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

RWTH AACHEN UNIVERSITY

# *Understanding User Behaviour When Interacting with Large Textile Interfaces*

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submitted to the
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# Abstract

In this work, we investigated how users interact with larger textile interfaces in the context of smart homes, focusing on haptic operations. Building on previous studies on single textile controls, we expanded our required textile controls by testing material design icons, alternative versions, and a round and rectangular textile trackpad in the first study. This was necessary because, especially in the context of smart homes, the applications require many different control elements for operation. Based on this and existing visual, non-textile haptic, and textile haptic guidelines, we created four larger textile interfaces that reflect the metaphor *room*, modularity (*dense*), *universal* control and together with an extension of the modular variant (*sparse*). These interfaces were then examined in the second study in a virtual smart home setup. First without visual feedback, then with visual feedback, and finally utilizing tasks. Here, *user preferences*, *interface recognition* and *task performance* were measured.

# Überblick

In dieser Arbeit haben wir untersucht, wie Nutzer mit größeren textilen Schnittstellen im Kontext von Smart Homes interagieren, wobei wir uns auf haptische Bedienelemente konzentrierten. Aufbauend auf früheren Studien zu einzelnen textilen Bedienelementen haben wir die benötigten textilen Bedienelemente erweitert, indem wir in der ersten Studie Materialdesign-Icons, alternative Versionen sowie ein rundes und rechteckiges textiles Trackpad getestet haben. Dies war notwendig, da gerade im Kontext von Smart Homes die Anwendungen viele verschiedene Bedienelemente zur Bedienung benötigen. Basierend auf diesen und bestehenden visuellen, nicht-textilen haptischen und textilen haptischen Richtlinien wurden vier größere textile Interfaces erstellt, die die Metapher *room*, Modularität (*dense*), *universal* control und zusammen mit einer Erweiterung der modularen Variante (*sparse*) widerspiegeln. Diese Schnittstellen wurden dann in der zweiten Studie in einem virtuellen Smart-Home-Setup untersucht. Zunächst ohne visuelles Feedback, dann mit visuellem Feedback und schließlich unter Verwendung von Aufgaben. Hier wurden *Benutzerpräferenzen*, *Schnittstellenerkennung* und *Aufgabenleistung* gemessen.

# Acknowledgments

First, I would like to thank Prof. Dr. Borchers and Prof. Dr. Steimle for examining my thesis.

In addition, I would like to thank my supervisor, Oliver Nowak, who has always helped me gain new insights and progress in my work.

Finally, I would like to thank my family, friends, and especially my girlfriend for their support during my thesis, which has helped me a lot, especially during stressful times.

# Conventions

Throughout this thesis we use the following conventions:

The names of the four larger textile interfaces produced for the main study are shown in italics.

The whole thesis is written in American English. The first person is written in the plural form.

# Chapter 1

# Introduction

Smart home devices are typically controlled using a touchscreen on the wall, a plastic remote, a smartphone, or a voice assistant. Touch screens on the wall and on-device controls are often beyond the reach of users. A plastic remote can counteract the reachability problem, but if it is misplaced, this leads to the same problem. Smartphones offer an alternative, as they are typically located close to users and allow multiple devices to be controlled simultaneously. However, as it should also be possible for visitors to control the smart home devices and people may have problems giving their smartphones to others, this limits the control to the people with access to the smartphone. Voice assistants counteract these challenges but have no graphical user interface. Users need to know which commands can be used to control which devices. Even if a user has learned this, it excludes people outside the household from using it. In addition, users have privacy concerns and perceive interaction with voice assistants as socially awkward, especially in a social context, as described by Ammari et al.

Smart home devices can be controlled through various methods, each presenting their own challenges.

Textile user interfaces, which are usually realized by embedding sensors, conductive yarn, or other electronic components in textiles [Varga and Tröster, 2014; Aigner et al., 2020; Wang et al., 2023] can counteract the problems mentioned above. Since wearable and non-wearable textiles are very present in the home, integrating textile

Textile user interfaces integrate sensors into fabrics, enhancing household items with intuitive and aesthetically pleasing controls.

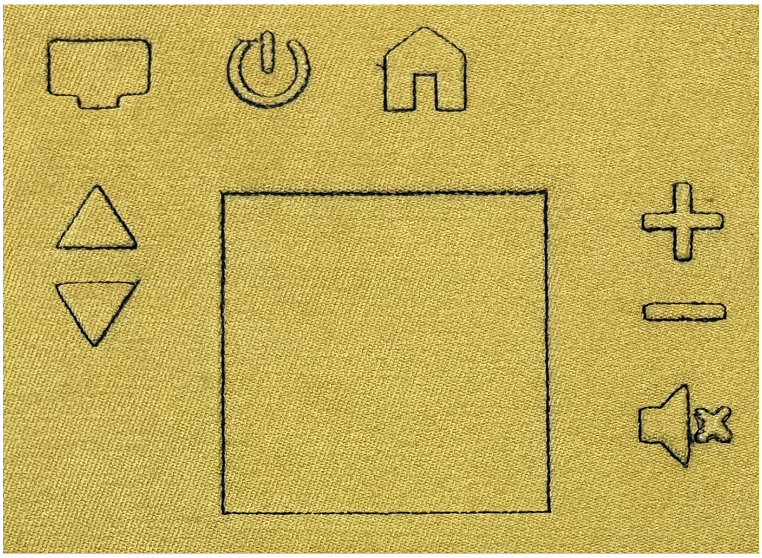


**Figure 1.1:** Example textile interface: This textile interface controls a smart TV within a smart home environment, incorporating touch-sensitive areas designated for mouse movement, home, channel switching, volume adjustment, and power functions.

interfaces into fabric surfaces can control smart home devices where they are needed. For example, integrating textile interfaces in sofa armrests, table runners, curtains, or cushions would support the adaptation of the look and feel of various devices. In addition, the visual aspect of textile interfaces, illustrated as an example in Figure 1.1, makes it possible to make them understandable and usable for new users without prior knowledge.

