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Modeling Reachability on Curved Mobile Touchscreens

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Abstract

Smartphones are gradually increasing in size over the last years to a point where they are currently transitioning into a size factor between smartphone and tablet, referred to as phablets. The increase in size provides a challenge to the thumb that is used for touch input during a single-handed interaction. This occurs due to the thumb's limited reachable area of the screen. The interaction with only one hand holding the device, however, is used often either due to user preference or because this leaves the other hand free to be utilized for other tasks like holding an umbrella, grasping the handle in a crowded bus, or providing a sip from a cup of coffee. While this hand can be utilized quite freely the thumb of the hand holding the smartphone struggles to hit touch targets out of its reach. The smartphone user does, therefore, need change her grasp on the device which makes the grip loose and leaves the smartphone prone to falling.

This thesis explores the possibility of moving the hard to reach areas closer to the thumb by curving the smartphone. The influence of different types of such a curvature and the increase of the angle of the curve on the size of the *functional area* of the thumb are investigated in a user study. Additionally, participants of the user study are asked to rank the comfortability of the interaction with the curved smartphone prototype. 3D printed prototypes with a white affixed sheet of paper which suggests a touch interaction surface are used to capture the *functional area* by using black paint which is applied to the participant's thumb.

The results of the user study show a significant increase in the size of the *functional area* with increasing angle of the curvature. However, while the size of the *functional area* increases the *comfortability ranking* decreases significantly with increasing angle of the curvature. This is in line with user feedback during the study in which participants state that the interaction with the prototypes with large angles of the curvature is cumbersome and feels unpleasant. It is, therefore, apparent that there is a trade-off between *comfortability ranking* and the size of the *functional area* when designing curved mobile devices. The different types of curvatures show no significant effect on either the size of the *functional area* or the *comfortability ranking*.

Überblick

Über die letzten Jahre wurden die Bildschirme von Smartphones immer größer. Dies ging soweit, dass teilweise Smartphones heutzutage als Phablets bezeichnet werden, eine Mischung aus Smartphone und Tablet. Diese Steigerung erzeugt eine Herausforderung für den Daumen der Hand, welche das Smartphone hält, da der Bereich des Bildschirms, welcher durch den Daumen erreicht werden kann eingeschränkt ist. Trotzdem ist die Interaktion mit einer Hand weiterhin eine beliebte Methode das mobile Gerät zu nutzen, weil der Nutzer es entweder bevorzugt, oder damit eine Hand für andere Tätigkeiten, wie zum Beispiel das Halten eines Schirms, das Festhalten im Bus, oder ein Schluck aus der Kaffeetasse, verwendet werden kann. Während diese freie Hand beliebig genutzt werden kann bemüht sich der Daumen der Hand, welche das Smartphone hält, Ziele auf dem Bildschirm zu treffen, die außerhalb seiner Reichweite liegen. Aus diesem Grund muss der Griff, mit dem das Smartphone gehalten wird, oft gewechselt werden, wodurch es schnell passieren kann, dass das Gerät herunterfällt.

Diese Arbeit untersucht die Möglichkeit die schwer zu erreichenden Bereiche des Smartphone Bildschirms näher zum Daumen zu bringen, indem das Gerät gekrümmt wird. Der Einfluss verschiedener Arten einer solchen Krümmung und der Stärke der Krümmung auf die, durch den Daumen zu erreichende, Fläche wird in einer Nutzerstudie getestet. Zusätzlich werden Nutzer der Studie gebeten die Prototypen in eine Rangliste danach einzuordnen, wie sie den Komfort der Interaktion mit dem Prototypen empfanden. Dabei werden 3D gedruckte Prototypen mit einem aufgeklebten weißen Papier, welches eine Interaktionsfläche suggeriert, verwendet, um mit schwarzer Fingerfarbe auf dem Daumen des Studienteilnehmers die vom Daumen erreichbare Fläche zu markieren.

Die Ergebnisse der Studie zeigen, dass die erreichbare Fläche signifikant größer wird mit zunehmendem Winkel der Krümmung. Gleichzeitig werden aber die Bewertungen des Komforts der Interaktion signifikant schlechter mit zunehmendem Winkel der Krümmung. Dies passt zu Kommentaren der Nutzer während der Studie, welche anmerkten, dass sich die Interaktion mit den am stärksten

gekrümmten Prototypen anstrengend und unangenehm anfühlt. Es liegt daher nah, dass es für den Entwurf eines gekrümmten mobilen Gerätes eine Austauschbeziehung zwischen dem wahrgenommenen Komfort und der Größe der zu erreichbaren Fläche gibt. Die verschiedenen Arten der Krümmung haben keinen signifikanten Einfluss auf die Größe der erreichbaren Fläche oder den wahrgenommenen Komfort gezeigt.

Acknowledgements

I thank all participants of the study for their time.

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I thank Christian Corsten and Dr. Simon Voelker for their input and their advice.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

EXCURSUS:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

Source code and implementation symbols are written in typewriter-style text.

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The whole thesis is written in Canadian English.

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Chapter 1

Introduction

Smartphone screens are showing a trend of getting bigger over the last years with current smartphones like the Apple iPhone X (Apple Inc. [2018a]) and the Samsung S8+ Samsung Electronics Co., Ltd. [2017] having a screen size of 5.8" and 6.2" (IDC Corporate USA [2017]). This increase in size creates issues for the reachability of the thumb during single-handed touch interaction. If the smartphone screen exceeds the reachable area of the thumb the user has to frequently change the grip on the device when reaching for the area which is outside the thumb's *functional area*(2.2.1 "The Functional Area"). This change of the grip on the smartphone makes the device more prone to falling out of the user's hand and introduces exertion for the user when closing in on those hard-to-reach areas. Still, the single-handed interaction is the most used one either because the user prefers this interaction or the other hand is being used for another task (Hoober [2013]). Those tasks include holding an umbrella during the rain, gripping onto a rail in a crowded bus, or taking a sip out of a coffee mug.

Smartphone screens are increasing in size over the last years.

Increase in smartphone size creates reachability issue.

People prefer single-handed interaction with their smartphone.

Related work addresses this reachability issue by either constraining the optimal position of interface elements to the *functional area* of the thumb or providing a virtual workaround like moving the content of the screen. The different methods are listed in the related work section 2.2 "The Reachability Issue". Those methods either restrict interface designers or introduce disadvantages like a lower

Related work proposes virtual improvements.

target acquiring accuracy, a slower task completion time, or necessary mode switching.

Curvature of the smartphone proposed as an improvement for the reachability issue.

Therefore,we are presenting an empirical study that explores the curvature of mobile device touchscreens as an improvement of the reachability issue. We are expecting that such a curvature of the touchscreen aligns better with the reach provided by the rotational joint of the thumb Jones and Lederman [2006] and could, therefore, increase the *functional* area. Additionally, the direct manipulation metaphor is maintained. Three different types of curvatures which are incrementally designed (see chapter 3) are being tested in a user study to identify how the angle and type of the curvature is influencing the functional area. This thesis will address the following research question.

RQ1 Do different levels and types of curvature of a mobile device touchscreen change the size of the *functional area* for single-handed thumb interaction?

Perceived comfortability is evaluated in the user study.

Issues of discomfort for the users have been mentioned due to a necessary frequent change of the grip on large smartphone devices. Therefore, the influence of the curvature on the user's perceived comfortability when interacting with the curved smartphone is evaluated. This is done because the curvature of the screen should not introduce additional discomfort for the user in comparison to the interaction on a flat smartphone. We introduce a second research question which is investigated in the user study.

RQ2 Do different levels and types of curvature of a mobile device touchscreen change the perceived comfortability for single-handed thumb interaction?

Chapter 2

Related work

2.1 Touch Input on Curved Surfaces

Curved surfaces come in a variety of shapes and sizes and have therefore been empirically evaluated in various ways. Roudaut et al. [2011] evaluated the error offset for single touch of the index finger on concave and convex spherical touch surfaces with a user study. They reported that a convex surface increases the pointing accuracy while a concave surface results in a larger error offset. The effect on the spread is intuitive when thinking about how for convex surfaces the touch point decreases while the touch point on concave surfaces increases because the surface wraps around the touching tip of the finger. Additionally Roudaut et. al. evaluated the effect of downhill and uphill slope on targeting. They showed that for uphill slopes on concave surfaces participants adopted a targeting technique where they hook their finger. This hooking gesture gives them a better view of the fingertip and therefore lets them observe their fingertip more effectively. However, this results in an offset in the opposite direction of the touch gesture. Uphill slopes on concave surfaces increase the error offset because users are forced to use a straight finger leading to the larger offset compared to the hooked finger method due to the covered fingertip.

Evaluation of the effect of concave and convex curvatures on error offset.

Evaluation of the effect of uphill and downhill slope on error offset.

Weiss et al. [2010] evaluated a larger curved device, a hybrid interactive desk with a combination of a horizontal and vertical touch surface with a curved touch surface connecting the two. The authors investigated the influence of the curvature in between the horizontal and vertical surface on the user performance during a dragging interaction along the curvature. They reported an impairment of the user's ability to aim at virtual targets on the touchscreen due to the curvature. Additionally, they report that dragging on the curved surface is slower than on a planar surface. It is assumed that the curvature is perceived as an obstacle by the user resulting in the slower dragging gesture, which is supported by the findings of Jax and Rosenbaum [2007] and contradicts the predictions from Fitts' Law (Fitts [1954]). The authors reason that perceiving the curvature as an obstacle is due to more complex motor activity experienced by users during the dragging interaction on the curved surface. Wimmer et al. [2010] presented a similar construction of a display covering the horizontal and vertical plane of a desk and evaluated the effect of the transition type (bezel, edge or curve) between the vertical and the horizontal plane on a dragging interaction (Hennecke et al. [2012]). They found no significant effect on the task completion time. Accuracy increased for the curved transition which was in line with the participant feedback. They conclude that a curvature is the recommended transition type but make the reader aware that the diameter of the curvature and the angle between the horizontal and the vertical surface has to be large enough. Otherwise, the curve feels similar to the edge type due to the sudden haptic break between the two surfaces.

