Chair for Computer Science 10 (Media Computing and Human-Computer Interaction)

RWTH AACHEN UNIVERSITY

Non-Linear Menus: A Comparison of Linear and Non-Linear Menus on Mobile Devices

Bachelor's Thesis
submitted to the
Media Computing Group
Prof. Dr. Jan Borchers
Computer Science Department
RWTH Aachen University

by
Maurice Schwarze

Thesis advisor:
Prof. Dr. Jan Borchers

Second examiner:
Prof. Dr. Ulrik Schroeder

Registration date: 20.07.2020
Submission date: 04.01.2020

Zentrales Prüfungsamt/Central Examination Office

RWTH AACHEN UNIVERSITY

Eidesstattliche Versicherung
Statutory Declaration in Lieu of an Oath

Schwarze, Maurice
Name, Vorname/Last Name, First Name

370661
Matrikelnummer (freiwillige Angabe)
Matriculation No. (optional)

Ich versichere hiermit an Eides Statt, dass ich die vorliegende ~~Arbeit~~/Bachelorarbeit/~~Masterarbeit~~* mit dem Titel
I hereby declare in lieu of an oath that I have completed the present ~~paper~~/Bachelor thesis/~~Master thesis~~* entitled

Non-Linear Menus: A Comparison of Linear and Non-Linear Menus on Mobile Devices

selbstständig und ohne unzulässige fremde Hilfe (insbes. akademisches Ghostwriting) erbracht habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt. Für den Fall, dass die Arbeit zusätzlich auf einem Datenträger eingereicht wird, erkläre ich, dass die schriftliche und die elektronische Form vollständig übereinstimmen. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.
independently and without illegitimate assistance from third parties (such as academic ghostwriters). I have used no other than the specified sources and aids. In case that the thesis is additionally submitted in an electronic format, I declare that the written and electronic versions are fully identical. The thesis has not been submitted to any examination body in this, or similar, form.

Aachen, 29.12.2020
Ort, Datum/City, Date

Schwarze
Unterschrift/Signature

*Nichtzutreffendes bitte streichen
*Please delete as appropriate

Belehrung:
Official Notification:

§ 156 StGB: Falsche Versicherung an Eides Statt
Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.
Para. 156 StGB (German Criminal Code): False Statutory Declarations
Whoever before a public authority competent to administer statutory declarations falsely makes such a declaration or falsely testifies while referring to such a declaration shall be liable to imprisonment not exceeding three years or a fine.
§ 161 StGB: Fahrlässiger Falscheid; fahrlässige falsche Versicherung an Eides Statt
(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.
(2) Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Abs. 2 und 3 gelten entsprechend.
Para. 161 StGB (German Criminal Code): False Statutory Declarations Due to Negligence
(1) If a person commits one of the offences listed in sections 154 through 156 negligently the penalty shall be imprisonment not exceeding one year or a fine.
(2) The offender shall be exempt from liability if he or she corrects their false testimony in time. The provisions of section 158 (2) and (3) shall apply accordingly.

Die vorstehende Belehrung habe ich zur Kenntnis genommen:
I have read and understood the above official notification:

Aachen, 29.12.2020
Ort, Datum/City, Date

Schwarze
Unterschrift/Signature

Contents

List of Figures

Abstract

When using a smartphone, a user quickly encounters context menus, as these are an important and frequently used control element on mobile devices. It allows the user to select various options that are related to a specific context of the selected object. It is noticeable that these menus in smartphones are almost all of the same menu type. Linear context menus are apparently the standard in mobile devices, especially smartphones. However, in other areas such as tabletop, virtual reality (VR) or desktop environment, it has been shown that non-linear menu types such as pie menu or square menu are faster than linear menu types. However, to our knowledge, there is no sufficient research on whether this is also the case for mobile devices.

In this thesis, we describe how we have developed four contextual menu types (one linear and three non-linear), specifically adapted to the smartphone. In order to have a suitable basis for developing the menu designs, we conducted a study to find out the "Sweet Areas" of a smartphone in portrait and landscape mode.

In our main study, we compared all four menu types and found out that the square menu and SAM performed the fastest and also rated the best in user satisfaction. The linear menu performed the slowest and the pie menu rated the worst in user satisfaction.

Überblick

Bei der Benutzung eines Smartphones trifft ein Nutzer schnell auf kontext Menüs, da diese ein wichtiges und häufig verwendetes Steuerelement auf mobilen Geräten sind. Es ermöglicht dem Nutzer verschiedenste Optionen, welche in einem bestimmten Kontext zu dem ausgewählten Objekt stehen, auszuwählen. Auffällig ist, dass diese Menüs in Smartphones fast alle von dem selben Menütypen sind. Lineare kontext Menüs sind im Bereich der mobilen Geräten, speziell Smartphones, augenscheinlich der Standard. Jedoch wurde in anderen Bereichen, wie zum Beispiel "Tabletop", Virtuelle Realität (VR) oder Desktop Umgebung gezeigt, dass nicht-lineare Menütypen wie zum Beispiel "Pie Menü" oder "Square Menü" schneller sind als lineare Menütypen. Jedoch gibt es nach unserem Wissen keine hinreichende Forschung dazu, ob dies im Bereich der mobilen Geräten auch der Fall ist.

In dieser Arbeit wird beschrieben, wie wir vier kontext Menütypen (ein Lineares und drei Nicht-lineare), speziell angepasst auf das Smartphone, entwickelt haben. Um eine geeignete Grundlage für das entwickeln der Menüdesigns zu haben, wurde von uns eine Studie durchgeführt, welche die "Sweet Areas" eines Smartphones im Hoch- und Querformat herausfindet.

In unserer Hauptstudie haben wir alle vier Menütypen mit einander verglichen und herausgefunden, dass das square Menü und SAM am schnellsten performt haben und ebenfalls am besten in der Benutzerzufriedenheit abschnitten. Das lineare Menü performte am langsamsten und das pie Menü schnitt in der Benutzerzufriedenheit am schlechtesten ab.

Acknowledgements

I would like to thank Prof. Dr. Borchers and Prof. Dr. Schroeder for examining this thesis.

Many thanks to Oliver, who always gave me helpful tips on my topic and guided me through my bachelor thesis.

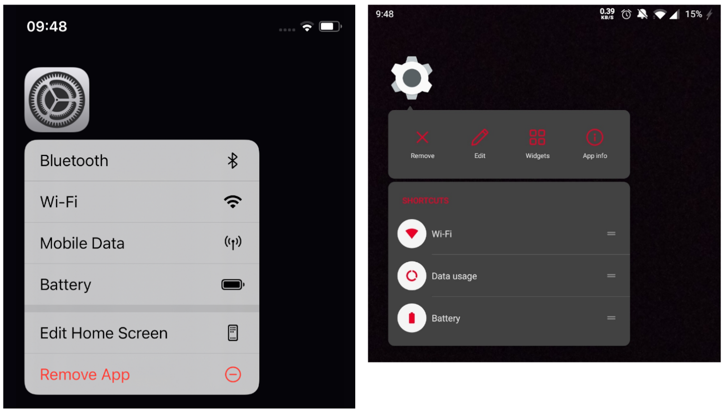
I would also like to thank all my friends and family who have supported me. Special thanks go to my mother, who gave me the special creativity for my work.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Menu size refers to the height and width of a menu. Number of items means how many items a menu contains.



(a) (b)

Figure 1.1: Context menu from the settings app in iOS (a). Context menu from the settings app in Android (b).

Chapter 1

Introduction

Smartphones are a big part of today's society. When using smartphones, we encounter context menus regularly, as they are an important control element on mobile devices. It offers the user various actions to choose from, dependent on the context of the selected object. Common examples of context menus are those used for individual applications on the home screen of operating systems like Apple's iOS or Google's Android. In Figure 1.1, we can see that the con-

Context menus are an important control element on smartphones text menu for the settings application offers several options dependent on the corresponding application functions. We notice that both menus are linear, which means that the menu items are displayed either as a horizontal or vertical list. Taking a look at various context menus on smartphones, one will notice that linear menus are prevalent, raising the question why the default context menu type is linear.

There are alternative menu concepts such as the pie menu or the marking menu which are illustrated in Figure 1.2. The pie menu arranges the menu items around the menu button [Kurtenbach and Buxton, 1993] and the marking menu extends this concept by a gesture aspect that allows the user to select items directly without opening the menu [Callahan et al., 1988]. We conducted an extensive literature review and concluded, to our knowledge, that there is no sufficient research in the field of menu comparisons on mobile devices, especially smartphones. We found one paper in the field of smartphones which compares a linear menu with non-linear menu types. The paper "M3 Gesture Menu: Design and experimental analysis of marking menus for touchscreen mobile interaction" [Zheng et al., 2018] describes a novel marking menu for mobile devices. The authors compare the M3 marking menu with a standard marking menu and a linear menu. The results imply that the M3 marking menu performs faster than the other two menus. Still, the use of a marking menu and a linear menu is quite different. A marking menu uses gestures, a linear menu uses taps. It compares an advanced menu to the "standard" menu on smartphones, but does not compare the basic effect of different menu layouts on user interfaces of smartphones.

Menu comparisons exist in other areas

We searched in other areas like desktop, virtual reality and tabletop and found several papers that conducted studies on linear and non-linear menu comparisons and which concluded that non-linear menus perform faster than linear ones.

In this thesis we will investigate whether non-linear menus are more efficient than linear menus in terms of target selection time and error rate. It is important to note that the

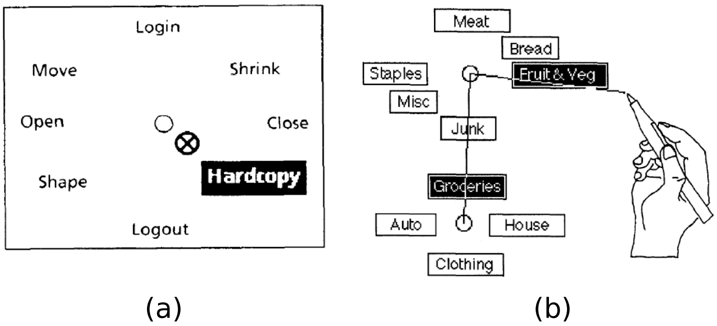


Figure 1.2: Pie menu concept (a). Image adopted from Callahan et al. [1988]. Marking menu concept (b). Image taken from [Kurtenbach and Buxton, 1993]

Smartphone characteristics are very different compared to the areas we have looked at

characteristics between a smartphone and the other areas we have looked at are very different. Typical characteristics for a smartphone are hand grasp and screen orientation. When using a smartphone, users typically use their hand which interacts with the screen also to hold the device [Mayer et al., 2019]. Mayer et al. have identified three areas for thumb reachability on a smartphone in portrait mode. However, this study only investigates the portrait mode of a smartphone, therefore in a first study we try to confirm the results for the portrait mode and find two new sweet areas (left and right) for the landscape mode. Based on these results, we will adapt a linear menu, a pie menu and a square menu to the smartphone and we will design an own menu called sweet area menu (SAM). We will then compare these menus in our main study in order to find out if non-linear menus perform faster than linear menus in terms of selection time and error rate.

1.1 Outline

In the following Chapter 2 “Related Work” we will describe the related work. In this we will show the found papers on menu comparisons from different areas and will also go into more detail about the characteristics of smartphones.

In Chapter 3 “Menu Designs”, we will look at Mayer et al.’s study in more detail and describe our first study, which confirms the previous study results in portrait mode and identifies two new sweet areas for landscape mode. Based on the results of our study, we will then describe the menu adaptations to the smartphone in detail.

In Chapter 4 “Study 2: A Comparison of Linear and Non-Linear Menu Types”, we describe our user study, which compares a linear menu with three non-linear menus depending on selection time, error rate and user satisfaction.

At the end of the thesis in Chapter 5 “Summary and future work”, we will conclude our results and recommend possible future work.

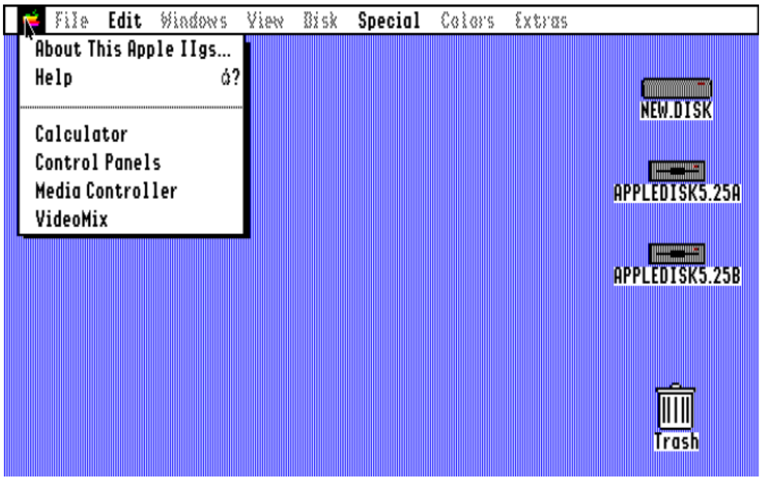


Figure 2.1: Apple GS/OS desktop in 1986. Image taken from `ByTakenbyme.,https://en.wikipedia.org/w/index.php?curid=3409475`

Chapter 2

Related Work

Graphical menus have been around since the beginning of the first graphical user interface (GUI). The first GUI was developed in the 1970s at Xerox PARC and already had windows, icons and menus. After Xerox Star, the first commercial GUI operating system was released in 1981, other companies like Apple followed the idea and developed their own GUI operating systems like in Figure 2.1.

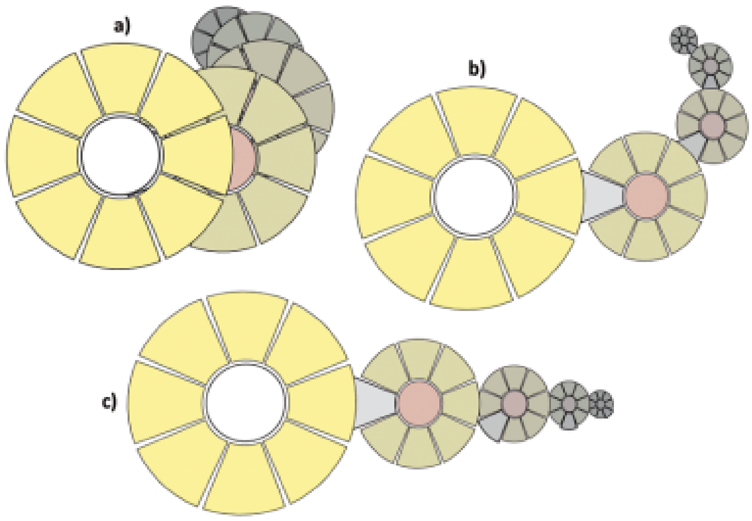


Figure 2.2: Example of a pie menu used in an immersive virtual environment. The menu places all items in a circular order around the center of the menu. Image taken from Gebhardt et al. [2013]

2.1 Menu Types

Various menu types exist in different domains of application, such as the pie menu.