Haptic properties are an important component of textile interfaces that allow eyes-free interaction. In addition to visual discoverability, there is also haptic discoverability.

The literature on textile interfaces focuses mainly on design and manufacturing principles for individual control elements.

Therefore, textile interfaces show potential for the control of smart home devices. Since there is usually more than just one device to be operated in the set context, the textile interfaces should be designed accordingly. While previous research has primarily focused on crafting techniques [Varga and Tröster, 2014; Aigner et al., 2020], textile affordances [Mlakar et al., 2021], and individual textile controls such as sliders [Nowak et al., 2022], icons [Schäfer et al., 2023], buttons [Goudswaard et al., 2020], and other textile-specific control elements [Zeagler et al., 2012], as far as we know, there remains a research gap in understanding how users interact with larger textile interfaces. Although there are known guidelines on interfaces in general, these are largely designed for the visual operation of interfaces, such as the gestalt principles [Koffka, 1935].

Our work explores potential issues in operating smart home textile interfaces.

Therefore, we investigate in this work whether problems occur when operating larger textile interfaces in the context of smart homes that use existing visual and single textile control guidelines, and the resulting controls are placed in a limited area. For this purpose, we built four larger textile interfaces designed based on the known guidelines. In the main study, we investigated how users understand the interfaces without prior knowledge and using eyes-free interaction, once without and once with feedback. In addition, we investigated how well users can perform atomic tasks in the context of the interfaces when they have been fully explained to understand how users interact with known textile interfaces eyes-free.

Smart homes show potential for reality-based studies with textile interfaces, particularly for common applications like temperature, light, TV, and blind control.

We will look at the operation of larger textile interfaces in the context of smart homes because a study of the user requirements of textile input devices by Hildebrandt et al. [2015] found that users would prefer textile interfaces in this context, especially in the living room. In this context, we specifically look at the applications of temperature control, light control, TV control, and blind control, as these are typical smart home applications. Since not all the required textile elements, such as icons, buttons, and trackpads, have been investigated specifically for these applications, we have carried out a first study to investigate the textile elements required for the applications so that they can be used. Google Material Design icons were used and compared with simpler versions of the icons themselves for recognizability, user preferences, visual recognizability, and recognition time.

## 1.1 Outline

In the following section, we describe related work in chapter 2. There, we deal with the basics of visual design guidelines for interfaces and describe the existing work on textile interfaces and their components, which includes crafting techniques, non-textile haptic exploration, textile haptic exploration, and existing larger textile interfaces.

In chapter 3, 'Study 1: Investigating Icon Shapes for Larger Textile Interfaces' we describe the preliminary study, in which we examined the textile icon samples created for recognition rate as well as the subjective preference of the participants.

In chapter 4, 'Design Decisions for Larger Textile Interfaces' we describe the designs of the larger textile interfaces we produce.

In chapter 5, 'A Fabrication Process for Larger Textile Interfaces', we deal with the fabrication process of the larger textile interfaces for the main study. Here, we describe step by step the design guidelines we used to design and how to fabricate a larger, functional textile interface using laser cutter, 3D printing, embroidery, and capacitance sensors.

In chapter 6, 'Study 2: Investigating User Behaviour When Interacting with Larger Textile Interfaces', we then describe our user study, which we conducted to find out whether problems can occur in the operation of larger textile interfaces in the context of smart homes if the interfaces are only designed based on the already known visual design guidelines and single textile control guidelines.

We conclude this work by summarizing the results and proposing future research regarding possible textile interface guidelines in chapter 7, 'Summary and Future Work'.

# Chapter 2

# Related Work

Although research into textile interfaces is still in its early stages [Dakova and Dumont], it has developed significantly from using smart materials for health monitoring [Jayaraman et al., 1997] to more complex interactive interfaces, such as the 'Musical Jacket' [Post et al., 2000]. Smart textiles are "a set of sensors, actuators, and processing elements embedded in or attached to a fabric backplane which routes data and power throughout the textile" [Nakad et al., 2007]. When e-textiles, a sub-set of smart textiles, enable input and/or output functionalities to interact directly with the fabric surface, they are called textile interfaces [Dakova and Dumont].
The related work is divided into different sections. First, we present existing visual design guidelines, such as from Norman. Then, we look at existing crafting techniques for textile interfaces. Next, we analyze research that examines haptics in a non-textile context and then in a textile context. Finally, we look at research that already includes larger textile interfaces but does not investigate the specific research question we have for this thesis. We have taken all the guidelines mentioned into account in our prototypes.

## 2.1 Visual Design Guidelines

Norman describes fundamental principles for designing user-friendly interfaces in the book 'The Design of Everyday Things'.

Norman's design principles, such as visibility, feedback, mapping, consistency, discoverability, and the concept model, are central to user-friendly interfaces.

Visibility is such a principle. According to Norman, visibility means that all important functions of a system should be easily recognizable and accessible to the user. The design of an interface should signal the possible actions to the user. In our textile interface designs, we transfer this concept haptically to signal the meaning and functions of certain interface elements to users.

Another principle is feedback. According to Norman, a system should give immediate feedback on the result of its actions. This helps users to understand better whether their action was successful or not. In our work, we also want to understand how important feedback is for haptic interaction, especially for larger textile interfaces, which is why we are also investigating this in our second study.

Mapping means how controls are placed on the interface about the devices to be operated with them. Good mapping is important to give users an intuitive understanding of the interface. In our work, we specifically use spatial mapping based on one of our larger textile interfaces.

Another important principle is consistency. According to Norman, the same actions and functions should be presented and executed in the same way in a system. We also use this principle in our designs.

The discoverability principle describes how easy it is for users to discover the system functions. Norman emphasizes that clear labels, understandable navigation, and intuitive design are important for this, which we have also considered in our designs.