Evaluation of user performance for a dragging interaction over a curved surface.

Evaluation of dragging interaction on a curved surface in comparison to a bezel and an edge.

Dijkstra et al. [2011] present an evaluation of the effect of how people hold a flexible display on the user performance of pointing and dragging touch interactions. The authors reported that the performance of the touch interaction is dependent on how much force users need to apply to trigger a touch event. With higher force, the flexibility of the display becomes an issue which users try to counteract by bending the surface in such a way that a rigid line is created on the surface at the position they want to touch. However, reported differences in user performance during the touch interaction were only caused by different levels of struc-

Evaluation of user performance of pointing and dragging touch interaction on a flexible surface.

tural integrity in the fold created by the user's hold on the flexible display.

In addition to the empirical evaluations of the previous related work several artifact contributions have been presented showing interaction possibilities on curved devices of different shapes or just presenting the feasibility of fabricating devices with curved surfaces. Benko et al. [2008] present a spherical display with multi-touch capability which provides collaboration interaction possibilities. Villar et al. [2009] introduce a mixture of curved and multi-touch enabled computer mice with which they present the technical challenges of adding the multi-touch capabilities to such devices. The options of objects with self-shaping capabilities (so-called "morphees") described by a metric which the authors call "shape resolution" are reported by Roudaut et al. [2013]. Such reshaping objects, which are also touch-enabled, end up adapting shapes that are curved and therefore create curved touch-enabled devices with a variety of different curvatures. Rasmussen et al. [2012] emphasized the need for empirical evaluation of such shape-changing devices due to the danger of a mismatch of the mental model between the designer and the user (Norman [1986]). Benko et al. [2012] present an interactive augmented reality system, which includes a curved screen. The system presents different projected objects with which the user can interact, enabled by a depth camera tracking the user's eyes, body, and hands. Brockmeyer et al. [2013] present a technique to produce a spherical touch-enabled display with 3D printed optics made of 3D printed light pipes. Approaches which facilitate the human skin as a display and touch surface like the work by Harrison et al. [2010] create a naturally curved interactive display which challenges designers with an array of different kinds of curvatures.

List of artifact contributions with curved surfaces presenting interaction techniques.

The given related work on touch input on curved surfaces provides insights into the variety of designs for touch-enabled curved surfaces and suggests that a concave curvature provides challenges for the user performance during touch interactions

2.2 The Reachability Issue

Design space for techniques that propose improvements for reachability.

Reachability on mobile devices during single-handed interaction becomes an issue the moment interaction elements are positioned in such a way that the user needs to switch the grasp on the device or extend the thumb in a cumbersome way to reach the target. Therefore, several techniques have been shown to address this problem and propose workarounds. To categorize those proposed techniques a design space has been proposed by Chang et al. [2015]. According to the authors, techniques that propose a solution to the reachability issue can be categorized by the targeting mechanism and the trigger mechanism. The targeting mechanism is either assisted touch with the user's thumb or a cursor based approach. Triggering mechanisms can be further divided into mechanisms that are always activated or are triggered by tapping, dragging, a mode change like tilting the device, back-side touch, or either a long- or a double touch.

Screen transformation technique.

Techniques like the one by Karlson et al. [2005], Tsai et al. [2016], and Le et al. [2016], apply a screen transformation to move the content of the screen closer to the thumb. This screen transformation is done by either zooming in on the screen content or moving it. This approach is also used by commercial manufacturers like the Reachability feature on current Apple iPhones, which shifts the content of the screen downwards after double tapping the home button (Apple Inc. [2018b]).

Proxy region technique

Roudaut et al. [2008] present a technique that they call *TapTap*. This technique presents a zoomed in cutout in the centre of the screen of a region of content which has previously been tapped by the user. A second tap can then select something in the shown popup after which it disappears. When the first tap is performed close to the edge of the reachable area of the thumb the popup appears in the center of the screen and therefore provides an easier access for the thumb to the edges of the reachable area. Chang et al. [2015] labeled this type of technique as a *proxy region*. A proxy region duplicates a view of the screen (or parts of it) and displays it at a more comfortable position for the thumb. The user can then interact with this *proxy region* if the interaction on the actual screen content would be more cumbersome.

Both the transformation of the screen and the *proxy region* are placed in the assisted touch category in the design space by Chang et al. [2015]. An example of the cursor based approach is *MagStick* by Roudaut et al. [2008] which creates a stick extending from the user's thumb by dragging the thumb away from the out-of-reach target. The extending stick bends and snaps towards possible targets in its reach which accelerates the interaction. This acceleration addresses the issue that dragging cursor techniques are slower than direct touch.

Cursor based technique.

Hasan et al. [2016b] facilitate the area above the screen of a mobile device which can be reached with the thumb and used for mid-air thumb-gestures. For unreachable items, virtual proxies could be placed in the space above the screen. These items would be highlighted when the thumb touches their virtual proxy mid-air.

In addition to these techniques, the fingers resting on the back of the mobile device can be used for back-of-device interactions. Le et al. [2016] use this technique to give the user the possibility to shift the content of the screen towards the thumb with the index finger on the back of the device.

This thesis presents a fixed deformation of the mobile device itself which moves the hard-to-reach part of the screen closer to the thumb. We expect that a curvature of the screen will address the reachability issue. To the knowledge of the author, there is currently few empirical data about the influence of a curvature of the mobile device touchscreen on the reachable area of the thumb during the single-handed interaction.

Fixed curved device proposed as reachability improvement.

2.2.1 The Functional Area

Bergstrom-Lehtovirta and Oulasvirta [2014] define the *functional area* of the thumb as "the area of the interface

Functional area is reachable area of the thumb.

reachable by the thumb of the hand that is holding the device". Additionally, they present a model which calculates an estimation of the outline of the functional area for a given surface size, hand size, and position of the index finger on the back of the device. To avoid reachability issues, the authors recommend designing the interface in such a way that frequently used interaction areas are within the *functional area*.

Chapter 3

Curved Mobile Touchscreen Prototypes

To increase the *functional area* of the mobile device screen during single-handed touch interaction we propose the curvature of the screen. This screen curvature is investigated by introducing different ways to curve the mobile device screen hereinafter referred to as *types of curvature*. Those different *types of curvature* have in common that they are designed such that the mobile device screen is aligned to the palmar and radial movement of the thumb. This chapter covers this movement of the thumb and goes into details how the alignment will be achieved and how the different *types of curvature* are designed.

Design process of the curvature types will be covered in this chapter.

3.1 Anatomy of the Thumb

During single handed touch interaction the mobile device rests in the palm of the hand and is operated by touch interactions with the thumb. The *functional area* is therefore limited by the potential movement of the thumb. This movement of the thumb is enabled by three joints, the *carpometacarpal-* (CMC), the *metacarpophalangeal-* (MP), and the *interphalangeal* joint (IP) (Jones and Lederman [2006]).

Joints of the hand which enable movement of the thumb.

- The *CMC* joint enables a *palmar abduction* (rotational movement on a plane parallel to the palm) which ranges to about $45°$ and a *radial abduction* (rotational movement on a plane perpendicular to the palm) of about $60°$ (Jones and Lederman [2006]).

- The *MCP* joint enables a *flexion* (movement of the extended thumb towards the palm by moving the *MCP* joint) of about $55°$ and a *(hyper)extension* (movement of the extended thumb away from the palm by moving the *MCP* joint) of about $10°$ (Jones and Lederman [2006]).

- The *IP* joint enables a *flexion* of about $70°$ and *(hyper)extension* of about $20°$ (Neumann [2013]).

Combining the joints of the thumb results in four degrees of freedom.

Altogether, this results in four *degrees of freedom* of the human thumb. In reality the thumb has five degrees of freedom with a fifth degree in *active abduction adduction* of the *MCP* joint. However, this movement is very limited and is therefore only considered as an *accessory motion* and is not counted as a *degrees of freedom* in literature (Neumann [2013]). The four *degrees of freedom* enable an *ulnar–radial motion* (fig. 3.6) of the thumb which defines the extrema of the *functional area* during *single handed interaction* (Bergstrom-Lehtovirta and Oulasvirta [2014]). This motion can be approximated by a parabolic curve as shown by Bergstrom-Lehtovirta and Oulasvirta [2014]. This concept will be used in the design of the different *types of curvature*, which will be described in following sections in this chapter.

3.2 Quantifying Curvature

To quantify and report the curvature of the screen the *degree of curvature* and the *angle of the circular segement* are used. Those quantifying measurements will now be described in more details.

3.2.1 Degree of Curvature

The *degree of curvature* is defined by the radius of the *osculating circle* that is the circle that approximates the curve of the curvature (Abbena et al. [2017]). The *osculating circle* is a *tangent circle* which is centered on the *normal line* of the curve and it approximates the curve by approaching the curve most tightly (Abbena et al. [2017]). Therefore, with increasing *curvature* of the surface the radius of the *osculating circle* decreases. A flat surface would be approximated with an *osculating circle* with an infinitely large radius and would therefore have an infinitely large *degree of curvature*.

Definition for the *degree of curvature*.

3.2.2 Angle of the Circular Segement

A *segment of a circle* or *arc* (s) is given by the *radius* (r) of the circle and an *angle* (α) in degree by the formula

$$s = 2r \cdot sin(\frac{\alpha \cdot \pi}{360}). \quad (3.1)$$

The *angle of the circular segment* is used as an *independent variable* in the main study of this thesis and sets the other variables of the models for the different *types of curvature*.

3.3 Types of Curvature

We investigate three types of curvature *Full Curvature*, *Top Curvature*, and *Corner Curvature*. The different types of curvatures have been identified by looking at different ways of how the screen of a mobile device can be curved. First concave curvatures are excluded because the curvature should be aligned to the movement of the thumb. When looking from the side at the movement of the thumb it is observable that due to the circular movement of the thumb a concave curvature would move the screen farther away from the thumb which we expect would result in a smaller *functional area*(fig. 3.3). Therefore, convex curvatures are used to move the top area of the screen, which is a hard to

Curved protototpes are designed to better align the surface to the thumb movement.

