Expanding Side Touch Input on Mobile Phones

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Expanding Side Touch Input on Mobile Phones: Finger Reachability and Two-Dimensional Taps and Flicks using the Index and Thumb

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We investigate the performance of one-handed touch input on the side of a mobile phone. A first experiment examines grip change and subjective preference when reaching for side targets using different fingers. Results show all locations can be reached with at least one finger, but the thumb and index are most preferred and require less grip change for positions along the sides. Two following experiments examine taps and flicks using the thumb and index finger in a new two-dimensional input space. A side-touch sensor is simulated with a combination of capacitive sensing and motion tracking to distinguish touches on the lower, middle, or upper edges. When tapping, index and thumb speeds are similar with thumb more accurate and comfortable, and the lower edge is most reliable with the middle edge most comfortable. When flicking with the thumb, the upper edge is fast and rated highly.

CCS Concepts: • **Human-centered computing → Gestural input**; **Touch screens**; **Interaction techniques**; **Empirical studies in HCI**.

Additional Key Words and Phrases: interaction techniques; controlled experiments

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1 INTRODUCTION

Phones are increasingly powerful, but the dominant form of phone interaction, touch input, still has issues like occlusion [28, 33] and imprecision [4, 34]. Moreover, limited screen real-estate means graphical user interface controls (like buttons) compete with the document of interest (like a photo being edited). When designers must choose between showing more of the document or more of the interface, the solution is usually hiding the interface inside menus or behind delimiters like press-and-hold, both of which slow down interaction. Consequently, researchers continue to investigate new forms of phone input. One general approach is to move input off the screen to the side. Examples include more expressive physical buttons [6], various forms of grip sensing [5, 21, 31, 35], as well as sensing side taps [26] and side touches [10, 13, 17]. With new bezel-less phones, wrap-around touch screens [37], and foldable phones [32], a move from side buttons to side touch input could be next. This also makes sense when you consider how phones already transitioned from front physical keys to full screen touch input to gain more versatility.

Accessing many commands with side touch input could reduce time for menu navigation and press-and-hold delays, but moving some touch interaction to the side has other advantages. The front display is not occluded by the finger, and the front display is nearby for side touch feedback and contextual help. Moreover, users already interact on the side using physical buttons for functions like power, volume, and triggering the camera shutter. Some forms of side touch input have been proposed before. For example, McGrath and Li detected side taps using an accelerometer [17],

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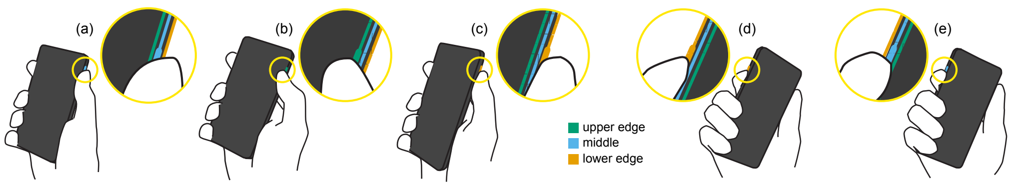

Fig. 1. Two-dimensional side touch input uses the two edges and middle surface, for example: (a) thumb on middle surface; (b) thumb on upper edge; (c) thumb on lower edge; (d) index finger on lower edge; (e) index finger on middle surface.

Kato et al. used conductive strips to extend standard phone screen capacitive sensing to the side [10], and Le et al. developed sensing methods for a fully touch sensitive phone that included one-dimensional capacitive sensors on the sides [13]. Our work extends these initial ideas with an empirically-grounded exploration of a larger side touch input space designed for one-handed usage.

Beginning with a "reachability" study, we examine comfort and grip stability when holding a phone one-handed and reaching to different side locations using one of the five fingers, measured with three representative phone sizes. The results show that virtually any location around the side of a phone can be reached with at least one finger assuming some grip change, but the most capable and stable fingers across phone sizes are the index and thumb when reaching along the left and right sides.

We use these reachability results to ground an investigation into an expanded side touch input space. We add a second dimension by distinguishing which part of the side "edge" is contacted: upper edge, middle surface, or lower edge (see Fig. 1). Similar to work exploring touch along and across the end of a table [8], we investigate two-dimensional side taps, based on the position along the side and which edge was touched, and two-dimensional flicks that can be performed along or across the edges. In two experiments, we investigate the comfort, speed, and accuracy of this expanded side touch interaction space using the index and the thumb. Our results show the index finger is more error prone, but likely usable for simple taps on one edge, while thumb taps and flicks can be performed quickly on different edges with acceptable accuracy and comfort.

This expanded input space could be used to augment, accelerate, or even replace widgets or commands in current phone interfaces. For example, index finger side taps at two positions could switch the mode for thumb touchscreen input (e.g. selecting landmarks or panning a map). Thumb taps along the lower side edge could switch between applications (e.g. between the last few active ones, or personal shortcuts); thumb taps and flicks along the middle surface of side could be used to access the application menu (e.g. tap to trigger the item, flicks to show the menu on screen and scroll through a longer menu); and thumb taps and flicks along the upper side edge could be used for more expressive access to global commands (e.g. taps for functions like opening system settings, showing notifications, returning to home, turning on the flashlight, and two directions of flicks at certain locations for adjusting volume, brightness, or zoom). In addition, two directional flicks across multiple edges at different locations could be used for common actions like answer or ignore a phone call, the contextual back button, or locking the phone. We provide more example applications later in this paper and in the accompanying video.

Our work contributes two new aspects to the study of side touch input: (1) key results and a comprehensive dataset of one-handed comfort and grip stability when reaching for different side locations; and (2) a more expressive two-dimensional side touch input space investigated in two experiments.

2 BACKGROUND AND RELATED WORK

The general problem we study is the reachability and performance of one-handed input on the side of mobile phone.

2.0.1 Reachability. Understanding how easy it is to reach touch screen locations can guide the design of applications and interfaces. Early work by Karlson et al. investigated one-handed phone use, including an empirical evaluation into how device size, input location, and movement direction influenced "thumb agility" [9]. Bergstrom-Lehtovirta and Oulasvirta [1] modelled reach locations of the thumb using multiple quadratic expressions. Eardley et al. [2] examined the effect of grip shifts and hand movements measured by resulting phone movement during a selection task. Across four different phone sizes, four different grips, and touch targets inside and outside Bergstrom-Lehtovirta and Oulasvirta's functional area, they found phone movement increased with larger phones and when using a one-handed grip. Two follow-up workshops examined how interaction designers considered the reachability of the thumb when designing for different grips, including one-handed thumb input [2].

Other works have looked are reachability beyond the front touchscreen. Yoo et al. [38] measured reachable areas on the front and back using the thumb or index finger, finding reachable areas on the back can compensate for those unreachable on the front. Le et al. [15] examined the natural placement of fingers when holding a phone for the purpose of minimizing false positives of back-of-device touches. Most related to our reachability study is Le et al.'s work [12]. They measured the comfort zone and extreme reach area for all five fingers on the front and back surfaces when using a phone one-handed. Their task asked participants to not change their grip and the sides were not explicitly tested. Unlike previous work, we specifically focus on reachability around the sides and corners of a phone. Moreover, we allow participants to change grip which we use as a quantitative objective measure for how difficult locations are to reach.

