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Finding the Limits of Textile Interface Design Guidelines

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Contents

List of Figures

List of Tables

Abstract

As smart fabric technologies continue to evolve, real-world applications of textile user interfaces are within reach. This raises the question of how textile user interfaces should be designed to ensure unobtrusive, simple and intuitive use. In the past research has mostly been limited to either the technical aspects or the extent to which people are able to use textile user interfaces eyes-free. Our aim is to extend this knowledge, but also to focus on the subjective perception of users. After all, users should not only be able to operate the user interfaces, they should also find them pleasant, in order for textile interfaces to provide a serious alternative to already existing user interfaces. For this reason, we are investigating six design aspects in a user study, to gain deeper insights into participants' perceptions. This user study identified a preferred icon size for shape-detection, a threshold for the detection of relative rotation and a preferred slider length. It also demonstrated the applicability of the Gestalt Law of Proximity to textile user interfaces and analyzed its limits for different icon spacing ratios. Furthermore, it provided insights into the directional perception of icons in different orientations and the effect of rectangular ratios on the perception as slider and touchpad, as well as resulting input methods.

Überblick

Mit fortschreitender Entwicklung im Bereich der Smart Fabrics rücken reale Anwendungen textiler Benutzeroberflächen in greifbare Nähe. Dies wirft die Frage auf, wie textile Benutzeroberflächen gestaltet sein sollten, um eine schlichte, einfache und intuitive Nutzung zu gewährleisten. In der Vergangenheit beschränkte sich die Forschung meist entweder auf technische Aspekte oder auf die Frage, ob und inwieweit Menschen in der Lage sind, textile Benutzeroberflächen ohne visuelle Komponente zu bedienen. Unser Ziel ist es, dieses Wissen zu erweitern, aber auch, die subjektive Wahrnehmung der Nutzer genauer zu untersuchen. Schließlich sollten Nutzer die Benutzeroberflächen nicht nur bedienen können, sondern sie auch als angenehm empfinden. Nur dann stellen textile Benutzeroberflächen eine ernstzunehmende Alternative zu bereits bestehenden Benutzeroberflächen dar. Aus diesem Grund untersuchen wir in einer Nutzerstudie sechs Designaspekte, um tiefere Einblicke in die Wahrnehmung der Teilnehmer zu gewinnen. In dieser Nutzerstudie wurden eine bevorzugte Icongröße für die Form-Erkennung, ein Schwellenwert für die Erkennung relativer Rotation und eine bevorzugte Sliderlänge ermittelt. Außerdem wurde die Anwendbarkeit des Gestaltgesetzes der Nähe auf textile Benutzeroberflächen nachgewiesen und seine Grenzen für verschiedene Ratios von Iconabständen analysiert. Darüber hinaus lieferte die Studie Einblicke in die direktionale Wahrnehmung von Icons in verschiedenen Ausrichtungen und die Auswirkung von Ratios rechteckiger Formen auf die Wahrnehmung als Slider oder Touchpad, sowie daraus resultierende Eingabemethoden.

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Finally, I would like to thank all participants of the study for their time and valuable feedback.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

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

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

Definition:
Excursus

The whole thesis is written in American English.

Download links are set off in colored boxes.

File: myFile[a]

[a] https://git.rwth-aachen.de/i10/thesis/thesis-erik-mueller-limits-of-textile-interface-design-guidelines/-/raw/main/file_number.file

Chapter 1

Introduction

Textile user interfaces have become an increasingly more relevant subject in recent years, as research into their technical possibilities has yielded promising results [Aigner et al. [2020], Luo et al. [2021], Liu et al. [2023]] and the number of real-life use cases for elements to be controlled in environments, such as smart homes, continues to grow.

Textile user interfaces become an increasing field of research.

There are already existing alternatives for controlling these elements, such as voice control, gesture control or simply remote controls. However, although all of these options have their areas of application, they each have their limits. Imagine being in a dark room with a television on. If one now wants to change the volume of said TV and has to choose between one of these three options, one would have to realize that gesture recognition tends to work less well in dark environments, voice recognition is more prone to errors when overlapping with other audio sources and remote controls, if even within reach, are typically designed to rely on visual feedback, making them unsuitable for use in the dark [Lloyd-Esenkaya et al., 2020].

Existing alternative control interfaces have their limits.

A user interface that can be operated without visual feedback can help in such situations. Textiles are a promising choice for the texture of this user interface, as people are already surrounded by textiles and fabrics in almost every environment. In this example, a subtle incorporation of a textile user interface into the seating furniture could pro-

Textile user interfaces could overcome these limits.

vide an intuitive and unobtrusive way to control the TV, which can be extended to many other devices and use cases in general.

Research has mainly been focused on the technical aspects.

There has been promising research into smart fabrics and their practical implementation, both in terms of measurement [Wu et al. [2020a], Rus et al. [2017]] and interaction with people on fixed objects or on the body [Wu et al., 2020b], e.g. in the form of clothing [Holleis et al. [2008], Karrer et al. [2011]]. Unlike the technical implementation, the design of textile user interfaces has not been part of active research in most publications.

Icons provide the necessary feedback for eyes-free interaction.

In order to provide users with an eyes-free way of interacting with user interfaces, such interface needs to offer tactile feedback to the user, typically by altering the surface where the control element is located. Mlakar and Haller [2020] have found that the easiest tactile contrast to recognize is height. This informs the user that there is an element that can be interacted with. However, in order to also provide a context which, for example, communicates a function of this specific element, a distinction between the different elements is required. This differentiation is made using different tangible shapes, also known as icons.

Textile icons are shapes that can be recognized by touch.

A textile icon is a shape that can be recognized by touch, which gives a user feedback about its own appearance and thus also about the context of the control element it represents. It can be the control element itself, such as a button, or located on or near a control element to which it should provide information. Some studies have already explored the recognizability of such icons [Mlakar and Haller, 2020], [Schäfer et al., 2023].

Design research has been focused primarily on ability.

However, much of this research has focused on the extent to which people are *able* to perceive shapes in a tactile way. Whereas people's subjective perception, i.e. what they *want* to do rather than what they *can* do and what they perceive to be pleasant rather than what they simply perceive, has not been a primary focus of this research. However, since the subjective perception of people is of equal importance, it makes sense to focus part of the research on this.

So our goal is to further explore some aspects of capability, but also to focus on the subjective experience of people, to ensure that when textile user interfaces are deployed in the real world in the future, they are an all-around better alternative to existing control methods. For this, we conducted six experiments, focusing on:

Our experiments distribute the focus.

- a preferred icon size for recognition
- the recognition of relative rotation of icons
- a preferred slider length for four different orientations
- the perception of relative distance differences between icons and a more detailed investigation of the applicability of the Gestalt law of proximity to textile user interfaces
- the influence of the aspect ratio on the input and interaction possibilities and the perception as a slider or touchpad
- the perception of the orientation of icons when they are not placed flat on a plane but vertically on a side wall

1.1 Structure

The thesis will be structured as follows:

In *Related Work* we discuss the previous research results on which the experiments in this thesis are based.

In *Experiment Design* we discuss the ideas and the conception of the individual experiments and the resulting plans for the prototypes used for the experiments.

In *Fabrication*, we will take a closer look at the production steps of the prototypes required for the experiments.

In *User Study* we discuss the structure and procedure of the user study.

In *Study Results* we will present the results of this study and provide an evaluation of further findings and limitations of the study.

In *Conclusion*, we will give a summary and talk about possible future work.

Chapter 2

Related work

Since the work in this thesis builds on the results of other publications, it is necessary to present the previous results in order to understand what we are building on.

2.1 Textile Interfaces

The idea of integrating conductive materials into textiles - the cornerstone of smart fabrics - dates back to the mid-20th century, although initially only for sensors and heating fabrics. In the mid-1990s, research began to bring these "smart fabrics" closer to people, first by incorporating them into clothing [Post and Orth, 1997], [Marculescu et al., 2003] and later also into external interactable objects [Challis and Edwards, 2000].

Research into smart fabrics began in the mid-20th century and gradually evolved into interactive textile user interfaces.

Challis and Edwards [2000] also started the first research on the general design of these tactile user interfaces. For example, they found that the size of such an interface should be no larger than approximately A4. Research into the haptic perception of individual objects followed around ten years later [Lebaz et al., 2012]. Brauner et al. [2017] have gained essential insights into the design and product development of textile user interfaces. Research into the actual design of icons, buttons and sliders, touchpads, and other

Over time, more and more small and individual aspects of textile user interfaces have been investigated.

elements began yet a few years later. Mlakar and Haller [2020] and Schäfer et al. [2023] have gained important insights into the design of buttons, Nowak et al. [2022] and Mlakar et al. [2021] into the design of sliders.

Comprehensive research on the composition of larger and more complex interfaces has yet to be conducted.

2.2 Icons

Textile icons must be distinguishable from the background by profile or texture.

A textile icon is a tactile icon on a textile medium. A tactile icon corresponds to a shape that differs from the surrounding material in a tactilely perceptible characteristic, such as profile or texture. This means that one should be able to distinguish the icon from the background by simply touching it, ideally in such a way that one can recognize and understand the shape of the icon.

These icons provide users with the context of the interactive control elements.

Whether the icon is an interactable element itself, such as a button, or merely an indicator of a nearby element, depends on the specific implementation. However, it would be suitable for both cases. The shape of the textile icon then provides context to the user of the element to be interacted with and makes it possible to distinguish it from other elements.

To ensure easy and intuitive eyes-free recognition of textile icons, there are several design aspects to consider.

- The easiest tactile contrast to recognize is height. [Mlakar and Haller, 2020]
- Textile icons should not be less than 13mm wide. This corresponds approximately to the size of a fingertip. [Mlakar and Haller, 2020]
- For easy recognition, raised textile icons should have a profile of at least 1.6 mm. [Mlakar and Haller, 2020]
- Raised icons are preferred over recessed ones. [Schäfer et al., 2023]

They are also seen as more important. [Mlakar and Haller, 2020]

- Simple shapes are preferred. [Schäfer et al., 2023], [Mlakar and Haller, 2020]
- *Raised filled* and *raised outlined* icons have the highest recognition success rate and were also preferred by participants over other fabrication variants. [Schäfer et al., 2023]

2.3 Sliders

A textile slider is a slider on a textile medium. A slider is a user interface element that allows users to adjust a usually continuous value on a 1-dimensional axis. In past research, sliders have already been investigated to some degree, especially with regard to the extent to which a simple and precise adjustment of the values can be guaranteed.

Textile sliders enable 1-dimensional continuous value adjustment on a textile medium

The following is a summary of the results to date:

- Recessed profiles are strongly preferred. [Nowak et al., 2022]
- *A* guidance path is generally preferred over a *closed-shape*. However, if recessed, the *closed-shape* is preferred. [Nowak et al., 2022]
- If flat, shapes such as rainbow, tick mark and horseshoe are preferred. If recessed and closed-shape, however, a rectangular shape is preferred. [Nowak et al., 2022]
- The texture of the slider can determine the direction of movement on it. The preferred movement is perpendicular to the ribbed surface. [Mlakar et al., 2021]
- Including reference points in the sliders can increase participants' confidence when adjusting values. Elevated and rotated ones seem particularly promising. Two to three tick marks are sufficient for a slider. [Nowak et al., 2022]

2.4 Touchpads

A textile touchpad is a touchpad on a textile medium. A touchpad generally works in a similar way to a slider, except that it also supports 2-dimensional movement gestures and a wider variety of input methods overall.

In past research, textile touchpad prototypes have already been built, but mostly integrated into clothing, e.g. by Heller et al. [2014]. As a result, the design guidelines found there are usually based specifically on use cases for on-the-walk operation and cannot necessarily be applied to fixed touchpads.

2.5 Composition

Fundamental research on haptics was conducted.

There is still a lack of comprehensive research into the composition of more complex textile user interfaces. However, some basic research has been done in the area of haptics in general.

Haptic user interfaces should not be too large.

Challis and Edwards [2000] found that a tactile user interface should not exceed a size of A4, be in a landscape orientation and avoid empty spaces, meaning "areas on a display that do not communicate anything useful to the user".

Several Gestalt laws are applicable to tactile user interfaces.

Further studies have shown that the Gestalt laws of continuation [Chang et al., 2007b], proximity, and similarity [Chang et al., 2007a] can also be applied to haptics. Details about the extent to which this is possible have not yet been investigated.

The following definitions of the Gestalt laws examined are quoted directly from the works mentioned. [Chang et al., 2007a],[Chang et al., 2007b]

Gestalt Laws:
Law of Continuation: Elements will be grouped together if a continuous pattern can be interpreted and this pattern will be assumed to continue even if some parts are hidden.

Law of Proximity: Elements which are close to each other will be grouped together.

Law of Similarity: Elements will tend to be grouped together if their attributes are perceived as related.

Definition: *Gestalt Laws*

Chapter 3

Experiment Design

This chapter discusses the aspects of textile user interfaces to be investigated in this thesis, and derives and presents the experiments designed for this purpose.

3.1 Preferred Icon Size

Mlakar and Haller [2020] have found that in order to recognize the shape of an icon eyes-free, it should be no smaller than 13 mm. This answers the question of ability. However, the smaller an icon gets, the more mentally demanding it becomes for a user to recognize its shape by touch alone. This raises the question of whether this is also the most comfortable size for the user. There is an upper limit to the size in that an icon should not take up too much space, assuming that the user interface should be on a limited surface. Furthermore, a large icon size requires a lot of physical effort in the sense that, in the worst case, the icon has to be completely circled with the finger in order to recognize its shape, which requires more movement with increasing size and can also lead to frustration.

Too small icons are mentally demanding, too large icons are physically demanding.

It is therefore useful to find a balance between mental and physical demand by finding a size that is neither too small to challenge the user mentally, nor too large to force the

A balance should be found.

user to make uncomfortably wide-reaching movements.

The experiment should contain a recognition task.

Participants in the experiment must therefore be asked subjectively. However, in order to simulate a real recognition situation, it is worth including an actual recognition task in the experiment. In this recognition task, it should be ensured that participants have to touch the entire icon so that they actually experience what it would feel like if they had to do this in a real situation. The icons used for this purpose should therefore only differ from each other to such an extent that the entire icon must first be touched in order to make a classification.

4- and 5-pointed stars are suitable shapes.

A suitable icon shape for this are 4- and 5-pointed stars. To classify an icon into one of the two categories, the entire icon must first be touched. If only part of the icon is touched, a reliable classification is not possible. To ensure that participants do not notice a distinguishing feature between 4-pointed and 5-pointed stars, such as an edge always pointing upwards on a 5-pointed star, and therefore only have to feel a small part of the icon, the stars should also be randomly rotated. This ensures that regardless of where the participant starts, he cannot be sure which of the two categories it is until he has explored the entire icon.

Figure 3.1: Construction plan for Experiment 1.

Note that due to the point symmetry, a 5-pointed star takes on an non-rotated appearance every 36°. With a 4-pointed star it is every 45°.

In the experiment, the participant is presented with a series of stars sorted by size. For each size, the participant is then asked to determine whether it is a 4- or 5-pointed star and to rate how comfortable they found that particular size for determining the icon. Thus, the experiment consists of a simple recognition task and a subjective survey.

The experiment consists of recognition and a subjective survey.

13mm was chosen as the minimum size here, as Mlakar and Haller [2020] had already found this to be the smallest possible size for detection. 67 mm was chosen as the upper limit to ensure that an preferred size does not exceed the largest size chosen by us. To keep the experiment within a reasonable time frame, we chose ten different sizes, each with a size difference of 6mm. We chose an icon profile of 3mm, based on the profile of 2.9mm found by Mlakar and Haller [2020] to be easily recognizable.

13 mm and 67 mm are reasonable limits.

More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

3.2 Icon Rotation

Rotary switches are common in physical user interfaces (see e.g. Figure 3.2). They allow for space-saving and precise adjustment of parameters such as temperature on ovens, volume on radios, or more complex inputs such as in aircraft cockpits. It is therefore worth considering rotary switches for textile user interfaces.

Rotary switches should be considered for textile user interfaces.

However, these rotary switches make use of visual feedback, for example by using a marker to indicate the current adjustment or by displaying additional values on the knob itself. Since we aim to make textile user interfaces be operable without visual feedback, the question arises as to what extent the rotation of icons can even be perceived haptically. Only if the user is able to perceive the rotation of an icon, it

It is not clear whether people can perceive rotation of icons.

