Investigating Screen Shifting Techniques to Improve One-Handed Smartphone Usage

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ABSTRACT

With increasingly large smartphones, it becomes more difficult to use these devices one-handed. Due to a large touchscreen, users can not reach across the whole screen using their thumb. In this paper, we investigate approaches to move the screen content in order to increase the reachability during one-handed use of large smartphones. In a first study, we compare three approaches based on back-of-device (BoD) interaction to move the screen content. We compare the most preferred BoD approach with direct touch on the front and Apple's *Reachability* feature. We show that direct touch enables faster target selection than the other approaches but does not allow to interact with large parts of the screen. While *Reachability* is faster compared to a BoD screen shift method, only the BoD approach makes the whole front screen accessible.

Author Keywords

Smartphone; back-of-device; one-handed use; reachability; screen shifting.

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies (e.g., mouse, touchscreen)

INTRODUCTION

Smartphones are the most used personal devices nowadays. People use their smartphones in mobile situations or during activities such as carrying objects or householding. Prior work found that these activities negatively affect the performance of touch input [8, 13, 17]. Often, users only have one free hand to operate the phone which also limits the input accuracy [17]. However, even for distraction-free situations, Karlsson *et al.* have shown that people prefer to operate their phone one-handed [10].

As the size of smartphones is steadily increasing, one-handed usage of smartphones is getting more and more challenging. A common problem is the limited length of the thumb which is why many users cannot reach targets in the upper half of the screen. This requires users to either use the second hand which is often not possible if the second hand is used for other tasks, or to change their hand posture which makes the grip less stable and may lead to dropping the phone.

Smartphone manufacturers, including Apple and Samsung, started to integrate software-based solutions into their phones to enable one-handed use of larger phones. Techniques such as Apple's *Reachability* or Samsung's *one-handed mode* shift the screen to an area which is easier to reach or shrink the complete screen to fit the reachable area. Furthermore, previous scientific work presented a number of software-based techniques to compensate the limited reachability of one-handed smartphone usage [4, 9, 11, 19].

Leveraging the fact that the index finger has a better reachability on the upper half of the phone, a body of previous work looked into extending the area reachable by the thumb using a back-of-device (BoD) touch sensor. Yoo *et al.* [27] identified the comfort area of the index finger on the rear side while Löchtefeld *et al.* [15] used a Apple Magic Trackpad as a cursor to interact with targets on the front screen. Previous work also investigated BoD input by attaching external touch pads or building so-called smartphone sandwiches by gluing two phones back-to-back [5, 7, 15, 20, 25]. However, this leads to device sizes that are uncommon for commodity phones which in turn may hamper one-handed grips or changes how people hold the device compared to ordinary smartphones. To the best of our knowledge, there is no prior work using a realistically sized dual-side phone prototype to investigate BoD input as a tool to improve one-handed smartphone operation.

In this paper, we build a smartphone prototype with sizes similar to current commodity phones to support realistic hand postures. Using this prototype, we first compare three BoD interaction techniques (*Normal BoD Shift*, *Inertial BoD Shift*, *Gestural BoD Shift*) to improve one-handed usage of smartphones by moving the screen content. Informed by the first study, we implemented a thinner prototype. We then compare the most preferred BoD technique to Apple's *Reachability*, which is the state-of-the-art technique to improve one-handed use, and *Direct Touch* which provides no aids at all. In our evaluation, we investigate how participants use the three techniques in the context of a target selection task. We show that while users achieve a lower task completion time with *Direct Touch* followed by *Reachability*, users are not able to reach all

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targets opposed to *BoD Shift*. Further, by moving targets into a comfortable and reachable position, users achieve a lower touch error rate with *BoD Shift* and *Reachability*.

The contribution of this paper is two-fold: (1) We present two prototypes with BoD interaction capabilities and (2) compare two screen shift techniques (*BoD Shift* and *Reachability*) and *direct touch* regarding task completion time, error rate and target reachability.

RELATED WORK

A large body of work investigated the interaction with touch screens. In the following we focus on previous work that investigated one-handed smartphone interaction and previous work that explored BoD interaction.

Enabling One-Handed Smartphone Operation

Previous work proposed a variety of techniques to ease one-handed smartphone interaction. These techniques can be grouped into three categories: (1) translating or resizing targets into a more reachable position, (2) using an offset cursor as thumb extension and (3) using a more accessible proxy space.

With recently released Phablets such as the iPhone 6 Plus or the Samsung Galaxy Note line, smartphone manufacturers started to equip their products with methods to ease one-handed interaction. Using Apple's *Reachability* feature, users are able to move down the screen by half its size by double-tapping the home button. Samsung integrated their so-called *one-handed mode* into their latest devices which enables users to shrink the screen content to an adjustable size. Users can set the desired size once and toggle the shrink by a swipe from the device's bezel. While these techniques avoid unreachable targets to a large extent, they also limit the display space. This may lead to more scrolling activity due to less display space which in turn may lead to further grasp instability during one-handed operation.