2.0.2 Side Touch Interaction. Previous works have proposed different interactions on the side of the phone housing. These differ from bezel taps [27] or bezel swipes [23] which may be near the side, but are performed physically and conceptually on the edges of the front screen. Perhaps the most direct way to expand side input is with more expressive physical buttons. For example, PseudoButton [6] used pressure levels captured by a microphone to create a five-level side button. Further extending how a side button can be used, Spelmezan et al. [30] created a side button that can detect six different mid-air gestures. Even more radical, Jang et al. [7] describe a Haptic Edge Display for bi-directional haptic and tactile interactions along the side of a phone using a row of button-like actuated pins.

Several works explore adding pressure sensors to the side of a phone for grip-based interactions. Unifone examines ways to use pressure on top, middle, and bottom side locations with fingers other than the thumb [5]. Spelmezan et al. use thumb and palm pressure for bidirectional navigation [31]. Wilson et al. use different combinations of finger presses for input similar to chording [35]. More recently, Quinn et al. [21] examine sensing and usability when squeezing a phone for input. They use a sensor that can localize a one-dimensional position of the squeeze along the side. Side touch can be considered complementary to grip input, since it uses more precise single finger touches instead of high force multiple finger touches.

Several works focus on sensing methods for one-dimensional side touch input. BackPat [26] distinguishes finger taps on the side (or back) using the built-in microphone and gyroscope. McGrath and Li [17] use the internal motion-sensor to detect side taps. ExtensionSticker [10] extends

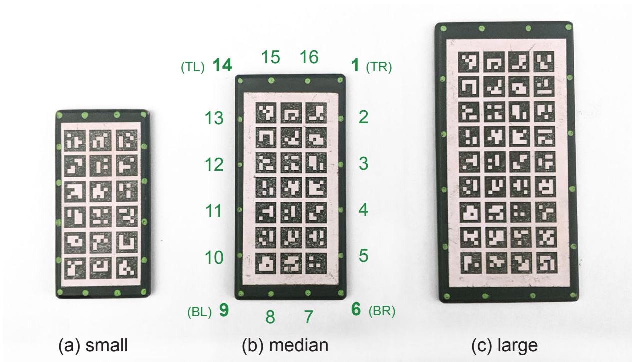

Fig. 2. Three sizes of phone mock-ups used in reachability study. The 16 green dots are target locations, in our results, each location is labelled 1 to 16 clockwise, starting at top-right.

a standard touch sensor to adjacent surfaces using adhesive stripes of conductive ink, and demonstrates touch-based slide and scroll gestures. InfiniTouch [13] uses front and back touch sensors, and one-dimensional capacitive side sensors to detect touch input all over a phone, including three sides. These sensing methods and demonstrations of side touch applications motivate our work, but there has not been a formal investigation into side touch speed and accuracy.

In summary, previous work modelled finger reach when touching the top or back of the device, and demonstrated sensing for simple one-dimensional side input like taps and slides. We combine and extend these areas by studying reachability around sides and use the results to motivate a human factors investigation into a more expressive two-dimensional side input space.

3 EXPERIMENT 1: REACHABILITY

The goal of this first experiment is to understand preference and ability when reaching for locations on the sides of a phone. All five fingers of the dominant hand are tested using three representative phone mock-ups. We use the results to scope our explorations of tap and flick side input in the experiments that follow.

3.0.1 Participants. We recruited 18 right-handed participants from a university, the average age was 24 years (SD = 3.7), with 13 males and 5 females. Participants were required to have full use of their right hand and fingers (e.g. no osteoarthritis). Average hand measurements are (in mm): thumb (64 SD = 6), index (74 SD = 5), middle (81 SD = 6), ring (73 SD = 6), pinky (59 SD = 5), palm width (83 SD = 7), and hand length (187 SD = 14, from 164 to 215). All participant hand lengths are in the 95th percentile of anthropometric measures [19]. Remuneration was $15.

3.0.2 Apparatus. We built three phone mock-ups to control for phone dimension and weight (Fig. 2). Each was 3D printed, sanded, spray painted, and weighted using lead pellets. To ensure dimensions and weight were representative of current phones, we analyzed characteristics of commercial phones released from 2015 to 2018 by eight major companies (Apple, Samsung, LG, Google, Motorola, Sony, HTC, Huawei) by scraping data from an online comparison website [18]. We calculated the minimum, maximum, and median of the largest diagonal measurement of the entire phone, then calculated the corresponding height, width, thickness, and weight with linear regressions. This resulted in these three mock-ups: *Small* (61 × 123 × 9 mm, 110 g); *Median* (73 × 148 × 8 mm, 157 g); and *Large* (91 × 184 × 7 mm, 220 g).

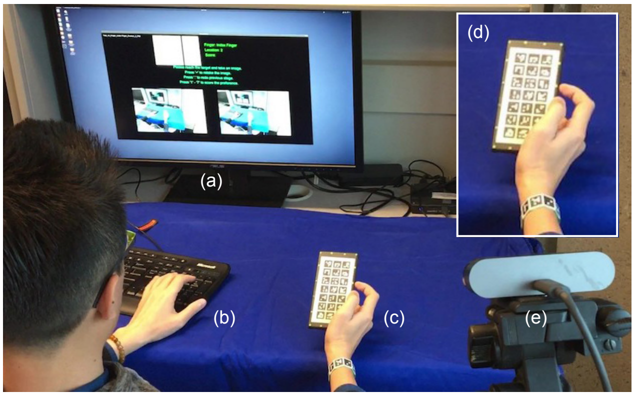

Fig. 3. Reachability apparatus and setup: (a) display showing stimulus and rating question; (b) keyboard to indicate trial start and end, and enter rating; (c, d) mock-up held in dominant hand with tracking markers on wristband; (e) over-the-shoulder camera.

Participants sat in a chair with no armrest in front of a desk, and they held a mock-up using only their dominant hand without resting it on the desk (Fig. 3). A keyboard operated with their other hand captured frames and entered numeric ratings. The screen area of each mock-up was covered with a grid of printed tracking markers [3, 22], and the participant wore a paper wristband covered with the same type of markers. This enabled the position and orientation of the mock-up and the participant's wrist to be tracked in 3D using a wide angle camera (82°, 1920 × 1080 px, 60 fps). A blue cloth covered the desk, so the phone and hand could be reliably isolated using skin detection and thresholding.

3.0.3 Procedure. Each trial was divided into three distinct steps. This normalized the initial grip across trials. First, the participant held the mock-up with a comfortable grip, and pretended to perform a left-to-right swipe gesture with their thumb (like the common unlock gesture). At the end of the swipe, they pressed a key with their other hand to capture an image of the mockup and their dominant hand with the camera. We call this the *initial grip*. Then, the target location and finger to use were displayed, and the participant touched the side of the phone at the requested dot location. Participants were instructed to balance speed and accuracy, and they could change their grip as long as they did not use their other hand and they could see the simulated mock-up screen at all times. They could declare the location to be unreachable, but in most cases a second image captured the positions of the mock-up and hand to calculate how much the grip changed. We call this the *reaching grip*. Third, the participant rated how easy and comfortable it was to reach the target using the required finger. The rating was a numeric scale from 1 to 7, with the addition of a special "0" rating used when the location was unreachable.

