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RESEARCH-ARTICLE

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ABSTRACT

People very often use mobile devices with one hand to free the second hand for other tasks. In such cases, the thumb of the hand holding the device is the only available input finger, making multi-touch interactions impossible. Complicating interaction further, the screen area that can be reached with the thumb while holding the device is limited, which makes distant on-screen areas inaccessible. Motivated by emerging portable object tracking technologies, we explore how spatial mid-air thumb-gestures could potentially be used in combination with on-screen touch input to facilitate one-handed interaction. From a user study we identify the 3D thumb-reachable space when holding a smartphone. We call this space ‘Thumbs-Up’. This space extends up to 74 mm above the screen, making it possible to create interactions for the thumb of the hand holding the smartphone. We furthermore demonstrate how such Thumbs-Up techniques, when combined with on-screen interaction, can extend the input vocabulary in one-handed situations.

Keywords

One-Handed Spatial Interaction; Around-Device Interaction; Thumb Input; Reachability; Limited Multi-Touch Interaction; Occlusion.

1. INTRODUCTION

The majority of smartphone users interact with the touchscreen while holding the phone with one hand when the second hand is busy performing other tasks, such as holding a shopping bag or while clinging onto a handlebar in a bus [7, 8]. In such situations, the thumb is the only available finger to interact with touchscreen. Prior research has pointed out several limitations with one-handed thumb input on mobile devices. For example, the length of the thumb sets a significant limit to what screen areas can be reached [2, 8]. This is often referred to as a reachability issue. Furthermore, one-handed thumb input does not allow for multi-touch interactions that require more than one finger [3], and information on the screen easily gets occluded by the thumb [12].

Although numerous approaches to improve one-handed smartphone interaction have been proposed, very little is known about extending the input possibilities available to the thumb. A promising complement to standard touch input is to use the mid-air space surrounding the device for hand gestures [4, 6, 9, 10]. This form of interaction assumes that the smartphone’s interaction plane extends beyond its physical boundaries and that users can access

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on-device information by directly pointing above, below or around the device. For example, Kratz et al. [9] detect hand movements above the device using infrared proximity sensors and Song et al. [10] track hand gestures below the device using the device’s built-in camera. Infrared sensors can also be used to detect multi-finger movements in the vicinity of a smartphone when it is placed on a surface [4]. These and similar projects clearly demonstrate the feasibility and social acceptability [1] of so-called around-device interaction.

Although around-device interaction has been widely explored, ways to leverage the void space just above the device which is reachable with the thumb of the hand holding the device is an unexplored interaction space. We present Thumbs-Up, the in-air space next to a smartphone that can be reached with the thumb on the hand holding the device. With Thumbs-Up, the in-air space could be used to access on-screen content by directly pointing with the thumb, as shown in Figure 1. Additionally, this surrounding space could be used in conjunction with current touch input to extend the input vocabulary.

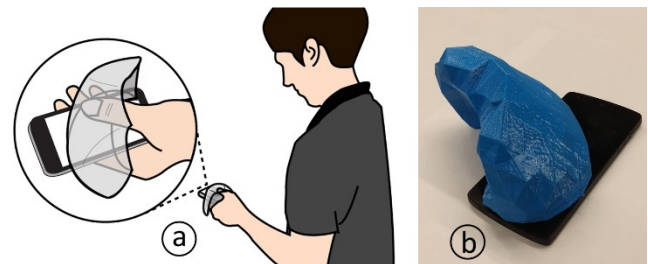


Figure 1. (a) Thumbs-Up interactions occur in the thumb-reachable in-air space around a smartphone. A 3D printed shape of this thumb-reachable space is shown in (b). During one-handed usage, users could utilize this space to overcome limitations of one-handed interaction.

We start with exploring the Thumbs-Up input range. Results reveal that study participants can reach a large in-air space (up to 74mm from the touchscreen) with their thumb. With a design workshop, we further elicit opinions from users about possible Thumbs-Up interactions to address commonly known limitations with one-handed smartphone usage. Workshop participants sketched a set of alternative designs that could potentially solve these limitations.