Kim *et al.* [11] presented a combination of two different techniques and activation methods to enable one-handed use. With the first technique, users can freely move the screen content using front-screen input. The second technique spawns an inverted cursor to reach targets on the top side of the phone. These modes are triggered by either a bezel swipe or by using the wide area of a finger (e.g. the full thumb pad). Chang *et al.* [4] presented similar methods (inverted cursor, screen slide and screen shrink) and used tilting gestures as activation triggers.

A number of authors investigated an offset cursor as a technique to extend the input space during one-handed device operation [7, 25]. While some of these techniques use a touchpad or a mouse attached to the rear side of the phone, such techniques can also be implemented using the phone's camera lens [24]. Shift [23] is a more sophisticated version of an offset cursor, which provides a callout as a kind of offset cursor to also address the fat-finger problem in a scenario of unreachable targets. Similar to the inverted cursor presented in Kim *et al.*'s work [11], MagStick [19] is an inverted cursor that sticks to selectable targets like a magnet.

In the domain of proxy spaces to improve smartphone interaction, ThumbSpace [9] has been proposed to show a user-defined proxy space which represents a miniature version of the full screen. Input performed in this region are transferred to their original positions on the full screen. Since smaller targets lead to worse accuracy due to the fat-finger problem [22], ThumbSpace highlights currently selected UI elements and provides the possibility to select desired UI elements by swiping in different directions. Similarly, TapTap shows a zoomed-in version in the form of a callout after users tapped a spot close to one or multiple targets [19]. In contrast, Escape [26] allows target selection using directional gestures on the front screen. Here, targets are represented by directional arrows and can be selected by performing a gesture into the respective direction.

The aforementioned approaches require the thumb to perform additional actions in order to increase the reachability. Moreover, some of them also require to augment the screen content with additional information, such as arrows, call-outs or proxy areas. This may reflect in a higher effort to complete a task due to more subsequent steps, and in information overload due to additional information shown on the screen. A possible solution is to use BoD interaction, as this allows simultaneous input by the thumb on the touchscreen and by the fingers on the back of the device.

Back-of-Device Interaction

Prior work investigated BoD interaction to extend the reachability on smartphone screens. Yoo *et al.* [27] conducted an experiment to determine the area that can be reached comfortably by the index finger on the device's rear. They show that the comfort zone of the index finger is located especially in the upper left corner (for right-handed users) of the device. Accordingly, the index finger can be used to extend the comfort area of the thumb using BoD interaction. Noor *et al.* [16] developed methods for front touchscreen prediction based on how the user grips the smartphone. They distributed 24 capacitive sensors around a mobile device to capture touch and grip events from a user. A significant correlation between grip and predicted touch area has been shown, which can be used to correct touch events. Differences between touch performances using touch sensors on the back and front of a device have been investigated by Bader *et al.* [1]. The performance of BoD interaction can be improved using a transparent screen inside the smartphone, which allows the user to see his own index finger on the BoD. Significant performance improvements have been shown during interaction with virtual content. Shen *et al.* [20] investigated the possibilities of extending three-dimensional manipulation modalities using BoD interaction. Different combinations by the usage of front and back screen are presented regarding dragging, pushing or flipping three-dimensional content on mobile displays. Shimon *et al.* [21] investigated different gestures as input modality for BoD interaction. Gestures, like swipes and taps, were mapped on different actions such as answering a call or locking the phone. Authentication can be performed using BoD where different pattern can be drawn on the BoD [5]. This can be used to hide sensitive information from shoulder surfing. Moreover, BoD interaction can also be used to avoid the fat finger problem [2].

Using BoD interaction, prior research focused on novel use cases as well as ways to improve the accessibility on large phones. Researchers presented different ways to augment commodity smartphones with BoD interaction capabilities, using the device's back camera, two phones glued back-to-back or touchpads attached to mobile phones. While these prototypes are sufficient for their respective use cases, they are not applicable for our use case. The device's camera provides a very small input space and is designed to not be easily reachable by the holding fingers. Moreover, two phones glued back-to-back and attached touchpads lead to bulkier prototypes nearly twice the size of a usual smartphone. As prior work show a relationship between device size and subjective fatigue as well as error rate [14, 18], we decided to build a BoD smartphone prototype with sizes similar to recent smartphones to investigate one-handed BoD interaction.

FIRST BACK-OF-DEVICE PROTOTYPE

We used a LG Nexus 5X as a basis for our BoD smartphone prototype. The Nexus 5X is a common smartphone and due to its size ($147.0\,mm \times 72.6\,mm \times 7.9\,mm$; $134\,g$), we assume that most people are not able to reach the upper parts of the touchscreen with the thumb during one-handed use. To add BoD interaction capabilities to this phone, we 3D printed a phone case for our device that attaches an external touch sensor to the device's rear. By 3D printing a case, we aim to minimize the impact on the user's hand grip by adding only minimal changes to the device's thickness.