3.0.4 Design. The experiment was within-subjects with three factors: phone SIZE with 3 levels { SMALL, MEDIAN, LARGE }; FINGER used with 5 conditions { THUMB, INDEX, MIDDLE, RING, PINKY }; and LOCATION with 16 levels { 1, 2, 3, ..., 16 } representing the 16 locations around the side of the phone (illustrated in Fig. 2). The order of SIZE was determined using a balanced Latin square and the orders of other factors was randomized. An experiment session lasted 1.5 h on average.

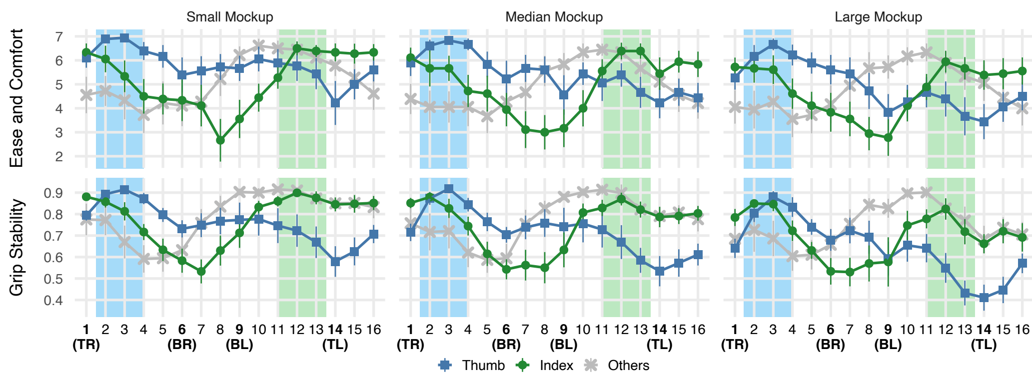

Fig. 4. *Ease and Comfort Rating* and *Grip Stability* by LOCATION and SIZE for THUMB, INDEX, and best rating/stability across *other* three fingers. Shaded areas show locations tested in later experiments. (Error bars 95% CI)

3.1 Results

The dependent measures are the subjective *Ease and Comfort Rating* and an objective metric for relative *Grip Stability*. Figure 4 summarizes the main results by plotting the thumb and index finger compared to the best performing across the remaining three fingers. A complete dataset and graphs showing results for each finger are available[1].

3.1.1 Ease and Comfort Rating. Overall, the thumb was rated highest followed by the index, and no finger had an average rating below neutral. Using an ART [36] due to a non-normal distribution, then an ANOVA, there is a main effect of FINGER ($F_{4,68} = 333.66$, $p < .0001$), with Bonferroni corrected pairwise comparisons finding all fingers significantly different ($p < .05$ between RING and PINKY, $p < .0001$ for all other pairs). Ratings in descending order, are THUMB (5.4, SD = 1.6), INDEX (5.0, SD = 1.8), MIDDLE (4.3, SD = 1.9), RING (3.7, SD = 2.1), and PINKY (3.4, SD = 2.3).

A smaller phone size is easier and more comfortable to reach overall. This is shown by a main effect of SIZE ($F_{2,34} = 43.76$, $p < .0001$), with all sizes significantly different (all $p < .001$): SMALL is rated highest (4.6, SD = 2.1) followed by MEDIAN (4.3, SD = 2.1) and LARGE (4.1, SD = 2.1).

When combining all finger and phone sizes, the locations on the left side are rated higher (likely because four out of five fingers can reach many locations on the left, but very few on the right). In addition, there is some preference for the middle-right position. There is a main effect of LOCATION ($F_{15,255} = 52.45$, $p < .0001$) with pairwise comparisons showing groups of location differences (all $p < .05$). First, the bottom-left side (LOCATIONS {10, 11, 12}) are rated higher than all other locations, the left locations LOCATIONS {9, 13} are higher than those around the right side (LOCATIONS {1, 4, 5, 6, 7, 15, 16}), and the top-left corner (LOCATION {14}) is rated more highly than the bottom-right corner (LOCATIONS {5, 6}) and nearby left locations ({13, 16}). Second, the middle-right location (LOCATION {3}) is more comfortable than bottom-right locations (LOCATIONS {5, 6}).

There is both a FINGER × LOCATION interaction ($F_{60,1020} = 36.65$, $p < .0001$) and a FINGER × SIZE interaction ($F_{8,136} = 2.95$, $p < .0001$). Pairwise comparisons are unreliable for interactions with ART data [36], so we discuss overall effects. The first interaction is unsurprising, it only confirms different locations are more easily reached with different fingers. For the second interaction with

[1]Complete dataset, additional graphs, and an interactive tool to visualize reachability results provided as supplementary materials.

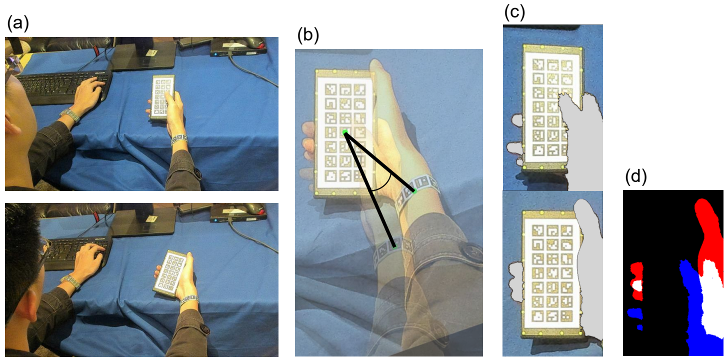

Fig. 5. Grip stability calculation. (a-top) initial grip image; (a-bottom) reaching grip image at end of trial when touching the target; (b) images superimposed after perspective rectification, translational and angular differences measured between wrist and phone centre; (c) skin detection results for initial (top) and reaching (bottom); (d) ratio of skin area change, blue is skin area only at initial grip, red is skin area only at reaching grip, white is skin area in both grips.

SIZE, Figure 4 and additional graphs in supplementary materials[1] suggest it is unlikely to involve the index and thumb finger.

3.1.2 Grip Stability. This is a dependent measure capturing how little the hand changes when reaching for a location with a finger. It is a relative measure calculated using the initial grip image (at the start of a trial) and the reaching grip image (at the end of the trial). The measure combines three different metrics of grip stability, all capture relative changes for the reaching grip: (1) phone *translation*; (2) phone *rotation*; and (3) visible skin area (i.e. visible area of the hand). Note Le et al.'s study of unintentional touch input [14] used a related "grip shift" metric based on grip range, finger movement speed and fingertip trajectory length. However, that metric requires full hand motion tracking which is time consuming to setup for each participant and is ultimately dependent on calibration quality and performance of the hand tracking software. Our metric uses a much simpler setup, and incorporates images of the actual hand in the form of the visible skin area. In addition, we consider phone rotation, a likely side effect of larger grip changes.

The fiducial markers on the phone and on the wrist are used to find their 3D positions and orientations in the captured initial grip image and reaching grip image. With these positions and orientations, the translation change and angular change can be calculated. To find the change in visible skin area, the initial and reaching images are rectified and scaled to a standard frame-of-reference using the 3D mockup position determined by the fiducial markers. This places the front face of the mock-up in a dimension-accurate rectangle, with the hand and fingers captured in the rectangle (over the mock-up) and around the rectangle (over the blue fabric covered desk). In each rectified image, Kolkur et al.'s skin detection algorithm isolates skin pixels [11]. The ratio of skin area that changed is calculated by finding the absolute difference between the skin masks in the two images, over the skin area in the initial grip. These three metrics are combined into a single grip stability measure by normalizing each metric per participant to range from 0 to 1 (using min and max for that participant), then averaging the three values. We subtract this average from 1 to create a measure of grip stability, where 1 is most stable (requiring the least grip change).