Finally, Norman describes the principle of the conceptual model as the mental representation of the system formed by a user. In our designs, we have made the operation of the interfaces as simple and intuitive as possible so that users can form a clear and helpful mental model.

In addition to Norman's design principles, the '8 Golden Rules of Interface Design' by Shneiderman and Plaisant are important for designing user-friendly interfaces. Shneiderman and Plaisant offers further aspects that should be considered.

Consistency is also mentioned by Shneiderman and Plaisant. The author argues that consistent design elements allow users to use previous interactions' experiences effectively, improving the learning curve and error rate.
Shneiderman and Plaisant also sees feedback as important for user interaction. While Norman suggests immediate feedback, Shneiderman and Plaisant goes one step further and considers immediate and informative feedback important.
Another principle is to reduce the short-term memory load. Shneiderman and Plaisant emphasizes that it is important not to overwhelm the user with information, which we have paid attention to in our designs and study design.
Finally, Shneiderman and Plaisant emphasizes the importance of meaningful help, which stresses the need for easily accessible and contextualized support.

Shneiderman and Plaisant's principles, including consistency, feedback, memory load reduction, and meaningful help, complement Norman's approach and are key in designing our textile interfaces.

Another design guideline is the Gestalt Laws of Perception, originally developed by Gestalt psychologists such as Kurt Koffka and Ellis [Koffka, 1935; Ellis, 1997]. These laws describe how users organize and interpret visual information, which we integrated into our larger textile interfaces.
The Law of Proximity states that elements close to each other are perceived as belonging. This principle is used in interface designs to visually group related functions or information.
The Law of Similarity states that elements similar in appearance, shape, color, or texture are perceived as belonging together.
The Law of the Common Region describes the item perceived as belonging together within a boundary.

The Gestalt laws, such as proximity, similarity, and common region, help determine the perceived grouping of elements in interface design.

The visual design guidelines described in this subchapter provide a basis for our larger textile interfaces. However, as these guidelines are visual and our interfaces focus on haptics, we use additional non-textile haptic and single textile control guidelines.
In the following chapter, we will examine which smart textile construction methods exist, what specific challenges and opportunities are for haptic perception, which single

**Figure 2.1:** Second proof of concept by Goveia da Rocha et al.: Conductive traces were embroidered onto cotton fabric to securely position and solder the FSR sensors. The cotton fabric was then integrated into an off-the-shelf hallux sock.

textile control guidelines we can incorporate into our work, and which larger textile interfaces already exist.

## 2.2 Textile Interfaces

### 2.2.1 Crafting Techniques

There are various techniques for producing smart textiles, all of which have advantages and disadvantages. Our requirements for building our larger textile interfaces were scalability and customizability. Our choice of fabrication techniques was based on this.

We use digital machine embroidery as part of the production process for our textile interfaces.

Goveia da Rocha et al. investigated digital machine embroidery to produce smart textiles. This manufacturing method makes it possible to embroider precise designs on textiles and also integrate electronics directly (Figure 2.1). We have therefore decided to use digital machine embroidery, even if we do not integrate electronics directly into the textile.

Varga and Tröster presents a method to integrate electronics seamlessly into textiles. This technique allows

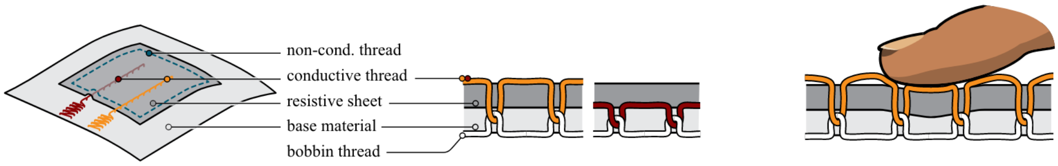



**Figure 2.2:** Concept of embroidered resistive pressure sensors by Aigner et al.: The basic components of the embroidered pressure sensor are shown on the left, with the bobbin thread securing the conductive yarn. On the right, it illustrates how the degree of contact and compression between the yarn and resistive material influences the change in resistance.

electronic components to be placed between two textile layers, creating a flexible and modular structure. We found the seamless integration approach interesting and have adopted it for our interfaces by placing electronics in textiles.

Aigner et al. developed a method to use resistive pressure sensors via embroidery by embedding conductive threads in textiles to measure pressure changes. The technique, illustrated in Figure 2.2, makes it possible to integrate sensors directly into the textile, which is sensitive to physical pressure. However, we decided against resistive pressure sensors for our larger textile interfaces. The main reason for this is the modularity of our process, where the electronics integration is done separately from the production of the embroidered surface to reduce complexity.

The elemental idea of integrating sensor technology into textile interfaces was used in our process.

Poupyrev et al. have integrated capacitive sensors into textiles using capacitive threads. The method allows precise recognition of touch and proximity. We adopted the idea but decided against using conductive yarn, as this would violate the separation of the production of the textile surface and the integration of electronics.

We use capacitive sensors in our larger textile interfaces.

Schäfer et al. combined machine embroidery, capacitance sensors, and laser cutting to produce single textile controls. We have adopted this approach to produce larger textile interfaces, as it ensures high precision and scalability.

### 2.2.2 Non-Textile Haptic Exploration

Developing haptic interfaces requires special design principles, as conventional approaches are often insufficient to ensure intuitive operation.

Since we develop textile interfaces focusing on haptic operation, a fundamental understanding of haptic recognition and differentiation from non-textile materials is important. In order to design textile interfaces so that they can be operated intuitively by touch, it is essential to understand the mechanisms of haptic perception. This chapter reviews studies on haptic perception outside textile material contexts to gain insights for designing our larger textile interfaces. It focuses on understanding shapes, textures, and haptic recognition limits to inform design principles for creating distinguishable haptic interfaces.
Challis and Edwards researched the complexity of creating haptic interfaces. The authors argue that haptic interfaces cannot be used simply by applying design principles for graphical user interfaces (GUIs). Instead, haptic interfaces require specific design principles for haptic perception. This shows the complexity and challenges related to the development of haptic interfaces. Since, according to the authors, no widely acknowledged standards for haptic interaction are directly applicable, the design should be approached systematically. In our work, we have adopted this approach and ensured in the first study that our selected designs function haptically.