We used the Nintendo DS touch sensor[1] which is a $55.9\,mm \times 69.9\,mm \times 1.5\,mm$ sized resistive digitizer. Our 3D printed case attaches the touch sensor on the phone's rear side and bundles all wires. Wires are directly soldered to the touch sensor to save additional space and are in turn connected to an external Arduino Uno microcontroller. Since the Nexus 5X's camera is standing out by $2.7\,mm$ from the phone cover, we decided to attach the touch sensor on the bottom side of the phone and turn it up-side down to save further space. Since the phone's front side is symmetric (e.g. no hardware keys), this decision should not be noticeable as we also turned the whole screen content using software modifications. The resulting dimensions of our prototype are $149.5\,mm \times 73.5\,mm \times 10.9\,mm$ with a weight of $166.5\,g$. We provide the 3D models for this case on our website[2].

Touch input from the Nintendo DS touch sensor is received by the Arduino at 100 Hz and is sent directly to a computer via an USB Serial port. The computer then forwards those information via UDP packages to our prototype. To avoid any delay caused by activities in shared WiFi networks, we created our own WiFi network to connect the phone with the computer. Received touch input are translated into movements in our application to implement different screen shift techniques.


(a) (b)

Figure 1. Images of the first BoD phone prototype, (a) shows the full prototype with the 3D printed case (b) shows the case and the LG Nexus 5X to highlight the size of the case.

COMPARING BACK-OF-DEVICE TECHNIQUES

In a first study, we collected feedback on our prototype and compared three BoD techniques derived from related work to move the screen content. The results are used to further refine our prototype and determine the most preferred BoD screen shifting technique. This study consists of a target selection task to compare screen shifting techniques, as well as a questionnaire and a semi-structured interview.

Design and Techniques

The study is based on a repeated-measures design with the following four technique as conditions: *Normal BoD Shift*, *Inertial BoD Shift*, *Gestural BoD Shift*, and *Direct Touch*. While the first three techniques use the BoD touch sensor to move the screen content to a more accessible position, *Direct Touch* is the control condition with the BoD touch sensor disabled. *Normal BoD Shift* translates touch input on the BoD touch sensor to a shift of the screen content matching the BoD movement. *Inertial BoD Shift* works similar to *Normal BoD Shift* but adds an inertia to the movement similar to Google Maps. *Gestural BoD Shift* enables users to move the screen content by half its size into eight directions (in 45° steps) using swipe gestures. The order of these conditions are counterbalanced using a balanced Latin square.

Participants used one of these techniques during the target selection task, which aids them to touch targets by moving the screen (and the targets indirectly) into a more reachable position. Targets in the target selection task were displayed within a 6 × 12 grid. The size of each target is 48 dp × 48 dp which equals 9 mm × 9 mm and is recommended by Google's layout guidelines for Android [6]. Every target position was repeated three times in a randomized position within its grid. This leads to the following amount of targets overall: 12 participants × 5 repetitions × 72 tiles = 4,320 targets overall per condition.

Procedure

After welcoming, filling out the consent form and being seated on a chair without armrest, we briefed participants about the prototype. Participants proceeded to fill out an introduction questionnaire. Besides the demographics, this involved questions about the participants hands and handedness as well as smartphone experiences.

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[1] SparkFun Nintendo DS Screen Kit: `https://www.sparkfun.com/products/13631` - last access 2016-08-11

[2] 3D models of first prototype: `http://projects.hcilab.org/bod-phone` - last access 2016-08-11

We gave participants one minute per condition to get used to the technique in a trial session. Participants then proceeded with the target selection task for all conditions. After participants finished all four conditions, we asked them to rank the conditions. Furthermore, we conducted a semi-structured interview in which we asked participants about advantages and disadvantages of all approaches as well as feedback on our prototype.

Participants

We recruited 12 participants (3 female) with an average age of $M = 25.2$ ($SD = 3.2$) from the university campus. All participants were right-handed with an average hand size of $M = 194.2\,mm$ ($SD = 12.6$). The hand size was measured from the tip of the middle finger to the hand carpus.

Results & Discussion

We evaluated the results with focus on the most preferred BoD screen shift technique and feedback on our prototype.

Ranking and Comparison of Screen Shifting Techniques

Participants rankings of the interaction methods are summarized into a preference score which is calculated as the sum of $4-R$, whereas R is the assigned rank. The results in Figure 2a shows that *Normal BoD Shift* (26 points) is the most preferred technique to move the screen followed by *Inertial BoD Shift* (22 points) on the second place. *Direct Touch* (18 points) ended up in the third place while participants liked *Gestural BoD Shift* (6 points) the least.

While 3 participants perceived *Gestural BoD Shift* as the most systematic approach, 8 participants reportedly had trouble to perform gestures into the right direction. Results of the calibration at the beginning of the task are confirming this (see Figure 2b). Here, the black lines indicate the average angle while the blue areas are indicating the standard deviation between angles of all participants. We see that gestures to the right, right-bottom or bottom are close to each other while these are also the most used. Performed gestures are therefore not clearly separable to each other which leads to screen shifts into unwanted directions.