Since our protocol allowed participants to declare a location unreachable, some *Grip Stability* data is missing, making standard ANOVA unsuitable. In addition, data residuals from linear mixed modelling (LMM) are not normally distributed, so an LMM-based analysis is also not reliable. Instead, we make observations based on simple effects in Fig. 4b.

The THUMB has high grip stability for centre to top right side locations peaking around (LOCATION 3). The top right corner (LOCATION 1) is the only right side location where the thumb did not have the highest stability across sizes (the INDEX appears more stable there). On the top left side, INDEX stability is comparable to the best performing of RING, MIDDLE, or PINKY, and much more stable than the THUMB. At most locations, there appears to be a trend of decreasing stability as size increases, most pronounced with left side locations when moving to the LARGE mockup. In addition, little grip change was detected for the location nearest that finger's rest area with little impact from SIZE: around LOCATION 3 for THUMB, 12 for INDEX, 11 and 12 for MIDDLE, 10 and 11 for RING, and 9 and 10 for PINKY. This trend confirms the suitability of our combined grip stability measure.

3.2 Discussion

To our knowledge, this study is the first to explore side-touch reachability, but our results do relate to previous front-touch reachability studies, in particular Le et al. [12]. For example, we observed larger comfortable areas for side touches, possibly due to the geometry of side versus front touches or that users are comfortable changing their grip to reach further with side touches.

Overall, the thumb and the index alone can reach most of a phone's side, exclusive of the very bottom-left area. For every side location, at least one finger was rated greater than 5 in preference, suggesting all locations can be comfortably reached. The bottom side is least comfortable and should be used only for infrequent functions. The most promising side locations are the middle to top-right for the thumb and top-left for the index (blue and green shading in Fig. 4). Both are good candidates for primary side touch interaction, which we investigate in detail in experiments 2 and 3. To make our results accessible to designers, we created an interactive "reachability viewer" showing interpolated measures for each finger on any device size between our small and large mockups (see supplementary materials[1]).

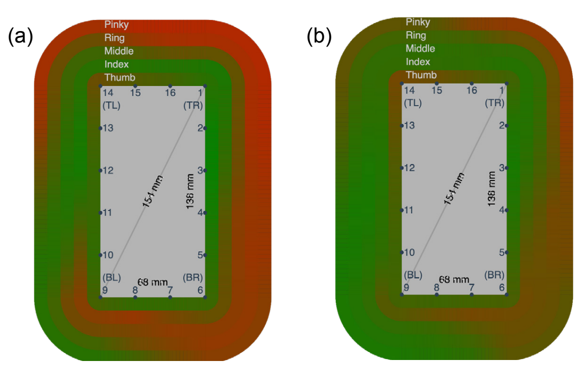

Fig. 6. Visualizations created with the interactive reachability viewer[1], showing results for a Nexus 5 size for: (a) ease and comfort; (b) grip stability. Interpolated measures are shown as a green-to-red gradient in bands for each finger.

Grip stability is moderately correlated with ease and comfort ratings ($r(4081) = 0.44, p < .001$), less grip change is generally associated with a higher preference score. However there are exceptions, such as the bottom right corner on the largest phone, where thumb ease and comfort was rated higher than the right-most bottom side, despite reduced grip stability (see Fig. 4). It is possible that corner locations are more comfortable, even if reaching them requires more movement.

3.2.1 Comparisons to Related Reachability Studies. Previous work showed the reachability of the topmost touch screen locations is a problem on large phones [1], our results confirm this is also true for phone sides. Indeed, locations on the side of the smaller phone were easier to reach.

Our results reveal nuanced differences when compared to previous reaching studies for front and back displays. The reason is likely due to how reaching for side positions requires slightly different grips and finger movements, and that our study allows the grip to change when reaching. Yoo et al. [38], Bergstrom-Lehtovirta et al. [1], and Le et al. [12] all report a general trend where the reachable display area with the thumb is about halfway between the top and bottom, for locations near the right side. Our ease and comfort ratings and grip stability support this pattern, but also remain high when near the top. Results for side reachability with the index, align more closely with previous studies examining reachability of the back of a phone [12, 38].

4 EXPERIMENT 2: TAPPING

The results of Experiment 1 demonstrate the thumb and index fingers are the most comfortable for side touch interaction, and that the upper portion of the left and right side is preferred. In this experiment, we investigate thumb and index tapping along those side surfaces in detail, with the addition of controlling for which "edge" is contacted: either the upper edge, lower edge, or the space in between (the "middle edge"). This creates a two-dimensional side touch input space. A phone instrumented with three strips of capacitive sensors determines what edge is touched, and optical motion tracking determines the touch position along the side. With this task and apparatus, we measure speed and accuracy, and we also record subjective preference for edge and side position.

4.0.1 Participants. We recruited 12 right-handed participants, average age 25.5 years (SD = 2.7), 3 females and 9 males (one also participated in experiment 1, but the experiments were conducted about one year apart). Again, participants were required to have full use of their right hand and fingers. Average hand measurements (in mm): thumb (64 SD = 5), index (72 SD = 5), palm width (82 SD = 7), and hand length (180 SD = 12, from 157 to 205). Hand lengths are in the 95th percentile [19]. Remuneration was $10.

4.0.2 Apparatus. We combined capacitive sensing with a motion tracking system to simulate touch events on the side of phone (Fig. 7b). Two devices were created, one for sensing touches on the right side with the thumb, and one for sensing touches on the left with the index finger. Three 1 mm wide copper foil strips were attached to the side of a Google Nexus 5, (138 × 69 × 8.6 mm), which is slightly smaller than the median-sized mockup. The strips are attached to a MPR121 capacitive sensor and Arduino Uno, both mounted to a PCB and attached to the back of the phone with a USB cable connected to a laptop. For the position of the touch along the side, we use a Vicon motion tracking system. One tracking marker is attached to the nearest top corner of the phone and three markers are attached to the participant's thumb or index fingernail. The Arduino and Vicon both stream raw input to the laptop, then combined to identify the edge and position of the side touch. The laptop sends a stream of these events to the experiment web application running on the phone using a websocket.

The capacitive strips register when a touch occurs, but each strip does not strictly represent an edge. Participants are told to touch the position where they think the target edge is, regardless if they contact one or more strips. With this in mind, the input edge is determined as follows: (1) if only the lower strip or both lower and middle strips were touched, then the input is lower edge; (2) if only the middle strip or all three strips were touched, then the input is middle edge; (3) if only the upper strip or both upper and middle strips are touched, then the input is upper edge. Note that each pattern of strip touches is mapped to one input edge. When the index finger is tested with only lower and middle edge targets, any touches that would have resulted in an upper edge input,

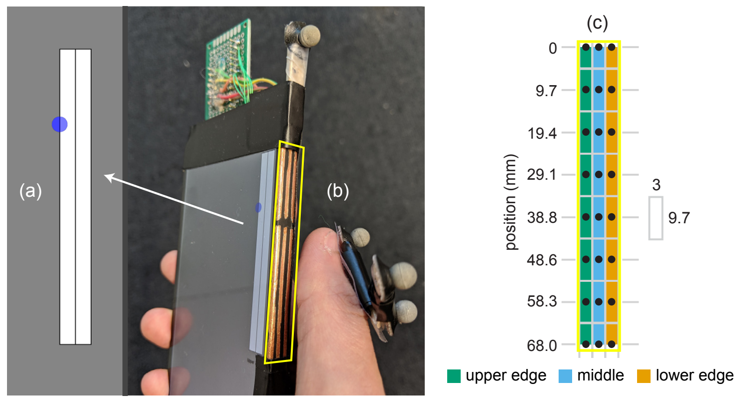

Fig. 7. Experiment 2 apparatus and task: (a) example tapping task stimulus; (b) simulated side touch sensor using capacitive strips to detect edge and marker-based tracking for finger position; (c) schematic showing tapping task target positions and sizes.

like touching only the upper strip, or both upper and middle strips, were considered a non-touch, meaning no edge input was registered at all. This means touching the middle edge with the index was no easier than the thumb in terms of sensing rules.