Figure 3.2: Audio control panel on an A320.

is possible to adjust it precisely and only then would rotary switches be a serious input option for textile user interfaces.

Rotatable icons should have an aspect ratio of 1:1.

Most physical rotary switches have a circular shape. This is not possible for icons because a circle always feels the same, regardless of how far it is rotated. Since Challis and Edwards [2000] recommend avoiding empty space, icons used should still be approximately the same size in all directions, as they require the space of their longest dimension in all directions when rotated. An aspect ratio of 1:1 is therefore desirable.

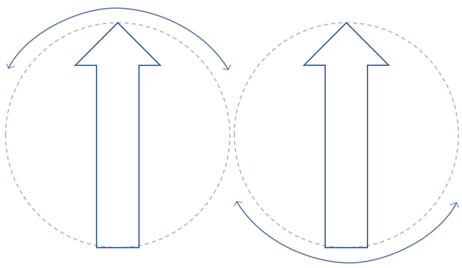


Figure 3.3: Minimal space required by icons with unequal aspect ratio.

We chose 13mm plus shapes for the icons.

The recognizability of the rotation may vary depending on the icon shape. For more complex icons with round shapes and short, less concise lines, rotation is probably more difficult to recognize. For icons with simple shapes and long straight lines it could be easier. We have settled on a middle ground by choosing a plus shape as the form. This has straight edges and right angles, but is not as simple as a square, for example. We choose an icon size of 13 mm, and an icon profile of 3 mm as this has already been found to be recognizable by Mlakar and Haller [2020].

To measure rotation, a standard orientation in a reference frame must be defined. In the visual world, this reference frame is usually oriented by gravity. The direction of gravitational pull defines a downwards direction, and the other directions are defined based on that. In the haptic world, this does not work so easily as the proprioception of the fingers does not work as well as the vestibular organ and the resulting visual recognition of rotation [Mooti and Park, 2022, Cheron et al., 2014].

Rotation is always relative to a reference frame.

PROPRIOCEPTION:
The awareness of body position in space.
(The Oxford Dictionary of Sports Science & Medicine)

Definition: *Proprioception*

Since every rotation is dependent on a reference frame and can therefore also be seen as a rotation relative to this reference frame, it makes sense to measure a rotation of the icon relative to a non-rotated icon that provides this reference. Consequently, in this experiment, we look at pairs of two icons, one of which is not rotated. The other will have a varying rotation, and to put the results in context, there are also cases where the second icon is also non-rotated.

A non-rotated icon will provide this reference.

As we are now always looking at icon pairs, a new variable comes into play, namely the distance between the reference icon and the icon to be recognized. To investigate whether the success rate in recognizing rotation also depends on the distance between the two icons, it makes sense to conduct the same experiment for two different distances to see whether there is a difference in the results.

The effect of the distance between the icons should be investigated.

So we consider two sets of eight samples each with rotations between 0° and 28°, increasing in 4° steps. In the first set we have a distance of 25 mm between the centers of the icons, in the second set 100 mm. The large difference is due to the fact that we wanted to determine whether the distance makes a difference at all. This can be determined more clearly with a larger distance difference.

More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

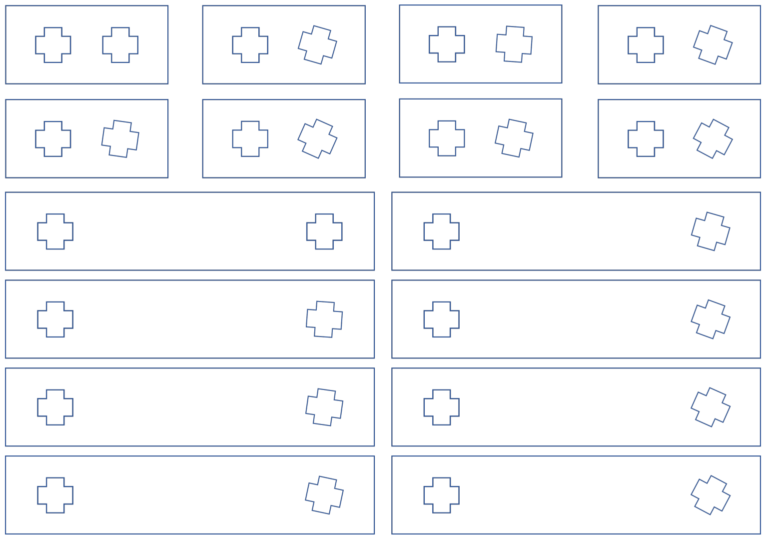


Figure 3.4: Construction plan for Experiment 2.

3.3 Preferred Slider Length

Textile sliders look promising.

Sliders are a popular control element in graphical user interfaces. They provide an intuitive way to adjust a single, usually linear and continuous, value. Studies have been conducted on the implementation of sliders in textile user interfaces, and have yielded promising results. [Nowak et al., 2022], [Mlakar and Haller, 2020]

A preferred length and width of sliders was not yet investigated.

Aspects examined were a preferred direction, preferred shape and intuitive interaction, as well as the introduction of tick marks for better orientation. Aspects that were not investigated are the preferred length and width of the sliders. Mlakar and Haller [2020] have used a 13×64 mm rectangle, Nowak et al. [2022] have used a 13×100 mm rectangle for their final measurements. In both cases, length and width were not varied during the study.

We investigate the preferred length of sliders.

Our aim is therefore to take a closer look at these two aspects. In this experiment, we start with a user-preferred slider length. Since Nowak et al. [2022] have found that recessed, closed-shaped sliders are the preferred variant, we will also use them. Since only the length is examined here, we will keep the width constant at 13 mm, using the previous work as a guide. The length should be longer than any user would possibly want to exceed, so that we cover all possible movements. It is therefore set to 300 mm. The slider is also recessed 3 mm, as in the study by Nowak et al. [2022].

More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

Figure 3.5: Construction plan for Experiment 3.

3.4 Proximity-based grouping

The Gestalt laws represent fundamental principles of human perception and have been extensively studied in the past. They are crucial for designing intuitive and user-friendly interfaces. Consequently, there is an interest in whether they can also be applied to textile user interfaces. In the following, we are particularly interested in the Gestalt law of proximity.

The applicability of the Gestalt law of proximity to textile user interfaces is of interest.

As mentioned in the previous chapter, the applicability of the Gestalt law of proximity, similarity, and continuation to textile user interfaces has already been demonstrated by Chang et al. [2007a]. However, this study only proved that haptic grouping by proximity follows the same principles as visual grouping. We want to concretize this knowledge and determine more tangible values. In order to do so, we investigate to what extent proximity can be perceived haptically and at what distance-ratios objects are subjectively perceived to be groups in textile user interfaces.

We want to concretize previous knowledge and determine tangible values.

This experiment is strongly inspired by the original experiment that led to the founding of the Gestalt psychology by Wertheimer [1923].

In the series of points shown above, Wertheimer defined

Figure 3.6: Series of dots from Wertheimer's *Untersuchungen zur Lehre von der Gestalt. II.*

two distances, namely s_2 = distances between the groups and s_1 = distances between the grouped points themselves.

We define proximity as a ratio of the standard distance.

Therefore, we will also consider rows of circles. To determine whether proximity is perceived, we must first define proximity. We define a standard distance (s_2) between the circles and a distance that will be considered 'proximate' (s_1). Any distance less than the standard distance is considered proximate. Since it depends on the standard distance which distance is considered proximate, we will define the proximate distance as a ratio of the standard distance.

The experiment is conducted with two different standard distances.

In order to find out at which ratio a proximity is perceived as such, we will present several series of circles in which different proximities are tested. To see whether certain aspects of perception depend on absolute distances rather than ratios, we conducted the experiment with two different standard distances. If there are differences for the same ratios, this indicates that a factor may depend on the absolute distance rather than on the ratio.

We now consider rows of six circles each, of which a maximum of two circles are closer together than the other circles at a distance of $s_1 = \frac{n}{10}s_2$ with $n \in \{4, 5, 6, 7, 8, 9\}$ and s_2 being the standard distance for this row. There are also equidistant rows.

The icons have a size of 13mm and a profile of 3mm.

As in previous experiments, the icons have a size of 13mm and a profile of 3mm, as these dimensions were recommended by Mlakar and Haller [2020]. The distance between the icons is measured from the centers and is 50mm in the first test series and 60mm in the second. The actual distance between the icons is therefore $s_1 = \frac{n}{10}s_2 - 13$ in mm with $n \in \{4, 5, 6, 7, 8, 10\}$ and $s_2 \in \{50, 60\}$.

After finding out whether the proximity was recognized, it can then be asked whether a grouping of the nearby icons was subjectively perceived. More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

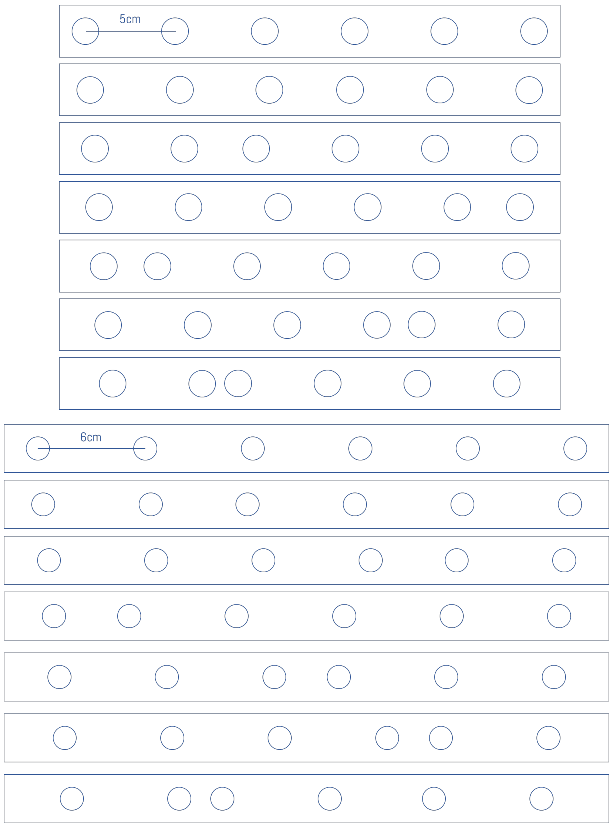


Figure 3.7: Construction plan for Experiment 4.

3.5 Ratio-dependent perception of rectangular shapes

Both sliders and touchpads are promising control elements on textile user interfaces, as discussed in previous sections. The slider type found by Nowak et al. [2022] to be the most suitable, as well as touchpads, are rectangles. They differ only in their aspect ratio. This raises the question of the aspect ratio at which a rectangle is perceived to be a slider or a touchpad.

Sliders and touchpads appear promising. But the line between them is not clear.

We produced prototypes with different aspect ratios.

To find the separating value, we produced various rectangular shapes with different aspect ratios, in order to present them to participants and ask them what type they personally perceive this particular sample to be.

The width remains constant at 100mm, the height ranges from 13mm to 55mm.

The width remains constant at 100mm for all samples, as this was the slider length used by Nowak et al. [2022] and is a reasonable size overall. The size that changes is the height. For the smallest sample, this is 13mm, as this corresponds to the slider height used by Nowak et al. [2022] and Mlakar and Haller [2020]. There are eight samples in total, with a height increasing in 6mm steps. The maximum height is therefore 55mm.

The experimental possibilities go beyond a binary distinction.

In addition to the simple differentiation between touchpads and sliders, these samples are also suitable for determining the interaction possibilities of the different rectangular shapes. More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

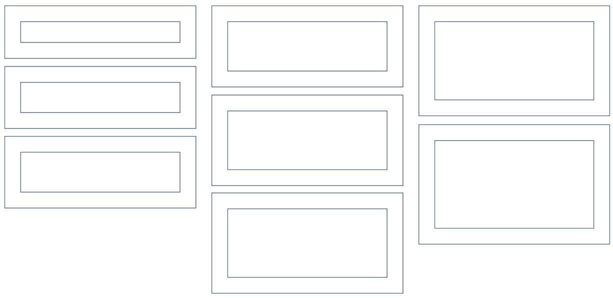


Figure 3.8: Construction plan for Experiment 5.

3.6 Directional perception

In the visual perception a clear direction is always defined.

As mentioned in Section 3.2, there is a natural "down" in the visual world due to the direction of gravity. When people look at objects, they naturally assign the "down" direction and derive the other directions from that [Cheron et al., 2014]. In haptics, the definition of direction is not so clear. In previous experiments, objects were presented in such a way that the direction from which a person's finger came was also the 'down' direction. So the fingertip was always pointing up.

However, this only works if a person is sitting across from the interaction object and interacts with it in a constant orientation. If, on the other hand, the interaction object is positioned on the side of a chair and the person reaches down from above, it is not clear whether that person would perceive the object in its actual or upside-down orientation. The question to be answered is therefore: Is the orientation given by gravity more important or the personal orientation towards the interaction object?

Haptic direction is not necessarily given, and it is not clear which directional factors are most important.

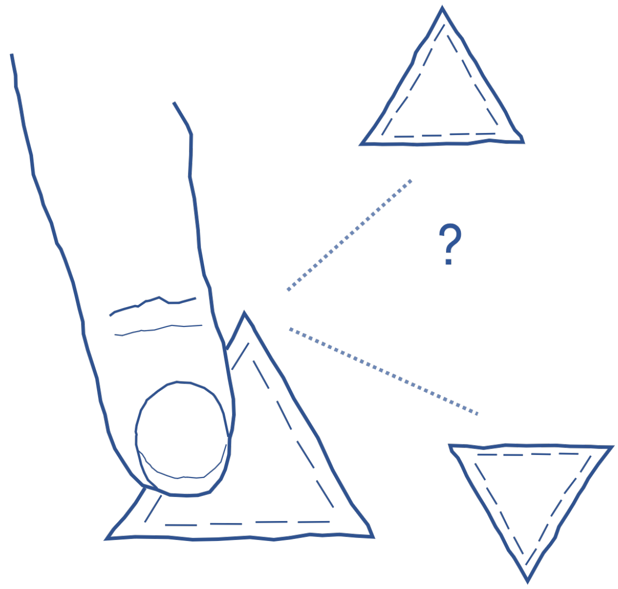


Figure 3.9: The orientation of perception is unclear.

To find this out, one should choose icons that are not radially symmetric and do not already trigger associations in participants, such as a house where the roof is rather seen as "up" regardless of the actual perceived orientation. Therefore, one should use non-radially symmetric abstract icon shapes. To obtain more reliable results, the experiment should also be repeated with different shapes to rule out the possibility that a particular shape behaves completely differently and thus distorts the results.

Multiple icons should be used that are not radially symmetrical and do not evoke any previous associations.

We have therefore opted for the abstract forms shown in Figure 3.10. According to the guidelines in the related work by Mlakar and Haller [2020], the icons have a size of 13mm and a profile of 3mm.

These icons are abstract in the sense that they do not represent any known objects that are indicating a bias in their orientation. They are simply designed and if rotated by 0°, 90°, 180° and 270°, they always have a different appearance.

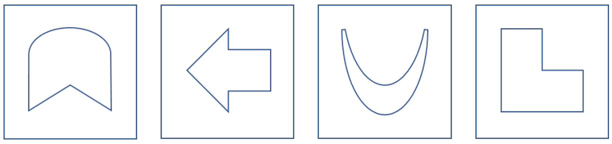


Figure 3.10: Construction plan for Experiment 6.

More information on the specific procedure and the questionnaire will follow in Chapter 5 *User Study*.

Chapter 4

Fabrication

This chapter describes the fabrication process of the prototypes required for the study, and delves deeper into the selection of fabrication materials and the implementation of the measuring instruments.

Suchmann [2022] had already conducted more detailed investigations of production methods, which were further developed by Buttkus [2023]. We used the findings of these two previous works and developed them further.

4.1 Material and equipment

All samples used the same materials. The solid base of each sample was a 3mm thick MDF, sewn over with a yellow sofa fabric. We chose MDF because Suchmann [2022] found it to be the most suitable material. An explanation of the MDF thickness can be found in the previous chapter about the *Experiment Design*. The use of the sofa fabric was intended to simulate a situation as close to reality as possible in the study.

All textile samples were made of MDF and sofa fabric.

The technical devices used to measure the movement in Experiment 3 *Preferred Slider Length* were an *OptiTrack Flex 3* camera and an *Arduino Uno* with an additional *Real Time*

We used an OptiTrack and an Arduino with an RTC module.

Clock module attached.