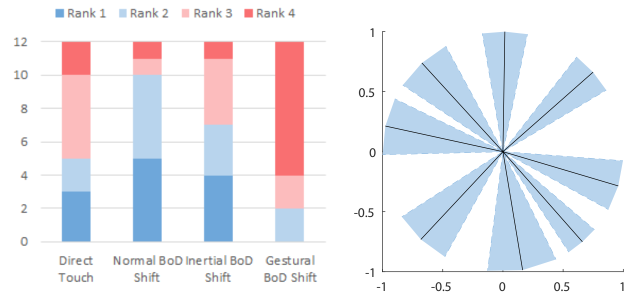
While all participants are already used to *Direct Touch* for a longer time, 8 participants stated that they are not able to reach the upper half of the screen without changing their hand posture which in turn lead to instability.

The advantage of both *Normal BoD Shift* and *Inertial BoD Shift* is the improved reachability which enables users to reach targets at every position on the screen. Nine participants valued the controllability of *Normal BoD Shift* due to a simple relative mapping of the touch input. In contrast, 3 participants argued that *Inertial BoD Shift* requires less effort due to an inertia moving the screen after releasing the finger.

Based on this subjective rating and feedback, we concluded that participants liked *Normal BoD Shift* the most although *Inertial BoD Shift* is the close second.

Feedback on the Prototype

Eight participants complained about the size of our prototype as it is difficult to hold the device one-handed. Three participants even accidentally dropped our device during the study while trying to reach targets on the screen. Due to an unstable grip, participants concluded that they could neither stretch their hand to reach targets on the upper half of the phone nor perform input on the BoD touch sensor. Further, 3 participants stated that by just holding the device one-handed already strained their musculature (".. *close to having cramps*" – P6). Hence, participants suggested that BoD input would be easier on smaller devices since they would then be able to hold the phone in a more stable grip which in turn eases the input on the device's rear. Besides feedback on the prototype's size, two participants criticized the roughness of the case edges.



(a) (b)

Figure 2. Figure (a) shows participants' ranking of all conditions. Calibration results of *Gestural BoD Shift* are shown in Figure (b). The lines represent the average angle, in which gestures were performed while the blue area represent the standard deviation between the angles.

Conclusion

Firstly, despite our effort to keep the prototype as small as possible while adding BoD interaction capabilities, an increment of $3\,mm$ in thickness already shows a significant impact on the user's hand grip stability during one-handed use. Since performing input on a BoD touch sensor requires a stable grip to perform fairly accurate input, a thinner smartphone prototype is required to compare BoD screen shifting methods with other one-handed reachability solutions.

Secondly, we found that *Gestural BoD Shift* does not work well with gestures performed on the rear side as these are too inaccurate and similar to each other. On the one hand, this could be due to the instable grip which leads to inaccurate input. On the other hand, this could be due to the limitations of the index finger and the joints responsible for the respective movements of the finger.

In summary, it is important that the dimensions of the used prototype are comparable to usual smartphone sizes to allow a stable grip during one-handed use. Furthermore, we can conclude from the study that *Normal BoD Shift* has the highest potential for further exploration among the BoD screen moving techniques.

IMPROVED BACK-OF-DEVICE PROTOTYPE

Based on the feedback we received in the first study, we built a thinner prototype to enable a stable hand grip. For this prototype, we used the same components as before (LG Nexus 5X, Nintendo DS touch sensor and an Arduino Uno). To minimize the device's thickness, we partly disassembled the phone by


(a) (b)

Figure 3. Images of the improved BoD phone prototype. Figure (a) shows the LG Nexus 5X partly disassembled to minimize the thickness. Figure (b) highlights the position of the touch sensor as seen from the rear. The touch sensor is black as we added a printed sheet of paper behind the sensor to block view to the underlying device electronics.

removing the back cover, the camera lens, and the inner plate that covers the circuit board (see Figure 3a). The additional touch sensor is framed by our new 3D printed back cover which replaces the original back cover of the LG Nexus 5X (see Figure 3b). As we also recreated the hooks of the original cover, our cover snaps directly to the partly disassembled phone so that no glue is required. We provide the 3D models for the case on our website[3].

As the surface of the 3D printed cover feels rather raw due to how objects are 3D printed, we sanded the back side to make it feel smooth like most mobile phone back covers. We also soldered four connection wires directly to the sensor to save additional space and connected them to an external Arduino Uno microcontroller which is in turn connected to a computer. The resulting dimensions are $147.0\,mm \times 72.6\,mm \times 8.8\,mm$ with a maximum depth of $10.2\,mm$ at the upper edge of the prototype. With $134.0\,g$, the device's weight did not change through our modification and stayed exactly the same. Nothing changed in terms of data transfer from the Nintendo DS touch sensor to the phone in comparison to our first prototype.

EVALUATION OF SCREEN SHIFTING TECHNIQUES

Based on the knowledge of the first study, we use the second prototype to evaluate the *Normal BoD Shift* technique (now referenced as *BoD Shift* to keep it short) which was the most preferred method by our participants based on the results of the first study.

Design

The study is based on a repeated-measures design. We have the following three interaction methods as conditions: *BoD Shift*, *Reachability* and *Direct Touch*.