The first menu researches mostly contained only linear menus. Nevertheless, other menu concepts were developed that went beyond horizontal or vertical arrangement of the items. An example is the pie menu shown in Figure 2.2. One of the first researchers who examined a pie menu were the aforementioned Callahan et al., which we will discuss in more detail in the following section. Gebhardt et al. have designed and evaluated a pie menu especially for the immersive virtuel environment. The development was iterative and after a first study, which focused on item selection, the menu was optimized and extended with additional functionalities. Finally, they conducted an expert review with five participants, which concluded that the design was efficient and provided high performance.

Pie menus were also observed in other areas. Banovic et al. have investigated how to design a context menu for efficient unimanual-multitouch use on horizontal tabletops.

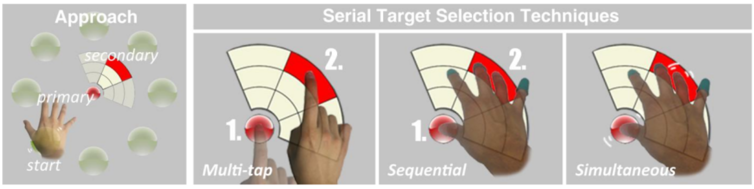


Figure 2.3: On the very left is the start position of the hand and the location of the pie menu. Next to it are the three target selection techniques, that are compared with each other. Multi-tap (left), sequential (center) and simultaneous (right). Image adopted from Banovic et al. [2011]

The limitations of the arm, wrist and fingers were examined in detail. They compared several serial target selection techniques as illustrated in Figure 2.3 and concluded that using multiple fingers simultaneously perform faster than single finger use. Following these results, the authors created their own menu and provided six design guidelines.

Marking menus are similar to pie menus, extended by gestures.

An extension of pie menus are marking menus. The characteristic of a marking menu is that a user has two different methods to perform a menu selection. Either by opening the radial menu and then selecting the item or by drawing a straight mark in the direction of the item to be chosen. If the user decides to perform the gesture, the menu will be not opened and instead the item is selected directly. Based on three design principles (guidance, rehearsal and self-revelation), Kurtenbach et al. developed and evaluated the marking menu. Guidance means that a marking menu guides the user in the selection of an item. Rehearsal means that the guidance through the marking menu is a rehearsal to make the marking required to select an item. Guidance and rehearsal train a novice user to operate the marks as an expert. Self-revelation, on the contrary, helps a novice to determine what features are available. The authors concluded that in the marking menu, illustrated in Figure 2.4, in a practical application, users later used the marks 100%. Also that four, eight and twelve items per menu is the optimal number for marks and that using marks in a practical application is 3.5 times faster than opening the menu and then selecting the item. In a further study, Kurtenbach et al. also investigated the cognitive and articulatory as-

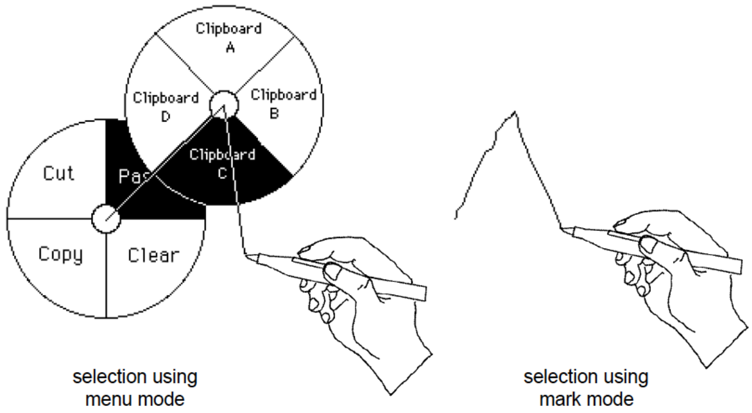


Figure 2.4: Hierarchical Marking Menu which is used either by opening the menu and selecting the item or by directly drawing a mark. Image adopted from Kurtenbach et al. [1993b]

pects of the marking menu. Three different input devices (mouse, stylus and trackball) together with four different numbers of items in the menu were analyzed. They found that users perform faster and made fewer mistakes when using a mouse or stylus instead of a trackball. They also noticed that as the number of menu items increased, the performance of the users became worse. The performance did not deteriorate as fast with a hidden menu and an even number of items. As the above mentioned studies revealed the potential of the marking menu, Kurtenbach and Buxton tested the menu in a real work situation. The study confirmed the potential of marking menus and showed when users became expert users, marks were mainly used. However, it is noticeable that even experts have used the different usage variant to recall the menu design. The speed of the marks was also confirmed and, as described in the study above, was 3.5 times faster than opening the menu and then selecting the item.

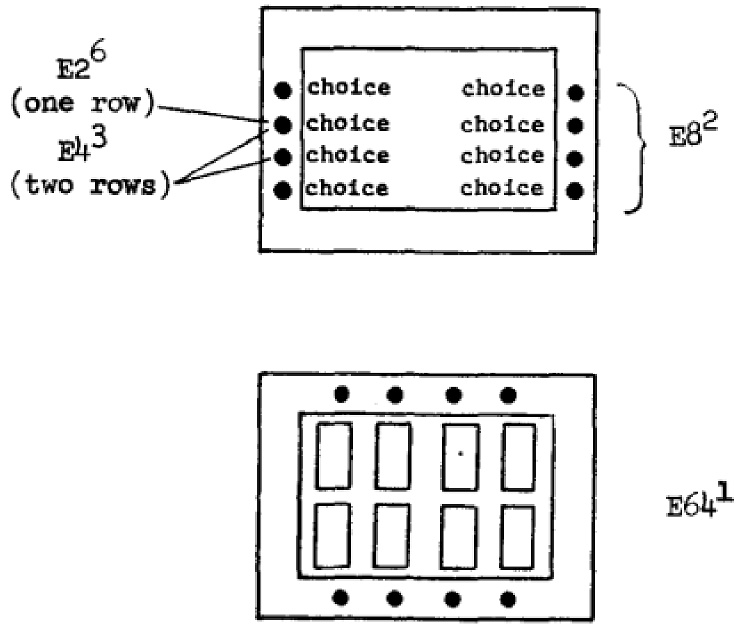


Figure 2.5: Four possible menu variants denoted with Eb^d. The menu breadth is b and the menu depth is d. Image adopted from Miller [1981]

2.2 Menu Researches

First researches in the field of menu theory started after the first menus were used in GUI operating systems. Kiger investigated the role of depth and breadth of menus and tree structures in user interfaces for information-retrieval systems. The author compared five specified tree structures. The five variants were two choices at each of six levels (2-6), four choices at each of three levels (4-3), eight choices at each of two levels (8-2), four choices at level one and 16 choices at level two (4-1 + 16-1) and sixteen choices at level one and four choices at level two (16-1 + 4 - 1). He concluded that variant 8-2 is the fastest and most accurate. Therefore, it is recommended to minimize the menu depth and keep the breadth to a maximum of nine items. Thus, these results are in correlation with the results of Miller [1956]. He had found out that the limit of human information processing capacity is seven plus/minus two chunks.

First research on menus was conducted as early as 1981, dealing with menu depth and width.

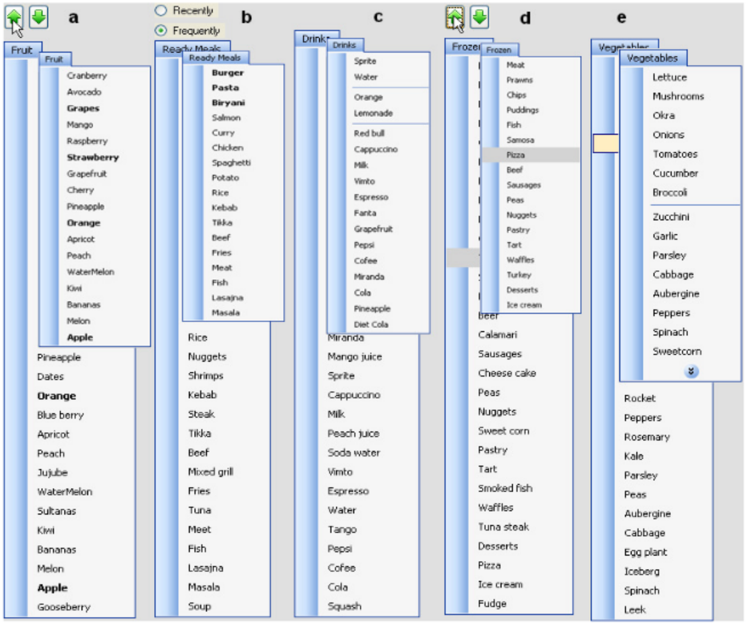


Figure 2.6: Five interactive menu conditions: (a) adaptive highlight menu (b) mixed-initiative menu (c) adaptive split menu (d) adaptable menu (e) adaptive/adaptable menu (minimised and hide unused menu items). Image taken from Al-Omar and Rigas [2009]

Kiger's findings were not the first in this field, through his study was an extension of Miller's study. Miller [1981] had previously investigated the depth/breadth tradeoff in hierarchical computer menus. Figure 2.5 illustrates the four menu configurations that were examined. For example, $E4^3$ means that the menu has a depth of 3 levels and four items are displayed per level. He came to the conclusion that a menu depth of two in conjunction with a menu breadth of eight is the variant, which is the fastest and produces the fewest errors.

Considering not only the distribution of items within a menu is important, Al-Omar and Rigas [2009] investigated two different menu sizes (small and large) applied to five different interactive menu conditions, which are shown in Figure 2.6. They focused on menu personalization, which can be either adaptable, adaptive or a mixture of both. This means that with an adaptable menu, the user can determine the order of items. With an adaptive menu, on the other hand, this is done automatically, for example on the basis of the most frequently selected items. The authors specifically analyzed user satisfaction and concluded that for a large menu size the mixed-initiative variant was preferred and for a small menu size the minimized condition variant was favored.

An equally important aspect of a menu is the arrangement of the items. Card was one of the first to examine the effects of item order regard to the speed of finding a command. Three sorting approaches (functionally, randomly or alphabetically) were considered. Functionally means that words with a similar function such as insert and delete are grouped together. The author discovered that no arrangement is significantly faster or slower if the user knows the menu. However, if the user is not familiar with the menu, the alphabetical order is fastest followed by the functionally grouped order.

The arrangement of the menu items is also an important aspect that Card was investigating in 1982.

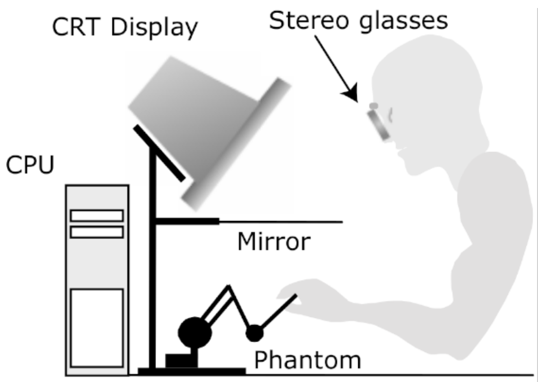


Figure 2.7: Haptic-GeoZui3D VR environment uses a horizontal mirror to display virtual computer graphics on the PHANToM 1.0 workspace. Visual and haptic images are registered at any time, because the eye position of the user is used to calculate the CG images. A proxy for the pen held in the user's hand is also shown. To make this possible, a monitor, placed 45° above the mirror, is additionally used. The stereoscopic display is realized through stereo glasses. Image taken from Komerska and Ware [2004]

2.3 Menu Comparisons

With the increasing number of different menu types, there has been more research on menu comparison, which compares the performance in terms of selection time and error rate of different menu types.

Callahan et al. compared a linear menu with a pie menu in 1988.

The study by Callahan et al. was one of the earliest that compared a linear menu to a pie menu in a 2D desktop environment. The authors investigated whether pie menus improve item selection time and if they are more suitable for menu applications that fit a circular format, and if linear menus are more suitable for sets of linear items (e.g. an enumeration of items). Menu applications which are suitable for a circular format are, for example, directions (e.g. left/right), opposite functions (e.g. open/close) or even linear sets of items. It was found that pie menus increased productivity by 15-20%. However, the authors emphasize that the experiment only considered a fixed number of items within the menus (eight items per menu) and therefore it

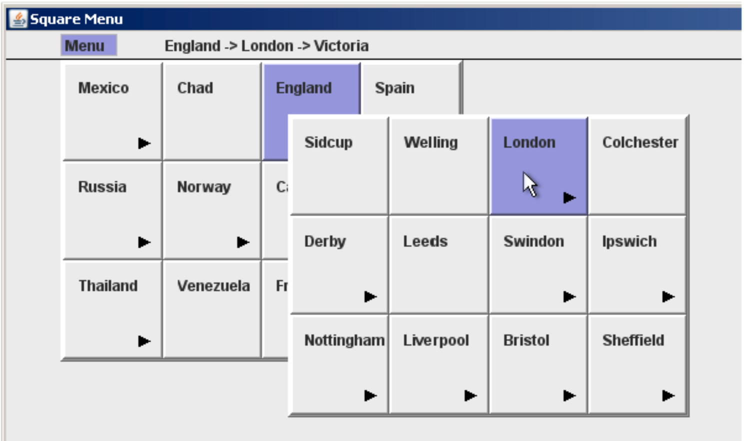


Figure 2.8: A hierarchical square menu in which all items, each of them shown as a square, are grouped in a large rectangle. Image adopted from Ahlström et al. [2010].

is not possible to say whether this is also applicable to a lower or higher number of items. They concluded that pie menus had great potential, but that more experiments had to follow before a recommendation could be made.

