreen at the front. A landmark design of dots on a 3×5 grid significantly improved eyes-free tapping accuracy and reduced target sizes by 14% to 17.5 mm. HaptiCase, however, did not isolate a potential error induced by this pinching.

The related work on proprioception and back-to-front touching shows evidence for a pinch error. Our experiment provides systematic quantified insight into this problem.

EXPERIMENT: PINCHING PERFORMANCE

We hypothesized that a pinch error exists (H_1) and that it increases with device THICKNESS (H_2) and device ANGLE (H_3), i.e., its tilt around the horizontal left-to-right axis, and that the error is affected by TARGET (H_4), i.e., the position at the back at which the pinch starts.

Apparatus, Task, and Participants

To measure users' back-to-front pinch error, we attached two 5" touch digitizers, each sensing up to five touches at a resolution of 800 × 480 pixels over 109.6 × 66.4 mm. Note that the digitizer at the back is only used for measurement purposes and would not be present in typical interaction, e.g., as in HaptiCase [3]. THICKNESS varied by stacking lightweight cardboard slices (weight: 18 g per 5 mm thickness) between the digitizers. With a thickness of 1.1 mm for each digitizer and a required 2.0 mm shielding, the minimum device thickness was 4.2 mm. In total, the measurement device weighted between 88 and 176 g (thinnest to thickest). We used a Vicon tracking system and optical markers attached to our prototype to measure ANGLE (Fig. 2). To eliminate the mapping error and control that all users pinched at the same locations, we created tactile landmarks for our targets by puncturing small holes into a transparent conductive foil that was then carefully aligned on top of the rear digitizer. The digitizers were connected to two Arduinos feeding our software which recorded touch positions and the angle obtained from the Vicon.

The user was sitting at 1 m distance in front of a 23" screen while holding the prototype with a particular thickness with both hands. The chair had no armrests, preventing the user

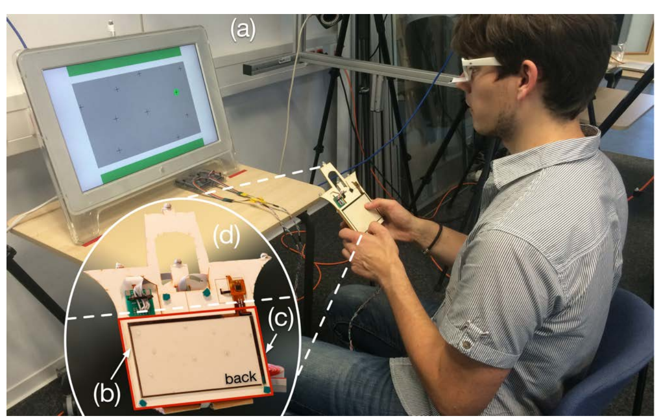

Figure 2. Study setup (a) and prototype with 5" digitizers at the front and back (b). The digitizer with frame (c) measures 125.25 × 88.33 mm excl. an extension with reflective markers (d) that is used to track tilt.

from physically stabilizing her arms, obtaining a similar posture as when sitting in front of a TV. The screen displayed targets that corresponded to the landmark positions. Indicators at the top and bottom of the screen directed the user to tilt her device to match ANGLE. A tolerance of ±15° was allowed to mitigate jitter. When a target was highlighted, the user had to touch the equivalent landmark at the back and pinch with the thumb to touch the front digitizer. Users were free to start the pinch from wherever they wanted. Our software verified that the user touched the right landmark at the back before pinching. Users wore glasses with paper strips at the bottom to prevent them from watching their fingers. Overall, 30 users (aged 21–58, M = 29.63, SD = 10.10, 4 left-handed, 8 female) participated.

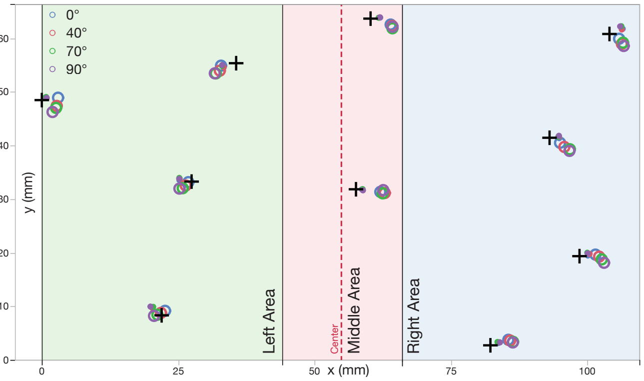

Figure 3. TARGETs (+) (grouped by left, middle, and right area), mean for touches at the back (dots) and at the front (circles) for each ANGLE.