Using *BoD Shift*, participants can move the screen content into arbitrary positions by moving the finger on the BoD touchscreen. We re-implemented Apple's *Reachability* technique that enables participants to move the screen down by half its height. This can be triggered by double-tapping an on-screen button placed on the bottom-center of the screen. *Direct Touch* is the control condition where participants have to reach targets without any aids. The order was counterbalanced using a balanced Latin square.

The conditions were compared using a target selection task and multiple questionnaires. Targets were grouped into 12 tiles (3×4 grid) on a $1920 \times 1080\,$px screen which makes $360 \times 144\,$px per tile. Each tile contains 4 targets with $48 \times 48\,$dp in size which results in $9 \times 9\,$mm to conform with target sizes recommended by the Google Layout Guidelines for Android [6]. The grouping of targets per tile was necessary to imitate a more realistic input scenario in which users do e.g. menu selections, interact with groups of buttons or enter text via on-screen keyboards. We had five repetitions per tile which lead to the following amount of targets: 24 participants $\times 5$ repetitions $\times 12$ tiles $\times 4$ targets = 5,760 targets overall per condition.

Participants were instructed to not change their initial hand posture during the whole study to avoid them changing into hand postures that are less stable or unrealistic but favorable for this target selection task.

Procedure

After filling out the consent form and being briefed on the prototype, participants proceeded to fill out an introductory questionnaire. Besides the demographics, this involved questions about the participants hands and handedness, smartphone experiences, usual hand postures during smartphone use and their first impression on our prototype. We further asked participants to hold our prototype and play around with it in order to determine their usual hand grip.

In the context of a short trial session afterwards, we asked participants to perform the target selection task for one minute per interaction method. This is to get participants used to the size of the phone and especially used to the handling of the BoD touch sensor. Once the participant understood all interaction methods and got used to them, the user study started with the first condition.

Since one-handed grip changes may lead to grasp instability, we instructed participants to retain their usual hand grip to simulate a mobile situation in which a one-handed grip change is likely to result in dropping the phone. In case participants are not able to reach a target, they were instructed to press a key on a keyboard in front of them to skip the grid to which the target belongs. At the end of each condition, we asked the participant to fill out a NASA-TLX and a SUS questionnaire [3] about the recently used interaction methods.

The study is closed up with a questionnaire about impressions, advantages and disadvantages of all three conditions as well as further qualitative feedback on improving them.

Participants

In total, we recruited 24 participants (5 female) which were aged between 22 and 57 ($M = 26.6$, $SD = 7.0$) from two local universities. All participants except one were right-handed with an average index finger length of $M = 75.0\,mm$ ($SD = 6.3$), thumb length of $M = 66.5\,mm$ ($SD = 6.7$), and total hand length (measured from the tip of the middle finger to the carpus) of $M = 186\,mm$ ($SD = 12.3$).

Eight participants were using phablets ($5.1''$ - $6.99''$) at that time, ten used $4.5''$ to $5''$ smartphones, five participants owned

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[3] 3D models of second prototype: `http://projects.hcilab.org/bod-phone` - last access 2016-08-11

(a) (b) (c)

Figure 4. Hand postures classified according to [12]. The upper row shows the hand postures from behind and while interacting with the BoD touch sensor. The bottom row shows the same hand postures from the side. Names of the postures from left to right: (a) Four-finger posture, (b) small-finger posture, (c) clutch posture.

a smartphone smaller than 4.5″ in size, and one did not own a smartphone. Rated on a Likert scale from 1 to 7, 16 participants tend to use their phone one-handed (< 4), 5 prefer a two-handed use (> 4) while 3 reportedly cannot decide between one-handed and two-handed ($MD = 2$, $IQR = 2$).

RESULTS

We analyzed the study results and present a comparison between the three methods in terms of accessibility of targets, task completion time, error rates, as well as qualitative feedback on all three methods.

Hand Postures

Participants were asked to hold our prototype as they would usually hold their own smartphone during one-handed use. We divided their hand postures into three categories which conforms with the classification in [12]. In all hand postures, participants used their thumb to interact with the front touchscreen while operating the BoD touch sensor with their index finger. Hand postures are shown in Figure 4. There was no significant correlations between hand postures and hand size ($r = .083$, $p = .698$ (Pearson)).

Six participants used four fingers to hold the smartphone on the rear side and the palm as an additional stabilization on the phone's edge (see Figure 4a). Five participants used three fingers to support the smartphone on the rear side and the small finger to support the bottom side while the right edge of the phone lies against the palm (see Figure 4b). Twelve participants stabilized the phone by slightly clutching it with four fingers (see Figure 4c).

Skipped Targets

Participants were instructed to skip targets in case they could not reach the target without changing the hand posture. The heatmap presented in Figure 5 depicts the frequency in which targets' tiles were skipped due to unreachability.

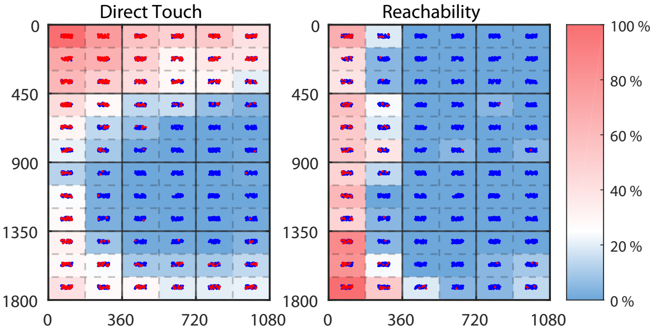

Figure 5. Heatmap showing the skip rate in percent for every target. Completed targets are represented by blue points while skipped targets are represented by red points.