Komerska and Ware also compared a linear menu to a pie menu, however, in a 3D fish tank VR environment (Figure 2.7). More precisely, they compared three menu types (slant linear menu, straight linear menu and pie menu). The authors concluded that pie menu item selection performs much faster and more accurate compared to the two linear menu types in the 3D fish tank VR environment.

Komerska and Ware compared a linear with a pie menu in a VR environment.

Not only pie menus were compared with linear menus. Ahlström et al. developed three hierarchical menu designs and compared them in an empirical study. A traditional linear pull-down menu, a pie menu and a new square menu were created (Figure 2.8). The authors have filtered out a crucial performance principle from an SDP model that predicts menu performance, namely that experts spend proportionally much more time in the pointing phase than novice users. By this principle, two candidate designs (pie menu and square menu) were determined in the preliminary stage, which were supposed to deliver a high perfor-

Many comparisons exist between linear and non-linear menu types in various areas.

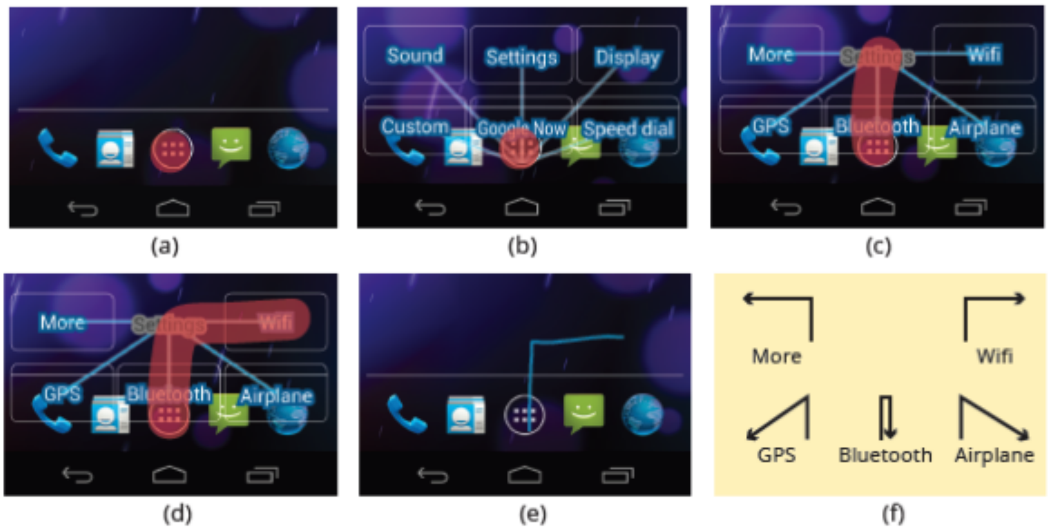


Figure 2.9: M3 Gesture Menu (M3) shown with the two control options. Either you can display the items in the menu and then use the gesture to select an item (a-d) or you can draw the gesture directly and select the item without opening the menu (e). Image taken from Zheng et al. [2018]

mance. The empirical comparison partially confirmed the prediction, with square menu fastest (5.14 seconds), then the traditional linear pull-down menu (5.45 seconds) and finally the pie menu (6.04 seconds).

The menu comparison in the mobile area is not sufficiently researched.

Menu comparisons were also conducted in the area of mobile devices, especially smartphones. Zheng et al. developed, implemented and evaluated the M3 Gesture Menu (M3), a variation of the traditional marking menu specifically adapted for a smartphone (Figure 2.12). The differences to traditional marking menus are that an M3 is defined on a grid and is not displayed in a radial form, gestural shapes are drawn instead of straight marks and constant/stationary space is used. In the first controlled experiment the authors found that the M3 was less error-prone and performs faster in comparison to a traditional marking menu and a linear menu (Figure 2.9). Furthermore, a second controlled experiment, which focused on learning gestures/marks, showed that users were able to learn a dozen commands within three ten-minutes sessions of practice in both the M3 and the multi-stroke marking menu. The authors concluded that the M3 offers a more practical working solution for the application of marking menu concepts in the smartphone area.

2.4 Smartphone Characteristics

As we look at a menu comparison especially in the area of mobile devices, it is very important to consider the characteristics of the smartphone. This includes, for example, the touch screen aspect and the hand grasp.

Design principles of smartphone operating systems correspond mostly to the usability heuristics for touchscreen-based mobile devices.

Inostroza and Rusu [2014] have mapped four sets of design principles of iOS, Android, Windows Phone and TizenOS against a set of usability heuristics for touchscreen-based mobile devices (TMDs). As a result, it was observed that the usability heuristics for TMDs cover almost all design patterns. In addition, two further dimensions were added, the cognitive load and the user experience. Cognitive load means that users are protected from unimportant disturbances (e.g. unimportant notifications are not shown to the user).

Hand grasp is an important aspect of smartphone characteristics.

As mentioned above, the hand grasp is an important characteristic of the smartphone. Lee et al. [2016] studied the effects of hand length, phone width and task type on grasp, muscle activation, index finger reach zone and discomfort. Two devices with a width of 60 mm and 90 mm were used. Five interaction tasks (neutral, comfortable, maximum, vertical and horizontal strokes) were investigated in combination with three hand lengths. The authors discovered that maximum strokes caused 43.8% more discomfort compared to neutral strokes. They also found that the vertical (horizontal) strokes deviated from the vertical (horizontal) axis and that discomfort was 12.3% greater at a width of 90 mm than at 60 mm. Therefore, it is recommended that the interaction areas on the rear of popular smartphones should be lowered by 20 mm to 30 mm to make the rear interaction more comfortable. Le et al. [2016] have also investigated the grasp of a smartphone, especially the finger positions during certain tasks. The authors tried to understand exactly how users naturally hold a smartphone in order to develop ergonomic back of device (BoD) interactions. They looked at three common tasks and measured the areas of the smartphone covered by the hands and the positions of the fingers. The tasks were to write a text message, read an article and watch a video. From the data ob-

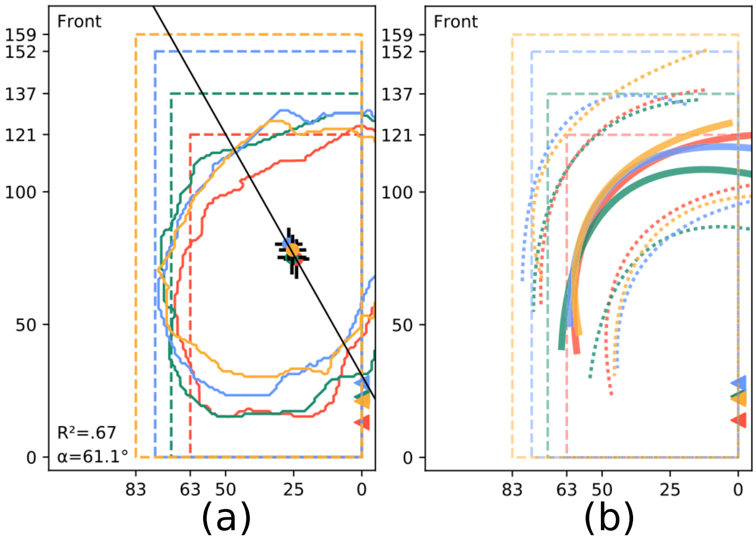


Figure 2.10: (a) Comfortable areas for four unit sizes, represented by 4 brands. The dotted lines represent the screen sizes of the individual devices. (b) Maximum range for four unit sizes, represented by 4 brands. The dotted lines represent the screen sizes of the individual devices. Images adopted from Le et al. [2018]

tained, heatmaps were created and three approaches for ergonomic BoD interaction were developed. First, that the upper third of the right corner can be operated with the thumb. Second, that pressure sensors on the sides of the smartphone can be used to enable grasp interaction. Finally, that the upper third of the back of the device can be used with the index finger and the middle finger to perform taps and gestures. In a further study, Le et al. [2018] investigated the comfortable area and the maximum range for one-handed smartphone use with the thumb. The comfortable area is defined as the area that can be reached without changing the hand grip and without loss of grip stability. The maximum range, on the other hand, is the area that can be reached with stretched fingers without changing the hand grip. In a first task, users have freely moved their thumb over all areas of the display without changing the hand grip to collect data for the comfortable area. In a second task, users stretched their thumb and made movements in an arc to obtain data for the maximum range. The

The comfortable area is the area of a smartphone that can be reached without changing the hand grasp.

(a) (b)

Figure 2.11: Flappy Easter (a) and 2048 (b), which were used for the in-the-wild studies. Image adopted from Mayer et al. [2019]

results are illustrated in Figure 2.10.

The sweet area and the sweet spot extend the comfortable area.

Based on the results of the previous study, Mayer et al. [2019] extended the comfortable area by a sweet area and a sweet spot in a additional in-the-wild study. The authors were interested in finding out how users operate a smartphone with one thumb outside of laboratory conditions. For this, two mobile games were published in the application store. The two games differes not only in the game itself, but also in the operating technique. The first game, Flappy Easter, is identical to Flappy Bird, except that it uses different designs (Figure 2.11). Flappy Easter is operated by tapping on the screen. The second game, 2048, on the other hand, was played with swipe gestures. The game objective is to connect two equal number blocks with up, down, left and right gestures, which then merge into one number block with twice the value. This will be repeated until the value 2048 is reached on one block(Figure 2.11). In

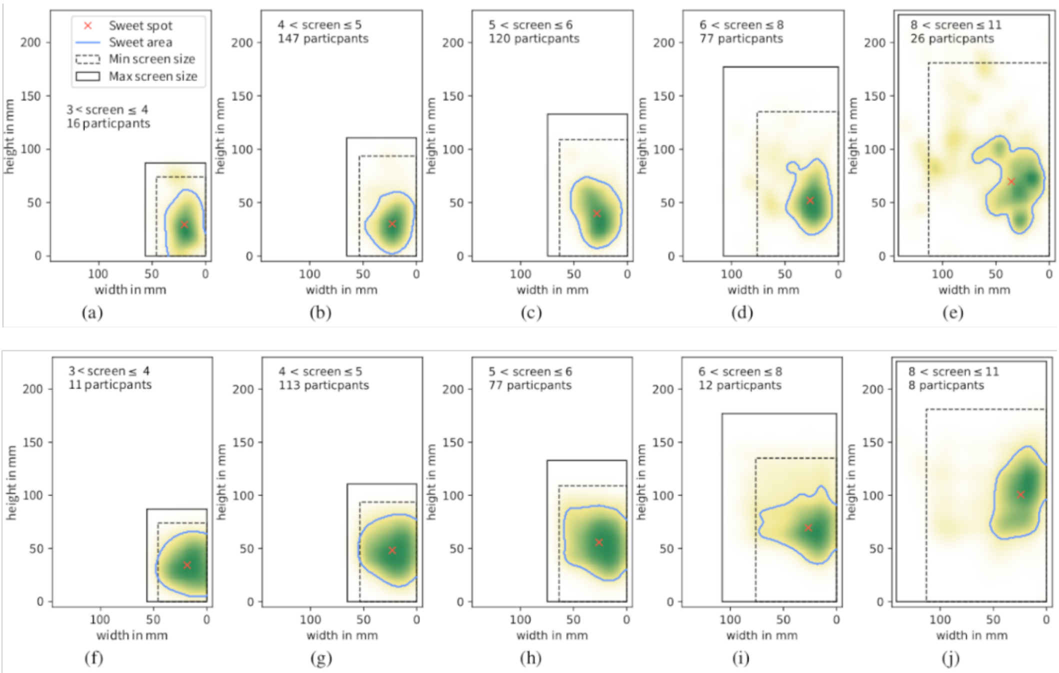


Figure 2.12: Heatmaps of five device size classes, which present the sweet area in combination with the sweet spot. In the upper row (a-e) the heatmaps of the Flappy Easter game are shown (tap control) and in the lower row the heatmaps of the 2048 game (swipe control). Image taken from Mayer et al. [2019]

both games the tap/swipe area was not restricted, therefore users could choose freely at which screen positions they wanted to tap/swipe. In total, both games were installed on 607 devices and 45,899,268 touch events were collected (both games were played in portrait mode). Heatmaps were created from the obtained data, grouped by screen size (Figure 2.12). From these results, the average distribution was determined by various calculations, as illustrated in Figure 2.13. Thus, the sweet area defines the users' preferred area for touch interaction. The sweet spot is located at the densest point within this area. We will discuss the sweet area in more detail in the following chapter and conduct a further study, which tries to verify the results in portrait mode and to find two new sweet areas for smartphone use with both thumbs in landscape orientation.

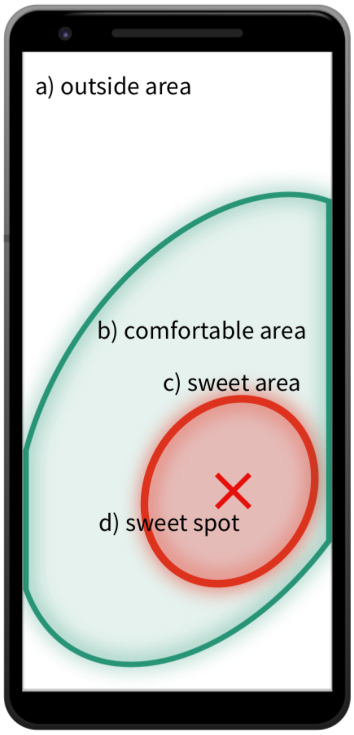


Figure 2.13: The three areas of a smartphone for thumb use (outside area (a), comfortable area (b), sweet area (c)) displayed together with the sweet spot (d). Image adopted from Mayer et al. [2019]

Chapter 3

Menu Designs

In this chapter we take a closer look at Mayer et al.'s paper "Finding the Sweet Spot", which describes the preferred area of a smartphone when using the thumb and with no restriction of the touch area. Based on this, we programmed two game applications, which differ from the two game applications from the paper mentioned above, but which use the same two operating techniques (tapping/swiping). Using our own programmed apps, we will describe a study which confirmed Mayer et al. results and found two new sweet areas for smartphone use with both thumbs in landscape mode. According to the results of our first study, we adapted four menu types to the smartphone, which we then compared in Chapter 4 "Study 2: A Comparison of Linear and Non-Linear Menu Types". Therefore, one linear menu type (linear menu) and three non-linear menu types (pie, square and sweet area menu) were used.