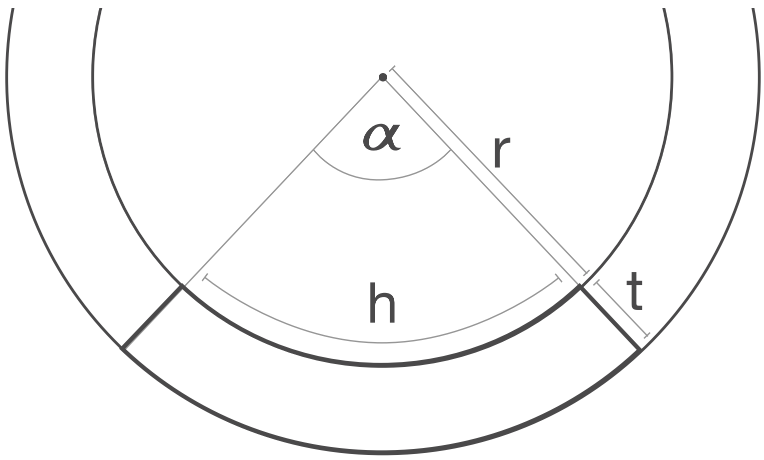


Figure 3.1: Variables used to calulate the circular segment (h). Radius (r), angle of the circular segment (α), Thickness (t)

reach area (Wroblewski [2012], Bergstrom-Lehtovirta and Oulasvirta [2014]), closer to the thumb.

3.3.1 Full Curvature

Process to design the 3D model of the *full curvature* prototype

Fully curving the screen is a first simple approach to investigate whether the curvature of the screen influences the size of the *functional area* by aligning the mobile device screen to the rotational movement of the thumb. The curvature type *Full Curvature* is achieved by a curve along the side of the mobile device. The resulting curved object can be described by the circular segment with a given length. The circular segment is defined by the angle α in *degrees* and the radius r of the circle in *mm* (eq. 3.1, fig. 3.1). α and r are constrained such that the length of the resulting circular segment matches the device height h. A second circular segment is added with the radius $r + t$ where t is the device thickness and with the same angle α as the previous segment. These two circular segments define the outline of the side view of the mobile device prototype (fig. 3.1). To create the 3D model for the prototype the outline defined by the two segments is extruded to the width of the device (fig. 3.2).

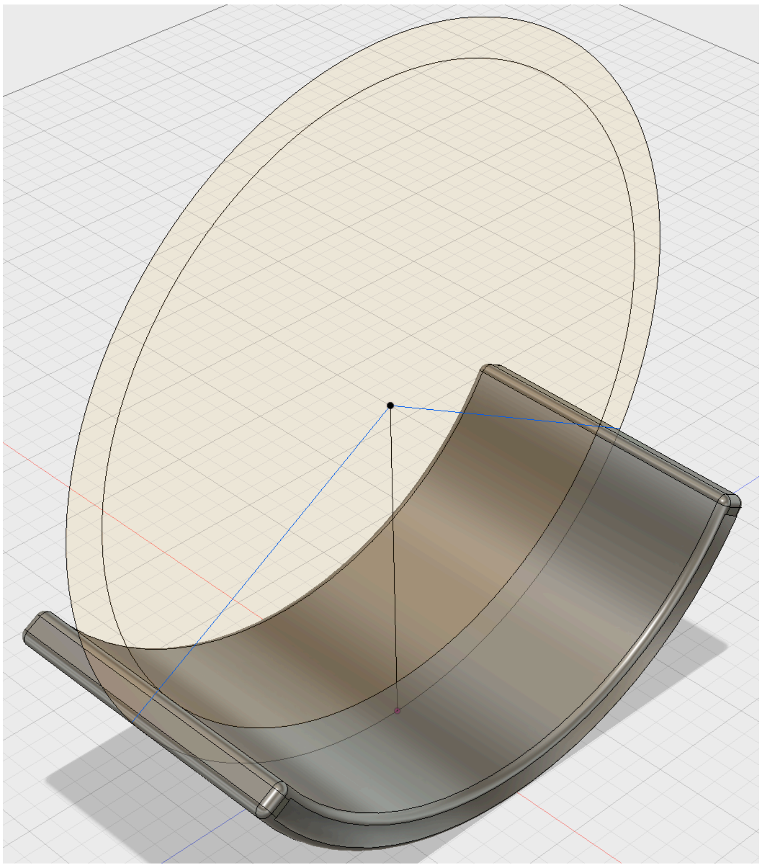


Figure 3.2: Extrusion of the full curvature shape.

The first created 3d printed prototype of the *curvature type full curvature* is given to people and they are asked to think of this prototype as a smartphone and hold it in one hand. They are further asked to perform some swipe gestures and touch interactions on the prototype as if they were using an application like the mail application. It is observable that users are holding the device differently than a regular smartphone by grasping the prototype in the center instead of at the bottom. Therefore, we create two further proto-

Initial observation showed people hold the *full curvature* prototype different than a flat device.

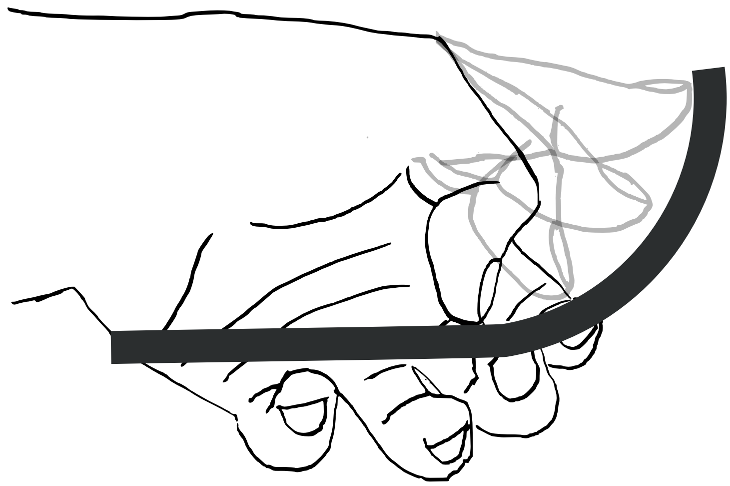


Figure 3.3: Rotary movement of the thumb during single handed interaction.

types that maintain the flat bottom part of a smartphone, which enables a firm grip for the user, and still curve the top part of the screen.

3.3.2 Preliminary Study

A preliminary study is conducted to determine variables for the following prototypes.

When holding a smartphone relaxed in one hand the thumb of the user hovers at around 20mm above the screen of the device (Hasan et al. [2016a]). To maintain the comfortability of this relaxed position while curving the screen towards the thumb we want to design the curvature of the top part in such a way that it meets the tip of the thumb (fig. 3.3). To set the beginning of the curvature of the top part of the mobile device to a feasible point we conducted a preliminary study with 18 participants. In this study we ask participants to hold a 3d printed prototype which resembles the size of an Apple iPhone X ($143.6mm \times 70.9mm \times 7.7mm$) (Apple Inc. [2018a]), hover the thumb relaxed over the screen and point the thumb towards the top corner of the screen. We then marked the position of the thumb tip on the prototype and measured the distance to the corner (d) and the angle (α) (fig. 3.4).

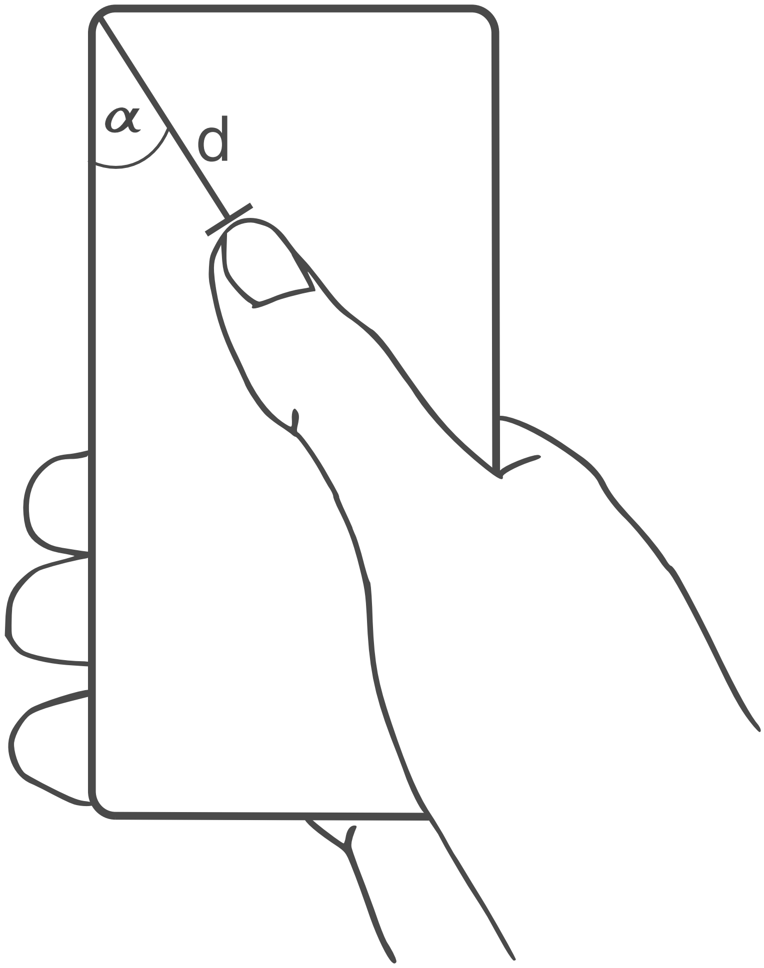


Figure 3.4: The two variables that were measured in the preliminary study. The angle (α) and the distance of the tip of the thumb to the corner of the device (d).

Results of the preliminary user study.

The results for the 18 participants were distance to corner (d) ($M = 58.61mm, SD = 4.97mm$) and angle (α) ($M = 35.72°, SD = 3.88°$). For the design of the following prototypes for the distance to corner we are adding the standard deviation to the mean and round it. Resulting in $64mm$ By doing so 95% of the preliminary study participants would be able to reach the curvature with their fingertip when using the curved prototype with a curvature at $64mm$ distance to the corner of the prototype. For the angle $35°$ are used in the top curved prototype design.