Initial tests showed the bottom of a strip may be unintentionally touched by the palm or other fingers when reaching for the top portion of the side. To compensate, we implemented a simple type of "palm rejection" by splitting each 68 mm strip into two sections with a 3 mm gap. The right "thumb" side has a 25 mm top section and a 40 mm lower section. The left "index" side has a 53 mm top section and a 12 mm lower section. The split point differs to accommodate how the hand grips the phone. Each strip section is sensed independently, so when combined with the tracked finger position, we can reject unintentional touches when reaching for the top part of the strip.

The tap event is triggered when the finger is lifted, known as a "take-off strategy" [20] commonly used in touch interfaces. The tap location uses the tracked finger position at the median timestamp between the first and last capacitive contacts. Note this introduces no additional latency. The finger tip angle also changes for different touch points along the side, so the motion-tracked finger position must be calibrated. We use a method similar to Joshi and Vogel [8] where the participant completes a sequence of taps at known target locations to interpolate a position correction offset. In our case, we had 9 targets from combinations of the 3 edges and 3 positions along the side (strip top, strip split point, and strip bottom). The logged positions for top and bottom targets are used to create a linear interpolation of tracked-finger to intended-touch position offsets. The strip split location is used for rejecting unintentional palm touches from the palm or other fingers.

4.0.3 Task. Each trial begins by tapping a 9 by 9 mm start button on the screen, always using the right thumb. The button is positioned 38 mm from the bottom and 8 mm from right side of the device, putting it near the comfort "sweet spot" [16]. This normalizes the initial grip on the phone. After, a stimulus shows the target tap position and edge (Fig. 7a). If the trial is successful, the recognized touch position is displayed for 0.5 s for additional feedback. If the trial was an error, the recognized position is shown in red for 3 s as a penalty (the penalty time is not included in analysis). Participants are told to complete the task both quickly and accurately, but when we piloted the task, we found they favoured speed without this additional error penalty. Fig. 7c illustrates the locations of the 3 mm by 9.7 mm targets. Our pilot tests found touching only the upper edge with the index finger was very error-prone, so only the lower edge and middle are tested for that finger. All three edges are tested with the thumb.

4.0.4 Procedure. The experiment is divided in two parts, thumb and index finger. Each part began with instructions and attaching tracking markers to the participant's finger. After an initial calibration (described above), the participant completed a practice block of all task trials, then six blocks of recorded trials. Pilot tests found that some participants continued to make slight adjustments to their grip and finger angles as they became more comfortable with the task, so the calibration procedure was repeated between each of the first four blocks. After all blocks were completed for a part, the participant rated their preference by considering the comfort and ease-of-use for each target position at each edge using a numeric score from 1 to 7 score. The experiment lasted approximately 60 min.

4.0.5 Design. The design is within subjects with BLOCK and three main factors: FINGER { THUMB, INDEX }; POSITION along side of phone from the top in mm { 0, 9.7, 19.4, 29.1, 36.8, 48.6, 58.3, 68 } (see Fig. 7c); EDGE { UPPER, MIDDLE, LOWER } in THUMB condition, and { MIDDLE, LOWER } in INDEX condition. The order of FINGER was counter balanced. The order of the other factors was randomized, with each combination of EDGE and POSITION occurring once per block. We recorded 240 trials per participant, 2880 trials in total.

There are three dependent measures. The *Ease and Comfort* preference rating describe above. The *Time* elapsed between the start button press, and the tap on the sensor, measured in seconds. An an erroneous trial should not result in a different or longer motor action by the participant, and visual inspection of the patterns of *Time* data including or excluding trials with errors revealed little difference between the two. Following Soukoreff and Mackenzie [29], our *Time* analysis includes both correct and erroneous trials. The *Error Rate* is the number of trials where one or more errors occurred over the total number of trials. Error tolerance was 4.9 mm for along-edge positions.

4.0.6 Analysis. ANOVA and Bonferroni corrected pairwise comparisons were used. Because the design is not identical for each FINGER, and we are primarily interested in examining performance of each finger for given positions and edges, we conduct primary analysis separately for INDEX and THUMB. To compare INDEX and THUMB directly, we remove UPPER and use the remaining levels in a complete design.

4.1 Results: Thumb Tapping

Learning Effect — An ANOVA found a significant effect of BLOCK on *Time* ($F_{5,55} = 5.28$, $p < .001$, $\eta^2_G = .016$). Pairwise comparisons show significant differences between block 1 and blocks 4, 5, 6, and between block 3 and block 6 (all $p < .05$). Given the small effect size for *Time*, and no effect on *Error Rate*, all blocks are used in analysis.

Time — Tapping on the bottom position is 0.41s slower than the other positions (Fig. 8a right), but no difference in time was found between edges. There was a main effect of POSITION ($F_{7,77} = 3.812$, $p < .01$, $\eta^2_G = .071$), with pairwise differences between POSITION 68mm (the bottom target) and all others (all $p < .05$). The mean time of POSITION 68mm was 1.75s while other position means ranged from 1.19 to 1.34s. There was no significant effect of EDGE. The mean time for UPPER, MIDDLE, and LOWER are 1.24s, 1.27s and 1.41s.

Error Rate — Errors can be due to wrong POSITION, the tap point is outside the target cell (Fig. 7b), or wrong EDGE. Any unintended touches also count as errors. Overall, selecting upper and lower edge targets was 11% more accurate than the middle edge (Fig. 8b right). There was a main effect of EDGE ($F_{2,22} = 5.01$, $p < .05$, $\eta^2_G = .084$), with pairwise differences between LOWER and MIDDLE ($p < .001$) and between UPPER and MIDDLE ($p < .001$). Error rates for UPPER, MIDDLE, and LOWER were 11%,