Other machines used for production include an *Epilog Zing 6030* laser cutter and a *Bernina 880* embroidery machine.

4.2 Process

First, a blueprint was created.

Once the idea was conceptualized, a blueprint of each experiment was created in Inkscape. These plans can be seen in the previous chapter. They were created as *SVG* files and first converted to *PDF* format as required by the Epilog laser cutter.

They were then cut into the MDF. Initially with a frame for fixing to the fabric, later without it.

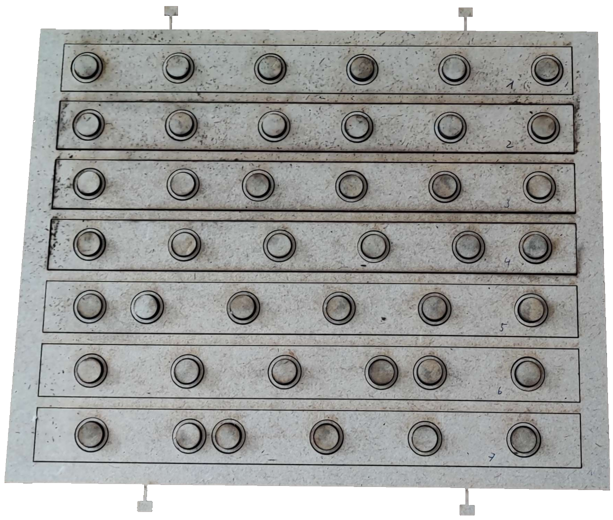


Figure 4.1: MDF cut-out with fixing frame.

The MDF parts were then sewn in.

Once cut out, the next step was to sew it on. First we had to convert the blueprints into embroidery files using the Bernina software. Then the yellow sofa fabric was clamped into one of the hoops of the *Bernina 880* embroidery machine and an outline of the design was embroidered onto the fabric.

The fixing frame was then glued in place with textile glue.

This was followed by the parts to be sewn. After the glue dried, the frame was removed. A second layer of fabric was put on top and sewn into place using the embroidery file created from the blueprints.

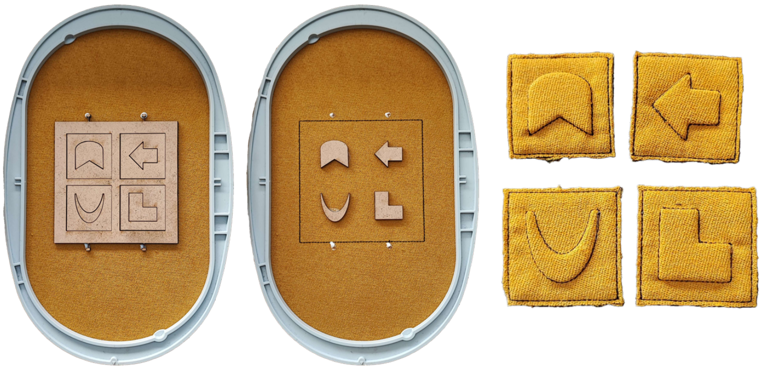


Figure 4.2: Sewing procedure with fixing frame.

The same process was repeated for all samples. After the sewing, the individual samples were cut apart with textile scissors.

There is one more thing to consider, especially for the touchpads and the slider. When sewing in the frames of these elements (see Figure 4.3), a seam must be sewn on the inside as well as on the outside. It is important to sew the inside seam first. When sewing the outside first, the fabric will already be stretched. When then sewing the inside, the already stretched fabric can no longer be optimally recessed. The same applies to the slider and, to a lesser extent, to raised icons, although the difference is not as significant. Therefore, for all shapes, it is recommended to sew the innermost seams first and then work from the inside to the outside for best results with recessed and raised shapes. This can be achieved by assigning different colors to the relevant seams in the Bernina software and then defining the chronological order of these colors.

When multiple seams are being sewn, the inside seams should always be sewn first.

4.2.1 Slider

The slider from Experiment 3 *Preferred Slider Length* will be discussed separately as it involves a few more steps. Af-

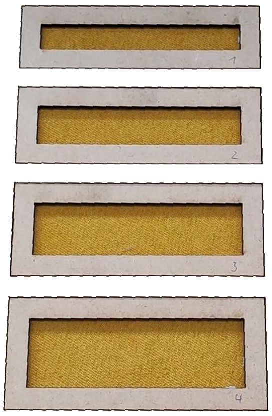


Figure 4.3: Frames to be sewn in.

ter the fabrication process described above, the Arduino measurement device is attached. This is used to determine the position of the finger on the slider, providing a motion tracker needed for distance measurement.

Copper foils measure a difference in capacitance.

For this purpose, 23 self-adhesive copper foils were attached to the bottom of the slider. Cables were soldered to each of them and connected to an Arduino Uno. These copper foils act as capacitive sensors that measure a difference in capacitance when an object, in this case a finger, comes near them.

A real-time clock module was also connected to the Arduino to record the time of the measured data so that it could later be compared with the data recorded by the OptiTrack camera at the same time.

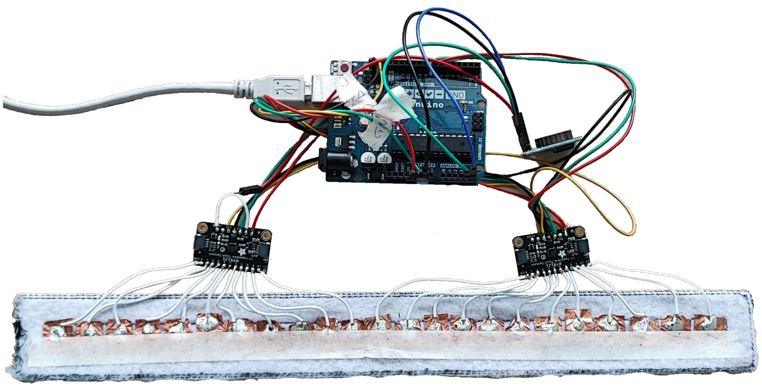


Figure 4.4: Wired capacitance measuring copper foils.

Furthermore, two reflective markers were glued to the top of the slider with textile glue, which should be recognizable as the ends of the slider during the OptiTrack measurement.

Figure 4.5: Reflective markers at the ends of the slider.

More information on the two measurement methods will follow in the next chapter.

4.3 Result

The fabrication resulted in 63 samples according to the experiment designs presented in the last chapter.

Figure 4.6: Set of 63 samples for the experiments.

Chapter 5

User Study

This chapter discusses the structure and procedure of the user study, as well as the approach, objectives and techniques used in it.

5.1 Aim

The aim of this user study is to investigate the unclear aspects described in Chapter 3, both of subjective and perceptual nature, and to derive guidelines from them that will be essential for the realization of textile user interfaces in the future. In particular, but not exclusively, we want to examine people's subjective opinions, as these have mostly been ignored in previous studies.

The aim is to investigate unclear aspects of subjective and perceptual nature.

5.2 Structure

The study was divided into the six individual experiments described above. These were conducted in a different order for each participant according to the Latin square model. Table 5.1 shows the order in which the experiments were conducted. The number indicates the number of the experiment. This way, we want to avoid effects and biases that

In the study, six experiments were conducted in rotating order.

might arise due to a particular sequence of experiments. There are six different sequences. After six participants, the sequences were repeated.

1	2	4	5	6	3
2	5	1	3	4	6
5	3	2	6	1	4
3	6	5	4	2	1
6	4	3	1	5	2
4	1	6	2	3	5

Table 5.1: Sequence of experiments.

Information on the order of execution within the individual experiments is provided in the sections of each experiment.

5.3 Setup

There were two different locations during the study, depending on which experiment was conducted. Experiments 1, 2, 4, and 5 were conducted with a curtain *(Location 1)*, while experiments 3 and 6 were conducted at another location without a curtain *(Location 2)*.

Figure 5.1: Conductor's perspective on the study setup.

As can be seen in Figure 5.1 and Figure 5.2, the textile samples were placed not visible to the participants behind a partition. From the conductor's point of view, *Location 1* is to the left of this partition. At the time of the experiment, the samples were attached to the Velcro strips and the participants could touch them by passing their hands underneath the curtain. This location was furthermore equipped with a tripod from which the participant's movements during the experiment could be filmed with a mobile phone. From the conductor's point of view, *Location 2* is even further to the left. Here, two Velcro strips were attached crosswise. The slider used in *Experiment 3* could be placed here in different orientations. This was supposed to be visible to the participant and therefore did not require a curtain. This location was covered by another tripod and filmed by the OptiTrack camera attached to it. The table on the far left was used to store documents and the computer for measurements during the study.

The samples were placed behind a partition, not visible to the participants. They were then presented individually behind a curtain on a Velcro strip.

Figure 5.2: Participant's perspective on the study setup.

There was a different chair used at *Location 2*. This is because a movable foam wall (see Figure 5.3) was placed next to it, requiring the same height and distance for all participants. A rotating chair was therefore unsuitable for this location.

The foam wall used in *Location 2* required a different chair.

The setup also consisted of said movable foam wall with Velcro strips attached to it to hold the slider in Experiment 3 and the icons in Experiment 6. More on this in the corresponding experiment sections.

Figure 5.3: Movable foam wall with Velcro.

5.4 Preparation

5.4.1 Software

Four different programs were used for the study.

The first program creates the study documents.

The first program was responsible for generating the respective study documents (see Appendix A). These were different and randomized for each participant. It is a simple Python program that generates LaTeX code, which can then be compiled and output as a PDF.

The second program performs the OptiTrack measurement.

The second program was responsible for measuring the coordinates of the OptiTrack. It measures all markers currently in the frame and outputs their x and y coordinates, as well as a timestamp for later synchronization with the Arduino data which it then saves in a CSV file that it creates itself. Originally, the program was a ready-made program from the OptiTrack *Camera SDK* that just needed to be slightly altered. In the end, however, the program was effectively rewritten and only contains small parts of the original program.

The third program performs the Arduino measurement.

The third program was for measuring the Arduino's capacitive touch sensors. This is also a pre-written program, but its content has been almost completely replaced. The program receives the values of the 23 capacitive sensors from the Arduino Uno and outputs them as a vector. It sets the initial values measured without touching as a baseline and subtracts them from the values measured later, so that the output values represent only the change in capacitance compared to the normal state.

The fourth program was just a tool for creating directories and files. Since the measurements of the other programs had to be saved individually for each participant, this program automatically created a separate folder for each participant, each with a folder for the Arduino and OptiTrack measurements and four already created CSV files into which the Arduino values could then be dumped.

The fourth program creates the directories and files for storing the measurements.

All programs can be downloaded.

File: Programs[a]

[a] https://git.rwth-aachen.de/i10/thesis/thesis-erik-mueller-limits-of-textile-interface-design-guidelines/-/raw/main/Programs.zip

5.4.2 Study Setup

Prior to the study, both the OptiTrack and the Arduino Uno were connected to the computer. Test measurements were taken with both to make sure everything was working. If not already done, the necessary directories and files were created.

All devices were connected.

All textile samples were sorted before the study according to the order shown on the *Study Protocol* and placed behind the partition wall to ensure a faster process during the study.

All samples were pre-ordered.

5.5 Procedure

All participants took part in the study voluntarily and were informed in advance of the time and place of the appointment. Upon arrival, they were welcomed and asked

Participants filled out the Participant Documentation.

to complete both the *Participant Documentation* and the *Informed Consent Form*. The contents of the Informed Consent Form were explained to them verbally. A copy was offered and compensation in the form of sweets was provided.

Participants were informed of the nature of the study.

It was explained to the participants that this was a study of textile user interfaces and that we would use the results to derive guidelines for the design of these user interfaces. They were also told that there would be six experiments, four of which would consist of verbal responses only, one of which would track their movements, and one of which would require them to make some simple drawings.

After that, the experiments were performed. The order of execution was rotated according to the Latin square, as described in Table 5.1.

In the following, however, the experiments are presented in canonical order.

5.5.1 Experiment 1: Preferred Icon Size

We presented ten icon sizes.

To determine a preferred icon size, we presented the participants with ten different icons, each in 6mm increments. As a reminder, the icon samples are shown in Figure 3.1.

The samples were placed behind the curtain sorted by size.

Participants were told at the beginning that they would be given ten icons to touch. Two samples not used in the experiment were shown to them once before. The icons were placed behind the curtain sorted by size and divided into two rows to save space. From the participant's perspective, the first five icons were in the top row (further away from the participant), and the others were in the bottom row.

Participants were asked to identify each icon and rate its size.

Participants were then asked to touch each of the samples in the given order and to name whether the icon they had just touched was a 4-pointed or 5-pointed star. This task is designed to force the participant to actually feel the entire icon. They were then asked to rate how comfortable they found this particular size to determine the multi-pointedness of the star. The scale ranges from 1 (very uncomfortable) to 5 (very comfortable). It was explicitly stated that this was a subjective measurement and that there was no right or wrong.

Since the initial rating was made without further references, the participants were also offered the opportunity to revise their initial rating at a later time, when they had more references available, after they had felt the other icon sizes. However, none of the participants made use of this option.

They had the option to revise their inital rating.

After this first round, participants were asked again to decide on the optimal size for them. In this case, optimal means the most comfortable size for them in terms of recognizing the shape of the icon. Participants were explicitly not told, even when asked, which icons they had previously rated best. However, they were allowed to feel all the icons again until they had made their decision.

They were then asked what size they considered to be optimal.

This resulted in a rating for each of the sizes and a single choice for the optimal icon. There was no time limit for any of the tasks.

All icon sizes were produced in both 4-pointed and 5-pointed form. Whether a given size was 4- or 5-pointed for a participant was randomized beforehand by the aforementioned program. How the measurements were recorded can be seen on the first page of the Study Protocol.

The order of the samples was randomized by the program.

5.5.2 Experiment 2: Icon Rotation

To determine the extent to which icon rotations can still be detected, we presented participants with eight rotations of varying degree. To determine the false positive rate, the sample without rotation was presented three times, increasing the number of measurements per test series to ten.

Ten samples with eight different rotations were presented to the participants.

The participants were initially told that they would now get to feel ten different icon pairs. The one to the left was always unrotated and the one to the right may or may not have been rotated. The participants were also shown the

Participants were first informed of the design of the samples.

unrotated sample in order to get an impression of the type of icons they would be dealing with in the following. They were also informed that neither the size, shape nor spacing of the samples would change within each test series.

The test series with the shorter distances were always conducted first.

As described above, the experiment was performed with two different icon distances. However, the samples with different distances were not mixed, but the test series were performed one after the other. We always started with the smaller distances.

A recognition and a confidence rating were performed.

Only one sample was placed on the Velcro strip at a time. The participant then had the opportunity to feel the icons. How they did this (whether with one or two fingers, etc.) was up to them. There was also no time limit. Once the participant had made their decision, they were simply asked whether they felt that the right icon was rotated relative to the left one. We also introduced a confidence rating to find out how sure the participants were of their answer. This was on a scale from 1 (very uncertain) to 5 (very certain).

The test was repeated with the larger distances.

After the first run, the same test was repeated with the larger icon distance. The task remained the same. This was also communicated to the participants.

40 values were collected from this experiment.

This resulted in $2 \times 10 \times 2 = 40$ values for the experiment. The order in which the samples were presented was randomized beforehand by the aforementioned program. How the measurements were recorded can be seen on the first page of the Study Protocol.

5.5.3 Experiment 3: Preferred Slider Length

To determine a preferred slider length, we had the participants perform several movements on a slider at their own discretion and measured the distance of their movement.

Four directions were measured.

Four different directions were measured. Two on a flat table, parallel and perpendicular to the participant's arm, and two on the movable foam wall at the side, also parallel and perpendicular to the participant's arm (see Figure 5.3).

First, the participant's arm length was measured and noted on the participant documentation. This serves to find out whether the distance perceived as comfortable is related to the physical characteristics of the body. The candidate was then asked whether it was okay to attach a marker to the index finger of their strong hand. All participants agreed. The marker was attached slightly above the fingernail with double-sided adhesive tape. This is used by the OptiTrack camera to detect the position of the finger. An outline of each participant's hand was also made and the position of the marker was noted.

The participant's arm and hand were measured. A marker was attached to the finger.

It was then explained to the participants that we wanted to find out what slider length they found comfortable and that we would be taking two measurements each for four directions. On the one hand, the maximum of what can still be perceived as pleasant. That is, the distance at which it would be considered unpleasant to go any further. And second, the optimum. This is the distance that did not require any effort on the part of the participants and at which they would have liked the slider to stop. This was communicated to the participants in exactly the same way.