As expected for *Direct Touch*, only 43.3% of tiles in the upper row were touched while the rest was skipped. This applies especially for the upper left corner which is touched in only 38.3% of all appearances. The four tiles on the middle right part were touched most of the times (98.0%) which can be explained by the comfort zone of the thumb [27]. Surprisingly, there were also skips at the bottom left part of the grid which leads to a touch percentage of 76.7%.

While the heatmap for *Reachability* shows a lower skip rate, there are still tiles which are skipped. The heatmap reveals that this applies particularly for the left side of the grid (touch coverage of 89.7%) with most targets skipped in the bottom left tile (84.8% coverage).

No targets were skipped at all while using *BoD Shift* as this method allowed participants to reach all targets on the screen without changing the hand posture. Therefore, there is no heatmap for *BoD Shift*.

Task Completion Time

Figure 6 shows the task completion time for every condition as a heatmap. We retrieved these heatmaps as follows: We first calculated a heatmap for every participant. These heatmaps show the average task completion time for targets which are not skipped. We then averaged these heatmaps to finally retrieve the presented heatmaps.

Using a one-way repeated-measures ANOVA, we found significant differences between all three conditions ($F_{2,46} = 23.922$, $p < .001$). Bonferroni post hoc tests revealed that Direct Touch is significantly faster than *Reachability* ($CI_{.95} = .-492.721$ (lower) -95.076 (upper), $p < .001$) and BoD Shift ($CI_{.95} = .-1096.742$ (lower) -395.176 (upper), $p = .000$). In turn, *Reachability* is significantly faster than BoD Shift ($CI_{.95} = .-723.222$ (lower) -180.899 (upper), $p = .001$).

Target Touch Positions using BoD and Reachability

Figure 7 shows the absolute position at which participants touched a target when having the opportunity to move the screen with *BoD Shift* and *Reachability*. As expected, participants dragged the screen into a position so that targets can be

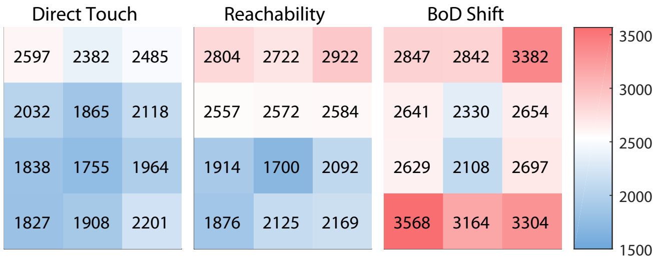

Figure 6. Heatmap showing the task completion time for every tile in ms.

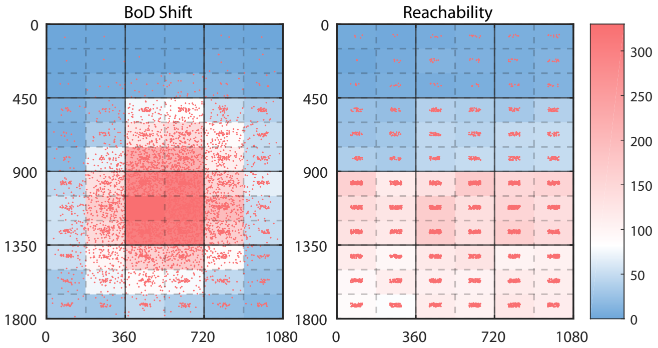

Figure 7. Heatmap showing the target positions in which participants touched them when having the possibility to use *BoD Shift* or *Reachability*. The center of the $9\,mm \times 9\,mm$ targets are represented by red points.

touched in a comfortable position for the thumb just below the center of the screen.

For *Reachability*, the majority of targets are touched at the bottom half of the screen. While there were still some participants who touched targets in the second row from the top, almost no participant touched targets located in the top row.

Error Rate per Grid Tile

Figure 8 shows the probability for failing to touch four consecutive targets of a tile correctly. Participants fail all four consecutive targets if they miss at least one single target at least once (e.g. touching besides a target) or skip one or more targets. For the whole screen, the most errors were made using *Direct Touch* ($M = 53.0\%$, $SD = 3.7\%$), followed by *Reachability* ($M = 43.7\%$, $SD = 3.9\%$) and *BoD Shift* ($M = 40.8\%$, $SD = 3.6\%$). A one-way repeated measures ANOVA reveals a significant difference between the error rates of the three conditions, $F_{2,46} = 8.519$, $p = .001$. Bonferroni post hoc tests show a significant difference between *Direct Touch* and *Reachability*, $CI_{.95} = 0.035$ (lower) 0.151 (upper), $p = .001$ as well as *Direct Touch* and *BoD Shift*, $CI_{.95} = 0.029$ (lower) 0.214 (upper), $p = .008$. No other comparisons were significant.