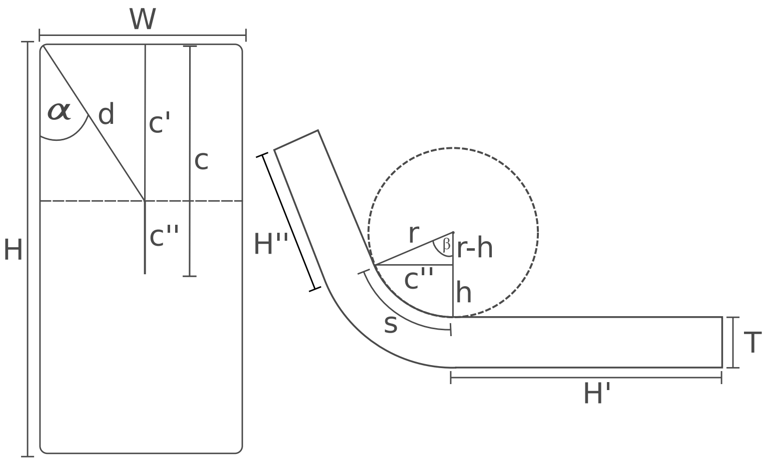


Figure 3.5: Variables of the *top curvature* prototype. Width (W), height (H), thickness (T), thumb hover (h), distance to corner (d), begin of the curvature (c), radius (r), circular segment (s). c′, c″, H′ and H″ are only used for the calculations (eq. 3.2 - 3.8).

3.3.3 Top Curvature

Process to design the 3D model of the *top curvature* prototype

The *top curvature* prototype is designed with a flat bottom part to enable a firm grip for the user such that the prototype rests steady in the user's hand. The top portion of the prototype has a concave curvature which is curved in such a way that it meets the tip of the thumb at the position determined in the aforementioned preliminary study. We expect that this prototype addresses comfortability concerns of people holding the *Full Curvature* prototype while still providing a larger *functional area* due to the fact that the top part of the screen is now closer to the tip of the hovering thumb. To create a model of this *Top Curvature* prototype the following equations need to be applied. Given are Width (W), height (H), thickness (T) of the prototype, and the height at which the thumb hovers (h). The angle (α) and the distance to corner (d) are determined by the preliminary study (chapter 3.3.2). The angle of the circular segment (β) will be an independent variable. The other variables of fig. 3.5 are calculated with the equations 3.2 - 3.8.

$$c' = cos(\alpha) \cdot d \tag{3.2}$$

$$r = \frac{-h}{\cos(\beta) - 1} \tag{3.3}$$

$$c'' = \sqrt{r^2 - (r-h)^2} \tag{3.4}$$

$$c = c' + c'' \tag{3.5}$$

$$H' = H - C \tag{3.6}$$

$$S = 2r \cdot sin(\frac{\beta \cdot \pi}{360}) \tag{3.7}$$

$$H'' = H - S - H' \tag{3.8}$$

The given equations (eq. 3.2 - 3.8) can be used to create a parametric model of the top curvature prototype which has the *angle of the circular segement* as an input parameter and can be used to create differently curved *Top Curvature* prototypes.

3.3.4 Corner Curvature

The movement of the human thumb can be approximated by a parabolic line (fig. 3.6) (Bergstrom-Lehtovirta and Oulasvirta [2014]). This parabolic line intersects with the line of the curvature in the *top curvature* curvature type as seen on the left hand side in fig. 3.6. We expect that due to this intersection the thumb cannot be pleasantly extended which might result in an uncomfortable interaction for the user of the prototype. Therefore, we are introducing a curvature along the line drawn from the tip of the extended

Process to design the 3D model of the *corner curvature* prototype

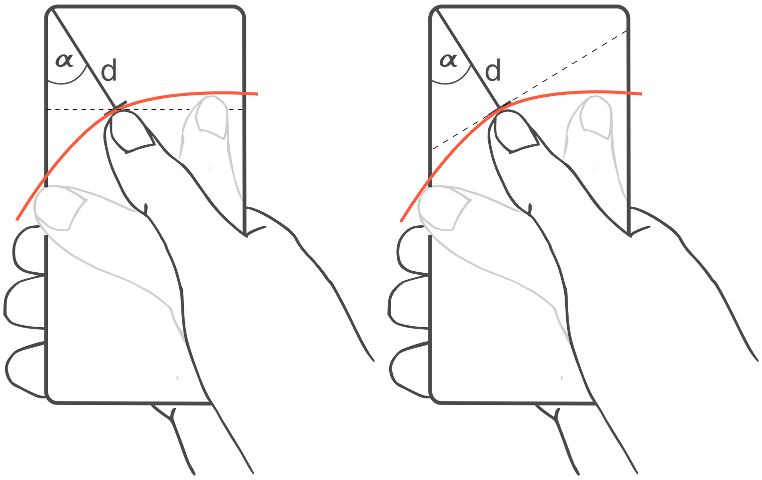


Figure 3.6: Parabolic approximation of the thumb movement in relation to the curvature line of the *top curvature* prototype (left) and the *corner curvature* prototype (right)

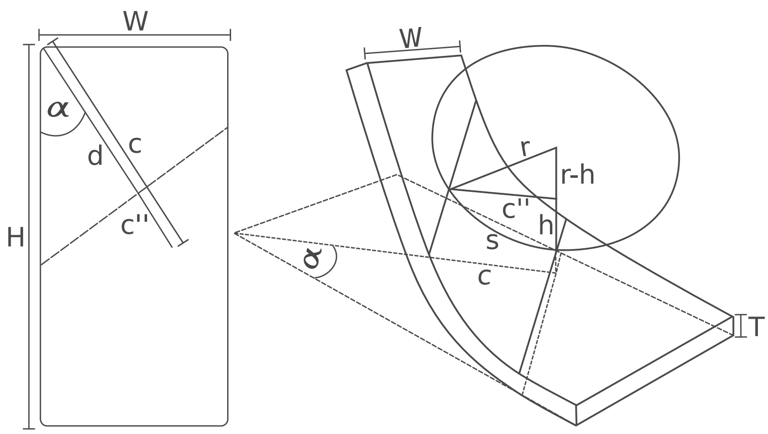


Figure 3.7: Variables of the *corner curvature* prototype. Width (W), height (H), thickness (T), thumb hover (h), distance to corner (d), begin of the curvature (c), radius (r), circular segment (s). c″is only used for the calculation (eq. 3.9)

thumb towards the top left corner of a smartphone (see line d in fig. 3.6). We expect that a slight extension of the thumb, which is necessary to reach the curved screen with the curvature along the line d in fig. 3.6, feels more comfortable than the necessary contraction of the thumb with the cur-

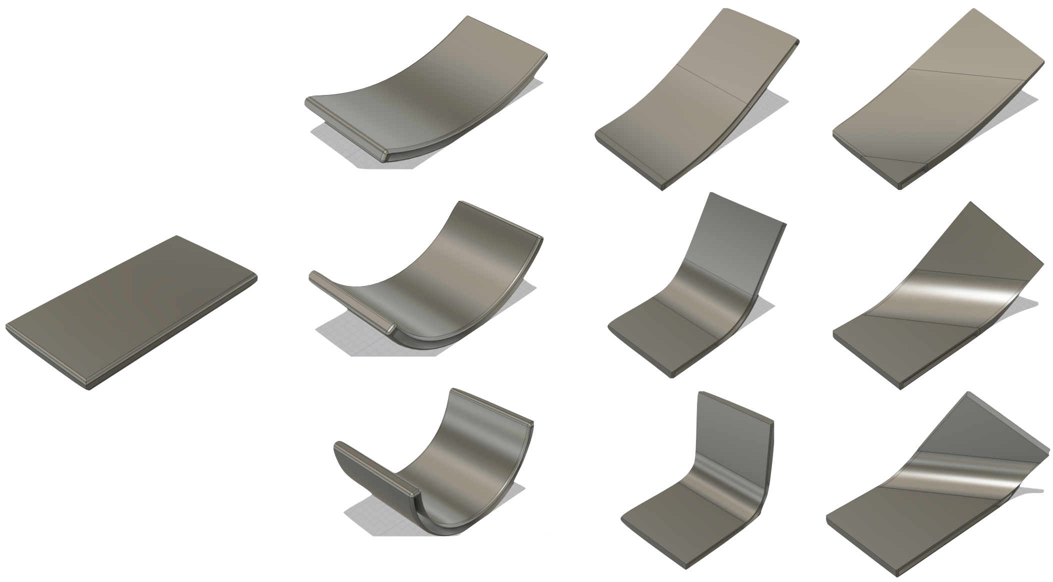


Figure 3.8: 3D Models of the final prototypes. Left to right: *baseline*, *full curvature*, *top curvature*, and *corner curvature*. From top to bottom (except baseline): 30°, 60°, and 90°

vature in the *top curvature* prototype. Additionally, we assume that a better alignment of the top part of the prototype can be achieved with such a curvature along the line d. To obtain such a curvature and create a parametric model the equations 3.3, 3.4, and 3.7 need to be applied. However, in contrast to the equation for the line c *Top Curvature* prototype (eq. 3.5) the result c″ is added to the distance to corner d (eq 3.9).

Calculations applied to achieve a curvature that meets the tip of the thumb better than *top curvature*.

$$c = c'' + d \tag{3.9}$$

By shifting the start of the curvature this way it is achieved that the curvature meets the tip of the finger (fig. 3.3). Similar to the design of the *Top Curvature* prototype the following variables are given, Width (W), Height (H), Thickness (T) of the prototype, and the height at which the thumb hovers (h). The angle (α) and the distance to corner (d) are determined by the aforementioned preliminary study (chapter 3.3.2). The angle of the circular segment (β) will be an independent variable.