The maximum and optimum distances were measured in four directions.

For the first two measurements on the flat table, the arm was placed perpendicular to the edge of the table and centered on the table. The wrist had to remain fixed during the movements. It was allowed to rotate, but not to lift. This is due to the assumption of realism, as this position is intended to simulate an armrest on which the arm rests. During the sidewall measurements, the arm was allowed to swing freely. This is also due to the proximity to the real application, since this position is intended to simulate the side wall of a seat armrest, where the arm would not rest on the side wall during real operation.

The wrist remained fixed during the armrest measurement, while the arm was allowed to swing freely during the side wall measurement.

The procedure for each direction and measurement was as follows. The participant was instructed in the task. They were allowed to try out and feel the slider. Then the hand had to be withdrawn, as the measurements had to be started and it was necessary for accurate measurements with the Arduino that there was no contact with the slider during initialization. After starting the measurement, the participant was asked to first show the maximum distance

At least three slide movements were made for each measurement.

described. To do this, he was asked to slide back and forth at least three times in order to obtain a better measurement and avoid a measurement becoming unusable due to a brief error. After this first movement, the measurements were allowed to run and a few seconds were waited so that the movements could later be distinguished in the data. The participant was then asked to indicate their optimal movement. The procedure was the same. After both movements were completed, the measurements were stopped. A new measurement was taken for each direction.

The conditions were exactly the same for every participant.

Participants sat in a fixed, immobile, non-height-adjustable chair (see Figure 5.2). The foam wall was attached to the chair by metal struts and was therefore the same for each participant. Because it is symmetrical, it was no problem to simply place it on the other side of the chair for left-handed people. This meant that all participants could perform the experiment with their strong hand and under the same conditions.

The order of the measurements was always the same.

This resulted in 8 individual measurements for this experiment. The order in which the measurements were performed in the experiment was always the same. How the measurements were recorded can be seen on the first page of the Study Protocol.

5.5.4 Experiment 4: Proximity-based grouping

14 different samples with different distance ratios were presented.

To determine the distance ratio at which haptic grouping of elements occurs, we presented participants with $2 \times 7 = 14$ different samples with varying icon distance ratios. To determine the false positive rate, the sample without any closer icons was presented three times, increasing the number of measurements per test series to nine.

Prior to the experiment a sample was shown and the tasks were explained to the participants.

At the beginning of the experiment, each participant was shown the sample without any closer icons to them in order to convey what kind of samples they would be dealing with in the following. It was explained to them that they would feel rows of circles. These circles would have a standard distance between them that would not change during the entire test series. However, it was possible that at most two circles would be slightly closer together than all the others. Their task was therefore to feel across each of the rows to see if there were two such circles and to indicate them. If they had the feeling that two circles are closer together, they should also state whether they subjectively felt that these two circles belonged to a group to which the other circles did not belong. Thus, whether their proximity makes them feel like they belong together. Finally, a confidence rating was also introduced here. Regardless of whether they discovered such a pair of closer icons, the participants were asked to indicate how confident they were about their answer on a scale of 1 (very uncertain) to 5 (very certain).

The experiment was performed twice for each participant, first with the test series with the 5cm standard distance, then with the 6cm. All samples were presented individually on the Velcro strip. The order of presentation was randomized beforehand by the program. There was no time limit. This resulted in $9 \times 3 \times 2 = 54$ individual measurements for this experiment. How the measurements were recorded can be seen on the second page of the Study Protocol. Each column shows the distance between the closer icons relative to the standard distance. 10/10 is the sample with no closer icons.

The experiment was performed twice with different standard distances.

5.5.5 Experiment 5: Ratio-dependent perception of rectangular shapes

To determine which initial associations people have with different rectangle ratios, we presented them with eight rectangles in different ratios. Starting from 13:100 and increasing in steps of 6 up to 55:100, the units being mm.

We presented participants with eight rectangles of varying ratios.

The participants were initially told that they would now feel 'elements of a textile user interface'. These were not specified. The task they were then given was to feel them and tell what they thought this element was, what input methods they thought it might have and, optionally, what they could imagine using it for. The smart home was named as an example, but the context was explicitly kept

Participants were asked to feel the samples and suggest what they might be and how they would interact with them.

open so as not to restrict people in their ideas.

The conductor wrote down the results as keywords and free text.

All samples were first presented individually on the Velcro strip. The participants then had the opportunity to verbally express their thoughts freely while feeling them. These were written down by the conductor. If something was unclear, the participants were also asked to demonstrate the intended action on the element. The results were recorded in the form of keywords and free text.

The 13:100 and 19:100 samples were also compared separately.

There is one peculiarity in this experiment. The rectangles with the ratios 13:100 and 19:100 were unanimously recognized and named as sliders by all participants. After the latter of the two appeared (the order was again random for every participant), they were both placed next to each other and the participants were asked which of them they prefer.

The number of results varied depending on each participant.

There was no time limit. Participants were allowed to talk until they indicated that they were finished. Because the results of the measurement depended on the imagination and talkativeness of each participant, the amount of results varied greatly between them. How the measurements were recorded can be seen on the second page of the Study Protocol.

5.5.6 Experiment 6: Directional perception

To determine how participants perceived icons from other directions, we had them touch and draw four different icons on the side of the foam wall.

Participants felt four icons on the foam wall. They were then asked to draw them.

The foam wall (see Figure 5.3) was returned to the side of the strong hand. Participants were told that they would now feel four different icons, one at a time. They had as much time as they wanted and were asked to form a mental image of the icon they felt. Once they had an image in mind, they were asked to draw it on the Drawing Sheet. Once they let go of the icon and started drawing, they were not allowed to return to the icon. However, no participant made such a request. When asked about the direction of the icons, the answer was "The way you imagine it" or "The way the picture looks in your head". Participants were not allowed to see the icons before or during the experiment.

The results were categorized after the study.

The order of icons was determined in advance by the program according to the Latin Square. The rotation of the icons was randomized, also by the program. The rows of rotated icons next to them is solely for ease of notation. This was sufficient for all but one participant. More on this in the next chapter. The results were only transferred from the Drawing Sheet to the Study Protocol after completion of the study. How the measurements were recorded can be seen on the second page of the Study Protocol.

5.6 Participants

15 participants took part in the study. Of these, seven were female and eight were male. They were between 20 and 31 years old with an average age of 23.4. Two of them were left-handed, the other right-handed. 13 of them were German, one Bulgarian, one Indian and one Turkish. All participants studied and/or worked in the field of computer science or closely related fields. None of them had a mental or physical disability. Six of the participants had previously participated in a user study on textile user interfaces. However, they had not been exposed to the samples used in this study.

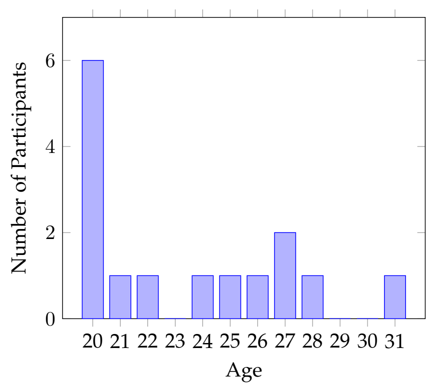


Figure 5.4: Histogram for the participants' age.

Chapter 6

Study Results

In this chapter we will present the results of the study experiments and discuss the limitations.

6.1 Experiment 1: Preferred Icon Size

The goal of this experiment was to find out what size of textile icons participants found most comfortable when asked to recognize the shape of the icon.

Participants were asked to differentiate between 4- and 5-pointed stars for each icon and to rate them from 1 (very unpleasant) to 5 (very pleasant). Ten different icon sizes were examined, ranging from 13 mm to 67 mm.

When recognizing the multi-pointedness of the stars, the number of points was recognized incorrectly only once in 150 runs. This can be attributed to a lack of concentration. In general, the participants found this task very easy.

The following two diagrams visualize the results of the ranking.

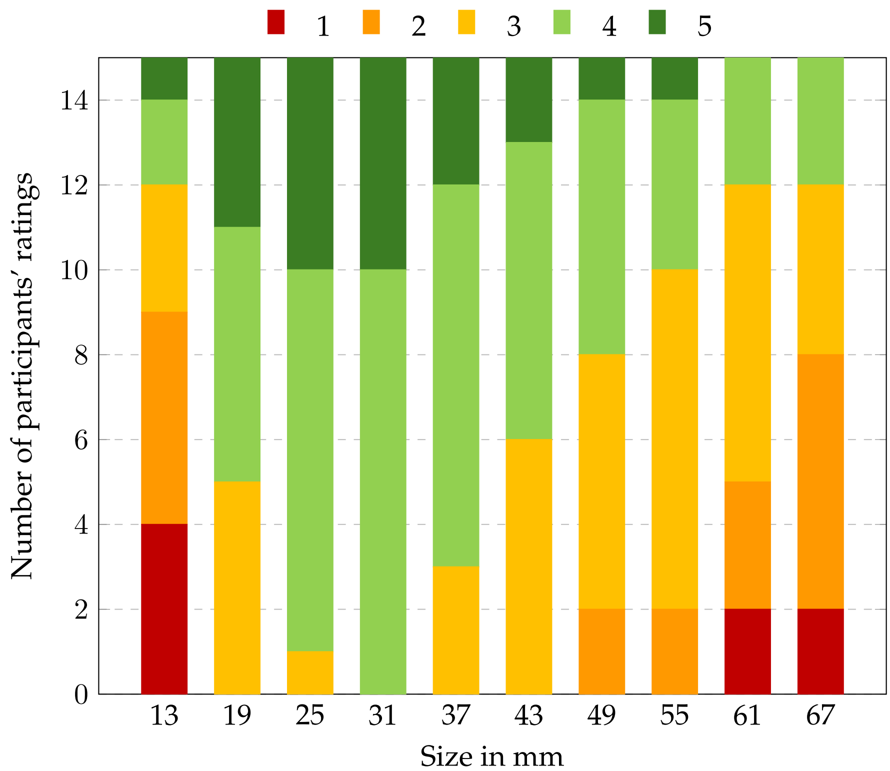


Figure 6.1: The distribution of ratings given for each icon size.

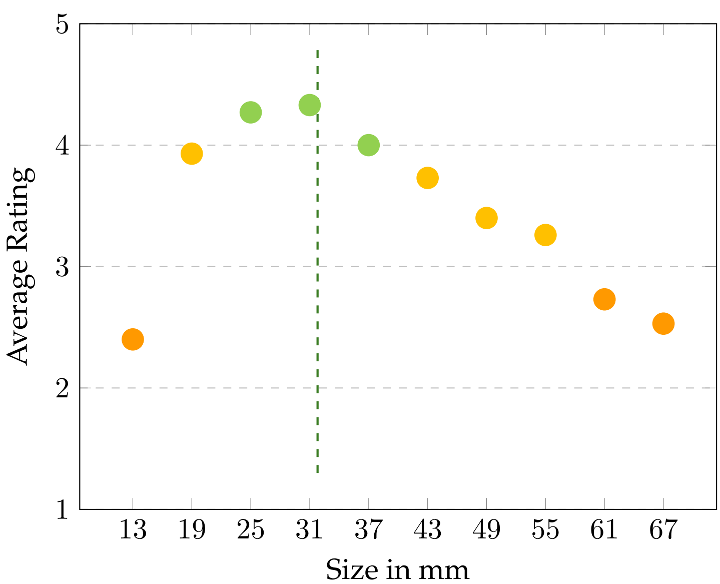


Figure 6.2: Average rating for each icon size.

Figure 6.2 shows that although the 13mm icon size recommended by Mlakar and Haller [2020] allows recognition, participants find this size extremely uncomfortable. When increasing the size slightly, there is a strong increase in the subjective perception of pleasantness. The best rating of 4.33 was given to the 31mm size. In the survey regarding the preferred size after the individual ratings, the average is 31.8, marked with a green vertical line in Figure 6.2. Furthermore, it can be seen in Figure 6.1 that size 31mm is the only size that none of the participants rated lower than 4. These three circumstances indicate that 31mm is a suitable icon size if the aim is to recognize the shape of the icon.

An icon size of 31mm was perceived as the most comfortable by participants on average.

In general, participants preferred an icon size between 25mm and 37mm for recognition.

An interesting observation is that the perception of what is pleasant can vary greatly from participant to participant. For example, there was one participant who rated the 13mm size as 5 and another who rated the 67mm size as their favorite. However, this is not consistent with his previous ratings. 31mm is therefore just the intersection of what is still considered comfortable for all groups.

The perception of what is pleasant can vary widely.

Furthermore, two different exploration strategies were observed. All participants began to circle the smallest sample with one finger. As the size increased, some participants switched to using two or even three fingers to feel the icon. However, the size at which this happened varied greatly. Some participants used only one finger throughout.

The exploration strategy for an icon can change depending on its size.

6.1.1 Limitations

One participant noted that he already felt much more confident when feeling the eighth sample. Perhaps not rotating the order of samples may have contributed to users finding later samples easier and therefore more pleasant to feel. However, the task was generally perceived as very easy, and only served to make people feel the whole icon, so this factor should not be a significant.

There may have been a learning effect.

5-pointed stars may have been perceived as more pleasant than 4-pointed stars overall.

Furthermore, one participant noted that he found the 5-pointed stars more pleasant than the 4-pointed stars, which could have given them a higher rating. However, as these were randomized for each participant and therefore 4-pointed and 5-pointed stars appeared statistically equally often for each size, this should not be a significant factor either.

Nevertheless, the experiment was only tried with two different shapes, all of them being 3mm raised. With other parameters, the results could therefore look different.

6.2 Experiment 2: Icon Rotation

The goal of this experiment was to find out whether relative rotation between icons is recognizable and whether rotative elements thus can be considered for textile user interfaces.

The following diagrams show the success rate of rotation detection and the self-reported confidence depending on the rotation.

The detection of small rotations barely exceeds the false positive rate.

Figure 6.3 shows that samples without rotation were identified as such with 71.1% and 75.56%. This corresponds to a false positive rate of 28.9% and 24.44% respectively. The detection rate of the 4° rotated sample for an icon distance of 100mm corresponds to 26.67% and is therefore only slightly above the false positive rate.

With increasing rotation, the detection rate increases too.

In general, the detection rates for a few degrees of rotation are very low. However, a rapid increase can be observed. For 20° rotation, detection is already at 80%, at 24° and 28° at 100% with one exception. The exception is the 24° rotated sample with an icon distance of 25mm. However, only one participant failed to identify this correctly.

Confidence is similarly high with both low and higher rotation.

Figure 6.4 shows the distribution of the self-reported confidence of each participant's answer. One anomaly that stands out with both icon-spacing values is that the confidence is similarly high with very small rotation values as with stronger ones, despite the poorer detection rates.

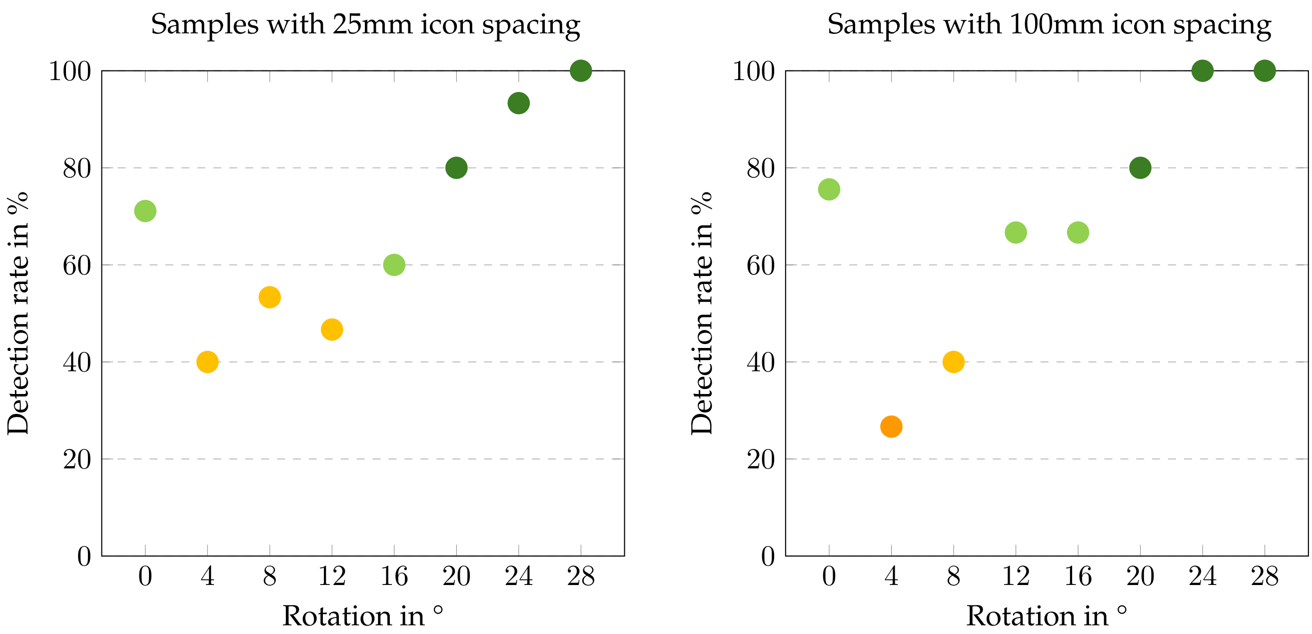


Figure 6.3: Detection rate for icon rotation.