The study from Cecchetto and Lawson extends our understanding of the challenges of creating haptic interfaces. The authors explore the complexity of identifying raised line drawings by touch and investigate whether additional aids can improve recognition. The specific line drawings examined in the study are illustrated in Figure 2.3. It was found that even well-designed haptic interfaces sometimes require additional help. This supports our assumption that only traditional design approaches are insufficient for haptic interfaces. We must also consider how users interact with haptic elements and what help is needed.

Haptic perception can be an effective object recognition method.

In addition to the challenges of haptic perception, however, this also shows potential, as described by Klatzky et al. Their study examines how effectively objects can be

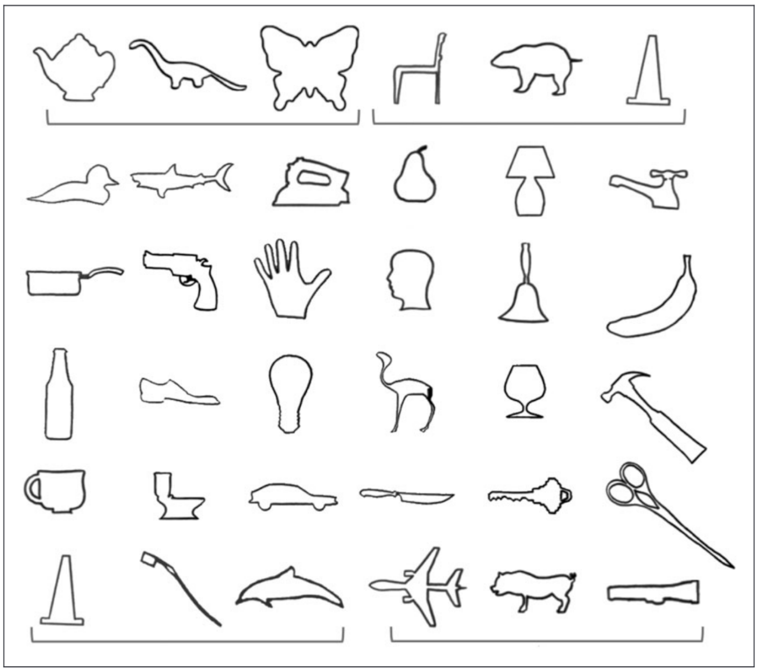


**Figure 2.3:** Tactile line drawings: Depict the outlines of familiar objects, which where utilized in the study by Cecchetto and Lawson.

perceived haptically. The authors found that people can process information about objects quickly and accurately by touch. The participants correctly identified familiar objects with a high percentage of cases. These results show that haptic perception can be an effective system for object recognition if the haptic interface elements are clearly and distinctively defined.

Challis and Edwards also mentioned that haptic interfaces require special design principles designed for haptic interaction. The authors identified seven principles that are relevant for developing haptic interfaces. For example, haptic and visual representations should be designed consistently, and haptic elements should convey the same information as their visual counterparts. Another principle is that height differences can be used as a filtering mechanism to signal important information or draw the user's attention to it. In addition, white space should be minimized, as this does not convey useful information and

Haptic interfaces require clear, consistent designs, utilizing height differences and simple shapes.

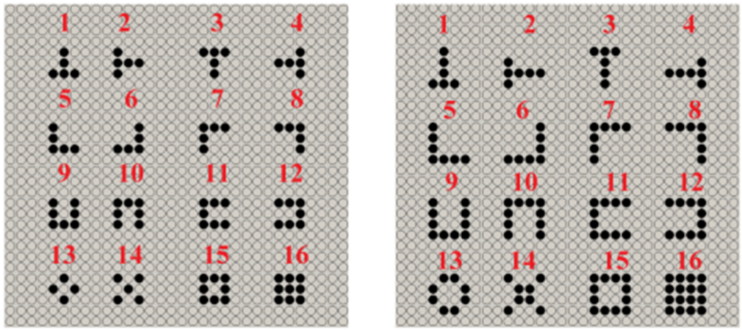


**Figure 2.4:** Pin array displays by Leo et al.: Tactile symbols on a 3x3 (left) and 4x4 (right) pin array display were investigated.

could hurt the user experience. Finally, haptic elements should be designed to be simple, as complex shapes are more difficult to recognize and distinguish.

Leo et al. also showed that simple shapes significantly increased the haptic recognition of symbols. The study found that users could identify simple, well-defined symbols on a small pin array display (Figure 2.4) faster and more accurately.

Shape, size, and texture play an important role in haptic recognition.

However, in addition to the shape, the size and texture of the icons also play a role in haptic recognition, as the study by Kalantari et al. shows. The authors investigated the perception of tactile elements on haptic tablets and found that haptic interface elements should have a certain minimum size to be reliably recognized. They also found that certain shapes and textures should be preferred. These results show the importance of paying attention to parameters such as size, texture, and shape when designing haptic elements and examining these more closely before they are used in haptic interfaces.

### 2.2.3 Textile Haptic Exploration

Now, we will focus on researching haptic interactions in the context of textile interfaces, specifically examining the hap-

**Figure 2.5:** Wearable textile interface example: Textile interface integrated into gloves by Holleis et al. Configurable buttons are positioned on the left palm, while the right index finger is used to initiate commands.

tic perception and operation of single textile controls. We aim to identify existing single textile control guidelines and incorporate them into our designs.

Fast and reliable recognition of controls and immediate feedback is critical to the success of wearable capacitive touch input on clothing.

Holleis et al. investigated the usability and applicability of capacitive touch input on clothing such as gloves, illustrated in Figure 2.5. In their study, they developed a platform for integrating capacitive sensors in various garments and accessories and conducted two studies. The results showed that fast and reliable identification of the control elements is important for the success of wearable controls. In particular, it was mentioned that immediate feedback is important and that there should be no delays between users action and result, as this can lead to frustration and incorrect operation.