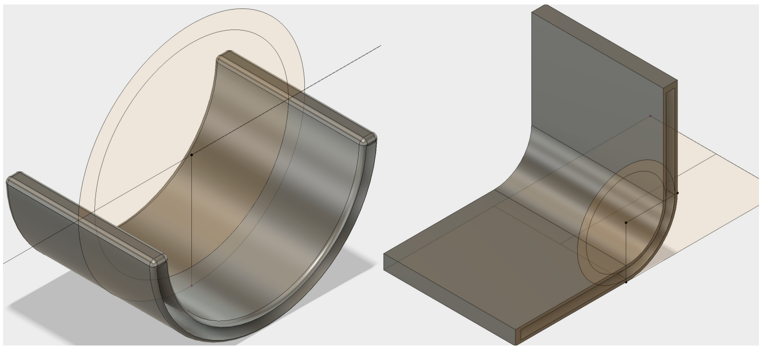


Figure 3.9: Extruded 3D models of the prototypes.

3.4 Fabricating the Curvature Prototypes

The prototypes are modeled in Fusion 360

3D models of the *curvature type* prototypes are created with the 3D modelling software Fusion 360 from Autodesk (Autodesk Inc. [2018]). The parametric equations 3.1 - 3.9 are used to create parametric models. For *Full Curvature* and *Top Curvature* the equations were used to create a sketch of the side of the prototype which was then extruded to a thickness (T) to create the 3D Model (fig. 3.9). To create the model for the *Corner Curvature* prototype the *Sheet Metal Workspace* was used. This workspace provides a *Refold* and *Unfold* feature. To utilize this feature a sketch similar to the sideview of the *Top Curvature* is created. However, this sketch is positioned at the angle α (fig. 3.4) and then extruded with the *Flange* feature of the *Sheet Metal Workspace* and the general extrude feature (fig. 3.10 1 & 2). The *Unfold* feature is then used to flatten the 3D model (fig. 3.10 3). Afterwards, the 3D model is trimmed to match the correct height (H), width (W), and thickness (T) (fig. 3.10 4). The Model is than curved again by using the *Refold* feature resulting in a model of the *Corner Curvature* (fig. 3.10 5 & 6).

Prototypes are designed hollow to allow a filling which matches the weight of current smartphones.

When 3D printed solid with 100% infill the prototypes are weighing around 50g. In comparison an Apple iPhone X weighs 174g (Apple Inc. [2018a]) and a Samsung Galaxy S8+ weighs 173g Samsung Electronics Co., Ltd. [2017]. Thus, the prototypes are too light to mimic a current smartphones. Therefore, the 3D models are designed hollow with interior walls of 1.5mm thickness to allow for filling

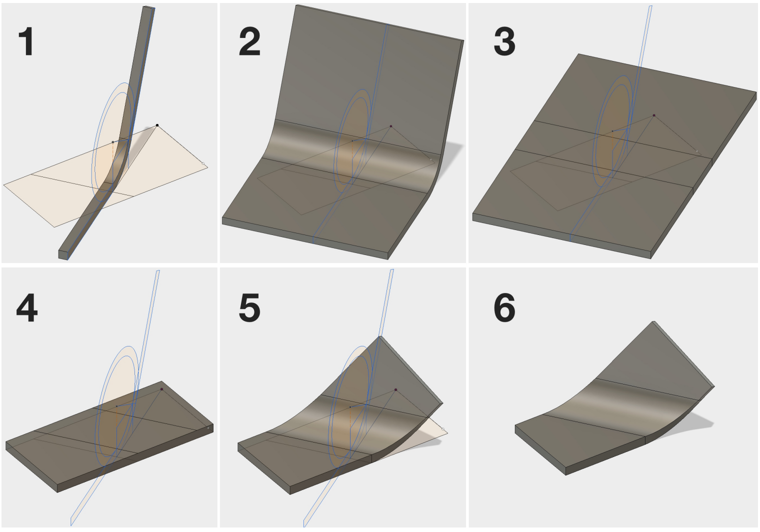


Figure 3.10: Step by step process of creating the *corner curvature* prototype (explained in 3.4 "Fabricating the Curvature Prototypes")

the printed prototype with sand afterwards to match the weight of current smartphones.

The models are then 3D printed with a *Stratasys Dimension Elite 3D Printer* (Stratasys Inc. [2016]) using black ABS filament. Afterwards, the 3D prints are sanded and the edges are rounded down to increase the comfortability when holding the prototypes. After filling the prototypes with sand the hole on the side of the prototype is sealed off with a mouldable self-adhesive silicone (FormFormForm Limited [2018]) resulting in the finished prototype.

Prototypes are 3D printed after the design process.

Chapter 4

Study

In the previous chapters assumptions and expectations are mentioned which are formalized in two research questions and hypotheses within this chapter. An empirical evaluation to test the hypotheses is conducted in form of a user study, which is described in detail in this chapter.

4.1 Research Questions

RQ1 Do different levels and types of curvature of a mobile device touchscreen change the size of the functional area for single-handed thumb interaction?

RQ2 Do different levels and types of curvature of a mobile device touchscreen change the perceived comfortability for single-handed thumb interaction?

4.2 Hypotheses

The following hypotheses (stated in null form, i.e. expected to be rejected) are tested in the user study of this thesis.

H1 Increasing the *angle of the circular segment* will not change the *functional area*.

H2 Increasing the *angle of the circular segment* will not change the *comfortability ranking*.

H3 There is no significant difference in *comfortability ranking* between the *curvature types full curvature*, *top curvature*, and *corner curvature*.

H4 There is no significant difference in the size of the *functional area* between the *curvature types full curvature*, *top curvature*, and *corner curvature*.

4.3 Limitation of the Angle of the Circular Segment

Angles larger than $90°$ result in screen occlusion.

With a constant device size and a constant starting point of the curvature the radius r of the osculating circle will decrease with increasing curvature. With decreasing radius r the central angle α of the circular segment will increase (fig. 3.1). When α gets larger than $90°$ the circular segment will begin to be curved in a way that it covers the screen when looking at the mobile device. We consider this unpractical in a real world use case and will therefore only test curvatures until α will be at $90°$.

4.4 Study Variables

4.4.1 Dependent Variables

- **Size of the Functional area** [percentage covered]. The *functional area* of the thumb on a touchscreen surface is the area of the touchscreen surface which is reachable by the thumb that is holding the device without changing the grip on the device (Bergstrom-Lehtovirta and Oulasvirta [2014]). The *functional area* is measured as the percentage of the whole device screen which is covered by the *functional area*.
- **Comfortability** [10-point exclusive ranking]. Participants are asked to rank the *comfortability* of the task

during the study in relation to the prototype that was used. It is explained that a comfortable interaction means that the participant does not feel any strain or pain while performing the study task. The higher the ranking the better the feeling of comfortability (10 = highest comfortability, 1 = lowest comfortability)

4.4.2 Independent Variables

- **Curvature type** [*full curvature*, *top curvature*, *corner curvature*]. For the curvature type the curvatures described in chapter 3.3 are tested in this study
- **Angle of the circular segment** [0°(baseline), 30°, 60°, 90°]. Due to the physical limitation of the *angle of the circular segment* (section 4.3) 90° is the upper limit of this variable. Therfore, the range between the baseline (0°) and the upper limit (90°) is distributed into three equal parts to create a meaningful diffierence between the conditions which shows the influence of the angle on the dependent variables.

4.5 Task

Participants of the user study are presented the prototypes of the different *curvature types*. To capture the functional area, the participants are asked to hold the prototype in one hand and perform a parabolic gesture with the thumb beginning at the top right side of the prototype and ending on the bottom right side (fig. 4.5). Participants are asked to extend their thumb as much as it still feels comfortable during the gesture. It is emphasized that the participants should not feel any strain or pain during the interaction such that the gesture itself does not confound the comfortability ranking. If they cannot reach the bottom right part of the device because it feels uncomfortable the participants are asked to stop the motion the moment it begins to feel uncomfortable.

Study participants are asked to perform a parabolic gesture to mark the *functional area*

This motion will mark the outline of the *functional area*

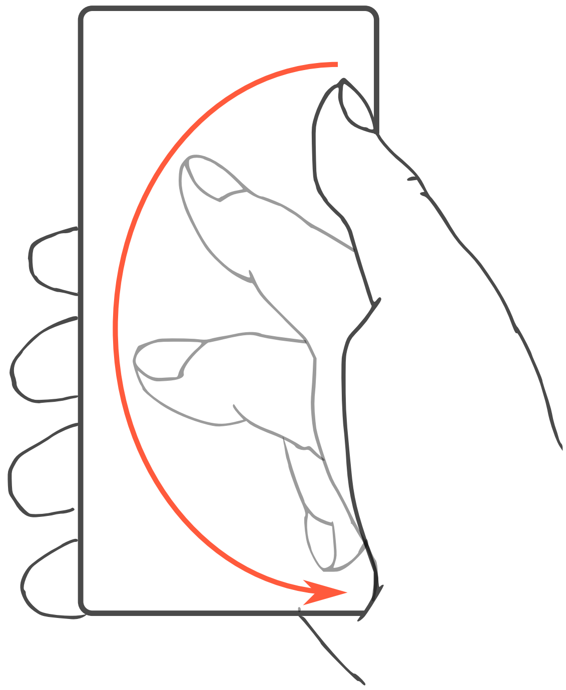


Figure 4.1: Parabolic gesture of the study task.

Participants are asked to fill the previously marked outline of the *functional area*.

(Bergstrom-Lehtovirta and Oulasvirta [2014]). To further mark the *functional area* participants are requested to cover the inside surface (the surface between the line and the right side of the device) of the drawn line by dragging their thumb over the surface of the prototype (fig.4.2). Again, this gesture should not feel uncomfortable and if that is the case participants should discontinue the movement and cover other parts of the surface. By doing so the participants are covering the whole *functional area*. During the

Figure 4.2: The task performed by participants during the user study, which marks the *functional area*.