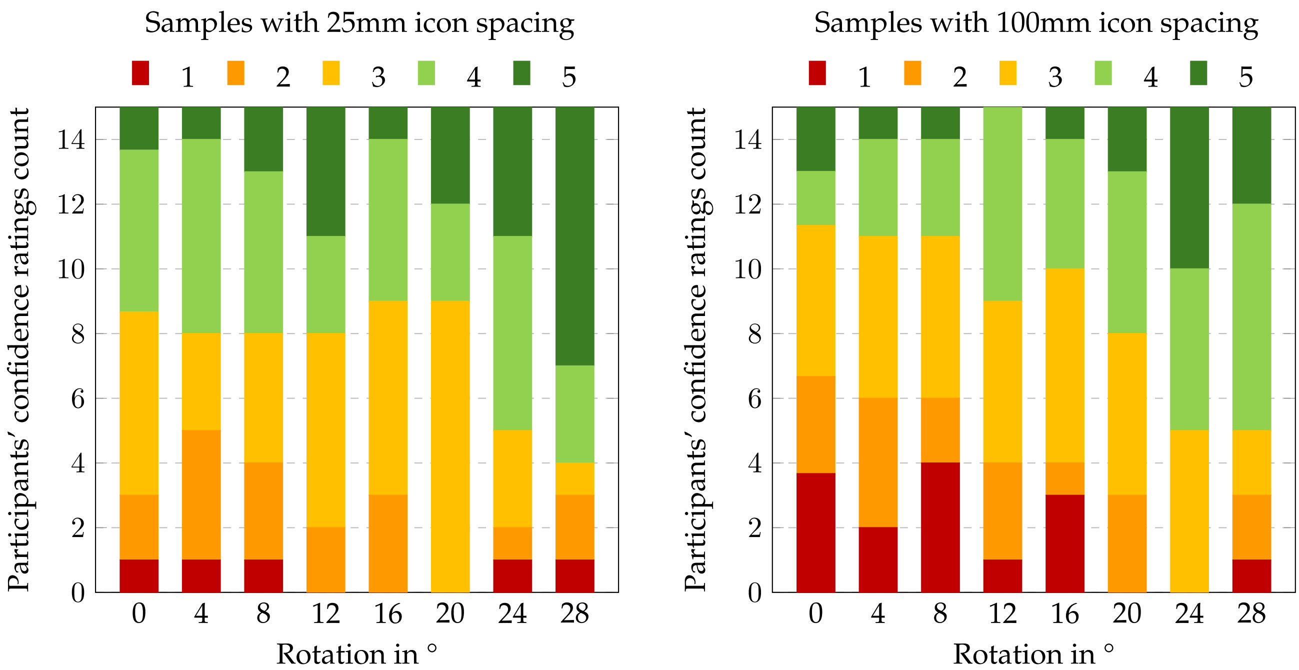


Figure 6.4: Confidence rate for icon rotation.

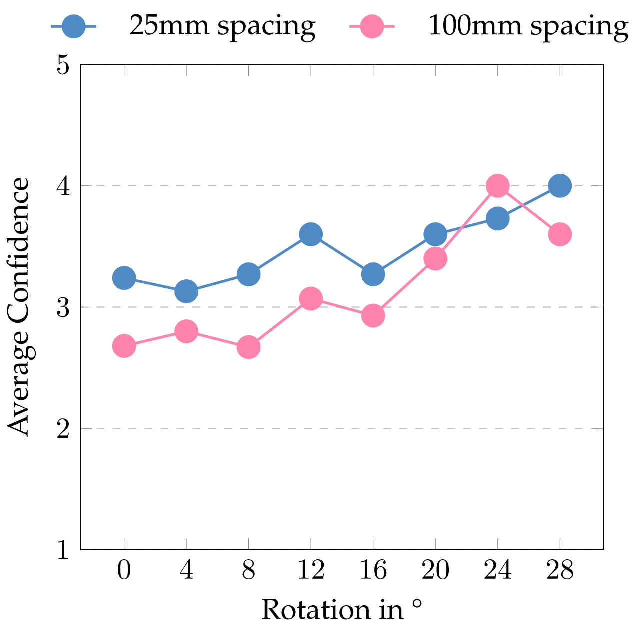


Figure 6.5: Average confidence for each sample spacing.

With a small rotation, high confidence often stemmed from incorrect answers.

However, it should be noted that the answers with high confidence were generally incorrect for small rotation values. For the 4° and 8° rotations, the average confidence for incorrect answers was 3.05, while it was 2.79 for correct answers. This means that participants were more confident about not feeling a rotation even though the sample was rotated. The high confidence therefore exists not despite, but precisely because of the high rate of misclassifications. Across all rotations, however, it was 2.91 for incorrect answers and 3.39 for correct answers. Nevertheless, it can be stated that the confidence is not a good indicator of the accuracy of the detection, particularly in the case of small rotations, meaning that participants were hardly able to assess how well they can perceive rotations themselves.

The detection rate did not decrease with greater icon spacing.

Figure 6.5 shows that the average confidence is slightly higher with an icon spacing of 25mm than with an icon spacing of 100mm. However, this difference becomes less significant with increasing rotation. If we look at the detection rate across all rotations, we find an average detection rate of 69% for the 25mm spacing and 71% for the 100mm spacing. This indicates that, contrary to expectations, the detection rate does not seem to decrease with greater distance between the icons.

Participants used different strategies during the experiment. Some tried to feel both icons simultaneously with pointed fingers, others pinched the corners or tried to use the seam at the edge of the sample as a reference line. Some participants stated that this technique helped them. However, this is not reflected in the results. Almost without exception, all participants stated that they found this task extremely strenuous and unpleasant. As the experiment had no time limit, the participants often needed a lot of time and were frustrated. Some openly stated that they did not like this task.

Participants used various strategies, none of which proved successful.

Combined with the detection and confidence rates, it can therefore be concluded that continuous rotation is not a suitable feature for textile user interfaces. However, since the detection rates for rotations of 28° were already 100%, discrete rotation could be considered, e.g., rotary switches that can only be rotated in adequately large fixed steps such as 0°, 45°, 90°. Users should be able to recognize these as rotated, provided that the icon shape used does not have 45° rotational symmetry. Small rotations are not suitable.

Continuous rotation is not a suitable feature for textile user interfaces.

6.2.1 Limitations

Participants stated that the plus shape of the icon made it difficult to recognize the rotation and that they preferred straight edges. However, as the plus shape has straight edges, it is reasonable to assume that it is not the shape that is the problem, but the size. With regard to Experiment 1, the size used for this experiment (13mm) based on previous work may not be optimal and made the task more difficult. Whether a larger icon size would have led to better results remains speculation.

The small icon size may have made the experiment more challenging.

Since the 100mm icon spacing trial was run for each participant after the 25mm icon spacing trial, it is possible that the better results for the 100mm trial were due to a learning effect. This would be contradicted by the fact that confi-

A potential learning effect may slightly distort the data.

dence was lower for the 100mm trial. In addition, participants were not told whether their answers were correct or incorrect. However, a learning effect cannot be ruled out.

Modifying other parameters may lead to different results.

Since only the plus shape was tested, no statement can be made about how rotation detection would work with other, e.g. rounder shapes. This experiment only provides a first overview, but there are many other variables that would have to be taken into account in a real application, such as profile height, shape, size, fabric, etc., which were not changed in this experiment.

6.3 Experiment 3: Preferred Slider Length

The goal of this experiment was to determine an optimal slider length based on the subjective perception of the participants. To do this, the maximum and optimum distances that were still perceived to be comfortable of each participant were measured in four different orientations. The results of these measurements are shown in the following diagrams. The measurements are abbreviated according to the following pattern:

F (Flat) means that this measurement was taken flat on the table.
V (Vertical) means that this measurement was taken vertically on the foam wall.
LR (Left-Right) means that the sliding direction was from left to right on the flat table.
BF (Back-Forth) means that the sliding direction was back and forth on the flat table.
FB (Forwards-Backwards) means that the sliding direction was forwards and backwards on the vertical foam wall.
TB (Top-Bottom) means that the sliding direction was from top to bottom on the vertical foam wall.
M (Maximum) describes the maximum distance that was still perceived as comfortable.
O (optimum) describes the distance that was specified as optimum in the context of comfort.

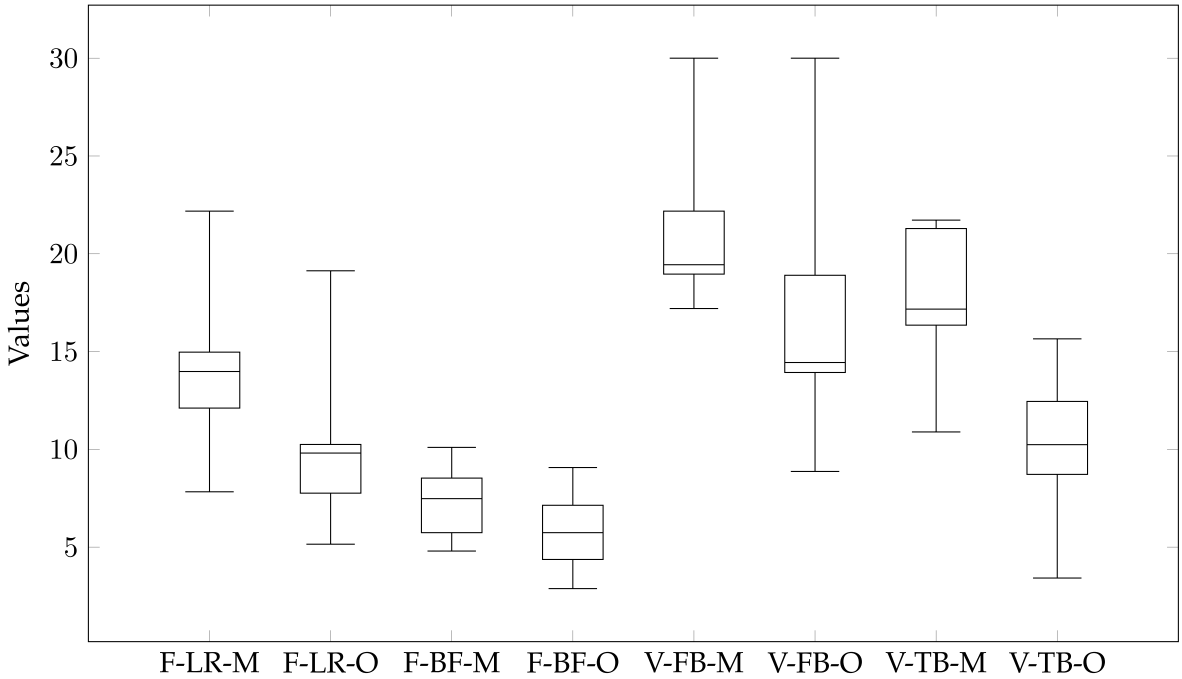


Figure 6.6: Box plots of maxima and optima for slider lengths.

Figure 6.6 shows the box plots of the individual measurements. It is noticeable that the individual opinions for F-LR and V-FB (swinging movements) diverge widely, whereas for V-TB and especially for F-BF (push-pull movements), they are very similar, regardless of whether the movement was limited by fixation of the wrist (F) or freely executable (V). In general, the interquartile ranges are small for all measurements and allow a reasonably accurate estimation of the common subjective preferences of suitable slider lengths.

The interquartile ranges are sufficiently narrow to allow for precise estimates of common preferences.

Figure 6.7 shows which distances were still comfortable or optimal for which percentage of participants, depending on the orientation of the respective measurement. The graphs can be read in the following two ways:

1. Choose a distance from the x-axis. The y-value at this point indicates the percentage of participants for whom this distance is still within the comfort zone.

2. Select a percentage from the y-axis, e.g. to find out

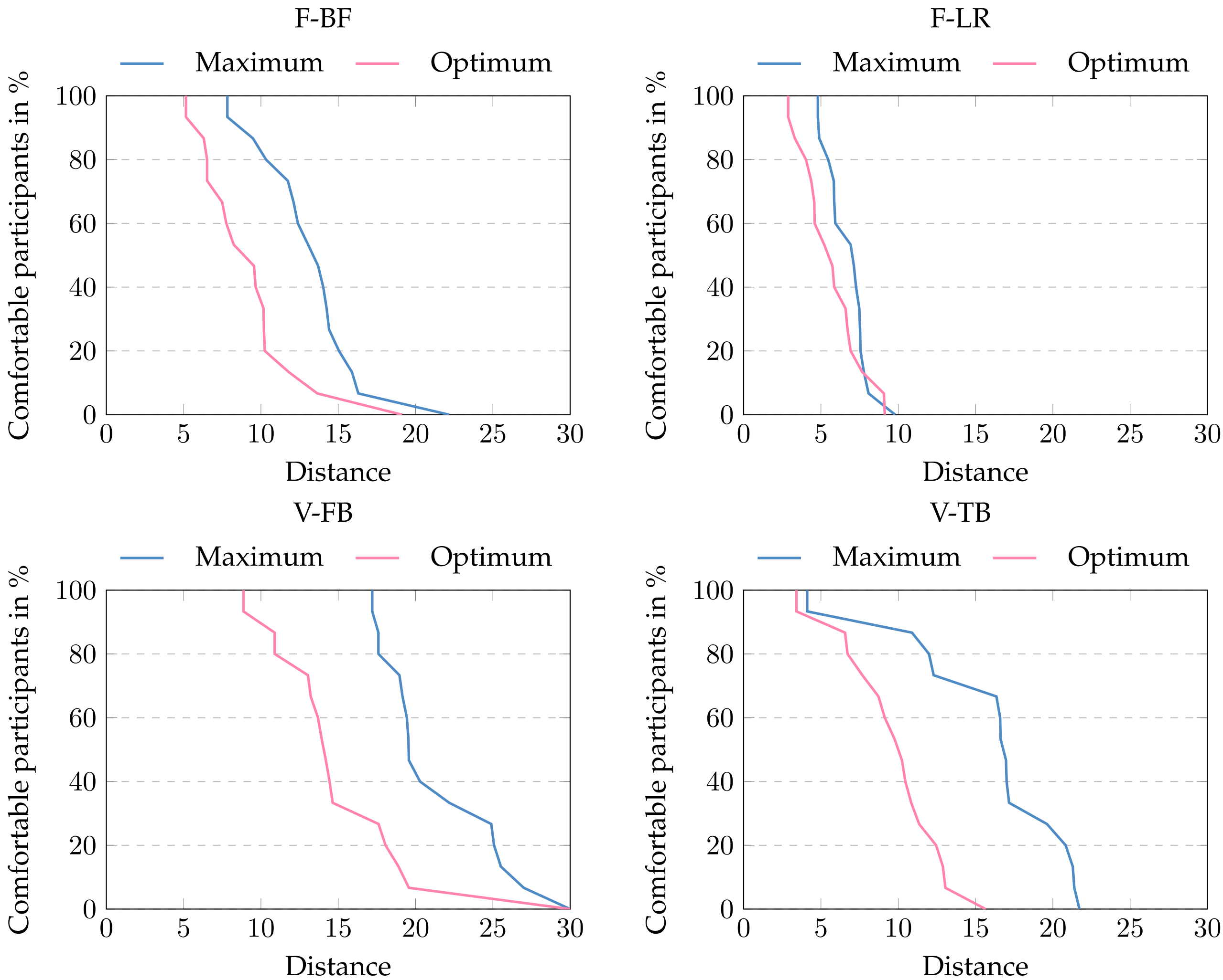


Figure 6.7: Percentage of participants finding distance comfortable.

up to which distance it was still perceived comfortable for 80% of the participants. The corresponding x-value can now be determined from the graph.