Based on Mayer's study, we conducted our own study to confirm the results and gain new insights into the sweet area.

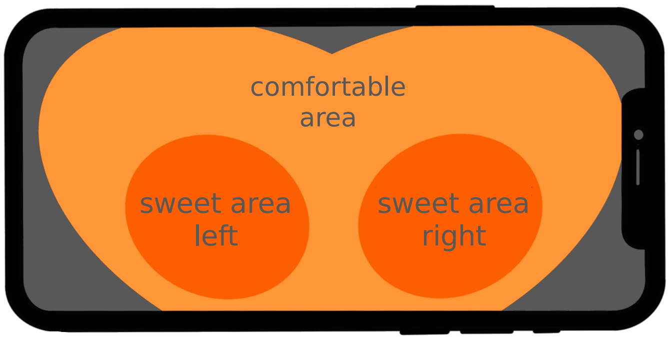


Figure 3.1: Representation of our assumption of how the two sweet areas for two-handed smartphone use in landscape mode could look like. The light orange area represent the comfortable area and the dark orange areas represent the sweet area.

3.1 Finding the Sweet Area

As mentioned in detail in Chapter 2 "Related Work", Mayer et al. extend the comfortable area defined by Le et al. by the sweet area and the sweet spot. The sweet area is most interesting in our context, as it reflects the intuitive area of the thumb on the smartphone. This is the area on which our menu adaptations to the smartphone are based. We have also taken it a step further and developed our own menu type, which has the property of always being displayed in the sweet area. Since the menu adaptations should not only be intended for smartphone use in portrait mode, but also for landscape mode, an initial study was conducted that confirmed Mayer's results and identified two new sweet areas for the landscape orientation. Figure 3.1 presents our assumption of the two sweet areas in landscape mode. Therefore, the sweet area in Figure 2.13 was rotated by 90° and doubled.

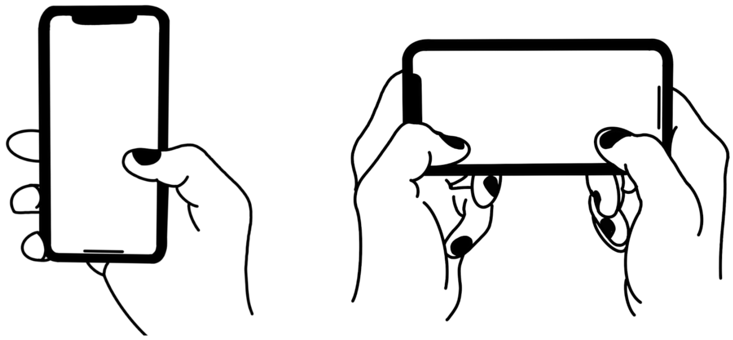


Figure 3.2: (a) Smartphone use with the right hand and the right thumb, one-handed in portrait mode. (b) Smartphone use with both hands and both thumbs in landscape mode.

3.2 Study 1: Sweet Area Study for Portrait and Landscape Mode

The sweet area is an interesting concept in the field of smartphone usage with the thumb. However, since Mayer et al. only investigated it for smartphone usage in portrait mode, we conducted a study using two of our own programmed games in which we confirmed Mayer's results and identified two new sweet areas for landscape mode.

3.2.1 Experimental Design

Two games were programmed with which the study was conducted.

In this user study, which had a within-group subject design, participants were instructed to play two game apps. All participants are right-handed and operated the smartphone one-handed with the right thumb in *portrait mode* and two-handed with both thumbs in *landscape mode* (Figure 3.2).

The first app, Sweet Bird (Figure 3.3), is based on the game Flappy Bird, where you have to try to navigate a bird, which flies in a 2D world in a constant speed to the right, safely between pipes. In landscape mode, the game differs from portrait mode by one aspect. In portrait mode,

Figure 3.3: The two game apps used for the first study. Sweet Bird, which is controlled by *taps* (a). Swiping Heroes, which is controlled by *swipe gestures* (b).

there is a constant gravity that pulls the bird to the ground. By tapping on the screen, the bird makes a flap and moves parabolic upwards. In the landscape orientation there is no gravity at the beginning, the bird moves only on the horizontal to the right which is a optical representation. In reality the background and the pipes move to the left and the bird stays on the same place in the horizontal until the participant presses the screen for the first time. When the user presses on the left side of the screen, a negative gravity is applied and the bird moves upwards. When the user presses on the right side, the opposite happens, so the bird moves towards the ground. The aim of the game is the same for both orientations. As mentioned above, the participants should try to control the bird through the pipes as collision-free as possible. At the moment of the start of the game, a clock starts, which is incremented by one per second and by five per collision (pipe, ground or sky). After 120 taps in portrait mode and a minimum of 240 taps in landscape mode (at least 120 left and 120 right), a round is

Sweet Bird is used to find out the tap touch locations.

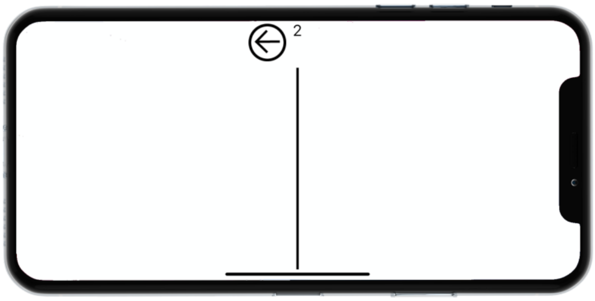


Figure 3.4: Swiping Hero Landscape: In this example, a swipe gesture to the left on the left half of the screen is required.

over and the value of the clock reflects the final score. The score is only used for the gamification aspect. In the first round of a game, the number of taps only starts to count after successfully flying through five pipes, so that the user could first adapt to the game controls.

The second app that was programmed is swiping hero (Figure 3.3). As the name indicates, the focus of the game is on *swipe gestures*. Sweet Bird is played with taps, while Swiping Hero is played with swipes. The difference between the portrait mode version and the landscape mode version is again one aspect. In portrait mode, the game consists of only one arrow, which can point up, down, right and left, and a score display. If the arrow points to the right, for example, the participant should make a swipe gesture to the right. If the gesture is correct, the arrow turnes green and the participant gets one point. If the gesture is incorrect, the arrow changes in the direction of movement, turnes red and a point is deducted from the score (with a score of zero, it remaines). An arrow pointing in a randomly selected direction appears immediately afterwards. In landscape mode, the screen is divided into two halves (left and right) and the arrow is displayed either in the left or right half (Figure 3.4). If the arrow appears on the right side, the participant has to perform the specific swipe gesture in the right half and vice versa. In both orientations, a round is over when a certain number of swipes are performed. In the first round of a game, the swipes are counted only after ten correct swipe gestures. Again, this is to allow the

Swiping Hero is used to find out the swipe touch locations.

participants to get used to the operation of the game. In portrait mode, a round is completed after 120 swipes and in landscape mode after 240. The final score, which is reflected by the number of correct swipes, also served only the gamification aspect.

In total, Sweet Bird and Swiping hero are played three rounds in each orientation.

3.2.2 Participants

Overall, 12 people (female: 3, male: 8, no specification: 1) participated in the study with an average age of 23 years. All participants were right-handed and experienced in the use of smartphones. The average smartphone use per day of the participants was approximately three hours. The minimum number of hours per day that was given was one to two.

3.2.3 Apparatus

In our study, we used an iPhone X, which is 143.6 mm high and 70.9 mm wide. The screen diagonal measures 5.8" (14.7 cm) with 2436x1125 pixels and a pixel density of 458 ppi. Overall, the device weighs 174g.

3.2.4 Task

The task was divided into 4 parts, in each part one game was played.

The participants' task was divided into four parts. In each part, they played Sweet Bird Portrait, Sweet Bird Landscape, Swiping Hero Portrait or Swiping Hero Landscape. The order of the games was determined by a latin square, therefore each game was played once. As mentioned above, participants played a game three rounds at a time. After each round, a break could be taken if desired. Likewise, a break could also be taken between games. After all four games were played, participants were asked to fill out a questionnaire in which we asked for general information about the users and daily smartphone usage in hours.

3.2.5 Study Procedure

The purpose of the study was explained to each participant at the beginning. This included a more detailed description of the paper by Mayer on which our study is based. Dependent on the latin square, which was the order of play of the particular participant, each game was explained in detail before it was started. After the first explanation, we put the study device in the user's hand, on which the first game was already opened and with which the user could start directly by tapping on the screen. After each game, we instructed the participant to put the device back on the table. The next game that followed was opened by us and the user received the device back. After four games, the smartphone was put aside and the participant was asked to fill out the end questionnaire.

Mayer's paper was explained in more detail to the participants.

3.2.6 Measurements

The purpose of the study was to confirm the sweet area for portrait mode and to find two new sweet areas for landscape mode. For this, the *touch locations* of the participants were measured.

In the game Sweet Bird, the touch location (x and y value) of each tap (except for the practice taps in the first round) was collected in both orientations. For each tap, it was also recorded in which round the participant was, in order to be able to infer the number of rounds in case of a possible deviation of the data.

Two types of touch locations were measured

For Swiping Hero each swipe was measured in both orientations. For this purpose, each touch location of the user was recorded that belonged to a swipe. The reason we used this approach instead of measuring the start and end location of a swipe is that a swipe is not straight, but rather slightly curved, allowing us to measure every position of the user's finger. We also detected if a swipe was right or wrong and in which round the participant was.

We collected 7,784 touch locations for Sweet Bird Landscape, 4,063 for Sweet Bird Portrait, 37,523 for Swiping Hero Landscape and 18,294 for Swiping Hero Portrait (67,664 total).

3.2.7 Results

Mayer's results were confirmed and two new sweet areas for landscape mode were defined.

Altogether, we measured four types of touch locations. Firstly, the touch locations that were executed once in portrait and once in landscape mode, and secondly, the touch locations that were executed once by taps and once by swipes. Sweet Bird Portrait delivered touch locations executed with taps and in portrait mode. Sweet Bird Landscape, on the other hand, provided touch locations executed with taps and in landscape mode. Analogously, the same with Swiping Hero, which delivered touch locations executed by swipes once in portrait mode and once in landscape mode. Based on the obtained data, we have generated heatmaps for each condition. The heatmaps of the portrait mode data were compared with the heatmaps of Figure 2.12. The heatmaps of the landscape mode data were used to find two new sweet areas for two-handed smartphone use in landscape mode. The kernel density estimate (KDE) plot from the python package seaborn was used to calculate and visualize the heatmaps.

Portrait Mode Tap Data

Our tap data in portrait mode confirms Mayer's tap data.

The generated heatmap, consisting of 4,063 received touch locations, can be seen in Figure 3.5. The used device (iPhone X) has a screen resolution of 375x812 points (1 point = 3 pixels) and a screen width of 61.8 mm and a screen height of 133.7 mm (portrait mode). Here, the sweet area is located in the lower right area. The touch locations are on the horizontal axis in the range from 71 pts (11.64 mm) to 320 pts (52.48 mm) and on the vertical axis in the range

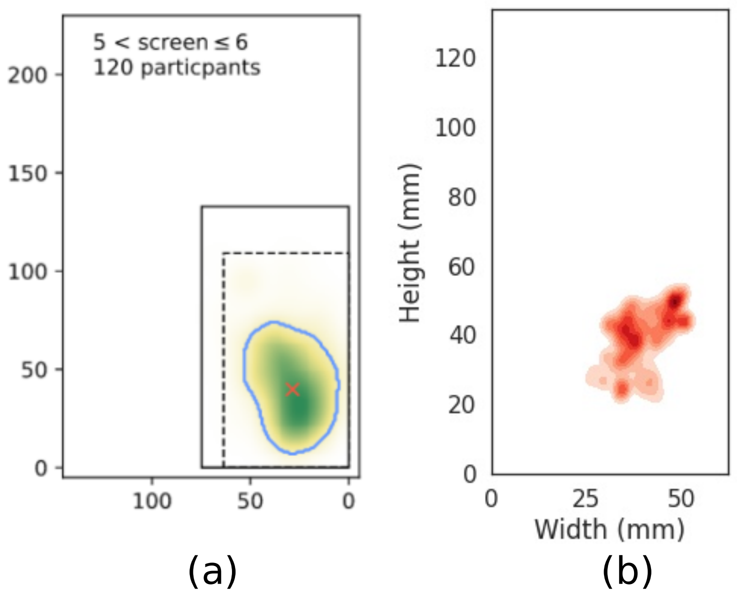


Figure 3.5: (a) shows the heatmap of the study from Mayer et al. for devices with a screen size of five to six inches, which were only controlled by taps. The rectangle with a solid line represents the maximum size of the devices (six inches) and the rectangle with a dashed line represents the minimum size of the devices (five inches). The y-axis is the height of the device in mm and the x-axis is the width of the device in mm. The blue outline marks the sweet area and the red cross marks the sweet spot. (b) shows the heatmap we generated for the tap touch locations in portrait mode.

from 120 pts (19.68 mm) to 316 pts (51.82 mm). The highest density is on the horizontal axis between 200 pts (32.8 mm) and 320 pts (52.48 mm) and on the vertical axis between 220 pts (36.08 mm) and 330 pts (54.12 mm). Mayer's result was scaled to fit the size of our study device and compared to our result. The comparison, which can be seen in Figure 3.6, clearly shows that the area of Mayer's heatmap is larger than our heatmap. This may be due to the much smaller amount of data we processed. However, our touch locations are exactly in the area around the sweet spot and furthermore the position where the data is most dense is almost identical to the position of Mayer's data. This shows that our touch locations from the study data are very simi-

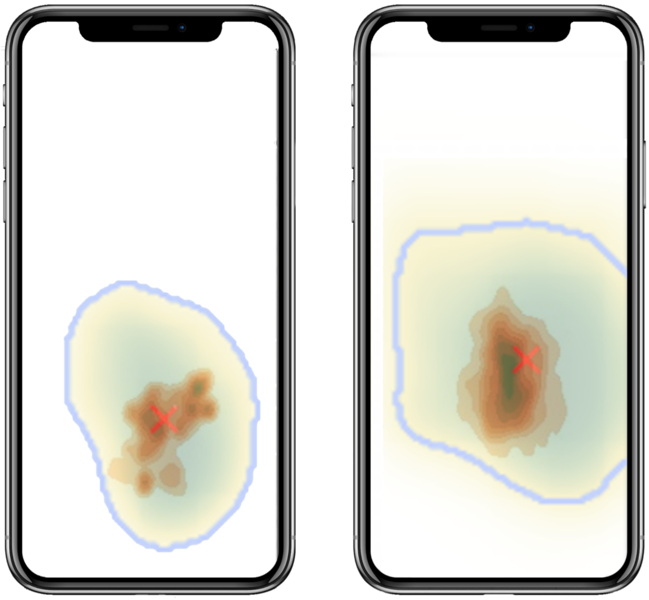


Figure 3.6: Heatmap comparison for tap touch locations is shown at (a). Heatmap comparison for swipe touch locations is shown at (b).

lar to Mayer's and our sweet area in portrait mode for data generated by taps is almost identical.