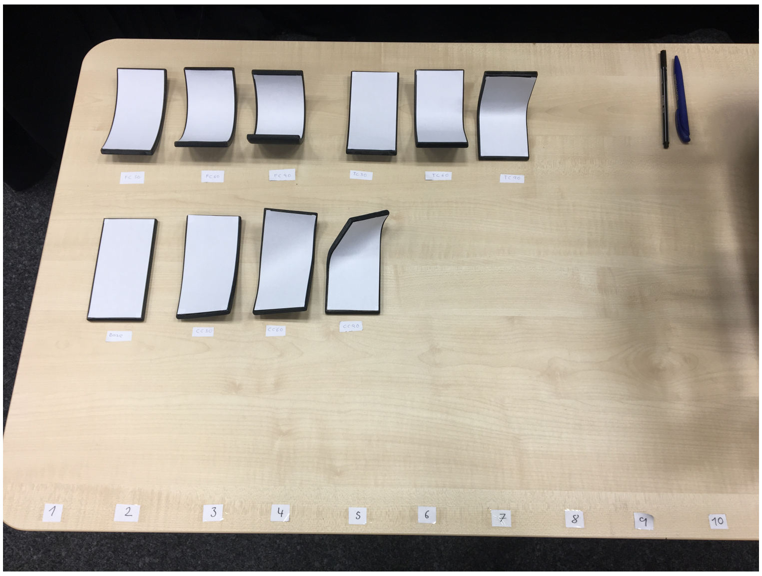


Figure 4.3: Study setup showing the prototypes and the ranking slots on the bottom.

whole interaction the participants are asked to not change their grip on the device.

4.6 Experimental Design

The study is conducted using a *within-subject design* to test every condition with each participant. This limits the number of participants and reduces confounding factors due to

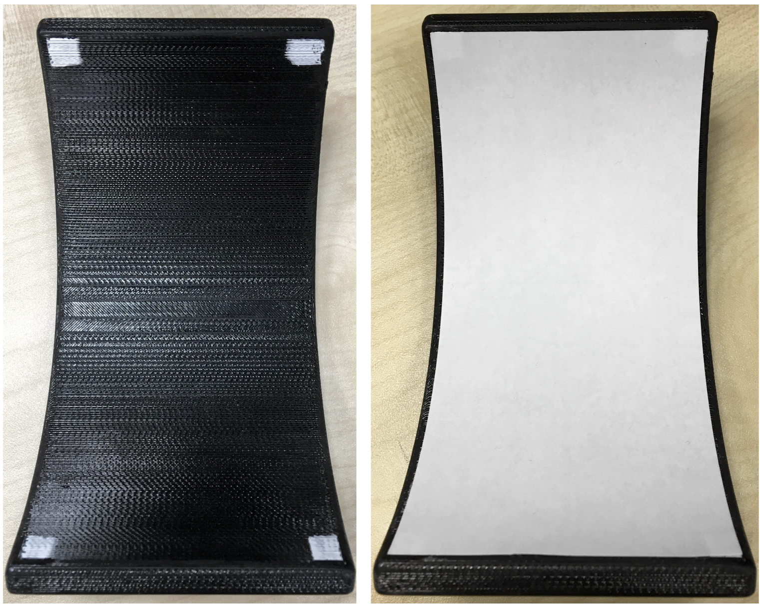


Figure 4.4: Markings to align the sheet of paper equally between participants.

Within-subject design with 10 trials per participant.

individual differences between the participants. Each participants needs to perform 10 trials (*curvature type* (*full curvature, top curvature, corner curvature*) × *angle of the circular segment* (30°, 60°, 90°) + *baseline* 0° = 10 trials per participant). To address potential carry-over effects the order of the conditions per participant is balanced using a *latin-square*. To reduce fatigue the participants are offered to take a break whenever they feel strained during the study.

Black finger paint on a white sheet of paper was used to capture the participant's movement.

To capture the users finger movement on the curvature prototypes while performing the study task black finger paint was used. Additionally a white removable adhesive sheet of paper was sticked onto the front side of the prototype. This white sheet of paper created a contrast to the black paint to identify the area that the participant covered during the study task. Additionally the dimension of the sheet of paper ($139mm \times 66mm$) gave the user the impression of a screen on the front of the prototype. The paper was positioned at the center of each prototype and the position was marked to ensure the same position of the sheet of paper for each participant (fig. 4.4).

To ensure that the interaction with the prototype feels familiar for the participants, dimensions close to current smartphones are used for the *curvature prototypes* (Apple Inc. [2018a], Samsung Electronics Co., Ltd. [2017], TrendForce Corp. [2018]). Height (H) 143.6mm, Width (W) 70.9mm , and Thickness (T) 7.7mm.

For every combination of the independent variables *Curvature type* and *angle of the circular segment* a physical 3D printed prototype is created with the techniques explained in section 3.3 except for the baseline angle where only one prototype was created because the angle 0° looks the same for every *curvature type*. At the beginning of the study, the prototypes are presented to the participant and she is asked to familiarize herself with every prototype. The process of familiarization is clarified by asking the participant to pick up each prototype, pretend that it is her smartphone, and do some touch and dragging gestures on the device. It is recommended to imagine a regularly used app like an e-mail application displayed on the white sheet of paper during the familiarization phase. Especially with the strongly curved (90°) prototypes, it can be observed that people are unsure how to hold the prototype because the shape is different to a regular smartphone. To avoid that this unfamiliarity becomes a confounding factor the familiracation process is applied

At the beginning of the study, the participant is asked to familiarize herself with the prototypes.

After the familiarication process one of the prototypes, it is placed in front of the seated participant. The prototypes are always placed in the same position. The participant is then asked to pick up the device with one hand and perform the study task (section 4.5) with the thumb covered in black paint. If the thumb is no longer covered in paint but the task is not finished, new paint gets applied to the thumb. When the participant has finished the study task with one prototype she is asked to rank the prototype according to the comfortability of the gesture performed during the task. To do so, numbers from one to ten are printed on small sheets of paper and stuck to the table that the participant is sitting at (4.3). The participant can then place the prototype above the number which she wants to give as a ranking. Changing the ranking of a prototype later is possible and the ranking is captured at the end of the study when the participant

The participant is asked to rank each prototype after the task was finished for the individual prototype.

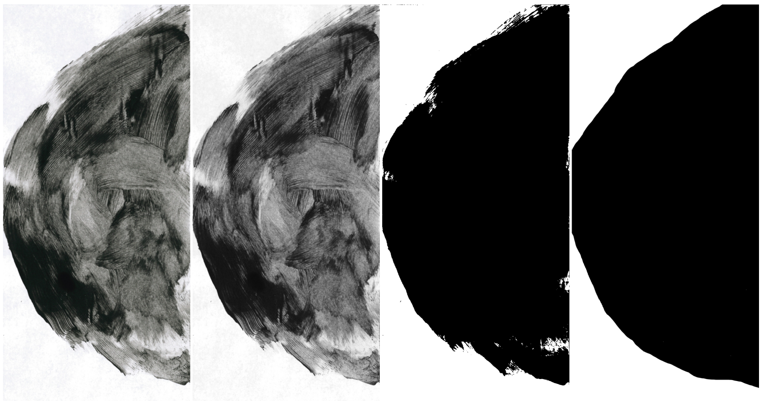


Figure 4.5: Editing process of the captured *functional areas* of the user study. From left to right: (1) Raw image. (2) Converted to greyscale. (3) Threshold algorithm marking a pixel either black or white. (4) filling of holes after the threshold algorithm.

confirms that she made her decision for the final ranking. The participant is always allowed to pick up a previously used prototype again to refresh the feeling of holding the prototype and compare it to the others. Additionally, participants were encouraged to give feedback about their impressions of the prototypes and their thoughts about them.

Only right handed participants participate in the user study because the *curvature type corner curvature* is designed for interaction with the thumb of the right hand.

Captured participant markings of the *functional area* are scanned and edited.

After the study is finished the sheets of papers with the participant markings on them are removed from the prototypes and scanned with a Triumph Adler 5056i document scanner (Triumph-Adler GmbH [2018]). The sheets of papers are scanned with $600 \times 600dpi$ and saved to a pdf file with the highest image quality of the scanner (image quality 5 in the scanner file format settings). The images are then converted to grayscale and a threshhold algorithm is applied by using the *colorspace grey* and the *threshold value* feature of the application ImageMagick (ImageMagick Studio LLC [2018b], ImageMagick Studio LLC [2018a]). The threshold algorithm converts every pixel above the threshold value of 90% that we are using for the conversion to white and every pixel below the threshold to black. Afterwards, holes in the captured shape that are caused by uneven coverage of the black paint are filled by hand using the image editor application Pixelmator (Pixelmator Team [2018]). An algorithm, written in Swift (provided by Dr. Simon Voelker) checks each pixel of the final image whether it is black or white and the percentage of black pixels is returned.

Chapter 5

Evaluation

15 people (five female) participated in the user study. For Five participants the data of the recorded *functional area* markings need to be discarded due to an error in the capturing method for the first five participants of the study. The ranking data of these five participants is still used because we do not expect that the capturing method did confound these data points. The baseline (0° *angle of the circular segment* was only tested once for every participant while the other angles were tested three times per participant (once for every *curvature type*. This results in a sample size of 10 for the *size of the functional area* for each of the condition (*Baseline* (*B0*), *Corner Curvature* 30° (*CC30*), *Corner Curvature* 60° (*CC60*), *Corner Curvature* 90° (*CC90*), *Full Curvature* 30° (*FC30*), *Full Curvature* 60° (*FC60*), *Full Curvature* 90° (*FC90*), *Top Curvature* 30° (*TC30*), *Top Curvature* 60° (*TC60*), and *Top Curvature* 90° (*TC90*)) and a sample size of 15 for the *comfortability ranking* of each condition. This was done due to the fact the angle 0° has the same shape (flat) for every *type of curvature*. However, this results in a smaller sample size for the baseline condition.

Study design resulted in a smaller sample size of the baseline condition.