More research, specifically focusing on textile interfaces, was conducted by Mlakar and Haller, providing detailed

**Figure 2.6:** Textile Prototypes: Mlakar and Haller used an embroidery machine to create a variety of different non-functional textile prototypes.

For textile interfaces, haptic elements should have clear texture, height, and shape contrasts, be at least 6.5 mm in size, and use simple shapes.

insight into haptic elements' design. The authors investigated the perception and recognition of interactive elements on non-wearable textile surfaces, illustrated as an example in Figure 2.6. A comprehensive design study was conducted using expert interviews and user studies to identify best practices for designing such interfaces. From this, five key design recommendations were defined. For better recognizability, there must be a tactile contrast between textures, heights, and shapes. It is also recommended that haptic elements be at least 6.5 mm, with an optimum size of 13 mm. Additionally, concave and convex shapes are perceived as interactive elements, which allows them to be used in different application contexts. Finally, it is shown that an element's shape should indicate the intended interaction and that all shapes should be designed to be as simple as possible.

Ergonomic design, visual cues, texture perception, direction of movement, and sparing use of design elements are crucial for the design of haptic textile interfaces.

Based on the results of Mlakar and Haller, Mlakar et al. provide further important insights for designing and using surface gestures of textile interfaces. This research expands the design space by exploring the affordances of surface gestures and creating and analyzing textile prototypes with different haptic features. The authors have created a collection of textile samples, illustrated in Figure 2.7, which test different designs, manufacturing, and sensing

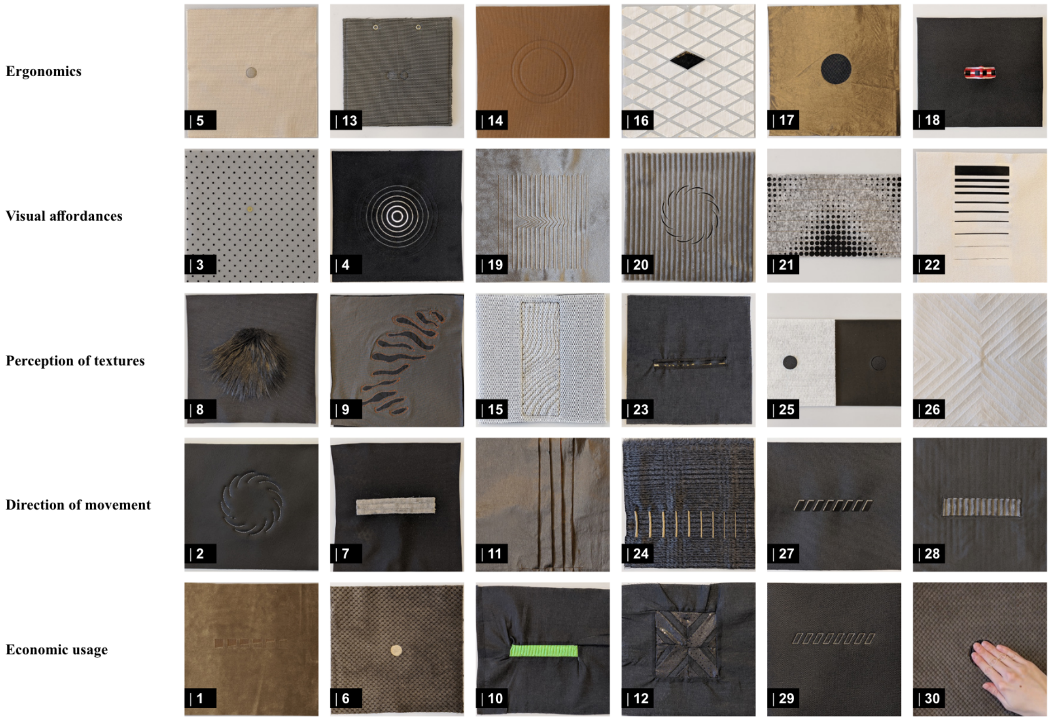



**Figure 2.7:** Textile samples investigated by Mlakar et al.: Covering different categories of insights.

approaches. It was found that ergonomic design, visual affordances, perception of textures, direction of movement, and economic use of design elements are important for designing haptic textile interfaces.

In addition, studies have also been carried out on single textile control guidelines, such as by Schäfer et al.. This study found specific design guidelines for textile icons. The authors examined a total of 84 different textile icon combinations (Figure 2.8), which differed in shape, *height profile* (raised, recessed, flat), and *affected area* (filled or bordered). The study investigated how well these are recognized haptically with the eyes-free operation and found that participants prefer raised filled icons. However, it was also found that recessed icons generally perform well, especially recessed filled ones. This allows us to use both fabrication methods for our designs to get a tactile difference in height.

Raised filled icons are preferred haptically, while recessed filled icons are also well recognized, which enables different production methods for a distinguishable height profile.


**Figure 2.8:** Investigated icon shapes by Schäfer et al.: These were investigated in six different fabrication variants per shape.

Recessed designs are preferred for textile sliders as they provide clear finger guidance and improve accuracy, while sliders with at least three markings aid orientation.

In addition to the research on textile icons, textile sliders were also examined, and design guidelines were created for them [Nowak et al.]. The focus here was on form factors and haptic features that are relevant for textile sliders. The study examined shapes and surface profiles, including raised, recessed, and flat designs. The results show that recessed sliders are well recognized and offer clear finger guidance, which improves operation accuracy. In addition to the form factor, the optimal number of tick marks on the slider was also investigated. It was found that sliders with at least three tick marks were preferred as they improved orientation.

An optimum size of 80 mm x 80 mm was determined for wearable textile trackpads.