Portrait Mode Swipe Data

Our swipe data in portrait mode confirms Mayer's swipe data.

The generated heatmap, consisting of 37,523 received touch locations, can be seen in Figure 3.7. Here, the sweet area is located in the lower right area. The touch locations are on the horizontal axis in the range from 51 pts (8.36 mm) to 366 pts (59.04 mm) and on the vertical axis in the range from 59 pts (9.67 mm) to 203 pts (33.29 mm). The highest density is on the horizontal axis between 200 pts (32.8 mm) and 300 pts (49.2 mm) and on the vertical axis between 240 pts (39.36 mm) and 340 pts (55.76 mm). For the obtained swipe touch locations, the same approach was used as for the tap data. The comparison of the heatmaps (Figure 3.6) also provides the same results. Thus, we were able to con-

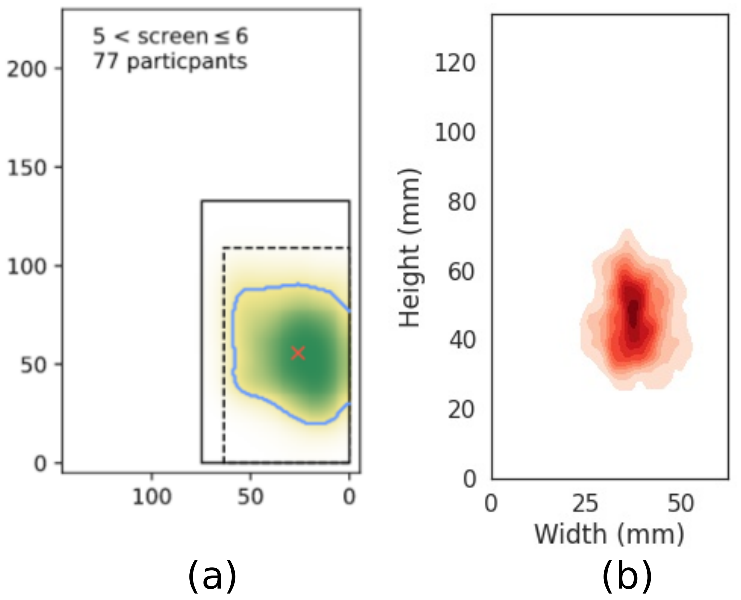


Figure 3.7: (a) shows the heatmap of the study from Mayer et al. for devices with a screen size of five to six inches, which were only controlled by swipes. The rectangle with a solid line represents the maximum size of the devices (six inches) and the rectangle with a dashed line represents the minimum size of the devices (five inches). The y-axis is the height of the device in mm and the x-axis is the width of the device in mm. The blue outline marks the sweet area and the red cross marks the sweet spot. (b) shows the heatmap we generated for the tap touch locations in portrait mode.

firm the sweet areas found by Mayer et al..

Landscape Mode Tap Data

Our tap data in portrait mode does not confirm our assumption of the positions of the sweet areas.

Furthermore, we created a heatmap for the tap touch locations in landscape mode using a KDE plot (Figure 3.8). The left sweet area is located in the middle left area and the right sweet area is located in the middle right area. The touch locations of the left sweet area are on the horizontal axis in the range from 71 pts (11.64 mm) to 261 pts (42.8 mm) and on the vertical axis in the range from 145 pts (23.78 mm)

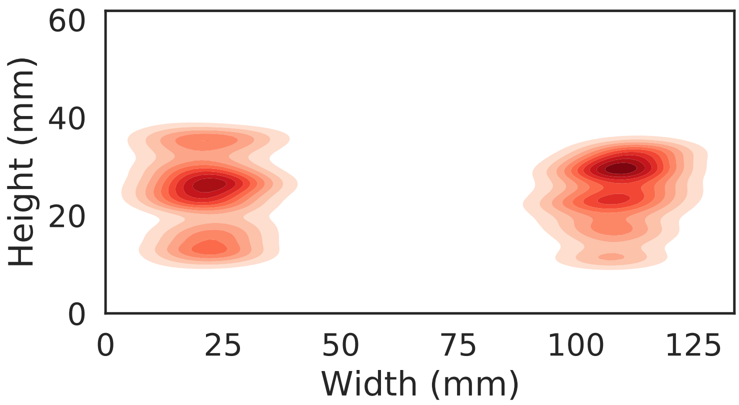


Figure 3.8: Generated heatmap resulting from the tap touch locations from the game Sweet Bird Landscape.

to 316 pts (51.82 mm) and the touch locations of the right sweet area are on the horizontal axis in the range from 444 pts (72.81 mm) to 720 pts (118.08 mm) and on the vertical axis in the range from 51 pts (8.36 mm) to 229 pts (37.55 mm). The highest density on the left side is on the horizontal axis between 100 pts (1.64 mm) and 200 pts (32.8 mm) and on the vertical axis between 100 pts (16.4 mm) and 200 pts (32.8 mm) and on the right side on the horizontal axis between 700 pts (114.8 mm) and 800 pts (131.2 mm) and on the vertical axis between 200 pts (32.8 mm) and 250 pts (41 mm). Our assumption, which is shown in Figure 3.1, is not confirmed. It shows that the touch locations are densest closer to the vertical edges left and right.

Landscape Mode Swipe Data

Our swipe data in portrait mode does not confirm our assumption of the positions of the sweet areas.

The same method was used for the swipe touch locations in landscape mode (Figure 3.9). The generated heatmap shows that the swipe touch locations in landscape mode are a bit more centered than the tap touch locations. The left sweet area is located in the middle left area and the right sweet area in the middle right area. The touch locations of the left sweet area are on the horizontal axis in the range from 0 pts (0 mm) to 450 pt (73.8 mm) and on the vertical

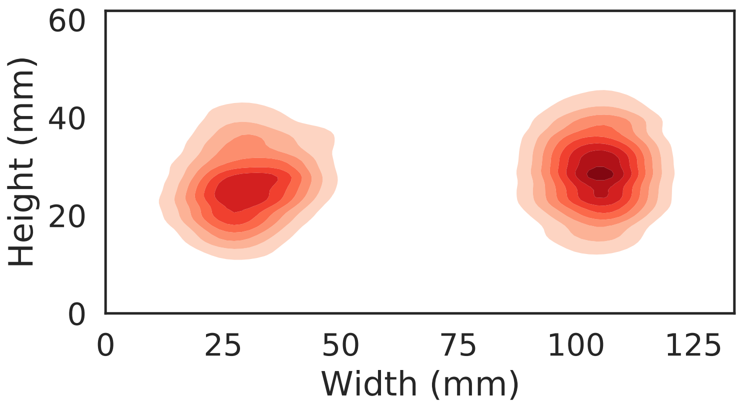


Figure 3.9: Generated heatmap resulting from the swipe touch locations from the game Swiping Hero Landscape.

axis in the range from 0 pts (0 mm) to 373 pts (61.17 mm) and the touch locations of the right sweet area are on the horizontal axis in the range from 407 pts (66.74 mm) to 802 pts (131.52 mm) and on the vertical axis in the range from 11 pts (1.8 mm) to 371 pts (60.84 mm). The highest density on the left side is on the horizontal axis between 120 pts (19.68 mm) and 220 pts (36.08 mm) and on the vertical axis between 150 pts (24.6 mm) and 220 pts (36.08 mm) and on the right side on the horizontal axis between 600 pts (98.4 mm) and 700 pts (114.8 mm) and on the vertical axis between 180 pts (29.52 mm) and 260 pts (42.64 mm). However, the generated heatmap does not confirm our assumption (Figure 3.1). Apart from that, the heatmaps in landscape mode are similar and therefore, based on the two results, we have defined two new sweet areas for smartphone use in landscape mode (Figure 3.10).

3.2.8 Discussion

The results of the study validate Mayer's result, even though our sweet area in portrait mode has a smaller area. The reason for this is probably, as mentioned above, the much smaller amount of study data. However, because the densest area is in close proximity to the densest area

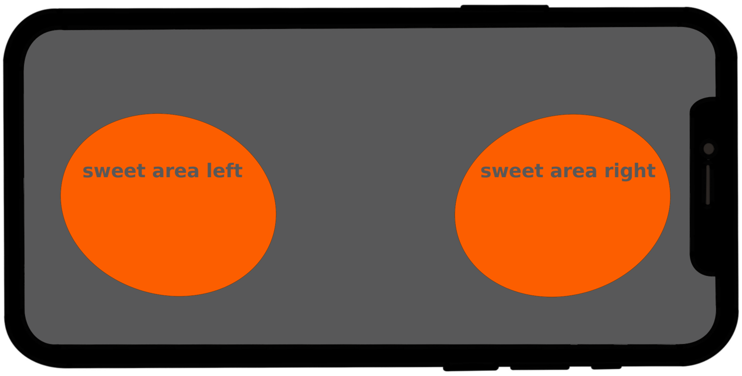


Figure 3.10: Resulting sweet areas for two-handed smartphone use in landscape mode, represented by the two dark orange areas.

of Mayer's sweet area, this is the reason for confirming Mayer's results and creating two new sweet areas in landscape mode. It is important to note that the sweet areas of Figure 3.10 are scaled up to the scale of Mayer's sweet area, as it is assumed that if we had obtained more data, the scale would be approximately matched.

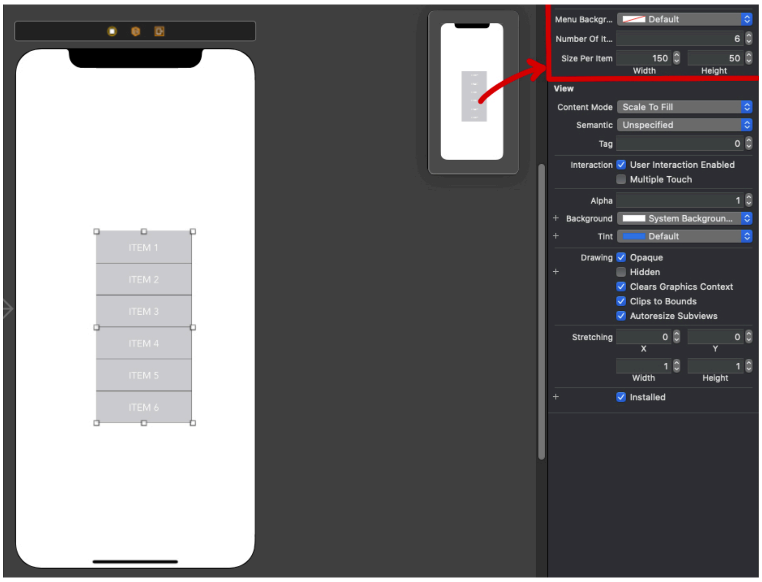


Figure 3.11: TXCode's storyboard is shown here. A custom UIView is selected, which in this case represents the linear menu. In the red box you can see the individual customization options of the menu, which can be changed directly in the user interface (live change inclusive).

3.3 Menu Adaptions

Based on the results of our study, we adapted three existing menu types to the smartphone and also designed our own.

The menu adaptations are based on the sweet areas.

The sweet area was used as an orientation area for the placement of the individual menu types, more precisely in which position a menu type appears. Each menu type was programmed in such a way that it can be easily integrated, modified and used in Apple's XCode. This includes compatibility with XCode's user interface, allowing for example to change the number of menu items directly in XCode's storyboard (Figure 3.11).

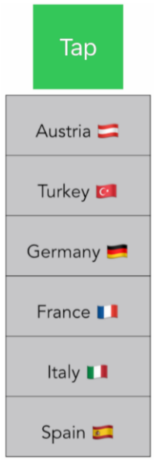


Figure 3.12: Linear menu adaption with six items open centered under the menu button.

3.3.1 Linear Menu

The linear menu (Figure 3.12) belongs to the linear menu types. Linear menu types are menus in which the menu items are arranged are arranged horizontally or vertically next to each other. Raising the number of items increases the size of the menu downwards and the item is added at the bottom accordingly. In our case, if there is no collision with the edges, the linear menu will open in the center under the menu button. If there is a collision with one of the four edges, the menu is pushed in the direction where the collision will be removed. For example, if the menu button is at the bottom and the linear menu collides with the lower edge when it opens, the menu is moved up along the vertical axis until there is no more collision. It can also occur that the menu button is covered by the menu. This adaptation keeps the menu close to the menu button and the linear menu will always point towards the sweet area on the vertical axis in portrait mode.

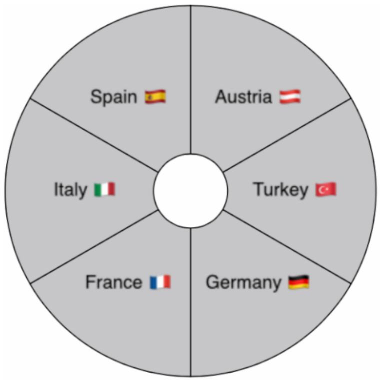


Figure 3.13: Pie menu adaption with six items, opened in the middle above the menu button which is covered thereby.

3.3.2 Pie Menu

The pie menu (Figure 3.13) belongs to the non-linear menu types. Non-linear menu types are menus where the items are arranged in a non-linear way, for example, circular as in this case. Our adaptation of the pie menu arranges all items circularly around an empty smaller circle, so that each item has the same area. As long as the number of items is not larger than six, the labels are displayed horizontally within the pie slices. If the number of items is more than six, the labels of the items are rotated to fit the corresponding slices. Thus the menu size remains constant and only the size of the pie slices decreases/increases when adding/removing items. If there is no collision with the edges when opening the menu, it is placed in the center of the menu button and covers it. The reason for this is that you have the same distance to all items when opening the menu and can therefore reach all items equally fast. If there is a collision with one of the four edges, the menu is positioned in the corresponding direction, so that the collision is resolved.