Two participants wanted to go beyond 30cm.

It is important to note that two participants stated during the V-FB measurement that they wanted to go further than 30cm. Since the slider is not built to exceed 30cm, assuming that no one would want to, these measurements were recorded as 30cm. The participants indicated that they would not go *much* further. So these are small deviations.

6.3.1 Data analysis

The distances were recorded in two different ways. Firstly with an OptiTrack camera that measured the markers attached to the slider and the finger, and secondly with 23 sensors attached to the back of the slider and an Arduino.

The distances were measured with an OptiTrack and an Arduino Uno.

The original plan was to use the Arduino measurements only as a test to try out the measurement system. The data actually evaluated was to be that from the OptiTrack. However, several problems arose with the OptiTrack that made it impossible to use the data. First, the marker on the finger was not always visible due to the way the OptiTrack was set up, for example due to the curvature of the finger. But an artificial stiffening of the participant's finger would have made the measurement unnatural. Second, the use of only one camera resulted in a flattened perspective/vanishing point illusion, which made the measurements inaccurate and different for each participant depending on the position of the camera.

The OptiTrack data was unsuitable for further analysis due to several issues.

So we decided to evaluate the data from the Arduino. To do this, we wrote a program that interpolates the sensor values and thus determines a position on the slider for each measurement. This allows the distances to be measured very accurately. The interpolation guarantees an upper bound error of 6mm, but is considerably more accurate in practice.

The position was determined through interpolation of the Arduino sensor data.

Figure 6.8 shows such an Arduino measurement. Both measurements are clearly visible. First came the maximum, later the optimum measurement. The distances of the two were determined from the differences between the averages of the maxima and minima of both movements.

File: Slider Distance Evaluation Program[a]

[a] https://git.rwth-aachen.de/i10/thesis/thesis-erik-mueller-limits-of-textile-interface-design-guidelines/-/raw/main/Exp3.zip

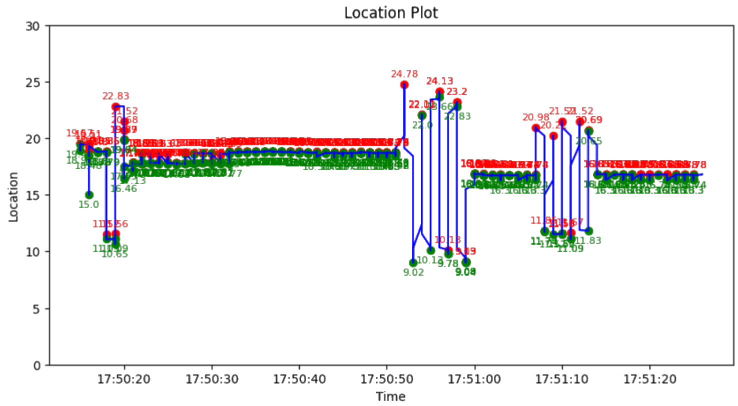


Figure 6.8: Arduino time-location graph.

6.3.2 Limitations

The experiment provides results about a comfortability-based upper bound for the slider length.

Instead of a universally optimal slider length, this experiment provides results about a comfortability-based upper bound for the slider length. It does not provide any results on how long a slider must be in order to make a sufficiently precise adjustment to it, for example. This lower bound still needs to be researched in future work. Together with these results, a trade-off between the required minimum length and the subjectively desired maximum length can then be determined using the data obtained here.

6.4 Experiment 4: Proximity-based grouping

The goal of this experiment was to find out whether and to what extent proximity-based grouping works with textile user interfaces and to what extent proximity can be perceived haptically at all.
The following diagrams show the results of the experiment for the different standard distances $stdD = 50mm$ and $stdD = 60mm$ and the different ratios of the closer icons. The detection rate, the confidence and whether the respective pair of icons located closer was seen as a group were measured.

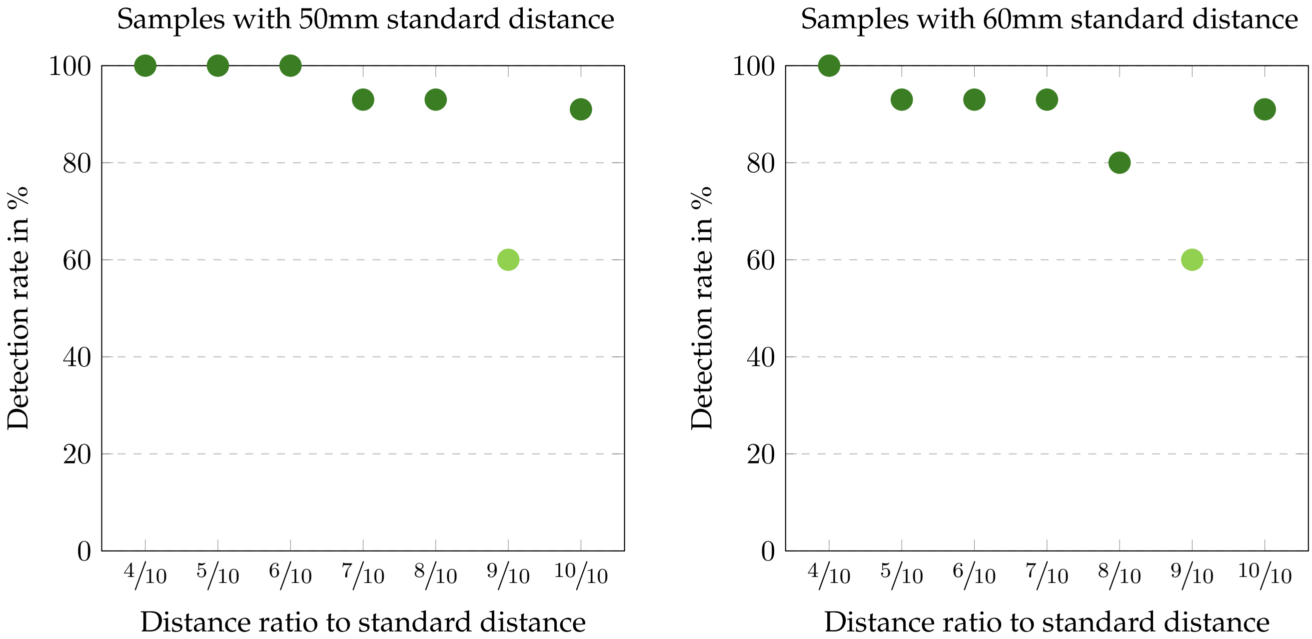


Figure 6.9: Detection rate for icon distance ratios.

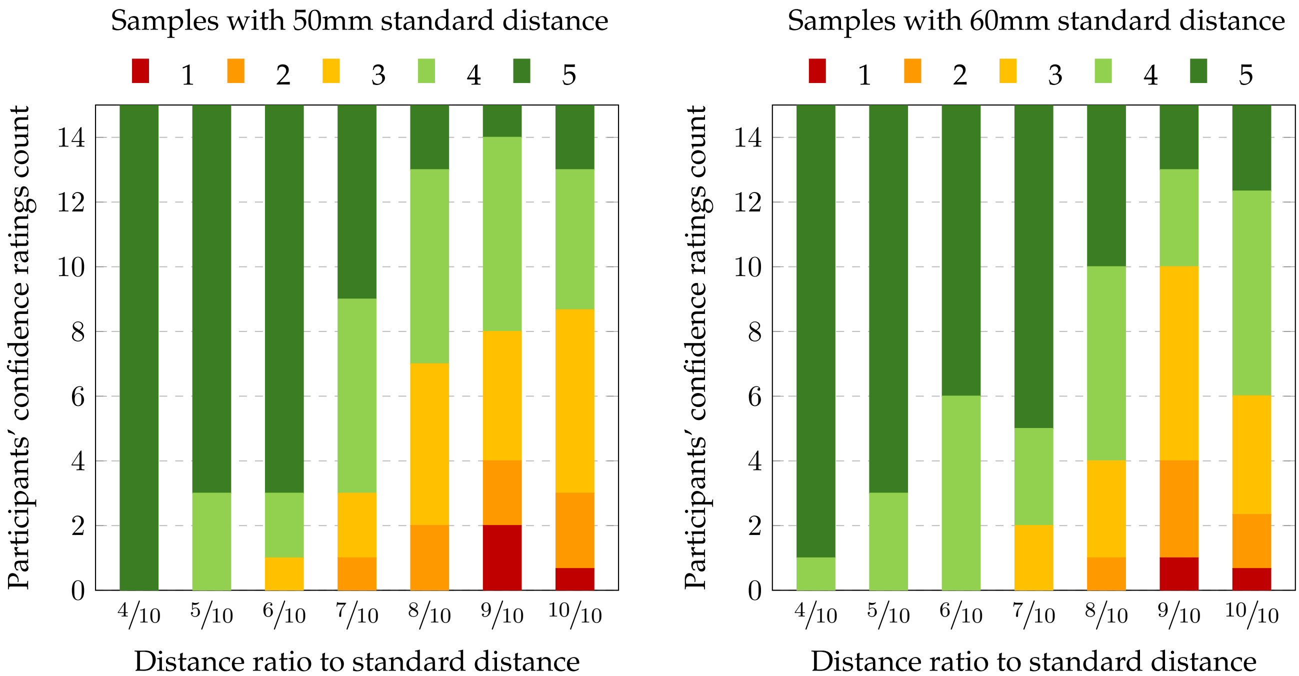


Figure 6.10: Confidence distribution for icon rotation.

The detection rate is consistently high for all samples, with a clear drop observed only at 9/10.

Figure 6.9 shows the average detection rate for all samples. It is noticeable that the overall results are very good. The sample with the closer icon pair with a distance of 4/10 of the standard distance was recognized by all participants in both sizes without exception. After that, the results are just under 100%. However, all incorrect results for both standard distances up to the ratio of 7/10 can be traced back to a single participant. All other participants recognized all samples up to 7/10 without error. The samples without a closer icon pair were recognized as such by 91%. There is therefore a false positive rate of only 9%. With the ratio of 9/10, a rapid drop in the detection rate can be seen for both standard distances.

The confidence rate is also consistently high.

Figure 6.10 shows the distribution of the self-reported confidence. Overall, the answers were given with high confidence. Exceptions here are the samples with a ratio of 9/10 and those without closer icons. The latter is mainly because participants were less confident about the absence of an icon pair when they didn't feel one than they were about its presence when they did.

Figure 6.11 summarizes the average confidence rate. The differences could be due to a learning effect. More on this in the limitations.

Subjective proximity-based grouping appears to depend not only on the relative distance between icons but also on their absolute distance.

Figure 6.12 shows the percentage of people who perceive the respective icon pairs with the ratio indicated in the x-axis as a group. It can be seen that there is a significant difference between the 50mm and 60mm samples, which indicates that the perception as a group does not only depend on the proximity ratio to other elements, but also on the absolute distance. For example, the icon pair with a ratio of 5/10 is perceived as a group by 86% at for $stdD = 50mm$, but only by 60% for $stdD = 60mm$. This means that distant icons are not perceived as a group simply because all other icons are even more distant. Instead, a balance can be assumed between absolute and relative proximity, which is necessary in order to clearly group elements.

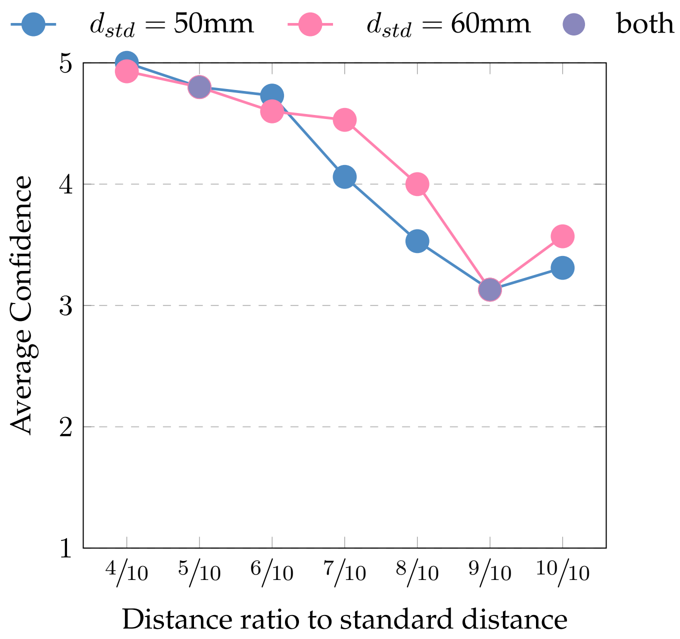


Figure 6.11: Average confidence for different d_{std}.

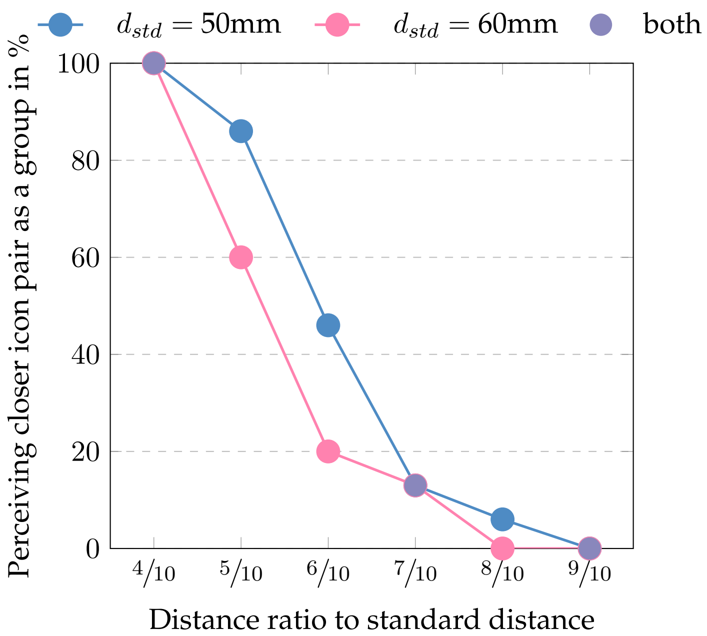


Figure 6.12: Percentage perceiving closer icon pair as a group.

6.4.1 Limitations

The experiment indicates a relationship between relative and absolute icon distance.

Rather than answering the question of the ratio at which elements are perceived as a group, this experiment has shown that the relationship between relative and absolute distance needs to be examined more closely in order to answer it. Consequently, no direct guideline can be given. Rather, the recommendation is to investigate this relationship further. The icon size itself likely plays a role too.

Strategies discovered by participants during the experiment may have introduced a slight distortion to the results due to learning effects.

Furthermore, in this experiment, like in experiment 2, there is a risk that a learning effect emerged throughout the trial, as the samples with $stdD = 60mm$ were always carried out after those with $stdD = 50mm$. Many participants developed strategies during the experiment that either led to better results or at least increased the confidence for the second sample series. Although this does not appear to have any visible effect on the results, it cannot be ruled out.

While improving the detection rate, these strategies are unlikely to be applied in real scenarios.

These strategies include, for example, placing several fingers in the gaps between the icons to get a better feel for how close they are. For the samples with $stdD = 50mm$, two fingers usually fitted exactly into the gaps of the icons that were not closer. If they did not fit into the gap, this was a good indicator that the icons were closer. For the samples with $stdD = 60mm$, three fingers fitted into the gap and the strategy could also be applied. Whether users in a real use case setting would also apply this strategy is questionable. Perhaps the detection rates are therefore lower in a realistic setting.

6.5 Experiment 5: Ratio-dependent perception of rectangular shapes

The goal of this experiment was to find out how the perception and intuitive interaction of participants changes with different rectangular ratios.

The 13:100, 19:100 and 25:100 ratios were mostly perceived as sliders. However, two participants found the 19:100 ratio to be too high. Here and in the following, 'high' refers to the direction in which we are varying the dimension throughout the experiment. At 25:100, eight of the participants found the height to be too large. Two explicitly mentioned that this shape was too high for a slider, but too low for a touchpad.

13:100 and 19:100 were clearly classified as sliders.