As we also want to use trackpads for our interface designs, the research by Heller et al. is relevant for us. The authors investigated the optimal size of textile trackpads on wearable surfaces. Heller et al. presented a textile-based trackpad and analyzed its effectiveness in several applications. The preliminary study, particularly interesting to us, found that 80 mm x 80 mm is optimal for wearable textile trackpads. We adopted this size and also designed the trackpads like the sliders from Nowak et al. to improve the tactile contrast.

Raised embroidery can be a tactile aid on textile interfaces by guiding the finger to the correct position.

Finally, research exists into textile aids that support the operation of interfaces. Gilliland et al. investigated the possibility of creating graphical user interface-like widgets on textiles using conductive embroidery. It was found that raised embroidery can be used as a tactile aid. These

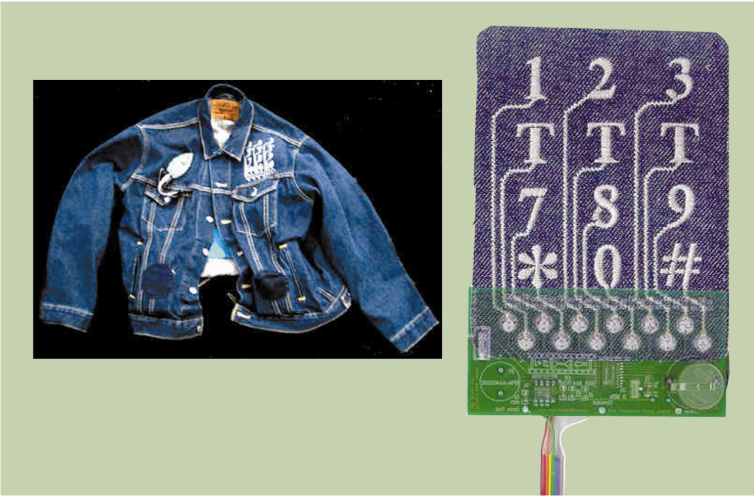


**Figure 2.9:** Musical Jacket: Example for a larger textile interface. Image adopted by Post et al.

raised embroideries guide the user's finger to the correct position of the operation, even without visual assistance. The authors emphasize that textile widgets that use these aids have an advantage, especially for operations in mobile or dynamic situations, such as wearable textile interfaces.

### 2.2.4 Larger Textile Interfaces

This subchapter presents an overview of existing research on developing larger textile interfaces.

Orth et al. investigated the production of textile sensors and how they are used as larger input devices. The authors focused on the technical challenges of integrating electronics into textiles and the flexibility of such interfaces for a wide range of applications. Figure 2.9 illustrates the 'Musical Jacket', an early example of an interactive textile interface with multiple controls. The investigations showed that the combination of electronics and textiles is promising, but the technical hurdles must be considered, especially robustness and durability.

The integration of electronics in textiles offers promising possibilities for interactive interfaces but requires special attention in terms of robustness and durability.

Post et al. work is based on the work of Orth et al. and deepens the investigation of the 'Musical Jacket'

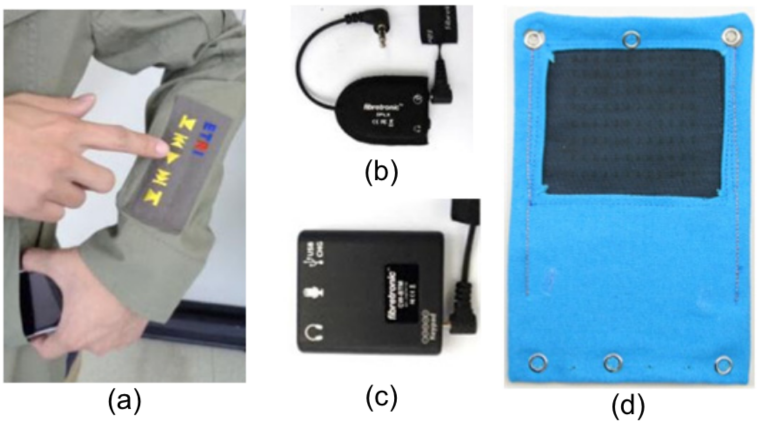



**Figure 2.10:** iPod Jacket: Example for a larger textile interface by Kim et al.. The iPod jacket (a) with embedded controller modules: iPod controller (b), Bluetooth controller (c), and Drop-n-Play pocket (d).

'E-Embroidery' enables the seamless integration of conductive yarns into textiles, creating aesthetically pleasing and functional interactive garments.

and other textile-based computer systems. The authors focused on developing and applying conductive yarns that can be integrated into textiles using embroidery. 'E-Embroidery' thus enables the production of larger interactive textiles. The aesthetic integration of electronics into textiles was examined in detail to produce wearable and functional garments that are visually appealing and interactive.

Textile control elements can effectively serve as an extension of mobile devices.

Kim et al. investigated the integration of mobile devices with electronic textiles. They aimed to create interaction between mobile devices and textile interfaces by using spatial data to create a seamless and intuitive user experience. Figure 2.10 illustrates the 'iPod Jacket', which allows users to control their iPod using textile controls on the sleeve. It was found that textile controls can function effectively as an extension of mobile devices. However, the focus here was mainly on the technical implementation.

Kazemitabaar et al. focused their work on the design of interactive, wearable technologies specifically developed for children. The authors investigated how modular and customizable textile-based interfaces can be designed to encourage children to be creative with technology.


**Figure 2.11:** Exmaple larger textile interface: Interactive environment on a table designed with Project Jacquard's textile interface by Poupyrev et al.

Again, however, the focus is more on technical feasibility and modularity rather than a detailed analysis of user interaction with larger textile interfaces.

'Project Jacquard' develops a method for large-scale, interactive textiles with conductive yarn.

In the work 'Project Jacquard', Poupyrev et al. have created a platform for producing interactive digital textiles on a large scale. The authors have investigated the development of conductive yarns integrated into textiles to transform everyday fabrics into interactive surfaces. One example is illustrated in Figure 2.11, which shows a textile interface that can be seamlessly integrated into clothing or furniture. However, the work focuses on industrial scalability and the aesthetic integration of electronics into textiles, not the user experience.