Experiment Design

The factors were THICKNESS (5 levels: 4.2 mm, 10.0 mm, 15.0 mm, 20.0 mm, and 30.0 mm), ANGLE (0°, 40°, 70°, and 90°), and TARGET (10 levels: 4 left, 2 middle, 4 right, see Fig. 3). At 0°, the front digitizer was facing the user, at 90° the ceiling. THICKNESS and ANGLE were counterbalanced using a Latin square; TARGET was randomized. THICKNESS represents the combined thickness of touch device, protection case, and raised landmarks. We included thicknesses ≥20 mm as representatives for touch-based mobile game controllers, such as Nintendo Wii U or Sony PlayStation Portable. For each THICKNESS, the user was asked to tilt the prototype to a given angle and hold it there until all highlighted targets were pinched. After all ten targets had been pinched, they were repeated twice. No visual feedback was given as to where the thumb hit the digitizer. Until the next THICKNESS was presented, the user could relax her arms. We measured touch positions (x,y) at the back and front, length of users' index finger (84.32–105.01 mm, M = 91.29 mm, SD = 4.87 mm) and thumb (26.89–62.39 mm, M = 73.30 mm, SD = 5.62 mm) of both hands, handedness, and actual tilt angle. The study was within subjects, resulting in 30 × 5 × 4 × 10 × 3 = 18,000 recorded pinches. On average, users needed 549 ms to perform a back-to-front pinch (SD = 535 ms). Users could stabilize the device before performing the pinch. While pinching, the user's exact angle deviated by less then 10°, fitting well within the ±15° tolerance.

Results

(H_1) We found evidence for a pinch error, since the distribution of touches around targets at the back differ widely from those pinched to the front. Fig. 4 shows an example for 4.2 mm thickness. On average, pinches at the front are shifted from touches at the back significantly stronger in x-direction (+2.57 mm, 99% CI: [2.52, 2.61]) than in y-direction (+1.58 mm, 99% CI: [1.56, 1.61]), ($F_{1,35961}$ = 267.16, $p < .0001$).

To identify factors affecting the pinch error, we defined ERROR$_x$ (ERROR$_y$) as the absolute distance between the x (y) position of a TARGET at the back and the corresponding touch at the front. TARGETs were grouped into left, middle, and right (Fig. 3). We ran a three-way ANOVA on the square root-transformed ERROR.

(H_2) THICKNESS had a main effect on ERROR$_x$ ($F_{4,17911}$ = 14.41, $p < .0001$) and on ERROR$_y$ ($F_{4,17911}$ = 9.08, $p < .0001$): the ERROR increases for both x and y with increasing THICKNESS (Fig. 5). For ERROR$_x$, a Tukey HSD post-hoc test revealed significant differences between THICKNESSes that are at least two levels apart (in ascending order), whereas for ERROR$_y$ differences were significant between the two classes (4.2, 10.0, 15.0) mm and (20.0, 30.0) mm ($p < 0.05$ for both x and y). Fig. 4 shows how users' pinching performance decreases as thickness increases from 4.2 mm to 30.0 mm. In comparison, users' landing error at the back, i.e., the difference between a target location at the back and a user's touch at the back, is far smaller. The means of these landing errors are similar across THICKNESS for x (M = 2.67 mm, 99% CI: [2.64, 2.71]) and y (M = 2.01 mm, 99% CI: [1.97, 2.04]).