Figure 3.14: Square menu adaption with six items, opened on the right under the menu button. Adaption is based on Ahlström et al.

3.3.3 Square Menu

The square menu (Figure 3.14) is a more unknown non-linear menu type, which was developed by Ahlström et al. for the desktop area. Our adaptation of the square menu arranges all items in a rectangle, whereas the item shape is quadratic. The number of items on the horizontal and vertical axis can be calculated by $v = \lfloor log_2(n) \rfloor$ and $h = \lceil log_2(n) \rceil$, where v is the number of items on the vertical axis, h is the number of items on the horizontal axis and n is the number of items in the menu. The items are arranged in a serpentine manner from top left to bottom right. If an item is added, the menu size is recalculated and the item is placed at the bottom right in the first free position. Since the menu has a rectangular shape, it cannot be completely filled with an odd number of items. In this case the shape of the menu remains the same and the area that cannot be filled remains empty. If there is no collision when opening the menu, it will be placed right under the menu button. If there is a collision with one of the four edges, the menu will be positioned in the corresponding direction so that the collision is resolved. This adaptation keeps the menu close to the menu button and the square menu will always point in the direction of the sweet area on the vertical axis in portrait mode and on the horizontal axis in the direction of the right sweet area in landscape mode.

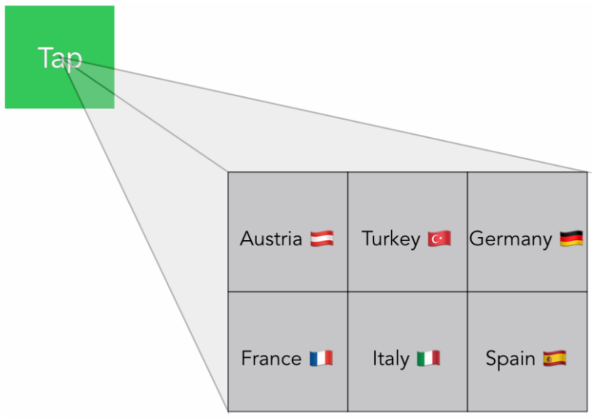


Figure 3.15: Self-designed sweet area menu with six items. The beam, which emanates from the green menu button, shows the affiliation of the menu to the menu button.

3.3.4 Sweet Area Menu (SAM)

The sweet area menu (SAM, Figure 3.15) is our own designed non-linear menu type based on the previously confirmed sweet area (portrait mode) and retrieved sweet areas (landscape mode). SAM behaves like the square menu described above, except that the position of the menu is always in the sweet area. The affiliation of the menu to the menu button is visualized by a beam outgoing from the menu button. In portrait mode, there is a sweet area in the lower right area, so regardless of the position of the menu button, SAM is always displayed there. In landscape mode there are two sweet areas on the left and on the right side of the screen, so depending on the position of the menu button SAM will be positioned either in the left sweet area or in the right sweet area. More precisely, if the menu button appears on the left half of the screen, the menu appears in the left sweet area and vice versa.

Chapter 4

Study 2: A Comparison of Linear and Non-Linear Menu Types

In this chapter, we examine the user study in which the four menu types were compared against each other.

4.1 Experimental Design

In our within-group subject user study, participants operated the four menus linear, pie, square, and sweet area menu in the dedicated study app. For this, the participants had the task of selecting countries in the menu types.

We have programmed a study app for item selection within the four menus.

The study app was used for item selections of specific *menu types* in conjunction with *screen orientation*, *hand grasp* and *number of items*, which was counterbalanced by a latin square. The participant started in either portrait mode or landscape mode. Per screen orientation, a user made a total of 80 item selections per menu type. 40 times with the thumb technique and 40 times with the eagle technique. Per technique and type, ten item selections were made for the specific number of menu items, which were either four, six, eight or twelve. In total, a participant made 640 item

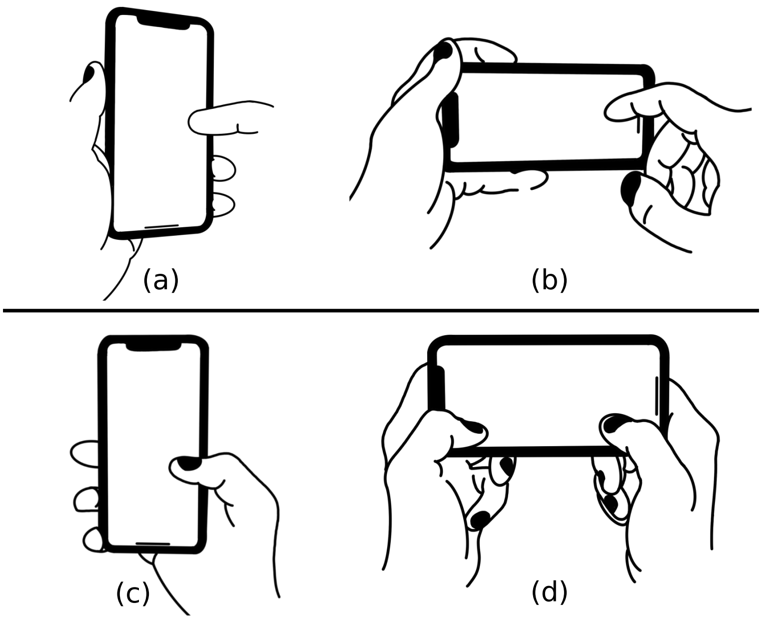


Figure 4.1: In the upper half, the eagle technique can be seen once in portrait mode (a) and once in landscape mode (b). The lower half shows the thumb technique in portrait mode (c) and in landscape mode (d).

selections.

Two hand grasps (eagle and thumb) were used.

All participants were right-handed and used the device once with the eagle technique and once with the thumb technique (Figure 4.1). Eagle technique means that the smartphone is either held in the left hand and operated with the right index finger or vice versa. All participants chose to hold the smartphone in their left hand and operate it with their right hand when using the eagle technique. It was important that the operating arm was not propped up, so that the data could not be falsified, as this would have an effect on the selection time and error rate. The thumb technique means that the smartphone was operated with the right hand and the right thumb in portrait mode and ambidextrously with both thumbs in landscape mode.

At the beginning of the study, the first combination for the next ten rounds (one round corresponds to one item selection) was shown (Figure 4.2). The combination provided

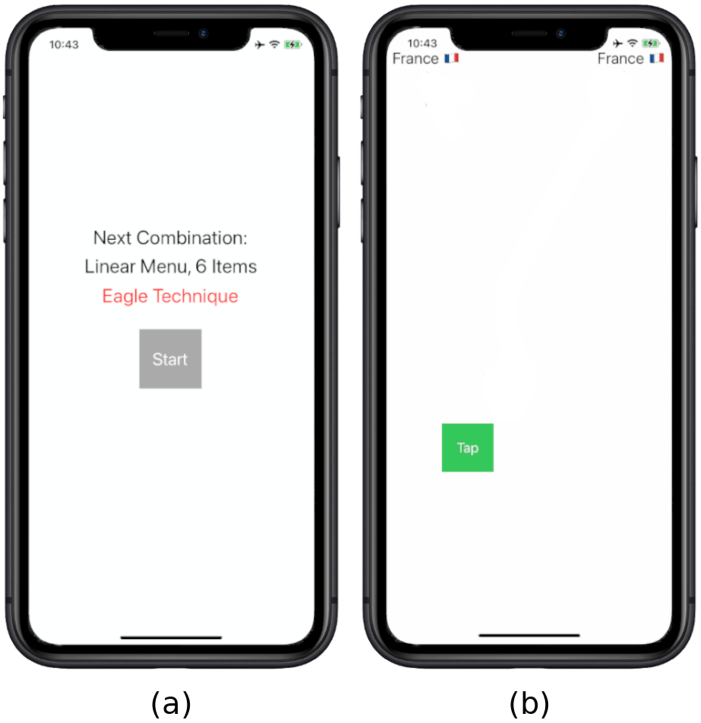


Figure 4.2: Combination indication for the next ten rounds is shown at (a). After pressing start, (b) appears and the country to be selected can be seen in the upper left and right corner and the menu button can be pressed to open the specific menu depending on the current combination.

the user with information about the menu type, number of items within the menu and which control technique was to be used. After the user tapped on the start button, a green tap button and a country name with the corresponding country flag were displayed in the upper left and upper right corner (Figure 4.2). The top left and top right were identical, because a menu could cover either top right or top left when opened. Therefore, at least one country was always visible to the user. The countries were randomly selected from a set of twelve European countries (Austria, Turkey, Germany, France, Italy, Spain, Poland, Czechia, Greece, Sweden, Portugal and Ukraine). In addition to the country names, the corresponding flag was also displayed, so that in addition to the country names,

Next combination shows which menu with which number of items and which hand grasp will be used next.

a visualization was also available for the participants and they could freely decide whether they wanted to search for a country by reading or by the flag.

The size of the menu items is based on Apple's human interface guidelines for buttons.

The size of the menu items was determined based on Apple's human interfrace guidelines for buttons[1] (44 x 44 pts). We tried to make all items approximately the same size, but this was not possible in all conditions. The menu items in the linear menu have a width of 120 pts. The height depends on the orientation of the smartphone and the number of items. In portrait mode with four to eight items the height is 50 pts and with twelve items 47 pts. In landscape mode, the height of the items is 40 pts for eight items and 28 pts for twelve items. The reason for the lower height of the items in landscape mode is the screen limitation. The items in the pie menu (pie slices) have an average size of 47 pts in all conditions. The items in the square and sweet area menus have a size of 82 x 82 pts in both screen orientations and for all number of items.

The green menu button clearly stands out from the menus with its color.

The green button is the menu button, which, when tapped, opened the specific menu type which depended on the current combination. The eye-catching color of the menu button was chosen so that it stood out clearly from the menus to avoid possible misinterpretation with a menu item. The screen was divided into a 5x10 (vertical x horizontal) grid on which the button was randomly placed. After an item selection, the previous position was excluded as a possible next position and a new grid position was randomly determined. Thus, after each item selection, the country and the menu button position were redefined and displayed. After the button is pressed, the specific menu opened and was displayed. The order of the menu items was fixed, because in this study we define our menu types as context menus which in reality also do not have a random item order. Pressing a menu item was represented by a button feedback in the form of darkening of the pressed item. It was also possible for the user to move the finger over the items while the finger was already on the screen. This was also represented by button feedbacks. Whether a selection was right or wrong was not shown to the user, as this would not

[1] https://developer.apple.com/design/human-interface-guidelines/sign-in-with-apple/overview/buttons/

be close to reality and the user might become slower in his selection in order to receive correct feedback each time.

After ten rounds, a new combination is displayed and the same procedure is repeated until all combinations have occurred once.

4.2 Participants

Overall, 15 people (female: 3, male: 11, no specification: 1) participated in the study with an average age of 24 years. All participants were right-handed and experienced in the use of smartphones. The average smartphone use per day of the participants was approximately 4.5 hours.

4.3 Apparatus

In our study, we used an iPhone 11, which is 150.9 mm high and 75.7 mm wide. The screen diagonal measures 6.1" (15.5 cm) with 1792 x 828 pixels and a pixel density of 326 ppi. Overall, the device weighs 194g.

4.4 Task

Participants had to memorize the displayed country and select it from the menu.

The task of the participants was to open the specific menu and select the country that was displayed in the upper right/left corner. In total, there were 320 rounds, which means 320 item selections. The orientation of the device changed automatically after exactly 160 rounds. After another 160 item selections in the opposite orientation, the app automatically ended and the participants should put the device aside.

Finally, participants were asked to fill out an end questionnaire (Figure A "Study 2: Questionnaire") that measured product satisfaction. Questions were asked about each menu type and each combination of hand grasp and orientation, focusing on the clear layout, accessibility, findability, selectability and general liking of the menu.

4.5 Study Procedure

At the end, participants were asked to complete an end questionnaire.

At the beginning of the study, the purpose and the task of the study were explained to the participants. Images of the specific menu types were shown and their special features were described. The participants were instructed to memorize the menu types and to ask questions if there were any uncertainties. In addition, the two hand grasps eagle and thumb technique were explained in more detail and the participants had to decide how they wanted to hold the smartphone when using the eagle technique. They were allowed to hold the device in their hands and familiarize themselves with the hand grasps. After the initial phase, the participants were instructed to start the study app and begin with the item selections. If questions arose in the meantime, they could be asked as long as the participant was not in an item selection. After the app automatically ended, participants were told to put the device aside and fill out the end questionnaire. This also included a ranking of the four menu types. It was important that no double allocation of places was allowed. For each menu and the ranking, the participants were able to write additional comments.

4.6 Measurements

Item selection time, error rate and user satisfaction were measured.

Throughout the study, we measured the *item selection time* for each item selection and whether it was a false selection or not (*error rate*). The selection time per item was measured from the moment the green menu button was pressed and it was stopped from the moment the item was selected. We distinguished between two errors, the error of selecting an item incorrectly and the error of tapping outside the menu. In addition to the item selection, the corresponding round, orientation, menu type, number of menu items, hand grasp and position of the menu button were recorded.

In total we measured 9600 item selections.

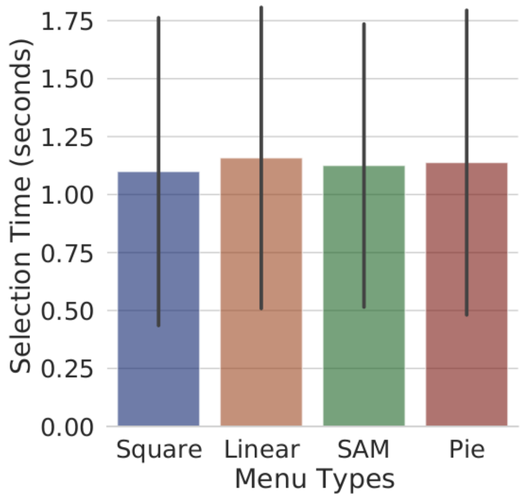


Figure 4.3: Selection time of the different menu types in general comparison. The bars show the mean selection time along with the standard deviation, represented by the vertical line in the middle of the bars.

4.7 Results

We have assigned the selection times and error rate to the respective menu types and analyzed and compared them depending on screen orientation, hand grasp and number of menu items. We also looked at all the data combined so that we could make a general comparison of the menu types. In each comparison, the mean and standard deviation of the selection times and error rates are considered.