Our contributions include: (i) the definition of Thumbs-Up, the thumb-reachable in-air input space around a smartphone; and (ii) a set of interaction techniques that could be applied in Thumbs-Up to resolve concerns of reachability, limited multi-touch interaction, and thumb occlusion for one-handed smartphone input.

2. Thumbs-Up Input Range

We start with a study to identify the suitable thumb input range when the user holds the smartphone in the hand. Previous work [5]

that has studied two-handed usage situations (where one hand holds the smartphone and the fingers on the other hand are used for on-screen input) shows that users frequently move or rest their input fingers in the air just above the screen between on-screen interactions. This observation motivated us to distinguish between: (i) *TouchSpace*: the space just above the screen (above screen-space) that people use to initiate or terminate touch gestures when these are performed with the thumb; and (ii) *Thumbs-Up space*: the in-air space around the device that is reachable with the thumb on the hand that is holding the device.

2.1 Participants and Apparatus

Twelve right-handed smartphone owners participated (three female, mean age 24.3 years, s.d. 5.8). All participants preferred to hold and interact with the phone in portrait mode. Participants' thumbs were on average 105mm long (from the carpometacarpal joint to the tip of the thumb). On average, their palm circumference, hand size (from tip of middle finger to bottom of the palm), and hand span measured 183mm, 184mm, and 200mm, respectively.

We used a Vicon MX system to track participants' thumb movements around a Samsung Mini S4 (screen size: 4.3", dimensions: 4.91×2.41×0.35"). We placed tracking markers on the smartphone and on a 3D-printed ring to track participants' thumbs (Figure 2). A Unity 5.0 application logged thumb movements in relation to the smartphone.

2.2 Tasks

Participants were instructed to hold the phone in their left/right hand with the left-bottom/right-bottom corner of the phone close to the centre of the palm (Figure 2). Participants performed two tasks:

- (i) *Map navigation task*: We asked participants to navigate a map using flick gestures with their thumb. We showed participants two familiar locations in the city in the Google Maps application and asked them to navigate from the first to the second location. To perform this kind of task, a user has to repeatedly tap the screen and then flick to pan the map. After a panning action, the user needs to readjust the thumb to start the next panning action. We included this task to identify the *TouchSpace* zone above the screen – the in-air space where the thumb moves after an on-screen thumb-operation.
- (ii) *Space filling task*: We asked participants to repeatedly move the thumb in mid-air, from left-to-right and right-to-left above the screen and thereby gradually increase the distance between the top of the thumb and the screen. We asked participants to do so until the top of the thumb had reached the maximum distance that could be managed without having to adjust the position of the device in the hand. These repetitive in-air movements generated a large thumb-reachable volume, which we refer to as *Thumbs-Up space*.



Figure 2. (a) Map navigation and (b) Space filling task.

Participants performed the tasks standing in a room equipped with the motion tracking system. We asked participants to imagine that one of their hands is holding a coffee mug and the other hand is available for on-screen interactions. All participants performed the two tasks with the right and with the left thumb. The tasks were performed three times with each thumb.

2.3 Results

TouchSpace: We found that during the map navigation task, participants moved the left thumb up to a maximum of 22mm above the screen (average 18mm, s.d. 2.7mm). The right thumb was moved to a maximum of 23mm above the screen (average 19mm, s.d. 2.3mm). Accordingly, we reserve this *TouchSpace* for completing or initiating on-screen gestures only.

Thumbs-Up space, height: The recordings from the space filling task revealed that participants could comfortably reach a maximum of 64mm above the screen with the left thumb (average 57mm, s.d. 5.8mm) and a maximum of 74mm (average 63mm, s.d. 9.6mm) with the right thumb. Accordingly, we can consider using this space (22 to 57mm above the screen for the left hand thumb and 23 to 63mm for the right hand thumb) for Thumbs-Up interactions.