The heatmap for *Direct Touch* indicates that participants struggled to reach targets in the upper row accurately which lead to error rates above 60%. Total error rates in the upper half are also higher (63.6%) than in the lower half (42.4%). In both *Reachability* and *BoD Shift*, surprisingly error rates for targets in the upper half of the screen were also higher (46.8% Reachability, 44.9% BoD) than on the lower half (40.6% Reachability, 36.8% BoD).

Figure 8. Heatmaps showing the probability in percent for failing to touch four consecutive targets in different grid positions. Participants failed to touch four consecutive targets if they missed or skipped at least one target.

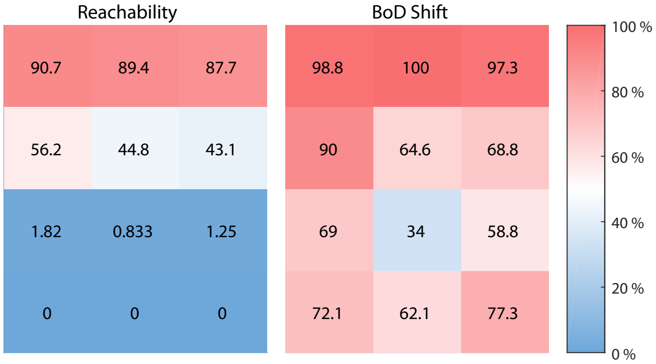

Figure 9. Heatmap showing the percentage of grids, in which *Reachability* or *BoD Shift* were used.

BoD Shift and Reachability Usage

Heatmaps in Figure 9 show how often participants used the screen shift capability to move targets into a more reachable position. We filtered out all shifts that were shorter than 10 px to remove unintentional input.

The heatmap for *Reachability* shows a gradient-like pattern, whereas targets in the first row from the top were shifted the most (nearly in 90% of all cases). Targets in the second row were shifted in 48.0% of all cases while *Reachability* was, as expected, nearly not used at all for the bottom two rows as this would move targets out of the screen.

Looking at the heatmap for *BoD Shift*, we notice that there are more shifts in general than in the heatmap for *Reachability*. Targets in the upper row are shifted almost always (98.7%) while targets in the left-most cell in the second row were also touched in 90% of all cases. Surprisingly, targets in the third and fourth row were shifted in 62.2% of all cases.

Usability, Perceived Workload and Subjective Rating

Table 1 shows results of the System Usability Scale (SUS) and NASA-TLX questionnaire as well as a subjective rating of the three interaction methods. As we can see, *Reachability* has the best rating for the SUS, followed by *Direct Touch* and *BoD Shift*. A one-way repeated ANOVA reveals significant differences between the SUS scores for the three interaction methods, $F_{2,46} = 3.389$, $p = .042$. Bonferroni corrected post hoc tests show a significant difference between *Reachability* and *BoD Shift*, $CI_{.95} = 5.477$ (lower) 29.939 (upper), $p = .003$. No other comparisons was significant.

	SUS	NASA-TLX	Rating
Direct Touch	75.21 (33.03)	17.67 (7.91)	2 (2)
Reachability	83.13 (12.92)	13.99 (8.41)	6 (3)
BoD Shift	65.42 (18.53)	19.18 (7.28)	5 (3)

Table 1. Table showing the average SUS score, the average perceived workload and the subjective rating for the three interaction methods. Numbers in brackets represent the standard deviation (IQR for rating).

In terms of perceived workload, the NASA-TLX results also show that *Reachability* has the lowest perceived workload, followed by *Direct Touch* and *BoD Shift*. A one-way repeated ANOVA reveals a significant difference between the NASA-TLX scores for the three interaction methods, $F_{2,46} = 3.486$, $p = .039$. Bonferroni corrected post hoc tests show a significant difference between *Direct Touch* and *Reachability*, $CI_{.95} = .451$ (lower) 6.893 (upper), $p = .022$. No other comparisons were significant.

Participants subjectively rated whether they would use respective approaches to reach targets across the whole screen. The median of the rankings indicate that participants prefer *Reachability* slightly over *BoD Shift*. However, one-handed use of *Direct Touch* on large smartphones is disliked.

Qualitative Feedback and Impressions

We collected feedback to all three conditions using questionnaires and semi-structured interviews.

Direct Touch: Being asked about the advantage of *Direct Touch*, five participants responded with the simplicity since it requires no further action to hit the targets (if reachable) and a low learning curve since touch is widely known nowadays. However, this approach does not work for all targets on the screen as our participants were almost unanimous about the difficulty in reaching targets on the upper half of the screen (21 participants). Moreover, six participants stated that their hands were hurting and that they were frustrated due to the reachability limitations. Further, four participants mentioned the unsafe handling of the phone while trying to reach the targets.