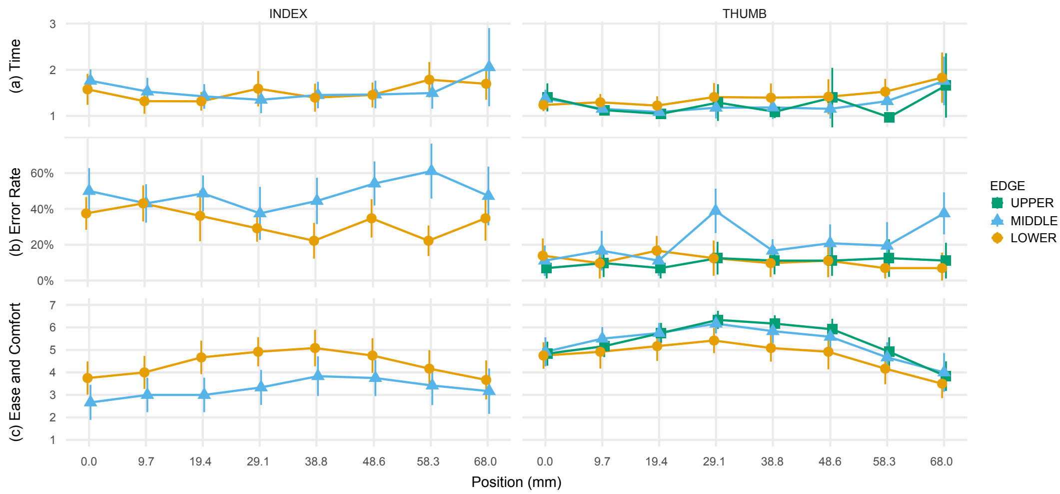

Fig. 8. Experiment 2 results for tapping: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

22% and 10%. There was also an interaction between EDGE and POSITION ($F_{14,154} = 2.95$, $p < .001$, $\eta^2_G = .025$), with pairwise differences between (MIDDLE, POSITION 29.1 mm) and all other pairs except bottom positions of MIDDLE (POSITION 48.6, 58.3, 68 mm) ($p < .05$). There are differences between (MIDDLE, POSITION 68mm) and all others except (MIDDLE, POSITION 9.7 mm), (LOWER, POSITION 19.4 mm) and the bottom part of MIDDLE (POSITION 38.8, 48.6, 58.3 mm) ($p < .05$). The bottom positions of MIDDLE are less accurate. The average error rate across participants is 14% (SD = 7%).

Ease and Comfort — Tapping upper or middle edge midway up the side is more comfortable than at other positions (Fig. 8c right). Using ART data, there was a main effect of EDGE ($F_{2,22} = 7.658$, $p < .001$) with post hoc tests revealing that LOWER was more uncomfortable (4.7) than UPPER (5.4) and MIDDLE (5.3). There was a main effect of POSITION ($F_{7,77} = 15.11$, $p < .001$). Pairwise comparisons show midway POSITIONS (29.1, 38.8 mm) are rated higher than POSITIONS (0, 58.3, 68 mm) ($p < .05$) and bottom POSITION 68mm is rated lower than POSITIONS (0, 9.7, 19.4, 48.6 mm) ($p < .05$).

4.2 Results: Index Tapping

Learning Effect — An ANOVA found a significant effect of BLOCK on *Time* ($F_{5,55} = 2.61$, $p < .05$, $\eta^2_G = .014$) and *Error Rate* ($F_{5,55} = 2.51$, $p < .05$, $\eta^2_G = .009$). However, pairwise comparisons showed no significant differences.

Time — Tapping on the bottom position is 0.51s slower than POSITION 19.4mm when using the index (Fig. 8a left). There was a main effect of POSITION ($F_{7,77} = 2.41$, $p < .05$, $\eta^2_G = .02$) with pairwise comparisons showing the bottom-most POSITION 68mm was slower than POSITION 19.4mm ($p < .05$). Mean times were 1.88s and 1.37s respectively.

Error Rate — Overall, selecting lower edge targets was 16% more accurate than the middle edge with lower edge targets closer to the bottom most promising (Fig. 8b left). There was a main effect of EDGE ($F_{1,11} = 18.65$, $p < .01$, $\eta^2_G = .03$) with pairwise comparisons showing LOWER was more accurate than MIDDLE ($p < .001$), 32% and 48% respectively. There was also an interaction between EDGE and POSITION ($F_{7,77} = 2.15$, $p < .05$, $\eta^2_G = .014$) with comparisons showing (LOWER, POSITION 58.3 mm) was more accurate than (MIDDLE, POSITION 48.6, 58.3 mm), and (LOWER, POSITION 29.1, 38.8 mm) was more accurate than (MIDDLE, POSITION 58.3 mm) (all $p < .05$). These lower edge targets had error rates close to 20%. The average error rate across participants is 40% (SD = 13%).

Ease and Comfort — Tapping on the lower edge is more comfortable than the middle edge (Fig. 8c left). There was a main effect of EDGE ($F_{1,11} = 55.12$, $p < .001$) with post hoc tests revealing that LOWER was rated better (4.3) than MIDDLE (3.3). There was also an effect of POSITION ($F_{7,77} = 3.51$, $p < .01$) with comparisons showing the midway POSITION 38.8 mm was rated higher (4.5) than the top POSITION 0 mm (3.2) or the bottom POSITION 68 mm (3.4) ($p < .05$).

4.3 Results: Index Compared to Thumb

There is no significant difference between fingers for *Time*, but tapping with the THUMB was 26% more accurate than INDEX. There was a main effect of FINGER on *Error* ($F_{1,11} = 42.84$, $p < .001$, $\eta^2_G = .266$), THUMB (14%) was much lower than INDEX (40%). In addition, tapping with the THUMB was more comfortable than INDEX. The main effect of FINGER on *Ease and Comfort* ($F_{1,11} = 106.64$, $p < .001$) shows the 5.1 rating for THUMB was higher than the 3.8 rating for INDEX.

4.4 Discussion

Overall, thumb tapping is more accurate and rated more highly than the index, but not significantly faster. Greater dexterity with the thumb, and more familiarity with using it one-handed with a phone, likely contributed to this finding. When using the thumb, the upper and lower edges were more accurate than the middle surface. This is likely due to greater tactile feedback on the edge. However, the lower edge was least preferred, perhaps because reaching it required more movement away from the touch screen, and sometimes required a looser grip where the palm pulled away from the back of the phone. As expected, with the thumb, midway side positions, closer to a rest position, were preferred compared to higher or lower positions. Overall, two-dimensional side touch input appears feasible with the thumb. The middle edge was difficult to reach with the index, and judged harder to use and less comfortable. Reaching the middle edge with the index can require a curling motion, introducing some finger strain. One-dimensional side input may be more suited to the index. Many errors with the index finger were due to accidental contact by the middle finger with the lower part of the sensor. Consequently, participants tended to keep the middle finger raised which is less comfortable. This may be alleviated by trimming the bottom portion of the capacitive strip, or by detecting the gripping posture [13].

5 EXPERIMENT 3: FLICKING

In this experiment, we investigate side input with another common touch action, short and fast dragging actions, commonly called swipes or "flicks". Initial pilot tests found performing flicks with the index finger was unreliable, so this experiment focuses on the thumb. The apparatus and basic protocol is the same as Experiment 2.

5.0.1 Participants. We recruited 12 right-handed participants, average age 26.3 (SD = 3.0), 5 females and 7 males. None participated in Experiment 2. Average hand measurements (in mm): thumb (62 SD = 4), index (71 SD = 4), palm width (80 SD = 7), and hand length (182 SD = 11, from 163 to 201). Hand lengths are in 95th percentile [19]. Remuneration was $10.