4.7.1 Item selection time

General Comparison

Square menu performs the fastest in our study.

In a general comparison of all four menu types (Figure 4.3), the square menu performs the fastest with an mean item selection time of 1.09 seconds in our study. Behind it is the sweet area menu with 1.12 seconds. The pie menu performs

0.01 seconds slower than the SAM. The linear menu performs the slowest in our result with an average selection time of 1.15 seconds.

Number of Menu Items Comparison

If we look at the item selection time depending on the number of menu items (Figure 4.4), we see that with four items the pie menu performs the fastest in our data with 0.82 seconds. Behind it is the square menu with 0.9 seconds, followed by the linear menu with 0.92 seconds. SAM performs the slowest with 0.93 seconds.

Pie menu performs the fastest in our study with four menu items.

If the number of menu items is increased to six, the order of the menu types depends on the performance remains the same, but the average item selection time increases for each menu. In our study with six items, the pie menu has an average item selection time of 0.97 seconds, the square menu has 0.98 seconds, which is equal to the linear menu, and SAM has 1.01 seconds.

Pie menu performs the fastest in our study with six menu items.

With a number of eight menu items, the order of the menus depends on the performance changes in our study. Here, SAM performs the fastest with 1.15 seconds, followed by the square menu with 1.17 seconds. With a difference of 0.01 seconds, the linear menu is behind it, and the pie menu performs the slowest with 1.22 seconds in our results.

Square menu performs the fastest in our study with eight menu items.

If we now look at the maximum number of twelve menu items in our study, the linear menu performs worst with 1.53 seconds. The pie menu is close behind with a difference of 0.01 seconds. The second fastest menu performance has SAM with 1.39 seconds and the fastest menu performance has the square menu with 1.33 seconds.

Square menu performs the fastest in our study with twelve menu items.

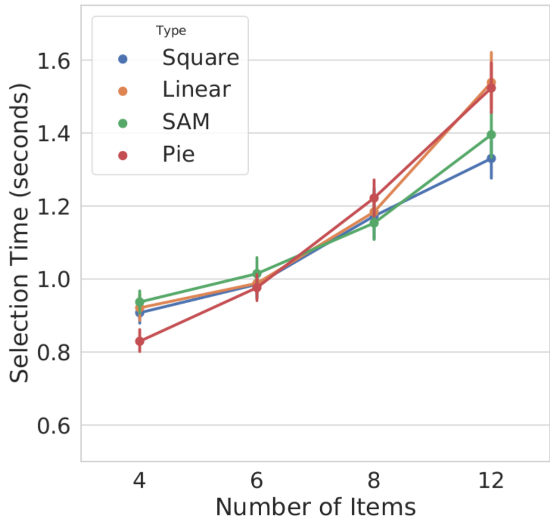


Figure 4.4: Item selection time of the four menu types linear, pie, square and sweet area depending on the number of menu items. The points show the mean selection time along with the standard deviation, represented by the vertical line in the middle of the points.

Eagle and Thumb Technique Comparison

Square menu performs the fastest in our study when using the eagle and thumb technique.

If we look specifically at the item selection times of the menus using the eagle technique on the one hand and the thumb technique on the other (Figure 4.5), each menu type perform faster when using the eagle technique than when using the thumb technique in our study.

With the eagle technique, the square menu performs in our case the fastest with 1.02 seconds, followed by SAM and the pie menu, which both have an average item selection time of 1.06 seconds. In our study, the linear menu performs the slowest in the eagle technique with 1.09 seconds.

For the thumb technique, the square menu has the best average item selection time of 1.16 seconds in our results, followed by SAM with 1.18 seconds. The linear and pie menus perform the slowest with 1.21 seconds.

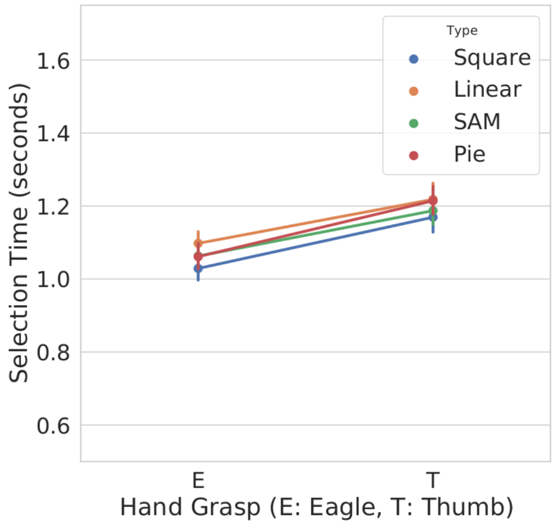


Figure 4.5: Item selection time of the four menu types linear, pie, square and sweet area depending on the hand grasps technique eagle and thumb. The points show the mean selection time along with the standard deviation, represented by the vertical line in the middle of the points.

Screen Orientation Comparison

SAM performs the fastest in our study in portrait mode.

In our study, the menu types linear, pie, and square perform faster in landscape mode than in portrait mode, whereas SAM performs faster in portrait mode than in landscape mode (Figure 4.6).

In landscape mode, the square menu performs the fastest in our case with 1.06 seconds, followed by the pie menu with 1.1 seconds. The linear menu has an average item selection time of 1.14 seconds and SAM performs the slowest with 1.18 seconds.

In portrait mode, however, SAM performs the fastest in our evaluation with 1.06 seconds, followed by the square menu with 1.13 seconds. The linear and pie menus perform the slowest in portrait mode with 1.17 seconds.

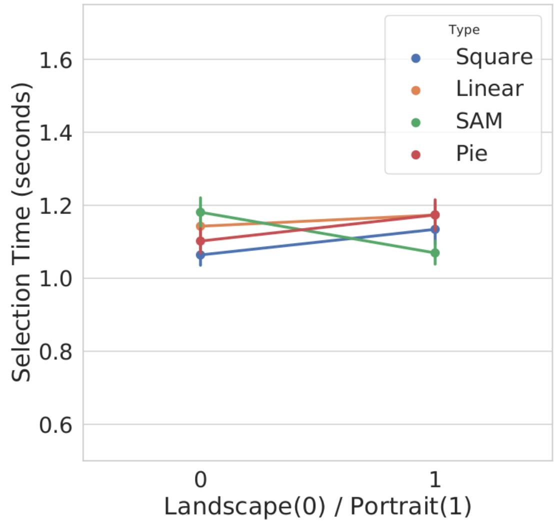


Figure 4.6: Item selection time of the four menu types linear, pie, square and sweet area depending on the screen orientation portrait and landscape. The points show the mean selection time along with the standard deviation, represented by the vertical line in the middle of the points.

4.7.2 Error Rate

The error rates of the individual menus and conditions differ not much from each other.

The error rates of the participants in our study are almost identical in the general comparison of the four menu types linear, pie, square and sweet area. The item selections in the pie, square and sweet area menus were on average 98% correct, whereas in the linear menu they were 97% correct. Depending on the number of menu items, screen orientation and hand grasp, the error rates of the menus change by a maximum of two percentage points.

Depending on the number of menu items, the error rate in our study of the linear menu is between two and four percent. The pie menu is between one and three percent, just like the sweet area menu. In our evaluation, the square menu has an error rate of two to three percent, depending on the number of menu items.

Depending on the screen orientation, the error rate in our study of the linear menu is 3% in landscape mode and 2%

in portrait mode. In our evaluation, the pie, square and sweet area menus have an error rate of 2% in both screen orientations.

Depending on the hand grasps eagle technique and thumb technique, the error rate in our study is 2% for the pie and square menu in both conditions. The linear menu has an error rate of 4% in our evaluation with the eagle technique and 2% with the thumb technique. SAM has an error rate of 3% with the eagle technique and 2% with the thumb technique.

4.7.3 User Satisfaction

The participants answered five questions per menu type. Each question consists of four answers, which were specifically designed for the combinations "Portrait x Eagle", "Portrait x Thumb", "Landscape x Eagle" and "Landscape x Thumb". It could be seen that there were only slight differences between the combinations. No difference was recorded between satisfaction in portrait and landscape mode in our study. The menus that were operated with the thumb technique had a higher satisfaction of five percentage points compared to the eagle technique. In the following, we therefore look at the questions individually, but not in dependence on all the conditions mentioned above.

Square menu performed best in user satisfaction in general and also in the individual conditions.

General Satisfaction

In the end questionnaire of our study, each question provided the answer options "Totally disagree", "Disagree", "Neither nor", "Agree" and "Totally agree". Each answer option was allocated a value from 1-5 (1: "Totally disagree", 2: "Disagree", 3: "Neither nor", 4: "Agree", 5: "Totally agree"). The overall satisfaction of the menu types is calculated by summing up all answers of all participants according to the menus (Figure 4.7). Each menu could reach a maximum of 1500 points. The square menu scored best with 1243 points (82%), followed by SAM with 1189 points (79%). The linear menu reached a general satisfaction of

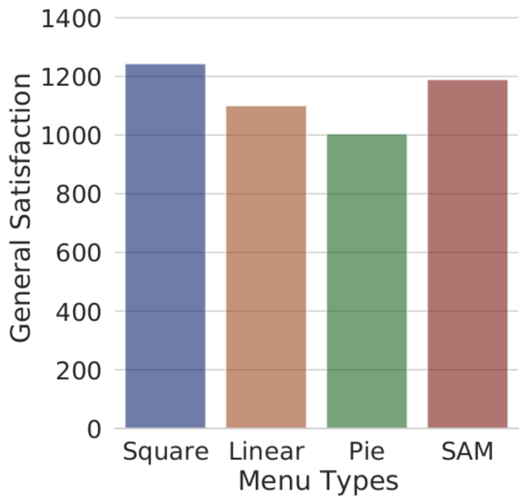


Figure 4.7: General satisfaction of the four menu types linear, pie, square and sweet area. The bars show the sum of all satisfaction points of all participants.

1100 points (73%) and the pie menu got the fewest points in our evaluation with 1004 points (66%).

Menu Aspects Satisfaction

The distribution of satisfaction points for the menu aspects "Menu is clear", "Menu items can be reached comfortably", "Menu items can be found easily" and "Menu items can be selected accurately" are illustrated in Figure 4.8.

For the aspect "Menu is clear", the square menu received the most points in our study with 253 (84%) of 300 possible points. Behind it is SAM with 246 points (82%). The linear menu received 229 points (76%) in our evaluation, followed by the pie menu with 191 points (63%).

In the aspect "Menu items can be reached comfortably", the square menu obtained 246 points (78%), followed by SAM with 236 points (82%). The linear menu and the pie menu got the lowest scores with 227 points (75%) and 225 points (75%) respectively.

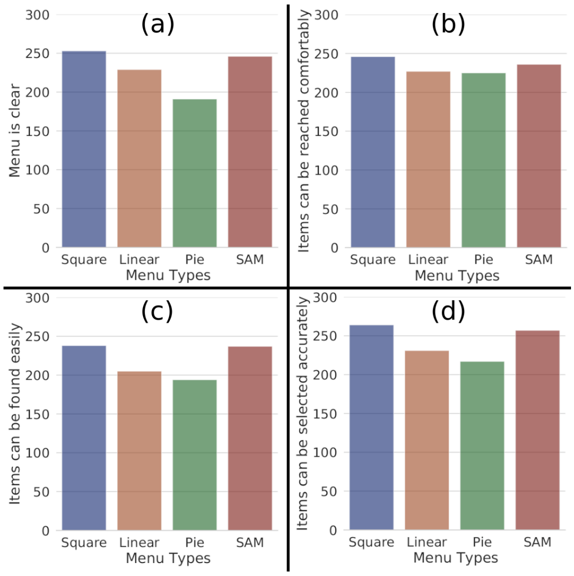


Figure 4.8: Summated satisfaction points of the respective menu types linear, pie, square and sweet area for the menu aspects (a) "Menu is clear", (b) "Menu items can be reached comfortably", (c) "Menu items can be found easily" and (d) "Menu items can be selected accurately". The bars show the sum of the satisfaction points of all participants.

In the aspect "Menu items can be found easily", the square menu and SAM achieved almost the same score. In our evaluation, the square menu scored 238 points (79%) and SAM 237 points (79%). The linear menu came third with 205 points (68%), followed by the pie menu with 194 points (64%).

In the aspect "Menu items can be selected accurately", the square menu received the most points in our study with 264 points (88%). SAM comes in second with 257 points (85%). The linear menu scored 231 points (77%) in our evaluation, followed by the pie menu with 217 points (72%).

General Liking of the Menus

Regarding the general liking of the menu types linear, pie, square and sweet area (Figure 4.9), the square menu was

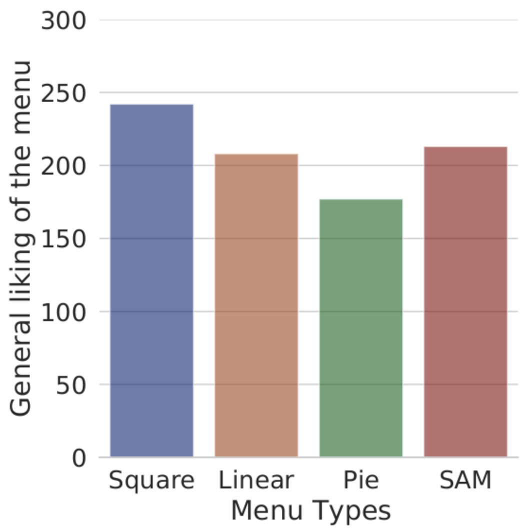


Figure 4.9: General liking of the four menu types linear, pie, square and sweet area. The bars show the sum of the general liking satisfaction points of all participants.

the best in our study with 242 (80%) out of a possible 300 points. SAM came in second with 213 points (71%), closely followed by the linear menu with 208 points (69%). The pie menu was the worst in our evaluation with 177 points (59%).

Ranking

Square menu was ranked best by the participants.

In all menu aspects, the satisfaction score ranking of the menu types linear, pie, square and sweet area is the same, which is also reflected in the user menu ranking (Figure 4.10). Each position in the ranking of the participants was assigned a number of points (1st place: 4 points, 2nd place: 3 points, 3rd place: 2 points, 4th place: 1 point) and at the end the points of all menu types were summed up. In total, a menu type could achieve a maximum of 60 ranking points by placing the menu in first place for each participant. The square menu is in first place with 48 points (80%), followed by SAM with 40 points (66%). The linear menu is in third place in the ranking with 37 points (61%) and the pie menu is the lowest ranked with 26 points (43%).