Thumbs-Up space, width: When regarding the phone's bottom edge as the horizontal axis, participants moved the left thumb sideways within an arc spanning from 10° to 150°. With the right thumb, the movements were within an arc spanning from and 0° and 150°. With both thumbs, the corresponding arc length decreased as the thumb's height-distance from the screen increased.

Our results indicate that people can comfortably reach a relatively large in-air region above and beside the device with the thumbs. Figure 3 visualizes the corresponding accessible in-air space for the left and right thumbs.

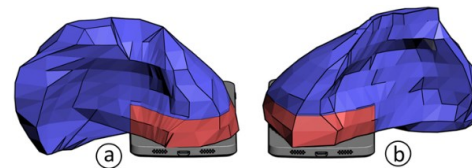


Figure 3. In-air thumb-reachable space with (a) the left and (b) the right thumb. The red areas indicate *TouchSpace* and the blue areas represent *Thumbs-Up space*.

We note that the in-air space for the right thumb is slightly larger than for the left thumb. On average it spans up to 64mm above the device with the left thumb and up to 74mm with the right thumb. We also observe that the region for the right thumb is larger in the horizontal direction than for the left thumb. We attribute these differences to the fact that all participants were right handed and frequently use their right thumb for one-handed smartphone interaction. This frequent usage provides them the flexibility to reach regions which are less intuitive/comfortable with the left thumb. A minor concern worth mentioning is the lack of significant diversity among our participant pool. However, we believe that more participants with balanced gender and handedness would further ascertain our findings.

3. Design Workshop

After having defined the accessible Thumbs-Up space, we explored how this space could be utilized in one-handed usage situations. We invited eight smartphone owners (all male, 22 to 29 years old, mean 24.9, s.d. 2.4) to participate in a design workshop. All participants were HCI students with significant interface design experience. We focused on three well-documented [2, 3, 8, 12] limitations of thumb-based interaction: i) *Reachability*: due to the bio-mechanical limits of the thumb it is difficult to access on-screen items located at the top region of the screen and in the lower corners of the screen; ii) *Limited multi-touch interaction*: as multi-touch gestures (such as zoom in/out a map) are difficult to perform with one finger (or a thumb), many of the touchscreen gestures are not available for one-handed thumb interaction; and iii) *Occlusion*: on-screen

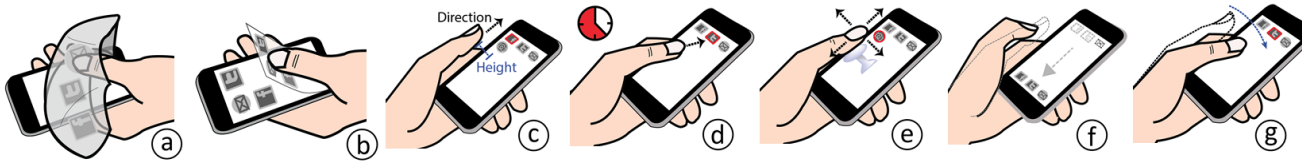


Figure 4. Proxies for unreachable items could be placed inside Thumbs-Up space (a and b). An on-screen item could be highlighted based on the directions of thumb movements and the distance from the screen (c) or depending on the dwell time (d). A virtual joystick could be used to control the currently highlighted item (e). Unreachable items could be moved to the thumb reachable area using a gesture, such as bending the thumb (f) or a quick left-to-right movement (g).

interactions with the thumb (as with the index finger) occlude large parts of the screen and so covers on-screen information.

Our design workshop was structured as follows. We first familiarized the participants with one-handed interaction and discussed several common situations in which the user only has one hand free for interaction (e.g., when navigating a map while holding the smartphone in one hand and a shopping bag in the other hand, or when scrolling a list of contacts while clinging onto a handlebar in a shaky subway train). We also demonstrated and discussed how one-handed interaction limits multi-touch operations, and how it could lead to reachability and occlusion problems. After this introduction phase we introduced the idea of using the thumb in-air space for interaction on a smartphone. We demonstrated the Thumbs-Up space by placing a 3D-printed volume of the Thumbs-Up space – as defined through our earlier study – on top of a smartphone (Figure 1b). We then asked participants to familiarize themselves with thumb movements in the Thumbs-Up space while holding their own smartphones.