(H_4) TARGET also had a main effect on ERROR (ERROR$_x$: $F_{2,17911}$ = 25.40, $p < .0001$, ERROR$_y$: $F_{2,17911}$ = 5.04, $p < .001$). For ERROR$_x$, a Tukey HSD post-hoc test revealed pairwise significant differences between left, middle, and right targets ($p < .01$): Middle targets led to the highest error, whereas left targets had the lowest error. ERROR$_y$ for left and right targets was significantly different from middle targets ($p < .05$), which had led to the highest error (Fig. 5). Taking users' index finger and thumb length into account (classified into small, medium, and large) showed no effect on the error in x- and y-direction ($F_{2,25} < 1.85$, $p > .1$, each).

(H_3) With increasing ANGLE, pinches move along a curve to the lower left for targets at the left resp. to the lower right for targets at the right (Fig. 3), yet—against our expectations—not significantly. We assume that with increasing tilt, users tend to touch diagonally with the side of their thumbs, thus changing the contact area slightly.

DISCUSSION

In summary, our experiments confirm that back-to-front pinching leads to an error (H_1). It increases with the thickness of the device (H_2) and is affected by the target position (H_4). We could not find evidence for tilt affecting the pinch error (H_3). Hence, using tilt as additional input, e.g., in games, is fine, as it will not influence the accuracy of thumb-to-finger matching significantly. Regarding thickness, the pinch error

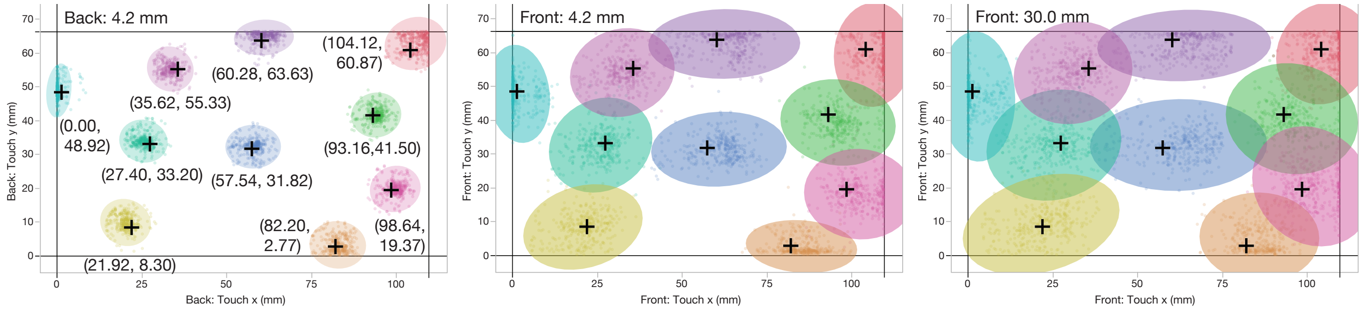

Figure 4. Targets (+) and 99% confidence ellipses for actual touches. Touches at the back (left) for 4.2 mm thickness are only slightly off the target positions. This *landing error* is similar for other thicknesses. The corresponding pinches (middle), however, are already widely spread—illustrating the pinch error. For 30.0 mm, the spread is largest (right).

in x- and y-direction is similar for targets to the left. For targets to the right and around the middle, the error for x is far higher than for y. Users' performance is worst in x-direction for targets around the middle, because these are harder to reach from the side as the prototype is in landscape format. Reversing the aspect ratio might flip these results. For middle targets using the 30 mm prototype, we observed that users started to reposition their grip and rather pinched from the top resp. bottom than from the sides as this was easier for such thick form factor.

More generally, we observed that the error shifts in x-direction towards the users' hands, i.e., left targets are left-shifted, right targets are right-shifted (Fig. 4). This matches previous observations [15]. We also determined that targets at the middle are shifted to the right. This observation was independent from whether the user was right- or left-handed, and occurred even though we had ensured that middle targets were alternately preceded by a left resp. right target. We assume that these targets were pinched from the right side since users noticed that middle targets were positioned slightly to the right of the horizontally centered monitor logo (Fig. 2).

Fig. 5 shows the mean pinch error and CIs. The trend lines indicate estimates for errors for thicknesses other than used in this study. Table 1 (top) lists the effective width (height) of left, middle, and right targets at the front that the user will be able to acquire by pinching at a success rate of 96% [9].