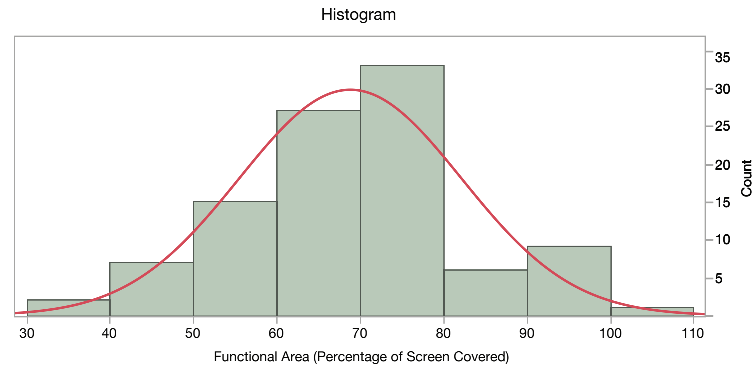


Figure 5.1: Histogram of the distribution of the sampled *size of the functional area*.

5.1 Normality Test

Data for the size of the *functional area* is close to normal distribution.

It is planned to test the interaction between the independent variables *curvature type* and *angle of the circular segment* and the dependent variable *size of the functional area* for significance. This is done by applying an analysis of variance with repeated measures which require that the dependent variable is approximately normally distributed (Lund Research Ltd [2013a]). Visually inspection of the histogram and the normal quantile plot give the impression that the gathered data of the dependent variable *size of the functional area* is approximately normally distributed (fig. 5.1, 5.2). Additionally, a *goodness-of-fit test* with a *Shapiro-Wilk test* (SHAPIRO and WILK [1965]) does not reject the H0 hyopthesis that the data is from the normal distribution ($W = 0.98, p = 0.18$). Therefore, the data for the independent variable *size of the functional area* is assumed to be normally distributed.

5.2 Test for Significant Effects on the Size of the Functional Area

No *significant effect* of the *curvature type* on the *size of the functional area*.

The analysis did not show a *significant effect* of the *curvature type* on the *size of the functional area* ($F_{2,72} = 1.33$, $p = 0.27$).

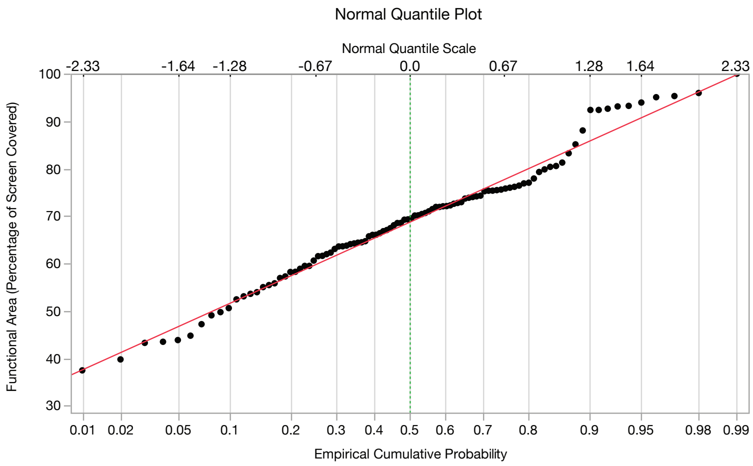


Figure 5.2: Normal quantile plot of the distribution of the sampled *size of the functional area*.

full curvature (M = 69.98%, SD = 4.32%), *top curvature* (M = 67.50%, SD = 4.32%), and *corner curvature* (M = 66.23%, SD = 4.32%). This result retains the hypothesis H4 which states that there is no significant difference in the size of the *functional area* between the *curvature types full curvature*, *top curvature*, and *corner curvature*.

However, the analysis did show a significant effect of *angle of the circular segment* on the *size of the functional area* ($F_{3,87}$ = 4.58, $p < .05$). With the angle 0° (M = 64.46%, SD = 4.36%) having the smallest *functional area*, followed by the angle 30° (M = 67.90%, SD = 4.13%) and the angle 60° (M = 68.89%, SD = 4.13%), with the angle 90° (M = 71.24%, SD = 4.13%) having the largest percentage of the *functional area*. A Tukey HSD post test showed that the levels 0° and 90° are significantly different with a difference of the mean of 6.78%. This result rejects the hypothesis H1 which states that increasing the *angle of the circular segment* will not change the *functional area*.

Significant effect of *angle of the circular segment* on the *size of the functional area*.

Since the baseline did have a lower sample size than the other *angles of the circular segment* a cross interaction effect of *angles of the circular segment* × *curvature type* was only tested for the *angles of the circular segment* 30°, 60° and 90°. However, the analysis did not show a significant effect of

No significant effect of *curvature type* × *angles of the circular segment* on the *size of the functional area* *curvature type* × *angles of the circular segment* on the *size of the functional area* ($F_{4,72}$ = 1.06, p = 0.39). The descriptive statistics for the cross interaction effect of *angles of the circular segment* × *curvature type* are given in table 5.1.

Condition	Mean	SD
full curvature 30°	69.98%	4.32%
top curvature 30°	67.50%	4.32%
corner curvature 30°	66.23%	4.32%
full curvature 60°	70.14%	4.32%
top curvature 60°	67.30%	4.32%
corner curvature 60°	69.24%	4.32%
full curvature 90°	70.16%	4.32%
top curvature 90°	70.77%	4.32%
corner curvature 90°	72.80%	4.32%

Table 5.1: Descriptive statistics for the cross interaction effect of *angles of the circular segment* × *curvature type* for the *size of the functional area*

5.3 Test for Significant Effects on the Comfortability Ranking

The *Friedman test*, a test for non-parametric related samples, is used to test for a significant effect of the independent variables on the *comfortability ranking* (Lund Research Ltd [2013b]). The *Friedman test* is applied due to the fact that the measurement scale of the dependent variable *comfortability ranking* is ordinal.

No significant effect of the *curvature type* on the *comfortability ranking*.

The analysis shows no significant effect of the *curvature type* on the *comfortability ranking* ($\chi^2(2)$ = 1.91, p = .39). The descriptive statistics are given in table 5.2. This result retains the hypothesis H3 which states that there is no significant difference in *comfortability ranking* between the *curvature types full curvature*, *top curvature*, and *corner curvature*.

However, the analysis shows a significant effect of the *angle of the circular segment* on the *comfortability ranking* ($\chi^2(3)$ = 23.24, $p < .001$) with the descriptive statistics given in table

Curvature Type	Min	Max	Mean	SD
full curvature	1	10	5.07	3.1
top curvature	1	10	5.60	3.06
corner curvature	1	10	5.38	2.74

Table 5.2: Descriptive statistics of the *comfortability ranking* for the *curvature type*

Angle	Min	Max	Mean	SD
0°	5	10	6.87	1.6
30°	4	10	8.22	1.76
60°	3	10	5.36	1.86
90°	1	8	2.47	1.77

Table 5.3: Descriptive statistics of the *comfortability ranking* for the *angle of the circular segment*

Sample1 - Sample2	p-value
full curvature 90° - *baseline* 0°	$< .001$
full curvature 90° - *full curvature* 30°	$< .001$
full curvature 90° - *top curvature* 30°	$< .001$
full curvature 90° - *corner curvature* 30°	$< .001$
top curvature 90° - *baseline* 0°	$= .002$
top curvature 90° - *full curvature* 30°	$< .001$
top curvature 90° - *top curvature* 30°	$< .001$
top curvature 90° - *corner curvature* 30°	$< .001$
corner curvature 90° - *baseline* 0°	$= .033$
corner curvature 90° - *full curvature* 30°	$< .001$
corner curvature 90° - *top curvature* 30°	$< .001$
corner curvature 90° - *corner curvature* 30°	$= .002$
full curvature 90° - *top curvature* 60°	$= .017$
full curvature 60° - *top curvature* 30°	$= .026$
full curvature 60° - *full curvature* 30°	$= .041$

Table 5.4: Significant pairs of the pairwise comparison for significant effect of the *curvature types* × *angle of the circular segment* on the *comfortability ranking*

Condition	Min	Max	Mean	SD
baseline 0°	5	10	6.87	1.60
full curvature 30°	4	10	8.47	1.89
top curvature 30°	6	10	8.60	1.40
corner curvature 30°	4	10	7.60	1.88
full curvature 60°	3	8	4.80	1.57
top curvature 60°	3	9	5.87	1.96
corner curvature 60°	3	10	5.40	1.99
full curvature 90°	1	5	1.93	1.10
top curvature 90°	1	6	2.33	1.54
corner curvature 90°	1	8	3.13	2.33

Table 5.5: Descriptive statistics of the related samples *curvature type* × *angles of the circular segment* for the *comfortability ranking*

5.3. A pairwise comparison shows a significant effect on the *comfortability ranking* of the pairs (90° - 0°, $p < .001$) and (90° - 30°, $p < .001$). This result rejects the hypothesis H2 which states that increasing the *angle of the circular segment* will not change the *comfortability ranking*.

Additionally, the analysis shows a significant effect of the interaction *curvature type* × *angle of the circular segment* (with the baseline 0° added as a single condition) on the *comfortability ranking* ($\chi^2(9)$ = 87.83, $p < .001$). A pairwise comparison shows a significant effect on the *comfortability ranking* of the pairs shown in table 5.4. The descriptive statistics are given in table 5.5.

5.4 Discussion

The significant effect of the *angle of the circular segment* on the *size of the functional area* indicates that increasing the angle results in an increased size of the *functional area*. Looking at the mean of the angle 0° (M = 64.46%) and the angle 90° (M = 71.24%) shows that there is a difference of 6.78%. The white paper on the prototypes, which suggests an interaction surface, is $139mm \times 66mm$ in size.