The next activity for our participants was to individually propose, sketch, and describe possible interactions that include the use of Thumbs-Up space. We instructed participants to focus on interactions targeted as solutions for the three key limitations of one-handed interaction. Each participant provided at least one Thumbs-Up interaction for each one of the three key limitations. We then discussed and refined the proposed interactions together with the participants. In the following sections we present the most promising interactions.

3.1 Limitation: Reachability

We collected a total of 26 sketches to tackle the reachability issue. We summarize the proposals under the following categories:

Placing items into the Thumbs-Up space: A common approach listed by the participants was to use the Thumbs-Up space to access unreachable screen items by placing virtual proxies in the Thumbs-Up space. An item would highlight on the screen based on the thumb position in Thumbs-Up space. Two variations are shown in Figure 4a and b, where the proxies are placed in the Thumbs-Up space or onto a bent surface inside the Thumbs-Up space.

Highlight an item based on the thumb position: Instead of placing proxies in Thumbs-Up space, this approach maps the thumb movement to the currently highlighted item. This mapping can be done in the following ways:

Direction+Height: In this style of interaction, the thumb of the hand holding the device acts as a ray-casting pointer and its height from the touchscreen defines the currently highlighted item in that direction (Figure 4c).

Direction+Dwell: Similar to Direction+Height, but a dwell-timer is used to define the currently highlighted. An item further away on the screen could be reached with a longer dwell time and a closer item could be attained with a shorter dwell time (Figure 4d).

Virtual joystick: An imaginary joystick is positioned centered above the screen and the thumb in Thumbs-Up space is used to control a screen cursor which highlights screen items according to thumb movements (Figure 4e).

Moving unreachable items to the thumb reachable space with a thumb gesture in Thumbs-Up space: Prior work has shown that items that are out of reach for the thumb require more effort to access as the user needs to readjust the way they hold the phone [2]. Moving such items to the thumb reachable on-screen region with a thumb gesture in Thumbs-Up space could be a potential solution to solve reachability issues. Many workshop participants suggested to use “micro-gestures”, such as quickly bending or moving the thumb left-to-right (or opposite) inside Thumbs-Up space, to temporarily move unreachable screen items to a reachable screen area (Figure 4f and g).

3.2 Limitation: Multi-touch Interaction

Participants sketched a total of 19 designs to address the problem with limited multi-touch interaction for one finger/thumb situations. We summarize the design into the following categories:

Pie menu based approach: When the user moves the thumb into Thumbs-Up space an on-screen pie menu, which contains menu items to trigger any applicable multi-touch operations, appears on the screen (Figure 5a). The user can now move the thumb in Thumbs-Up space to invoke the desired operation from the menu.

Dual-gesture: This approach requires that the user performs two thumb gestures in Thumbs-Up space to complete a multi-touch operation. The gestures could be performed sequentially – e.g., a horizontal thumb movement immediately followed by a vertical movement – or in parallel – e.g., moving and bending the thumb simultaneously. For instance, bending while moving the thumb could be used to simultaneous pan and zoom a map, as visualized in Figure 5b.

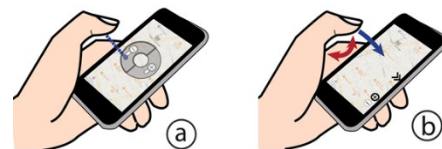


Figure 5. (a) A pie menu with multi-touch functionalities is displayed when the thumb enters Thumbs-Up space; (b) sequential/parallel multiple thumb gestures are mapped with on-screen multi-touch gestures.

Continuous gestures: Many workshop participants suggested to map different continuous gestures to multi-touch operations. For example, a continuous clockwise or counterclockwise in-air movement could be used to zoom-in or -out (Figure 6a).