This trend is reinforced for the 31:100 and 37:100 samples. 31:100 was considered equally suitable for a slider and a touchpad, although participants explicitly stated that this size was generally unsuitable for both. One participant even stated his dislike of this sample in the form of disgust. Some other participants thought that instead of one slider or a touchpad, it could be several 1-dimensional sliders that lie on top of each other on the surface and can be operated independently of each other (see Figure 6.13). However, the participants still only saw sliding as an input method. This changed with the 37:100 sample. Although they continued to complain that the size was neither suitable for sliders nor for touchpads, they could already imagine 2-dimensional interaction possibilities, such as drawing and mapping and furthermore tapping and swiping with more than one finger.

Participants found 31:100 and 37:100 to be an indistinct blend of both slider and touchpad and generally disliked them.

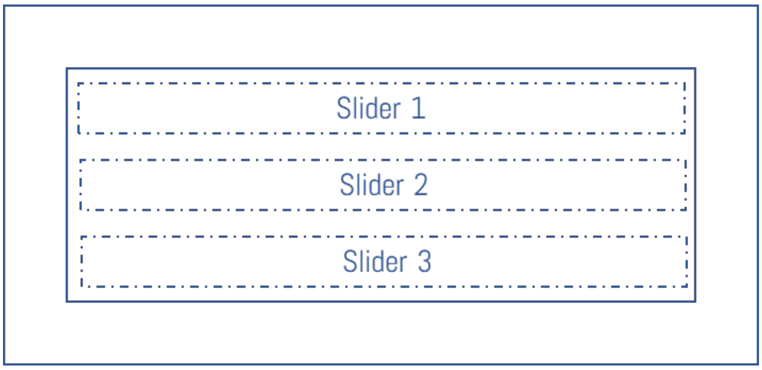


Figure 6.13: Multiple independent sliders on one interaction field.

The 43:100, 49:100 and 55:100 ratios were mostly regarded as touchpads. A few participants still found the 43:100 and 49:100 samples unpleasant, but the majority liked the 55:100 sample. Only two participants said that they would prefer a slightly greater height. The interaction options are in the same range as those just mentioned, with more natu-

The 43:100 - 55:100 samples were perceived as touchpads, which expanded the range of input options.

ral mapping, pressing/tapping and interactions for writing and drawing, even with pens for the 55:100 sample. One participant could imagine measuring his pulse or other vital signs by placing his wrist on the sample.

The majority preferred the 13:100 sample as the size for the slider.

When asked which ratio the participants preferred for a slider, ten participants stated 13:100, as this height corresponds approximately to the fingertip and therefore guides it better. Five participants preferred 19:100, as they preferred a little more space for the finger and did not want to feel cramped. This was particularly the case for participants with longer nails. No one preferred the 25:100 sample or any of the others for a slider.

6.5.1 Limitations

The experiment offers insights into the impact of absolute heights on perception rather than ratios.

The participants' answers suggest that the pleasantness of certain samples was less about the ratio and more about the absolute height. For example, the samples 31:100 and 37:100 were disliked because their height was not little enough to guide the finger like a slider, but also not large enough to provide a comfortable amount of space for the fingers to make 2-dimensional interactions. However, this depends solely on the height of the sample, not the ratio. The experiment therefore produced some interesting results, but not quite what was originally intended. The results are therefore more of an indicator of which absolute height of the element leads to a differentiation between slider and touchpad and which interaction options different heights support. However, no statement can be made about a suitable width of touchpads and therefore not necessarily about the ideal ratio. As far as the optimum width of sliders is concerned, please refer to Experiment 3.

6.6 Experiment 6: Directional perception

The aim of this experiment was to find out in which orientation participants perceive icons when they are positioned to a side wall below the participant's hand. Thus, whether

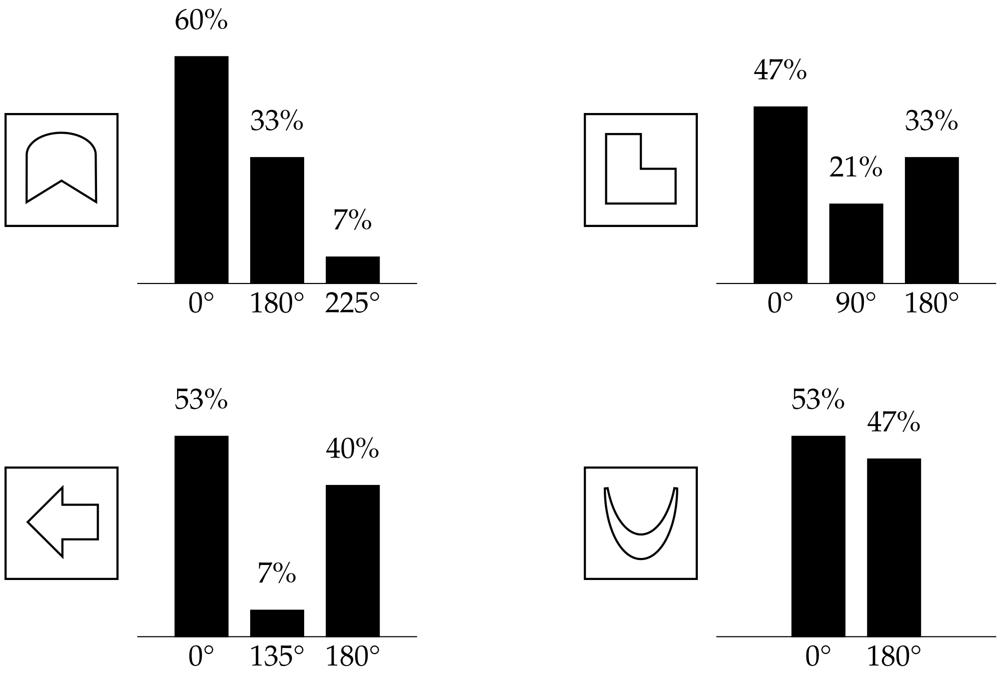


Figure 6.14: Perceived rotational difference from actual icon orientation.

the absolute or the relative orientation of the icons is more important.

Figure 6.14 shows the distribution of the perceived orientation. The number of degrees refers to the deviation from the actual orientation, where the actual orientation is defined as the bottom of the icon pointing towards the ground, as viewed from a person standing in front of it. All degree measurements describe the relative clockwise rotation.

For three of the four icons, there are basically only differences of either 0° or 180°. The 225° and 135° are outliers that both originate from the same participant. For all icons, the deviation of 0° from the actual orientation makes up the largest proportion. This means that the largest group of participants perceived the icons in their absolute position. The group of participants who perceived the icons rotated by exactly 180° was almost on a par.

The majority perceived icons either in their actual orientation or rotated by 180°.

The corner icon has a special feature, namely that three of the participants perceived it as rotated by 90°. However,

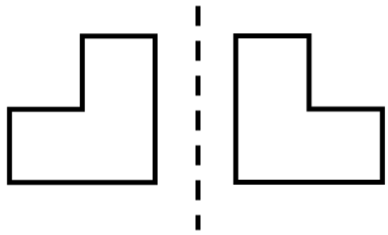


Figure 6.15: Corner icon rotated by 90°.

The corner icon was partially perceived as rotated by 90°, akin to a vertical reflection.

there is another peculiarity with this icon. Namely, depending on the current position of the icon, a 90° rotation always corresponds to a reflection on either the horizontal or the vertical axis. It is interesting to note that the participants always perceived a reflection on the vertical axis according to the same pattern shown in Figure 6.15.

This suggests that the participants perceived the vertical difference between their relative and absolute position, but not the horizontal one, which indicates that left and right are more easily confused than up and down.

Participants were not consistent in their perceptions.

It is also interesting to note that participants were not consistent in their answers. The fact that a participant perceived the first icon as 0° was not an indicator of how they would perceive the next one. The measurements of 15 participants resulted in 11 unique combinations of perceptions. The exact data can be viewed in Appendix B.

6.6.1 Limitations

The experiment does not provide a clear solution to the problem.

The results of this experiment do not provide the hoped-for clarity. Rather, they show that there can be no concrete guideline for a specific icon orientation, as perception differs from person to person and even from icon to icon for the same person. The insight of this experiment is therefore that there is no obvious clear solution to this problem, or at least that it needs to be researched further.

6.6.2 Remark

With regard to the discrete rotations proposed in Experiment 2, the following problem arises:

Imagine, for example, a clock hand that can only represent the discrete minutes 0, 15, 30 and 45. The results of Experiment 2 show that participants should be able to distinguish between them, as they each have a relative rotation of 90°. However, if the basic orientation of the icon is not reliably perceived in the desired way, half of the participants perceive a 15-minute hand as a 45-minute hand and another group as a 30-minute hand. The information conveyed by this clock hand would still be incorrect for approximately half of the group and therefore useless. This raises the question of whether relative discrete rotation makes sense if even the rotationless state is already unclear.

Due to uncertainty in directional perception overall, discrete rotation may also be unsuitable.

Chapter 7

Conclusion

In this chapter, we summarize the findings of the study and discuss possible future work.

7.1 Contributions

The results of the study provide the following insights:

1. Participants preferred icon sizes between 25-37mm for shape recognition, with 31mm being the most liked size overall.
2. Continuous rotation is unsuitable for textile user interfaces, as rotations of less than 24° were not reliably perceived.
3. The optimal and maximum slider lengths vary based on orientation and slide direction. The study offers upper-bound estimates for future slider design.
4. Proximity-based grouping works for textile user interfaces. We are providing estimates for the distances/ratios at which icons are perceived as a group.
5. The transition from slider to touchpad is seamless. The study provides dimensions where rectangles are

clearly identified as sliders or touchpads, along with intuitive input options. The preferred slider height was 13mm.

6. The directional perception of icons varied significantly among participants, indicating this is a complex issue without a clear consensus.

This thesis provides insight into underexplored areas of textile user interface designs, identifying their limits and future research directions.

7.2 Future Work

The study covered various fields but did not explore any in depth. Consequently, some variables remain unchanged and several questions unanswered, requiring further investigation. This includes:

- investigation of an optimal icon size for other shapes, other profiles, flat or recessed icons and other surface textures
- investigation of icon rotations with larger icons, non-symmetrical and rounder/ different shapes
- determining the minimum slider length for precise adjustments and finding the trade-off with subjective maximum lengths to determine the optimal slider length
- further investigations into the relationship between absolute and relative distances with regard to proximity-based icon grouping, as well as parameter changes such as icon shape and icon size
- further investigations into the influence of absolute heights for determining sliders and touchpads with changing rectangle width

- further and more in-depth studies on the directional perception of icons, especially in connection with discrete rotations

Appendix A

Study documents

All study documents used during the study are listed below.

Participant Documentation

Age: ____________________ Participant-Nr: ______________

Occupation: ______________ Gender affiliation: ___________

Nationality: ______________ Left-handed ☐ Right-handed ☐

Arm-Length: ______________

Figure A.1: The Participant Documentation for the demographic analysis.

Informed Consent Form

Finding the Limits of Textile Interface Design Guidelines

PRINCIPAL INVESTIGATOR Erik Müller
Media Computing Group
RWTH Aachen University
Email: erik.mueller2@rwth-aachen.de

Purpose of the Study: The aim of the study is to gain a better understanding of people's haptic perception and opinions when interacting with textile interfaces in order to derive design guidelines for such interfaces.

Procedure: The study is divided into six experiments. In the first of these, the participant's hand movement is measured. In addition, the outline of the hand and the length of the forearm are measured. In the other experiments the participant is asked to take part in tasks about tactile recognition and answer questions for those tasks. During these experiments, the participant's hand and voice are recorded. The face is not recorded. In the last experiment, the task will be to make four simple drawings. The study will last between 1 and 1.5 hours.

Risks/Discomfort: There are no obvious sources of discomfort in the study. There are no risks. If you feel unwell or exhausted, you can take a break at any time. The study can be terminated at any time at your discretion.

Benefits: The results of the study will be used to create design guidelines that help making textile user interfaces more user-friendly, intuitive and pleasant to use in the future.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue participation at any time.

Cost and Compensation: Participation in this study will involve no cost to you. There will be snacks and drinks for you during and after the participation.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.
_____ I have had the information on this form explained to me.

Participant's Name	Participant's Signature	Date
	Principal Investigator	Date

If you have any questions regarding this study, please contact Erik Müller at erik.mueller2@rwth-aachen.de.

Figure A.2: The Informed Consent Form.

Study Protocol

Participant-Nr: 1

Experiment 1: Icon Size

Size	13(5)	19(4)	25(5)	31(4)	37(4)	43(5)	49(4)	55(4)	61(4)	67(4)
Rating										
Detection										

Preferred Size: __________

Experiment 2: Icon Rotation

Rotation	12°(4)	8°(3)	20°(6)	24°(7)	28°(8)	0°(1)	16°(5)	0°(1)	4°(2)	0°(1)
Detection (25mm)										
Confidence										

Rotation	0°(1)	20°(6)	12°(4)	0°(1)	16°(5)	24°(7)	4°(2)	28°(8)	0°(1)	8°(3)
Detection (100mm)										
Confidence										

Experiment 3: Slider Length

Direction	Left-Right	Back-Forth
Maximum		
Optimum		

Flat (Armrest)

Direction	Front-Back	Top-Bottom
Maximum		
Optimum		

Vertical (Side)

Favourite Direction:__________

Figure A.3: The first page of the Study Protocol.

Experiment 4: Icon Distance

Ratio	7/10	10/10	6/10	4/10	9/10	10/10	10/10	8/10	5/10
Detection (5cm)									
Group-Perception									
Confidence									

Ratio	9/10	7/10	6/10	10/10	4/10	8/10	10/10	5/10	10/10
Detection (6cm)									
Group-Perception									
Confidence									

Experiment 5: Slider Ratio

31:100 ______________________________ 25:100 ______________________________

49:100 ______________________________ 43:100 ______________________________

19:100 ______________________________ 13:100 ______________________________

55:100 ______________________________ 37:100 ______________________________

Experiment 6: Directional Perception

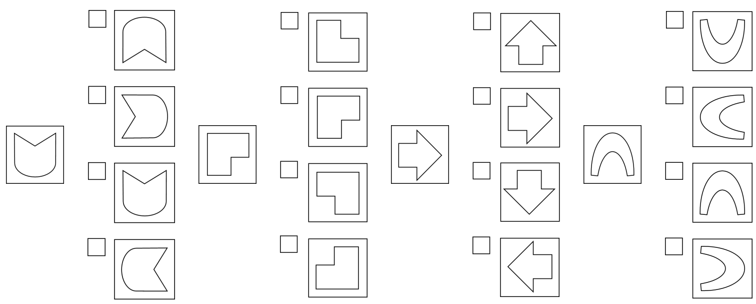
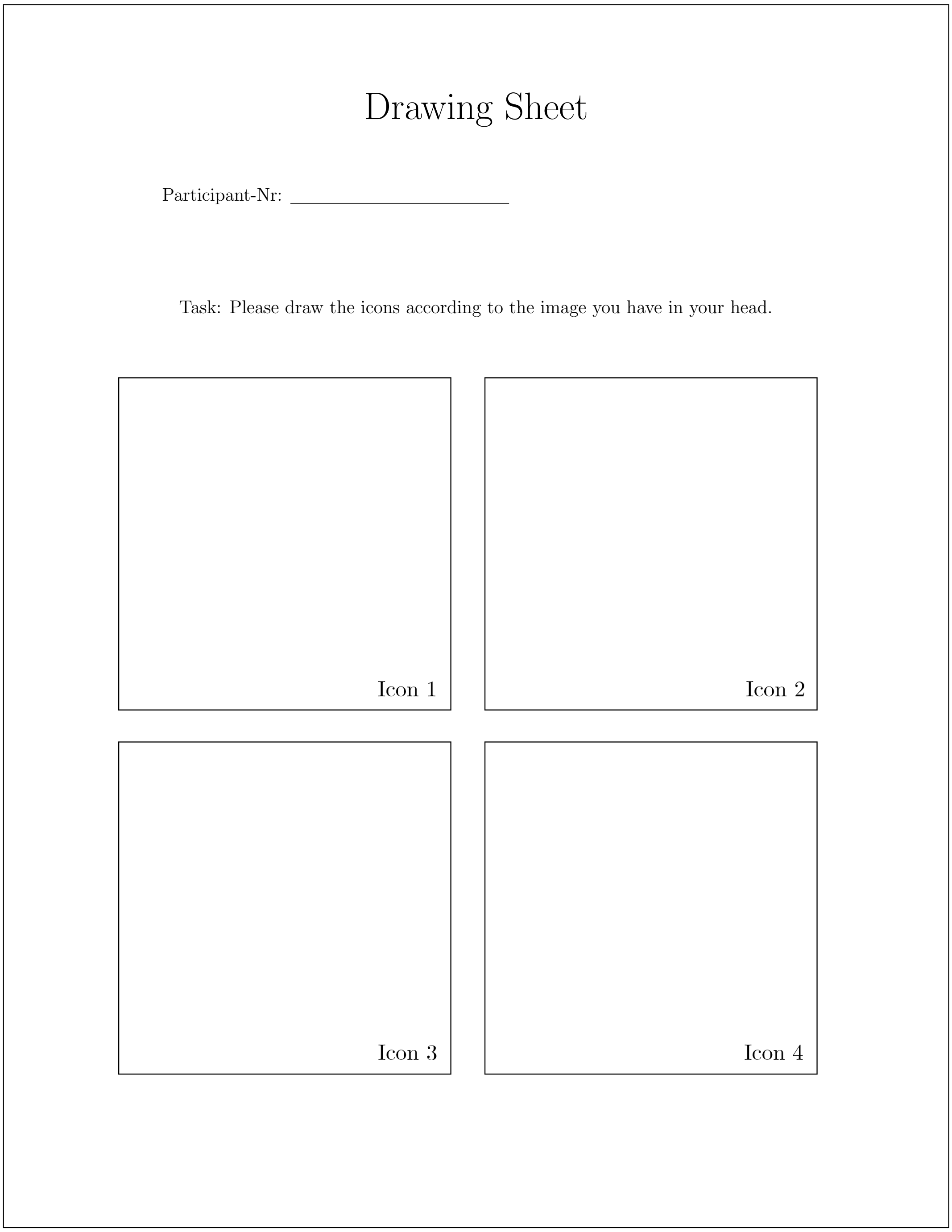


Figure A.4: The second page of the Study Protocol.