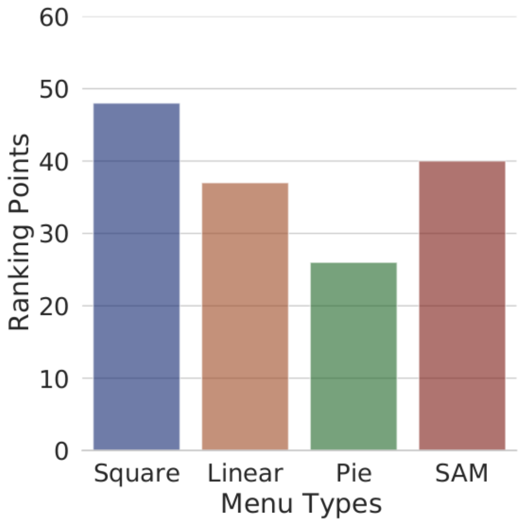


Figure 4.10: Ranking of the four menus square, linear, pie and sweet area. The bars show the sum of the ranking points of all participants.

4.8 Discussion

In our overall comparison, the pie menu performed among the slowest, even though it tended to perform better in menu comparisons in other areas. There are two possible reasons for this: firstly, the pie slices decrease in size as the number of items increases, and secondly, from eight items onwards, the item labels rotate according to the angle of the pie slices. One argument for this is the item selection time of the pie menu depending on the number of menu items. As long as the labels do not rotate, that is with four and six items, the pie menu performs fastest. This is not only recognisable from the data, it was also noted by the majority of the user group. The rotation of the item labels and the decreasing size of the items are also possible reasons for the pie menu performing lowest in user satisfaction.

Reasons for the slow performance of the pie menu could be the decreasing size of the pie slices and the rotating item labels.

The linear menu performed slowest in our evaluation. Reasons for this could be that with a larger number of menu items, the menu becomes unclear and the items are more difficult to find. These reasons were also reported by participants. In addition, at the end of the study, several users felt that the pie menu performed the slowest.

The performance of the square menu is the best in our study, both in terms of item selection time and user satisfaction. One reason for this could be that the square menu seems to be the most intuitive, which was also frequently mentioned by the participants. One user compared the arrangement of the menu items with the grid of the iOS (Apple's iPhone operating system) home screen.

A negative aspect of SAM is the double change of the hand grasp when the menu button is in a hard to reach position.

The sweet area menu performed worse than the square menu in our study, although they are identical except for the position of the menu. The reason for the poorer item selection time could be that if the menu button is in an inconvenient position, users have to change their grip to reach the button and then change their grip again to reach the sweet area where the menu opens (only occurs with thumb technique). This was also frequently noted by users and could also be the reason for the lower user satisfaction compared to the square menu. If we look at the individual combinations separately, the menu performs best in portrait mode and worst in landscape mode. The reason for this could be that SAM is always displayed in exactly one area in portrait mode, whereas there are two display areas in landscape mode. This was also noted by participants in the study and perceived as a negative aspect.

No menu can be clearly recommended more than the others.

Even though the square menu performs the fastest and has the best user satisfaction, we cannot make a clear recommendation which menu is the most appropriate in the area of smartphones. This depends strongly on the number of menu items and the screen orientation. We recommend using the pie menu if the number of menu items is low (maximum of six items). If the menu has a higher number of items and is operated in portrait mode, SAM is recommended. For dynamic screen orientation and number of items, we recommend the square menu.

Chapter 5

Summary and future work

5.1 Summary and contributions

In this thesis, we investigated menus for smartphones. The aim of this work was to compare the linear menu with the three non-linear menus and to find out which menu types perform best.

In order to achieve a reasonable adaptation of the menus to the smartphone, we took a closer look at the sweet area defined by Mayer et al.. However, since this has so far only been investigated in portrait mode, we conducted a further user study in which participants were asked to play two game apps in the portrait and landscape screen orientations. We identified two types of touch locations (tap and swipe data) and created four heatmaps from them. We compared the heatmaps based on the portrait data with Mayer's heatmaps and were able to confirm their sweet area. Using the two heatmaps from the landscape data, we then identified two new sweet areas for smartphone use in landscape mode with two thumbs.

Based on our results from the first study, we adapted the three menus linear, pie and square to the smartphone and additionally developed our own menu, the sweet area menu.

Finally, we compared these four menus in a further user study with 15 participants. In this study, we asked participants to select given countries from the menus and then complete an end questionnaire that we used to determine user satisfaction of the menus. In the overall comparison in our study, the menus performed about the same, both in item selection time and error rate. Differences were more evident in the individual conditions such as number of items, screen orientation and hand grasp. On the other hand, the square menu was rated best by our participants in terms of satisfaction and the pie menu was rated worst. This was also the case in all satisfaction subcategories.

In conclusion, depending on our data, we can say that the two non-linear menus square and sweet area performed best, both in terms of overall item selection time and user satisfaction. However, we cannot make a clear recommendation as to which menu is best suited for the smartphone area.

5.2 Future work

In our second study in Chapter 4, we compared the menus under laboratory conditions. We recommend further research that examines menu types outside of laboratory conditions to obtain even more intuitive user behavior. This could be achieved by, for example, an in-the-wild study.

The menu button was randomly displayed on a grid on the screen in our second study. This means that it could be located in any area of the screen.We recommend further research comparing different menu types with the menu button in a fixed position to find out whether menu types perform better depending on the position of the menu button or not.

We hope that this work can be an inspiration for further menu research in the field of smartphones. Further studies could investigate other menu types and possibly find out more information about the menus investigated here in order to clearly determine which menu types are best suited for which conditions.

Appendix A

Study 2: Questionnaire

End Questionnaire

General Questions

Age: ☐

Sex: ◯ male ◯ female ◯ no specification

Daily Smartphone Usage (in hours):
◯ 0-1 ◯ 1-2 ◯ 2-4 ◯ 4-6 ◯ 6-8 ◯ 8+

Linear Menu

The menu is clear (Das Menü ist übersichtlich):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The menu items can be reached comfortably (Das Menü kann komfortabel erreicht werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The items can be found easily (Die Items können leicht gefunden werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The items can be selected accurately (Die Items können akkurat getroffen werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

I generally like the menu (Ich mag im allgemeinen das Menü gerne):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

Additional comments on the menu:

Figure A.1: End questionnaire page 1. General questions about the participants and about the linear menu.

Pie Menu

The menu is clear (Das Menü ist übersichtlich):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The menu items can be reached comfortably (Das Menü kann komfortabel erreicht werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The items can be found easily (Die Items können leicht gefunden werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The items can be selected accurately (Die Items können akkurat getroffen werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

I generally like the menu (Ich mag im allgemeinen das Menü gerne):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

Additional comments on the menu:

Figure A.2: End questionnaire page 2. Detailed questions about the pie menu.

Square Menu

The menu is clear (Das Menü ist übersichtlich):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The menu items can be reached comfortably (Das Menü kann komfortabel erreicht werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The items can be found easily (Die Items können leicht gefunden werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

The items can be selected accurately (Die Items können akkurat getroffen werden):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

I generally like the menu (Ich mag im allgemeinen das Menü gerne):

Portrait x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Portrait x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Eagle	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree
Landscape x Thumb	○ Totally disagree	○ Disagree	○ Neither nor	○ Agree	○ Totally agree

Additional comments on the menu:

Figure A.3: End questionnaire page 3. Detailed questions about the square menu.

Sweet Area Menu (SAM)

The menu is clear (Das Menü ist übersichtlich):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The menu items can be reached comfortably (Das Menü kann komfortabel erreicht werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The items can be found easily (Die Items können leicht gefunden werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

The items can be selected accurately (Die Items können akkurat getroffen werden):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

I generally like the menu (Ich mag im allgemeinen das Menü gerne):

Portrait x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Portrait x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Eagle	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree
Landscape x Thumb	◯ Totally disagree	◯ Disagree	◯ Neither nor	◯ Agree	◯ Totally agree

Additional comments on the menu:

Figure A.4: End questionnaire page 4. Detailed questions about the sweet area menu.

Please rank the menus (1 is best; no double allocations) and write write a short justification into the box below:

1.

2.

3.

4.

Figure A.5: User ranking of the four menu types linear, pie, square and sweet area menu.

Bibliography

David Ahlström, Andy Cockburn, Carl Gutwin, and Pourang Irani. Why it's quick to be square: Modelling new and existing hierarchical menu designs. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, page 1371–1380, New York, NY, USA, 2010. Association for Computing Machinery. ISBN 9781605589299. doi: 10.1145/1753326.1753534. URL `https://doi.org/10.1145/1753326.1753534`.

Khalid Al-Omar and Dimitrios Rigas. The effect of size of personalised menus on user satisfaction. In *Proceedings of the 11th WSEAS International Conference on Mathematical Methods and Computational Techniques in Electrical Engineering (MMACTEE'09). World Scientific and Engineering Academy and Society (WSEAS)*, 2009.

Nikola Banovic, Frank Chun Yat Li, David Dearman, Koji Yatani, and Khai N. Truong. Design of unimanual multi-finger pie menu interaction. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, ITS '11, page 120–129, New York, NY, USA, 2011. Association for Computing Machinery. ISBN 9781450308717. doi: 10.1145/2076354.2076378. URL `https://doi.org/10.1145/2076354.2076378`.

J. Callahan, D. Hopkins, M. Weiser, and B. Shneiderman. An empirical comparison of pie vs. linear menus. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '88, page 95–100, New York, NY, USA, 1988. Association for Computing Machinery. ISBN 0201142376. doi: 10.1145/57167.57182. URL `https://doi.org/10.1145/57167.57182`.

Stuart K. Card. User perceptual mechanisms in the search of computer command menus. In *Proceedings of the 1982 Conference on Human Factors in Computing Systems*, CHI '82, page 190–196, New York, NY, USA, 1982. Association for Computing Machinery. ISBN 9781450373890. doi: 10.1145/800049.801779. URL https://doi.org/10.1145/800049.801779.

S. Gebhardt, S. Pick, F. Leithold, B. Hentschel, and T. Kuhlen. Extended pie menus for immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 19(4):644–651, 2013. doi: 10.1109/TVCG.2013.31.

Rodolfo Inostroza and Cristian Rusu. Mapping usability heuristics and design principles for touchscreen-based mobile devices. In *Proceedings of the 7th Euro American Conference on Telematics and Information Systems*, EATIS '14, New York, NY, USA, 2014. Association for Computing Machinery. ISBN 9781450324359. doi: 10.1145/2590651.2590677. URL https://doi.org/10.1145/2590651.2590677.

John I Kiger. The depth/breadth trade-off in the design of menu-driven user interfaces. *International journal of man-machine studies*, 20(2):201–213, 1984.

R. Komerska and C. Ware. A study of haptic linear and pie menus in a 3d fish tank vr environment. In *12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS '04. Proceedings.*, pages 224–231, 2004. doi: 10.1109/HAPTIC.2004.1287200.

Gordon Kurtenbach and William Buxton. The limits of expert performance using hierarchic marking menus. In *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*, CHI '93, page 482–487, New York, NY, USA, 1993. Association for Computing Machinery. ISBN 0897915755. doi: 10.1145/169059.169426. URL https://doi.org/10.1145/169059.169426.

Gordon P. Kurtenbach, Abigail J. Sellen, and William A.S. Buxton. An empirical evaluation of some articulatory and cognitive aspects of marking menus. *Human–Computer Interaction*, 8(1):1–23, 1993a. doi: 10.1207/s15327051hci0801_1. URL https://www.tandfonline.com/doi/abs/10.1207/s15327051hci0801_1.

Gordon P. Kurtenbach, Abigail J. Sellen, and William A.S. Buxton. An empirical evaluation of some articulatory and cognitive aspects of marking menus. *Human–Computer Interaction*, 8(1):1–23, 1993b. doi: 10.1207/s15327051hci0801_1.

Huy Viet Le, Sven Mayer, Katrin Wolf, and Niels Henze. Finger placement and hand grasp during smartphone interaction. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, page 2576–2584, New York, NY, USA, 2016. Association for Computing Machinery. ISBN 9781450340823. doi: 10.1145/2851581.2892462. URL https://doi.org/10.1145/2851581.2892462.

Huy Viet Le, Sven Mayer, Patrick Bader, and Niels Henze. *Fingers' Range and Comfortable Area for One-Handed Smartphone Interaction Beyond the Touchscreen*, page 1–12. Association for Computing Machinery, New York, NY, USA, 2018. ISBN 9781450356206. URL https://doi.org/10.1145/3173574.3173605.

Songil Lee, Gyouhyung Kyung, Jungyong Lee, Seung Ki Moon, and Kyoung Jong Park. Grasp and index finger reach zone during one-handed smartphone rear interaction: effects of task type, phone width and hand length. *Ergonomics*, 59(11):1462–1472, 2016. doi: 10.1080/00140139.2016.1146346. URL https://doi.org/10.1080/00140139.2016.1146346. PMID: 26943492.

Sven Mayer, Huy Viet Le, Markus Funk, and Niels Henze. Finding the sweet spot: Analyzing unrestricted touchscreen interaction in-the-wild. In *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, ISS '19, page 171–179, New York, NY, USA, 2019. Association for Computing Machinery. ISBN 9781450368919. doi: 10.1145/3343055.3359705. URL https://doi.org/10.1145/3343055.3359705.

Dwight P. Miller. The depth/breadth tradeoff in hierarchical computer menus. *Proceedings of the Human Fac-*

tors Society Annual Meeting, 25(1):296–300, 1981. doi: 10.1177/107118138102500179.

George A Miller. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological review*, 63(2):81, 1956.

Jingjie Zheng, Xiaojun Bi, Kun Li, Yang Li, and Shumin Zhai. M3 gesture menu: Design and experimental analyses of marking menus for touchscreen mobile interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, page 1–14, New York, NY, USA, 2018. Association for Computing Machinery. ISBN 9781450356206. doi: 10.1145/3173574.3173823. URL `https://doi.org/10.1145/3173574.3173823`.

Index

Typeset December 29, 2020