Touch+In-Air solution: Similar to prior work [5], some workshop participants suggested to interweave on-screen touches with in-air thumb gestures. In this approach, a gesture could start from the screen and end in the Thumbs-Up space, or vice versa (Figure 6b).

Additionally, these gestures can be directional (i.e., from a certain angle from mid-air to the touchscreen), complex (e.g., a lasso gesture in mid and then touch to the screen) or depend on a dwell-timer (e.g., 2 seconds inside the Thumbs-Up space and then a rapid touch on the screen to zoom in a map as shown in Figure 6b).

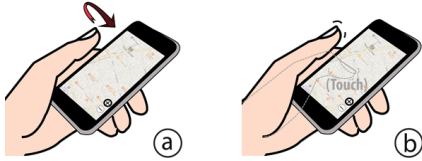


Figure 6. (a) A continuous clockwise movement inside Thumbs-Up space and (b) an in-air thumb gesture followed by a screen tap to zoom in a map.

3.3 Limitation: Occlusion

Workshop participants provided a total of 13 designs that could solve the occlusion problem. We summarize their proposals:

Use “Extended” Thumbs-Up space: The Thumbs-Up space could be divided into two areas: one area directly above the phone and the area other to the left of the phone (we called this area the Extended Thumbs-Up space), as shown in Figure 7a. Participants commonly suggested to use this Extended Thumbs-Up space to solve the occlusion problem.

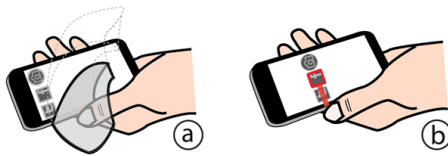


Figure 7. Occlusion problem could be resolved by using (a) the Extended Thumbs-Up space spatially located besides the phone’s physical boundary, or by using (b) a “cursor” offset where the thumb highlights an object from its in-air position.

Bent surface: Participants suggested to use an imaginary bent plane inside the Thumbs-Up space for on-screen interaction, as shown in Figure 4b. Since the thumb accesses on-screen items on a plane vertical to the screen, screen occlusion may be reduced.

Shadow thumb: Instead of using a one-to-one mapping between finger and touch location, an offset could be introduced to overcome the occlusion issue (Figure 7b). Hovering the thumb in Thumbs-Up space would move the on screen cursor with an offset. Thus, the input thumb would never cover any on-screen items.

3.4 Challenges

Based on the above designs, we identify the following challenges:

Mid-Air thumb detection: The previously discussed designs rely on precise thumb movement detection in the Thumbs-Up space. Though current smartphones have the necessary capabilities to detect thumb movements in the air around the device, attaching external sensors (e.g., an omnidirectional mirror on top of the smartphone’s camera [11] or wearing a magnetic ring on the thumb) could be used to track the thumb in Thumbs-Up space.

Initiate Thumbs-Up: Thumbs-Up interactions require a trigger mechanism to activate the Thumbs-Up space. A tap at the back of the smartphone (which produces a vibrational signal that is easily detected by the on-board accelerometer) or a quick swipe with the thumb back and forth across the screen bezel could be used.

Alternatively, a press on a physical button or a tap on a special screen button could activate/deactivate the Thumbs-Up space.

In-Air Selection: Thumbs-Up space allows the user to explore on-device items by moving the thumb. A selection is required when the user wants to invoke an item and put it into focus for more details. Specific finger movements such as a rapid thumb raise in Thumb-Up space could be used to trigger the selection.

4. Conclusion

We have defined Thumbs-Up space, the in-air space that is reachable with the thumb of the hand holding a smartphone. We have also presented several designs for interactions that rely on in-air thumb movements in Thumbs-Up space which could work as possible solutions to overcome three common problems encountered in one-handed smartphone interaction: limited reachability, limited multi-touch interaction, and occlusion issues. Our future work will include implementing these designs and to investigate how to incorporate them into current one-handed smartphone interactions. Additionally, further exploration is required to build self-contained smartphone approaches that can detect the thumb of the hand holding the device.

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