Although the works above are important contributions to the development and technical implementation of larger textile interfaces, their focus was mainly on production and technical challenges. These have not given us more understanding of how users operate with larger textile interfaces, especially in an eyes-free interaction. With our work, we want to fill this gap by using visual design guidelines, non-textile haptic guidelines, and textile haptic guidelines to build larger textile interfaces and investigate them through a user study.

# Chapter 3

# Study 1: Investigating Icon Shapes for Larger Textile Interfaces

For our main study, which is described in chapter 6, we need various textile control elements for our larger textile interfaces, such as textile icons, sliders and trackpads. Although Schäfer et al. has already investigated some textile icon shapes, we are still missing some for our icon set. We have selected Google Material Design icons[1] for this, as these are widely used and visually consistent. In addition, we have created alternative or simplified versions based on the suggestion by Challis and Edwards. Furthermore, research exists on wearable textile trackpads [Heller et al.]. However, there is a lack of research, as we know, on how the shape of a textile trackpad affects haptic recognition and user interaction and which shape is associated with possible functionality.

The study examines textile icons and trackpads, focusing on haptic perception and user interaction.

In our study, we explore which visual icons are suitable as textile icons, focusing on haptics. Furthermore, we fabricated two textile trackpad shapes for color selection and menu selection (round and rectangular) to investigate how users perceive the shape of a trackpad and how this influences the associated functionality with the trackpad.

[1] https://fonts.google.com/icons (access September 2024)

## 3.1 Experimental Design

In two experiments, the user study examines various textile icon shapes and round and rectangular textile trackpads.

The user study is divided into two sub-experiments. In the first experiment, we examine different textile icon shapes and their alternative versions, and in the second experiment, we examine a round and rectangular textile trackpad shape. First, participants are asked to complete the task for each *icon design*. An icon design was divided into *icon categories* (material design, alternatives).
In addition, in the second experiment, users were asked to explore either a round or a rectangular textile trackpad (*trackpad shape*) eyes-free.
In both experiments, the users could use their preferred hand when performing the task and exploring the trackpads.

### 3.1.1 Selection of Textile Icons and Trackpads

For the main study, 39 icons for smart home applications were examined, whereby raised and recessed icons were tested.

For our main study, we first selected the smart home applications 'TV Control', 'Light Control', 'Blinds Control', 'Temperature Control', and 'Robot Vacuum Cleaner Control'. We selected 13 suitable icon designs and designed alternative versions based on them, resulting in 39 icons to investigate. Since we want to use raised and recessed icons, we designed raised filled icons functionally as buttons and recessed filled icons as signifiers. Some icons look like raised outline icons but only consist of outlines, making them raised filled icons. We have also ensured that each icon has at least a 2 mm feelable area. In addition, we tested two icons consisting of several components with an additional border to explore the haptic recognition of bordered icons. In the following section, we explain all design decisions for each selected icon in detail.

*Toggle* The raised icon toggles applications on and off, with both icons sized at an 18 mm diameter. In the alternative design, the circle is closed with the middle line extended 2 mm upwards to preserve the haptic feature.

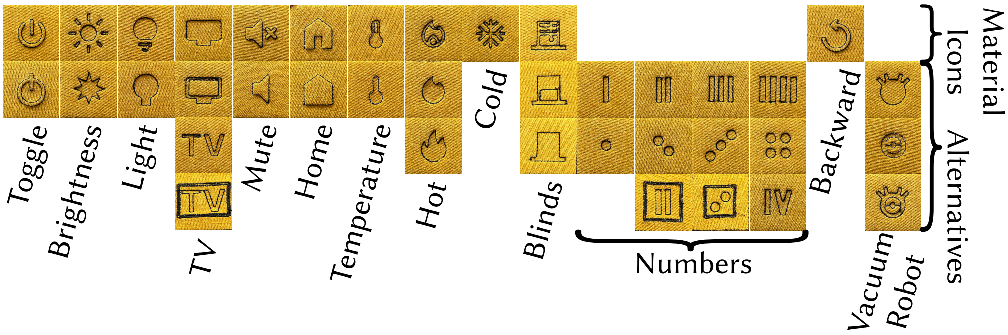



**Figure 3.1:** 39 raised and recessed icons, which were felt haptically in study 1, combined from material icons and alternative variants. Two icons, consisting of several components, are additionally provided with a frame.

*Brightness* The recessed icon signals a nearby control that dims the lights. The material icon has a diameter of 28 mm to ensure the sun's rays are large enough to feel, with an inner circle of 13 mm. The alternative icon includes spikes, making its total size 18 mm. We used spikes over sunbeams for their clear, sharp edges, which could be easier to distinguish haptically.

*Light* Recessed icon that can indicate a light application with an upper circle diameter of 18 mm. The material icon includes slightly widened lower details, extending 1 mm below, with dimensions of 18 mm in width and 24 mm in height. The alternative icon measures 18 mm in width and 22 mm in height. For that, we eliminated the lower semi-circle and integrated the circle with the lower details.

*TV* The recessed icon can signal a TV application with a height of 18 mm and a width of 25 mm. The TV stand has been enlarged in the material, and the first alternative is to make this haptic feature more present. The first alternative also has a flat-screen in the middle. The second alternative spells out 'TV' to investigate the effect of pictorial versus text-based icons in terms of haptic recognition. The third alternative is the same as the second but with an additional border.

*Mute* The raised icon can mute or unmute the volume. The height of both icons is 18 mm. The material icon is

22 mm wide, and the alternative is 12 mm wide. The cross was omitted from the alternative icon to create a simplified shape without additional features.

*Home* The home raised icon could be used to access the main menu of the TV application. The size of both icons is based on the icon's square (without the roof) and is 18 mm x 18 mm. The door has been made slightly wider in the material icon to reinforce this haptic feature. The door has been removed, and the alternative has to create a simplified shape with no additional features.