5.0.2 Task and Procedure. The task and procedure was the same as Experiment 2, except there were fewer targets (3 per edge), the targets were larger (3 by 19.4 mm), and the stimulus also indicated a flick direction (Fig. 9). Each trial required the participant to flick in a certain direction, starting at a certain position and edge. There are two orthogonal types of flicks, *along-edge* flicks that move along only one edge and *across-edge* flicks that move across two or more edges. For each, there

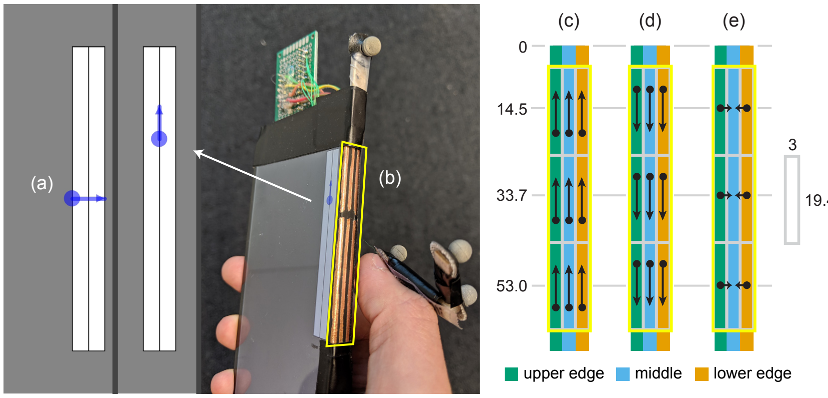

Fig. 9. Experiment 3: (a) example stimulus for across-edge and along-edge trials; (b) simulated side touch sensor; (c) schematic showing flick task target positions for along-edge flick abduction; (d) along-edge flick adduction; (e) across-edge flick abduction and adduction.

are two movement directions: *adduction* when moving the thumb towards the body (towards the phone front for across-edge flicks, towards the bottom end of the phone for along-edge flicks); and *abduction* when moving the finger away from the body (towards the phone back for across-edge flicks, towards the top end of the phone for along-edge flicks). In addition, along-edge flicks could be along the lower edge, the upper edge, or the middle. Flicks along an edge started at the end of the target opposite to the flick direction. Flicks across edges started on either the upper or lower edge, at the centre of longest dimension of the target. When flicking along an edge, the actual edge used for input is the average edge determined from the capacitive strips during the motion. The rest of the task and procedure was the same as Experiment 2. The experiment lasted approximately 30 minutes.

5.0.3 Design. The experiment was within subjects with four main factors: FLICK type, { ALONG-EDGE, ACROSS-EDGE }; DIRECTION { ADDUCTION, ABDUCTION }; POSITION along side of phone { 14.5, 34.0 and 53.4 mm, from top } EDGE { LOWER, MIDDLE, UPPER } (only in ALONG-EDGE conditions). The order of the factors was randomized, with every combination appearing once per block. We recorded 168 trials per participant, 2016 trials in total.

5.1 Results: Along-Edge Flicking

Time — Flicks are slower when performed on the lower edge, or when starting near the topmost position along the side (Fig. 10). Trial *Time* is measured on both correct and erroneous trials, from the moment the start button is pressed until the moment the finger leaves the sensor at the end of the flick. There is a main effect of POSITION ($F_{2,22} = 4.256$, $p < .05$, $\eta^2_G = .027$), with pairwise comparisons revealing the top POSITION 14.5 mm (2.26 s) was slower than the bottom *position* 53.4 mm (2.10 s) ($p < .01$). There is also a main effect of EDGE ($F_{2,22} = 5.66$, $p < .05$, $\eta^2_G = .048$), with pairwise comparisons showing the LOWER edge is slower (2.32 s) than the other two edges (2.18 s for MIDDLE and 2.09 s for UPPER) (both $p < .05$).

Error Rate — An error was recorded when the participant used the wrong POSITION (i.e. starting point of the flick), wrong EDGE (i.e. average edge input during the flick), wrong DIRECTION, or wrong FLICK type when performing the flick. There were main effects on *Error Rate*, and post hoc tests for a DIRECTION × POSITION × EDGE interaction ($F_{4,44} = 2.85$, $p < .05$, $\eta^2_G = .002$) found no significant

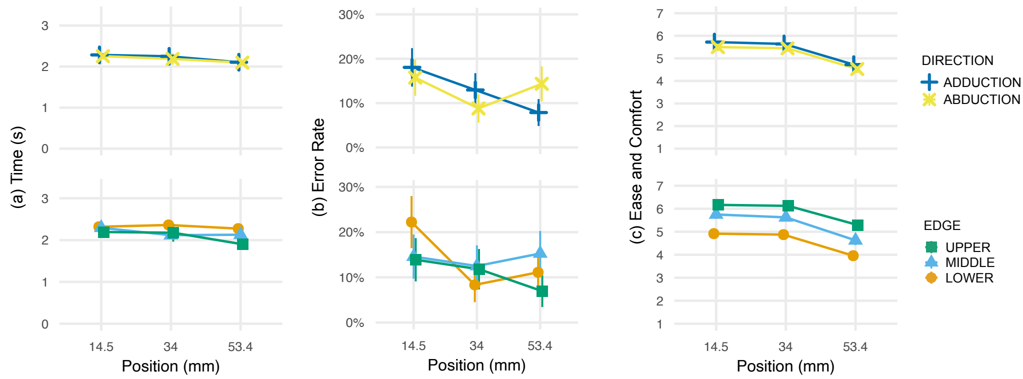

Fig. 10. Experiment 3 ALONG-EDGE flicks: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

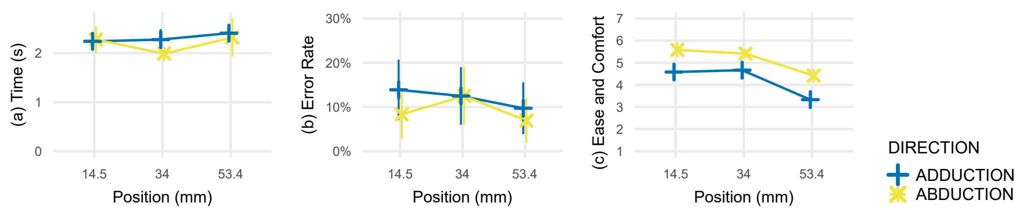

Fig. 11. Experiment 3 ACROSS-EDGE flicks: (a) Time; (b) Error Rate; (c) Ease and comfort rating (error bars are 95% CI).

differences (likely due to small effect size and multiple comparison corrections). The average error rate across participants is 13% (SD = 8%).

Ease and Comfort — Flicking near the top end of the side was rated less than other positions, and the lower edge was rated less than the upper edge. There is a main effect of POSITION ($F_{2,22} = 17.05$, $p < .001$), with pairwise tests finding topmost POSITION 53.4 mm (4.6) to be lower than the other two positions, POSITION 34 mm (5.5) and POSITION 14.5 mm (5.6) (all $p < .0001$). There is also a main effect of EDGE ($F_{2,22} = 22.12$, $p < .001$), with post hoc tests showing UPPER considered most comfortable to use (5.9) and LOWER least comfortable (4.6) ($p < 0.01$).

5.2 Results: Across-Edge Flicking

There were no effects of POSITION or DIRECTION on *Time* or *Error Rate* (see Fig. 11 for results). An error was recorded when the participant used the wrong POSITION (i.e. starting point), wrong DIRECTION, or wrong FLICK type when performing the flick. The average error rate across participants is 11% (SD = 7%).