Drawing Sheet

Participant-Nr: ____________________

Task: Please draw the icons according to the image you have in your head.

Icon 1	Icon 2
Icon 3	Icon 4

Figure A.5: The drawing sheet for drawing the sensed icons.

Appendix B

Exact Study Results

The exact results of the study are listed below, the content of which was previously summarized in the form of diagrams and charts. A download link is provided at the end of this section.

Experiment 1: Preferred Icon Size

	Icon size in mm										
Participant	13	19	25	31	37	43	49	55	61	67	Favourite
1	2	3	3	4	4	3	4	4	3	2	31
2	3	5	4	4	4	3	2	3	3	2	19
3	2	4	4	5	4	3	2	2	1	1	37
4	1	3	5	4	4	4	3	3	2	2	19
5	4	3	4	5	5	5	4	4	4	3	37
6	3	4	4	4	4	4	3	3	3	3	31
7	2	3	4	4	3	3	4	3	3	4	67
8	1	4	5	5	5	4	4	3	1	1	43
9	1	4	4	4	3	3	3	3	2	2	31
10	4	5	5	5	4	4	4	4	4	4	25
11	1	3	4	4	4	4	4	4	3	3	31
12	2	4	4	4	3	3	3	3	3	3	19
13	2	4	4	5	5	5	5	5	4	4	43
14	5	5	5	4	4	4	3	2	2	2	19
15	3	5	5	4	4	4	3	3	3	2	25

Table B.1: Rating per participant per size.

Experiment 2: Icon Rotation

Participant	Icon rotation in ° 0_1	0_2	0_3	4	8	12	16	20	24	28
1	1	1	0	1	1	0	1	1	1	1
2	1	1	1	0	1	1	0	1	1	1
3	1	1	1	1	0	1	1	1	1	1
4	1	1	0	0	0	1	1	1	1	1
5	1	1	1	0	0	0	1	1	1	1
6	1	0	1	1	1	0	1	1	1	1
7	1	0	0	1	0	0	1	1	1	1
8	0	1	0	1	1	1	1	1	1	1
9	0	0	1	0	1	1	0	1	1	1
10	1	0	1	0	1	1	1	0	1	1
11	1	1	1	0	1	0	0	0	1	1
12	1	1	1	0	0	0	0	1	1	1
13	0	0	1	0	0	1	0	0	1	1
14	1	1	1	0	1	0	1	1	0	1
15	0	1	1	1	0	0	0	1	1	1

Table B.2: Rotation detection for 25mm icon spacing.

Participant	Icon rotation in ° 0_1	0_2	0_3	4	8	12	16	20	24	28
1	4	3	2	2	4	3	3	4	4	5
2	4	4	3	3	3	5	4	4	4	2
3	4	3	3	1	4	3	4	5	2	5
4	3	2	1	4	4	3	3	5	5	4
5	4	4	2	2	2	3	3	3	1	2
6	3	4	5	4	5	5	4	4	3	5
7	2	2	3	2	4	2	4	3	4	5
8	5	4	4	5	5	5	5	5	5	5
9	4	1	3	4	2	2	3	3	4	5
10	3	1	3	4	1	4	2	3	5	5
11	4	3	3	4	3	4	2	3	5	1
12	3	3	3	3	3	3	2	3	3	3
13	4	2	3	2	3	3	3	3	4	5
14	5	4	5	4	2	5	4	3	3	4
15	3	4	4	3	4	4	3	3	4	4

Table B.3: Rotation detection confidence for 25mm icon spacing.

		Icon rotation in °									
		0_1	0_2	0_3	4	8	12	16	20	24	28
Participant	1	1	1	1	1	1	1	1	1	1	1
	2	1	0	1	0	1	0	1	1	1	1
	3	1	1	1	0	0	1	1	1	1	1
	4	0	0	1	0	1	1	0	1	1	1
	5	1	0	1	0	1	0	1	0	1	1
	6	1	1	1	0	0	1	1	1	1	1
	7	1	0	1	0	0	1	1	1	1	1
	8	1	0	0	1	0	1	1	1	1	1
	9	0	0	0	1	1	1	1	0	1	1
	10	1	1	1	0	0	0	0	1	1	1
	11	1	1	1	0	0	0	1	1	1	1
	12	1	1	1	0	0	0	1	1	1	1
	13	1	1	1	0	1	1	0	1	1	1
	14	1	1	0	1	0	1	0	1	1	1
	15	1	1	1	0	0	1	0	0	1	1

Table B.4: Rotation detection for 100mm icon spacing.

		Icon rotation in °									
		0_1	0_2	0_3	4	8	12	16	20	24	28
Participant	1	3	3	2	1	2	3	3	2	4	3
	2	2	3	1	2	4	4	3	3	3	4
	3	3	1	1	3	3	4	5	3	5	2
	4	1	1	1	1	1	2	1	2	5	5
	5	3	2	2	3	1	2	3	3	3	1
	6	4	5	4	3	3	3	4	5	5	5
	7	3	3	3	3	4	4	4	4	4	4
	8	5	3	5	5	5	4	4	4	4	5
	9	1	1	2	4	1	3	1	2	5	4
	10	1	2	1	2	1	1	2	3	3	2
	11	2	3	5	4	3	3	3	4	4	4
	12	3	2	3	2	2	3	3	3	3	3
	13	1	2	3	2	3	2	1	5	4	4
	14	4	3	5	3	3	4	3	4	5	4
	15	4	4	5	4	4	4	4	4	3	4

Table B.5: Rotation detection confidence for 100mm icon spacing.

Experiment 3: Preferred Slider Length

Participant	F-LR-M	F-LR-O	F-BF-M	F-BF-O	V-FB-M	V-FB-O	V-TB-M	V-TB-O	Arm-Length
1	14.03	9.55	10.1	4.37	30	20.26	4.11	3.42	27
2	14.25	11.81	8.08	4.59	25.52	18.9	21.72	12.89	26
3	22.18	19.13	7.27	5.21	19.54	10.89	16.59	13.05	30
4	14.41	10.25	5.47	3.31	17.6	13.93	10.89	6.56	27
5	13.7	8.24	7.98	7.78	18.96	14.2	21.29	15.65	30
6	15.89	10.19	9.8	6.92	30	30	20.83	7.68	24
7	12.11	6.3	4.8	2.88	19.16	8.87	17.17	8.72	26.5
8	13.05	13.65	8.53	5.86	19.57	13.69	12.29	6.72	22.5
9	7.83	6.52	5.83	4.03	22.18	19.57	11.99	9.13	23
10	16.3	10.17	4.89	4.57	17.2	13.04	21.39	9.76	28
11	11.74	5.15	9.87	9.07	20.29	14.44	19.62	10.46	28
12	12.39	6.52	7.48	5.74	19.44	14.64	16.62	11.35	28
13	15.05	9.66	7.13	4.89	17.6	13.22	16.35	12.45	26
14	10.33	7.49	7.56	5.93	25.08	17.61	17.01	10.84	30
15	9.48	7.76	7.53	6.59	24.9	18.06	16.97	10.24	26

Table B.6: Distance maxima and optima of comfortability.

Experiment 4: Distance-based grouping

	Ratio to d_{std}								
Participant	$4/10$	$5/10$	$6/10$	$7/10$	$8/10$	$9/10$	$10/10_1$	$10/10_2$	$10/10_3$
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	0	1	1	1
4	1	1	1	1	1	0	1	1	1
5	1	1	1	1	1	0	1	1	1
6	1	1	1	1	0	1	1	1	1
7	1	1	1	1	1	1	0	1	1
8	1	1	1	1	1	1	1	1	0
9	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	0	1	1	1
14	1	1	1	1	1	0	1	1	1
15	1	1	1	0	1	0	0	0	1

Table B.7: Correct icon pair detection for $d_{std} = 50mm$.

Participant	$^4/_{10}$	$^5/_{10}$	$^6/_{10}$	$^7/_{10}$	$^8/_{10}$	$^9/_{10}$	$^{10}/_{10_1}$	$^{10}/_{10_2}$	$^{10}/_{10_3}$
	Ratio to d_{std}								
1	5	5	5	4	3	2	3	4	3
2	5	5	4	5	4	1	2	3	1
3	5	5	5	4	2	4	4	2	3
4	5	5	5	5	5	2	4	4	5
5	5	4	4	1	3	3	3	2	3
6	5	4	5	5	4	4	4	3	3
7	5	4	3	4	3	1	1	3	2
8	5	5	5	5	3	4	5	3	2
9	5	5	5	5	4	3	2	3	2
10	5	5	5	5	5	4	4	5	5
11	5	5	5	4	4	3	4	3	4
12	5	5	5	4	4	3	4	3	3
13	5	5	5	3	3	4	3	3	3
14	5	5	5	3	2	4	5	4	4
15	5	5	5	4	4	5	4	4	5

Table B.8: Icon pair detection confidence for $d_{std} = 50mm$.

Participant	$^4/_{10}$	$^5/_{10}$	$^6/_{10}$	$^7/_{10}$	$^8/_{10}$	$^9/_{10}$	$^{10}/_{10_1}$	$^{10}/_{10_2}$	$^{10}/_{10_3}$
	Ratio to d_{std}								
1	1	1	0	0	0	0	0	0	0
2	1	1	1	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0
5	1	1	0	0	0	0	0	0	0
6	1	1	1	0	0	0	0	0	0
7	1	1	0	0	0	0	0	0	0
8	1	1	0	0	0	0	0	0	0
9	1	1	1	1	0	0	0	0	0
10	1	1	0	1	0	0	0	0	0
11	1	0	1	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0
13	1	1	1	0	0	0	0	0	0
14	1	1	1	0	0	0	0	0	0
15	1	1	1	0	1	0	0	0	0

Table B.9: Subjective group perception for $d_{std} = 50mm$.

Participant	Ratio to d_{std}: $^4/_{10}$	$^5/_{10}$	$^6/_{10}$	$^7/_{10}$	$^8/_{10}$	$^9/_{10}$	$^{10}/_{10_1}$	$^{10}/_{10_2}$	$^{10}/_{10_3}$
1	1	1	1	1	1	0	0	0	1
2	1	1	1	1	1	1	1	1	1
3	1	1	1	1	0	0	1	1	1
4	1	1	1	1	1	1	1	1	1
5	1	1	1	1	0	1	1	1	1
6	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	0	1	1	1
8	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	0	1	1
10	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	0	1	1	1
14	1	1	1	1	1	0	1	1	1
15	1	0	0	0	0	0	1	1	0

Table B.10: Correct icon pair detection for $d_{std} = 60mm$.

Participant	Ratio to d_{std}: $^4/_{10}$	$^5/_{10}$	$^6/_{10}$	$^7/_{10}$	$^8/_{10}$	$^9/_{10}$	$^{10}/_{10_1}$	$^{10}/_{10_2}$	$^{10}/_{10_3}$
1	5	5	4	3	4	2	2	2	3
2	5	5	5	5	4	3	1	1	3
3	5	5	5	4	4	4	3	4	3
4	5	5	5	5	5	2	3	4	4
5	5	4	4	3	3	1	3	3	4
6	5	4	4	4	4	4	5	5	4
7	4	4	4	4	2	2	3	3	2
8	5	5	5	5	5	5	5	4	5
9	5	5	5	5	3	3	2	3	2
10	5	5	5	5	5	4	5	4	5
11	5	5	5	5	5	3	3	4	4
12	5	5	5	5	4	3	4	4	4
13	5	5	5	5	4	3	4	4	4
14	5	5	4	5	3	3	4	4	4
15	5	5	4	5	5	5	5	5	4

Table B.11: Icon pair detection confidence for $d_{std} = 60mm$.

Participant	Ratio to d_{std} $^{4}/_{10}$	$^{5}/_{10}$	$^{6}/_{10}$	$^{7}/_{10}$	$^{8}/_{10}$	$^{9}/_{10}$	$^{10}/_{10_1}$	$^{10}/_{10_2}$	$^{10}/_{10_3}$
1	1	1	0	0	0	0	0	0	0
2	1	1	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0
5	1	0	0	0	0	0	0	0	0
6	1	1	0	0	0	0	0	0	0
7	1	1	1	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	0
9	1	1	1	1	0	0	0	0	0
10	1	1	0	0	0	0	0	0	0
11	1	1	1	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	0
14	1	1	0	1	0	0	0	0	0
15	1	0	0	0	0	0	0	0	0

Table B.12: Subjective group perception for $d_{std} = 60mm$.

Experiment 5: Ratio-dependent perception of rectangular shapes

All keywords and ideas that were mentioned for the respective ratio are listed below. Keywords that were mentioned more than once are marked with the number of mentions in the form [n].

13:100 Slider [15], 1D [6]

19:100 Slider [13], 1D [6], too wide [2], max. min. [2], 2D binary switch [1]

25:100 Slider [10], too high [6], 1D [5], too high for slider and too low for touchpad [2], 2D binary switch [1], tap [1], swipe [1]

31:100 Touchpad [4], slider [4], too narrow for touchpad [4], 1D [3], 2D binary switch [2], 2D [2], too wide for slider [2]

37:100 Touchpad [4], 2D [3], two sliders on top of each other [3], press [2], too narrow [2], mapping [2], tapping [2], swiping [1], sliding [1], 1D [1], drawing [1]

43:100 Touchpad [9], several sliders on the field on top of each other [2], pinching [1], mapping [1], pressing [1], tapping [1], swiping [1], sliding [1], too narrow, [1]

49:100 Touchpad [9], 2D [4], painting/writing [3], natural mapping [2], too high [1], fixed points [1], pressing [1], uncomfortable [1],

55:100 Touchpad [9], 2D [3], tapping [3], drawing/writing [3], pressing [2], interactable with pen [2], typing [2], mapping [1], measuring vital signs [1]

Experiment 6: Directional perception

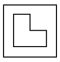
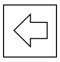
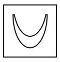
Participant	Icon 			
1	0°	180°	180°	180°
2	0°	0°	0°	0°
3	180°	180°	180°	180°
4	0°	90°	0°	0°
5	0°	0°	180°	0°
6	0°	0°	0°	0°
7	225°	90°	135°	180°
8	180°	180°	0°	0°
9	180°	180°	180°	180°
10	180°	180°	180°	180°
11	180°	0°	0°	180°
12	0°	0°	0°	180°
13	0°	0°	0°	0°
14	0°	0°	0°	0°
15	0°	90°	180°	0°

Table B.13: Perceived rotational difference from actual icon orientation.

Digital versions of the tables shown here are also available for download.

File: Study Results[a]

[a] https://git.rwth-aachen.de/i10/thesis/thesis-erik-mueller-limits-of-textile-interface-design-guidelines/-/raw/main/StudyResults.zip

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Index

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