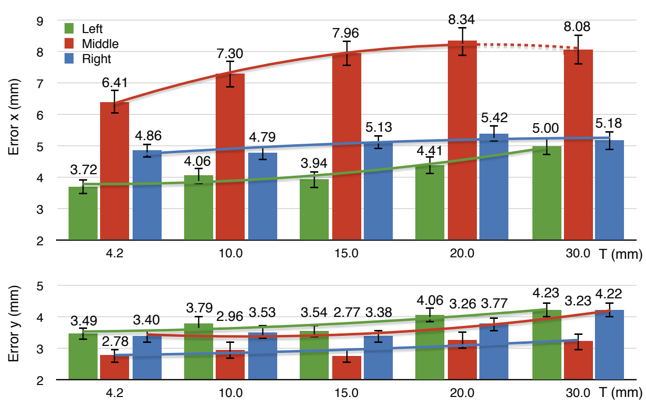

Figure 5. ERROR means (mm) split by THICKNESS T and TARGET position in x- and y-direction. Error bars denote 99% CI for the mean.

These sizes inform about how to design proper target sizes (at the front) based on target location and device thickness for back-to-front pinching. For example, targets at the middle should be twice as wide as high. To show how the error scales from back to front, Table 1 (bottom) lists the effective target width and height for touches at the back averaged over THICKNESS. For example, at 4.2 mm thickness for middle targets, 96% of users' touches at the back are located within 7.72×6.11 mm, whereas the corresponding pinch area at the front will scale more than four times to 28.89×14.59 mm.

Practically, thinner devices lead to more accurate pinching results. We do not recommend back-to-front pinching for thicknesses above 15 mm as the pinch error increases more drastically beyond this point. Targets should be placed at the sides as these are easier to reach and pinch more accurately than those located at the center. Taking these recommendations into consideration, a taget size of 20×20 mm should then lead to a good pinching performance.

LIMITATIONS AND FUTURE WORK

In our study, we did not vary the size of the digitizers. However, we expect the pinch error to increase with screen size as it becomes more difficult to reach targets towards the center. Furthermore, the digitizers only provide the center coordinates for touches. Using digitizers that output the major and minor axes of a touch ellipsis would help determine the finger orientation. Combined with additional data, such as the position of hands and thumbs around the device, this could be used to feed machine learning algorithms to obtain a model that counteracts the pinch error in software. Moreover, we used digitizers without touch location correction to obtain unmodified and manufacturer-independent data. For some commercial devices that use correction, e.g., a 1 mm shift at the area that can be reached by the thumb in portrait mode [1], the pinch error might be different. Finally, in HaptiCase [3], mapping and pinch error were combined. Although we know have isolated the pinch error, it is still not clear how it is affected by the preceding mapping error. We will address these ideas in future work.

CONCLUSION

We investigated users' performance on eyes-free thumb-to-finger pinching between a mobile touchscreen and back-of-device tactile landmarks. In a study, we collected data from

	Width (pinch, front)			Height (pinch, front)		
Thickness	L	M	R	L	M	R
4.2 mm	18.47	28.89	20.91	18.52	14.59	16.86
10.0 mm	21.66	27.07	19.67	20.21	16.04	18.10
15.0 mm	20.87	30.42	19.51	18.60	13.89	16.99
20.0 mm	23.02	34.06	22.40	21.33	16.90	19.05
30.0 mm	24.47	35.30	23.48	22.44	16.49	21.28
	Width (touch, back)			Height (touch, back)		
Avg.	7.49	7.72	7.26	7.16	6.11	6.91

Table 1. Top: Effective width (4.133 × SD_x) and height (4.133 × SD_y) in mm split by THICKNESS for Left, Middle, and Right targets at the front that will be acquired at a 96% success rate. Bottom: Effective width and height in mm for touches at the back in comparison (averaged over THICKNESS since numbers were similar).

18,000 pinches. When users pinch, their touches between back and front are shifted. This pinch error increases both horizontally and vertically with increasing device thickness. The horizontal error is stronger than the vertical, and pinches are shifted towards the users hands. Tilting the device around the horizontal axis has no significant influence on the error. Based on our findings, we presented minimum sizes for targets at the front that users will be able to acquire with back-to-front pinching at a 96% success rate.

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