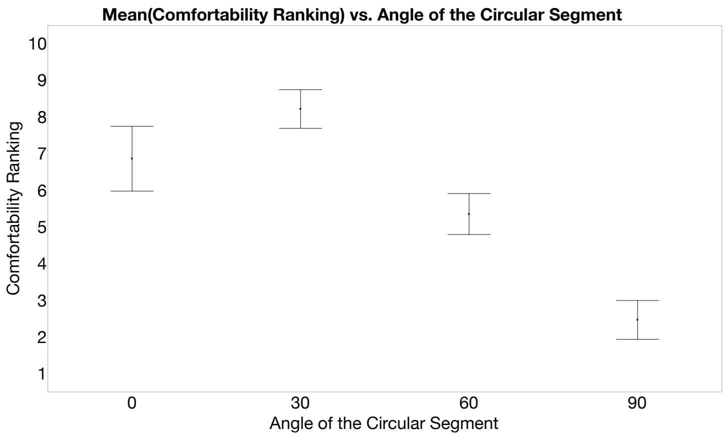


Figure 5.3: Mean *comfortability ranking* with 95% CI of the *angles of the circular segment*

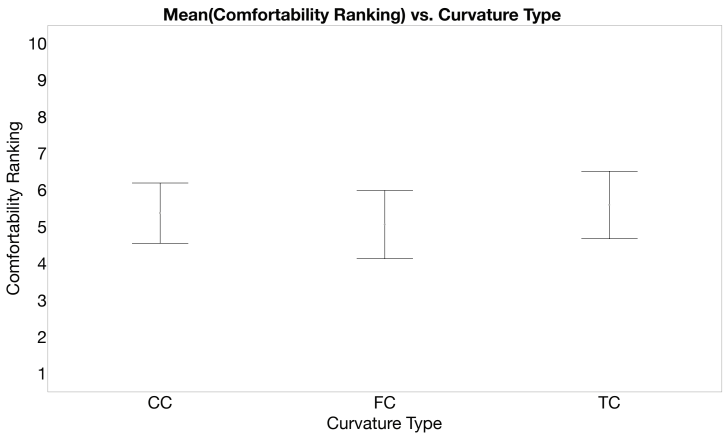


Figure 5.4: Mean *comfortability ranking* with 95% CI of the *curvature types*

An increase of 6.78% is, therefore, equal to a surface of $24.94mm \times 24.94mm$). However, this increase is only achieved for the largest angle of the circular segment 90°, which had the lowest *comfortability ranking* for all *curvature types*. This is supported by the user feedback where 10 of the 15 participants stated in some way that the interaction with the 90° prototypes feels weird. The participants stated as reasoning that the centre of mass of the prototype feels off which results in a feeling that the device can easily slip out of the hand. Additionally, two participants mentioned

The significant increase in the size of the *functional area* with increasing curvature angle results also in a significant decrease of the *comfortability ranking*.

that due to the small radius of the curvature of the $90°$ prototypes it was hard to touch the surface inside the curvature because their thumb felt too big. Therefore, it can be concluded that a small increase in the size of the *functional area* by increasing the *angle of the circular segment* of the curvature comes with a high discomfort for the user. This results in a trade-off that needs to be considered when designing a curved mobile device.

Process of improving the *curvature* type did not result in a significant effect on the dependent variables.

The process of improving the style of the curvature, which is described in chapter 3.3 "Types of Curvature", did not yield a significant effect of the *curvature type* on the *size of the functional area* or the *comfortability ranking*. Thus, when designing a curved mobile device other factors than comfortability and the size of the *functional area* can be considered (e.g. visual appearance).

The mean of the *comfortability ranking* for the $30°$ angle was higher in comparison to the baseline $0°$ angle.

Interestingly, the baseline angle $0°$ (M = 6.87) is ranked lower than the angle $30°$ (M = 8.22). This is supported by the feedback of one participant who stated "Feels very similar to [the] baseline but the bending seems to help [the] comfortability" for the *top curvature* $30°$ prototype. Another participant stated that she does not think that the prototypes with the small angles will increase the area she can touch but they feel pleasant. Apparently, the small curvatures do align better with the hand during single-handed interaction. The difference of the means for the *functional area* between the $30°$ prototypes and the baseline design is 3.44%. However, the standard deviation for both means is 4.13% which means that there could also be no increase in the *functional area* between the $30°$ prototypes and the baseline. Therefore, this suggests that there is potential for a small improvement by applying curvatures with an *angle of the circular segment* of around $30°$ for the comfortability but probably not for the *functional area*.

In addition to the lowering *comfortability ranking* increasing the *angle of the circular segment* of the curvature does also skew the screen and therefore distort the displayed content.

Overall, the positive effect of the increase of the size of the *functional area*, which is only significantly different for the angles $0°$ and $90°$ seems small in comparison to the low ranking of the *comfortability* for the 90° curvatures and the strong participant feedback against them.

Chapter 6

Summary and future work

6.1 Summary and contributions

We investigated how the curvature of a curved mobile device influences the *functional area* and the comfortability of interacting with the device. Three different kind of curvatures (*full curvature*, *top curvature*, *corner curvature*) and four different angles of the curvature (0°, 30°, 60°, 90°) have been evaluated in a user study with 15 participants.

Study capturing the *functional area* has been conducted.

To conduct the user study 3D printed prototypes have been fabricated for the baseline (0°) and every combination of the angles and curvature types. Participants marked the functional area that they were able to reach with their thumb using black finger paint on a white sheet of paper mounted on the prototypes. The white sheet of paper gave the impression of a screen and an interaction area for the users. During the study, participants ranked the interaction on an exclusive ranking. Afterwards, the percentage of the paper which was covered in black paint was calculated.

We found a significant effect of the *angle of the circular segment* on the *size of the functional area* and the *comfortability ranking*. Another significant effect was found of the interaction *curvature type* $\times$ *angle of the circular segment* on the *comfortability raning*

Smaller angles yielded better mean of *comfortability ranking* in comparison to the baseline.

The results indicate that the angle of the curvature increases the size of the *functional area*. However, the increase of $2.5cm \times 2.5cm$ seems small in comparison to the low comfortability ranking (mean of 2.47 for the $90°$ angles) and the participant feedback during the study. Participants mentioned that the $90°$ angle prototypes feel weird and that they fear to lose the grip on the device during the interaction due to the shifted centre of mass. Interestingly the $30°$ angle prototypes received a better average ranking of 8.22 in comparison to the ranking of 6.87 for the baseline $0°$ angle. This matches user feedback during the study where the $30°$ created the feedback that they are feeling nice in the hand. Yet, it needs to be considered that the standard deviation error bars of the two means do overlap.

6.2 Future work

The influence of type and angle of the curvature can be evaluated for further variables concerning the user performance on touch interaction. For example, the task completion time for dragging tasks along the curvature can be investigated to see whether the results of Weiss et al. [2010] also hold true for curvatures on mobile devices and the interaction with the thumb.

Low *comfortability rankings* for larger angles can be addressed to facilitate the increase in the size of the *functional area*.

The size of the *functional area* increases with increasing angle of the curvature. However, the comfortability ranking decreases with increasing angle of the curvature. The source for the low comfortability can be further investigated and designs or techniques can be explored to improve the comfortability. By doing so the positive effect of the increasing *functional area* could be utilized at best without any decrease in comfortability or at least a reduction in the trade-off between comfortability and size of the *functional area*. As a starting point, the weight distribution of the prototypes could be changed to examine whether this results in a more stable interaction and fewer concerns that the grip on the device might get lost.

Additionally, the finding that the 30° angle prototypes had a slightly better comfortability ranking than the 0° baseline can be further explored. If such a curvature brings a slight increase in the size of the *functional area* and the comfortability ranking further aspects of the user performance of the touch interaction can be studied. Maybe a slightly curved mobile device can provide a general improvement in comparison to the current flat smartphone designs.

Curvature with smaller angles seem promising.

Finally, the shape of the type of the curvature can be further improved. The current curvature types still have the straight line where the curvature meets the tip of the thumb. However, the movement of the thumb is close to a parabolic line (Bergstrom-Lehtovirta and Oulasvirta [2014]. Therefore, shaping the line where the curvature meets the fingertip parabolic instead of straight could improve the comfortability of the interaction. This improvement is expected due to a better alignment of the prototype along the movement of the thumb.

Shape of the curvature can be improved.

Appendix A

Study Questionnaire

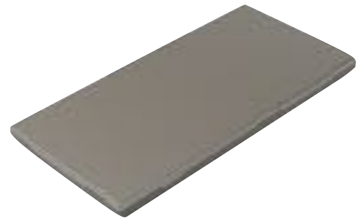
Study: Reachability on Curved Mobile Device Touchscreens

Participant Number : ____ Age: ____

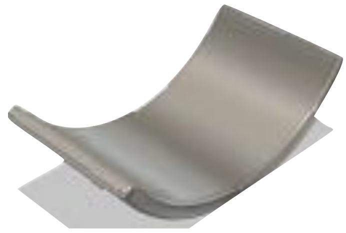
Gender: O Female O Male O ___________

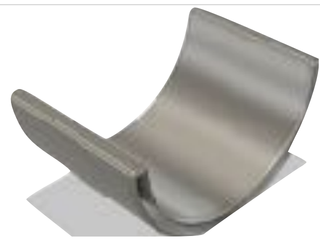
Hand Print Outline

Study: Reachability on Curved Mobile Device Touchscreens

Baseline	**Comfortability Rank:**	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

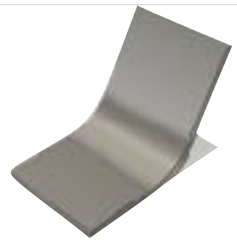
Full Curvature 30º	**Comfortability Rank:**	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Full Curvature 60º	**Comfortability Rank:**	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Full Curvature 90º	**Comfortability Rank:**	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

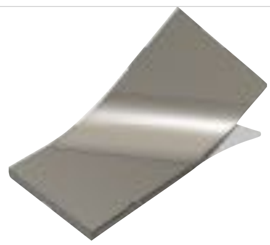
Top Curvature 30º	**Comfortability Rank:**	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

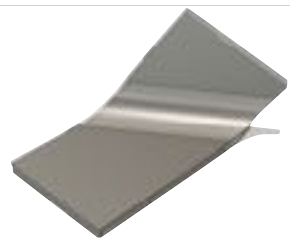
Study: Reachability on Curved Mobile Device Touchscreens

Top Curvature 60º	Comfortability Rank:	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Top Curvature 90º	Comfortability Rank:	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Corner Curvature 30º	Comfortability Rank:	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Corner Curvature 60º	Comfortability Rank:	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

Corner Curvature 90º	Comfortability Rank:	Rank: 1 = lowest, 10 = highest
Is there something besides the comfortability that you like or dislike especially about this prototype?		

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