Ease and Comfort — Bottom side positions were rated lower, and flicking away from the body (ABDUCTION) is rated higher than towards the body (ADDUCTION). Using ART data, an ANOVA found a main effect of POSITION on *Ease and Comfort* ($F_{2,22} = 10.57$, $p < .001$) with post hoc tests showing 53.4 mm (3.87) was rated lower than 14.5 mm (5.08) ($p < .001$) and 34 mm (5.30) ($p < .01$). There is also a main effect of DIRECTION ($F_{1,11} = 18.13$, $p < .001$), where ABDUCTION (5.1) is rated more comfortable than ADDUCTION (4.2).

5.3 Discussion

The ease and comfort of abduction across-edge flicks (towards the back of the phone) was rated higher. One participant said adductive across-edge flicks (towards the front of the phone) pushed the phone away from the palm, making it harder to maintain a firm grip. As a result, abductive across-edge flicks are a better candidate for frequent functionality.

For flicks along an edge, all positions, and both directions, were rated above neutral. However, those near the bottom were rated lower, even though they were quicker to perform. This follows the pattern of Experiments 1 and 2, likely due to how the thumb bends more acutely when reaching bottom side positions.

6 DESIGN IMPLICATIONS

We first summarize design recommendations based on overall results, then present a hardware prototype with demonstration applications for side touch, and finally, discuss limitations in our methods.

6.1 Design Recommendations

Location — Overall, middle to upper locations are more appropriate for frequent functions. Moreover, for each location, one finger in particular is often preferred. Consequently, Figure 4 provides designers with precise insights in how a side touch gestures are likely to be performed by users, with more details in our supplementary material.

Finger — The thumb, and the area where it is preferred, should almost always be prioritized. It is generally faster, more accurate, and more comfortable. In addition, it is able to comfortably reach a larger side area, and to interact on all upper, middle, and lower "edges", expanding the side touch input space. In contrast, the index is slightly slower, and more error prone. If restricted to non-edge specific 1D side-touch taps, and with more attention to palm rejection, it may be useful for less frequent commands. Based on the reachability of the pinky, ring and middle fingers, there could be some opportunity for using them as reduced side touch input, though this remains untested, and they are critical for gripping the phone. More work is required to evaluate their effectiveness.

Taps and Flicks — Taps are generally faster than flicks, and are more appropriate for frequent commands. However, bi-directional along-edge flicks can enable continuous control, for example to increase or decrease volume, or scroll up and down a page without occlusion.

Flick Position, Edge, and Direction — For both across- and along-edge flicks, using the upper side positions should be prioritized since they were perceived as more comfortable. For along-edge flicks, the lower edge should be privileged in most cases as it is most comfortable. However, using the middle surface is slightly faster, and would be a good compromise. Along-edge flicking is usable in both directions, but more comfortable when flicking from front to back.

Number of Edges and Phone Thickness — Our results show three different edges can be distinguished with the thumb. We used an 8.6 mm thick phone, comparable to 7 mm to 9 mm thicknesses in the market, although there exist very thin high-end phones approaching 5 mm thickness. It is unclear if more than three distinct edges could be reliably used, especially with very thin phones. However, even reducing the number of edges to two would still more than double the capability of a single 1D side touch surface, especially considering along and across edge flicks.

Side Profile Shape — Another factor for reliably sensing multiple edges along the side is the geometric profile of the side of the phone case. A faceted profile, potentially with built-in haptic cues like well-defined ridges, should make "feeling" different edges possible. A perfectly smooth, featureless profile would make feeling multiple edges more difficult. We intentionally designed our

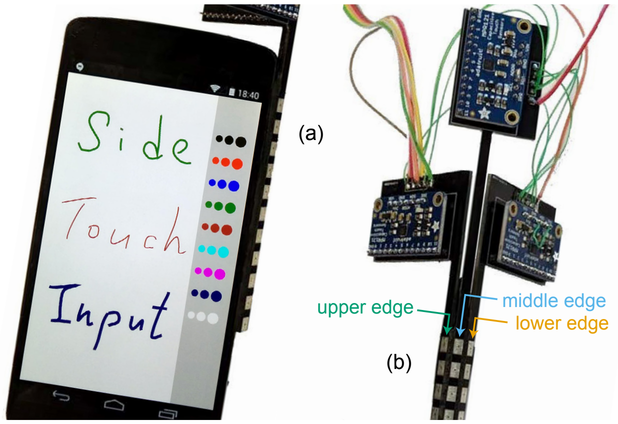

Fig. 12. Side Touch Prototype: (a) example application; (b) side electrode pad pattern.

the experiment apparatus, and the fully capacitive prototype introduced below, to have a faceted profile to make edges easier to distinguish.

Importance of Palm Rejection — Designing a robust palm rejection method is important part of making side touch techniques practical in real devices. Possible approaches include grip recognition [13] or probabilistic models trained to recognize patterns of unintentional touches along side touch capacitive sensors, similar to approaches for pen input palm rejection [25].

6.2 Prototype and Example Applications

To illustrate the potential of side touch input, we created a fully touch sensing two-dimensional side touch prototype using self capacitance (Fig. 12). It uses three custom PCBs, each with a MPR121 capacitive sensor and eleven electrodes. Readings from the boards are combined with an Arduino Mega, which streams touch events with 11×3 positions. Using the prototype, we created two simple demonstration applications (also see accompanying video).

A simple drawing application provides an example of a two-dimensional side tap command menu (Fig. 12a). Commands are arranged in rows and columns corresponding to side positions and edges. We mapped brush colour to row positions and brush width to edges. For example, a tap on the upper edge near the top sets the brush stroke to thin black. By default, the toolbar is hidden, so the drawing occupies the entirety of the screen. Flicking across the edges reveals or hides the toolbar, but expert users can select an item when the toolbar is hidden. This is a type of rehearsal-based interface [24].

A simple map application demonstrates how taps and flicks could be combined. Flicking along the edge zooms the map in or out, with zoom factor controlled by which edge is used: the lower edge zooms slowly, the upper edge quickly. Tapping the middle surface of the side centres the view at the user's current location, and tapping the upper edge re-centres the view to a predefined location.

6.3 Limitations

Our experiments used a simple method to reduce accidental touches, but high error rates for index in particular illustrate more refinement is needed. This becomes even more critical if both left and right sides are instrumented. A model similar to Le et al. [13] could track hand posture, so touches due to the grip may be differentiated. Also, the Vicon motion tracking system used in experiments 2 and 3 is accurate, but our participants sometimes adopted unusual postures causing the markers to become occluded. Tracking issues could increase error rates, but we did not attempt to filter these out in post processing because our observations suggest they were very infrequent and they are hard to identify automatically. Many of our results likely relate to hand size, for example women typically have smaller hands than men. Our first two experiments have approximately three times as many male participants as female, so there may be a sample bias. Finally, we did not test for more demanding usage settings, such as walking where previous work observed larger grip areas and more finger activity due to hand oscillations. [14] More examination is needed to understand how such settings affect side touch input.

7 CONCLUSION

We explored the potential of an expanded one-handed two-dimensional touch input space along the side of a phone. A first study shows that virtually every location around the phone can be comfortably reached with at least one finger. Two subsequent studies evaluate the performance and preference for side taps and flicks, showing that taps and flicks with the thumb has great potential, but the index is less suitable except for simple in-frequent input. We hope our investigation of side touch input provides ideas and evidence to inspire hardware designers to consider this alternative to physical side buttons: harnessing the expressive potential of smooth, touch-sensitive sides on a phone.

8 ACKNOWLEDGEMENTS

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