Reachability: While *Reachability* provided more accessibility across the entire screen than *Direct Touch*, seven participants stated that this is still not enough since targets close to edge opposite of the thumb and on all corners are still not reachable. Hence, these participants reportedly missed the possibility to move the screen to the left / right. Additionally, three participants stated that it is difficult to reach the button due to its position (both are holding the phone using posture 3) which makes it even more difficult to perform a double-tap – a rather unfamiliar action on smartphones. Five participants were skeptical about the button itself since it overlapped parts of the bottom center targets. Opposed to this, eight participants complimented the simplicity of this method while two participants already knew this method from their smartphones.

BoD Shift: Using *BoD Shift*, our participants were unanimous about the full accessibility of the targets without any grip changes and cramps. Four participants stated that this method is simple and easy to learn while two further participants felt that this method is faster than the other conditions. Individual participants stated that there are no interfering elements on the screen itself and that there is no finger occlusion. Two participants noticed that they prefer using the BoD touch sensor to move targets below their thumb instead of moving their thumb to the target itself.

While four participants complimented this method in general as being better than the other two method, seven participants criticized the lack of grasp stability while performing certain BoD movements (e.g. up and diagonal up). Further, four participants stated that they were unfamiliar with this method which also lead to uncontrolled behavior such as unintentionally moving the screen or moving the screen into the opposite direction. Accordingly, one participant felt that with enough practise, he would reach targets across the screen faster than with the other methods.

DISCUSSION

The results suggest that although *BoD Shift* enables users to reach all targets without changing their grip, the task completion time is higher than when using *Reachability* or *Direct Touch*. One reason might be that most participants hold the device using four fingers on the rear side. This does not only lead to unintentional input on the BoD touch sensor; there is also a lack of grip to hold the phone while input is made on the BoD touch sensor.

In contrast to the task completion time, our results show that using both *Reachability* as well as *BoD Shift* resulted in a significantly lower error rate than *Direct Touch*. While users might reach a target on the upper half of the screen faster by directly touching it, they have to tilt the phone and/or have to fully stretch the thumb which leads to a lower touch accuracy. However, when using *BoD Shift*, users move nearly all targets into the comfortable zone of the thumb. We also noticed that targets were moved more towards the thumb's comfortable zone despite being reachable without change of the hand posture. We suspect that our participants prefer using their index finger to move the screen instead of bending or extending their thumb to reach targets.

In terms of target reachability, the results showed that the majority of users cannot reach targets in the upper half of the screen without tilting the device, stretching the thumb or using the second hand. Moreover, while *Reachability* avoids many inaccessible targets, users with smaller hands still are not able to reach targets located on the opposite side of their thumb (e.g. left edge for right-handers). With *BoD Shift*, all targets could be reached.

A comparison of the qualitative feedback on our two prototypes showed that no participant complained about holding issues when using the improved prototype – contrary to the first prototype. No participant showed any difficulties in holding the improved prototype while the average hand size in the first study was even bigger than the average size in the main study. Based on the differences between our two prototypes, we conclude that an increment of $3\,mm$ in thickness may already cause difficulties in holding the device. Moreover, as we had to turn the first prototype up-side-down due to the phone camera's placement, we also suspect that the weight distribution of the phone (the battery was on the top side) may have an impact.

LIMITATIONS

We conducted our study in a controlled environment where participants sat on a chair during the whole study. Moreover, we used an abstract target selection task that modelled common touch patterns by grouping targets. Thus, users had to preserve their initial grip to prevent adaption to the specific task. It is left to future work to validate our results in a less controlled environment where participants can walk around and use real applications with possibly other touch patterns. This could influence the touch performance [17] especially if consecutive targets are far apart. Sensitivity of BoD touches could be improved with a capacitive touch sensor. However, this would require more input filtering to prevent unintended input.

CONCLUSION

In this paper, we present two smartphone prototypes with back-of-device (BoD) interaction capabilities. While the first one was designed as a phone case for the LG Nexus 5X to attach a resistive touch sensor, the second one was built to replace the back cover of the mobile phone to minimize the resulting thickness. This was required as qualitative feedback on our prototypes indicate that a slight increment of the device's thickness ($3\,mm$) already has a noticeable negative impact on grip stability.

In a first study, we determine the most preferred approach for screen shifting using BoD interaction. Results indicate that users prefer a simple and controllable approach which translates relative touch input on the BoD touch sensor to a front screen shift (referred to as *(Normal) BoD Shift*). In a target selection task in the main study, we then compared *BoD Shift* to Apple's *Reachability* and *Direct Touch*. While participants achieved the lowest task completion time with *Direct Touch* followed by *Reachability*, none of the two techniques enabled them to reach all targets opposed to *BoD Shift*. Moreover, participants achieved the lowest touch error rate with *BoD Shift* as they shift nearly all targets into an area which is comfortably reachable by the thumb.

While *BoD Shift* is slower in terms of task completion time, it enables full one-handed reachability and a lower error rate. Especially when using large smartphones in mobile or encumbered situations, task completion time gets less important while lack of reachability and a higher error rate can be detrimental. In future work, we plan to repeat this study in a more realistic situation in which participants are encumbered, e.g. while walking and carrying items. We are also interested in constructing prototypes that can be operated without additional devices. This makes them distributable, which enables us to investigate BoD interaction techniques and use cases in the form of a long term study and in a less controllable but more realistic environment.

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