*Temperature* The recessed icon can signal thermostat control nearby on the interface. Both variants are 20 mm high and 10 mm wide. This is necessary because otherwise, the upper area would not have a 2 mm tactile area. The temperature lines have also been removed from the material icon, as they are too small to feel, and the icon would otherwise be too large. For the alternative icon, we have only used the contours of the material icon to create a simplified form without additional features.

*Hot* This recessed icon represents heat and could be used, for example, in a temperature application. The material icon is 20 mm high and 16.8 mm wide, so the contours around the inner features still cover at least a 2 mm tactile area. The first alternative is the same size as the material one, except that we have removed the internal features to create a simplified shape with no additional features. The second alternative icon size is based on the main body of the flame, which is 18 mm wide and with the flames 22.2 mm high. We chose the second alternative design because the clear, three-pointed shape could provide strong tactile recognition.

*Cold* The recessed icon represents cold and could be used in a temperature application. Here, we only have the material icon, as we cannot find an additional visual metaphor for cold. The icon is 20 mm in size, so the lines still have a perceptible area of 2 mm.

*Blinds* A recessed icon that can signal blind control features three 20 mm high icons with a 2 mm tactile area inside. The window sill of the icons is enhanced for easier haptic identification. We explored two design alternatives for better recognition: the first abstracts the material icon into a surface, and the second simplifies the icon to its shape alone, removing internal features for clarity.

*Numbers* The numbers can be used to enumerate something, such as a lamp selection. We distinguish between lines and dots. The lines are 18 mm high and 4 mm wide. For 'Number 4 Line', we also used the Roman notation 'IV'. The dice dots measure 7.4 mm in diameter. We have also created a bordered version for 'Line 2' and 'Dice 2'.

*Forward/Backward* Next to the skip backwards raised icon, we designed a mirrored variant for skipping forward. Both icons are 18 mm x 18 mm in size. Here, we have not created simpler versions, as the original design already has a very simple shape with no features that can be omitted.

*Vaccuum Robot* We designed three icon options for a robot vacuum cleaner application due to the absence of a suitable Google Material Icon. The icons differ in features: the first shows bristles, the second internal details, and the third combines both.

We designed the trackpad shapes to be recessed based on the sliders from Nowak et al. with a height difference of 1.6 mm. We also made the two trackpads 80 mm x 80 mm in size based on the size recommendation by Heller et al.

### 3.1.2 Production of Textile Icons and Trackpads

We produced the textile icons and trackpads based on the fabrication method of Schäfer et al. Instead of MDF sheets, we used 3D printing with PLA filament. Raised icons were placed 1.6 mm higher, and recessed icons were placed 1.6 mm lower on the plate. The plate on which each icon is placed is 40 mmx40 mm, with the icons centered. The trackpads were made the same as recessed icons, only scaled larger.

## 3.2 Participants

14 persons (male: 9, female: 4, n/a: 1) with an average age of 24.6 years (SD = 2.03 years) participated. One participant was left-handed. The others were right-handed. 13 participants were STEM students (computer science: 12, chemistry: 1), and one was a software developer.

## 3.3 Apparatus

For the study, we used the textile icons and trackpads mentioned above. Using a 40 mm x 40 mm 3D printed plate consisting of conductive filament and a frame made of MDF, we built a holder where each icon could be placed without wobbling. We soldered a cable into the conductive filament to measure the capacitance using an MPR121 capacitive sensor [1]. The sensor was read out using an Arduino Uno[2], which allowed us to determine how long a participant touched an icon. In addition, an iPad Pro 12.9″ was used to name the icons visually and to fill out the digital questionnaires between rounds.

### 3.3.1 Study Setup

The study setup allowed participants to explore icons and trackpads eyes-free, with visual protection and markings ensuring uniform positioning.

The study setup is illustrated in Figure 3.2. The participants sat at the table in front of a sight-protection screen. The holder for the textile icons was behind the sight-protection screen, and the holder for the trackpads was to

[1] https://www.berrybase.de/mpr121-kapazitiver-touch-sensor-controller-mit-breakout-board (acces: August 2024)

[2] https://store.arduino.cc/en-de/products/arduino-uno (acces: August 2024)

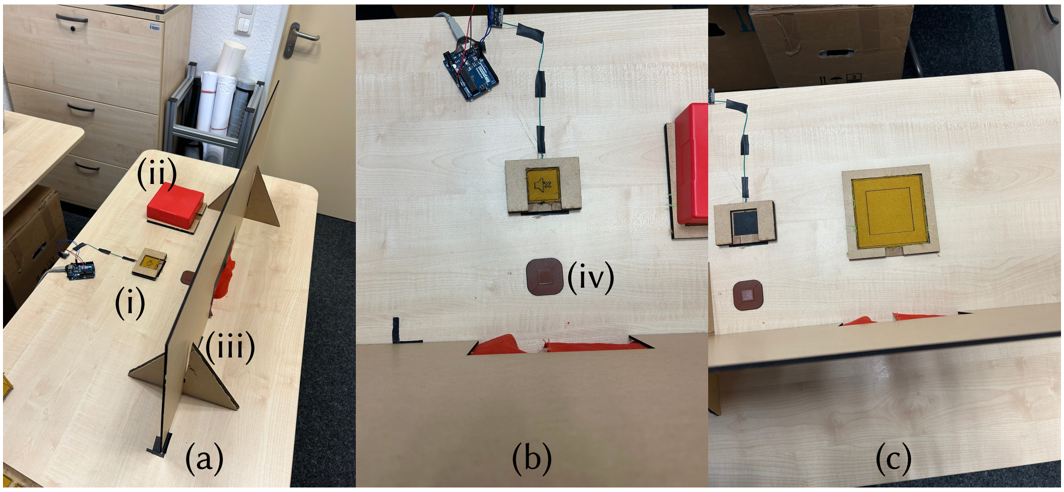



**Figure 3.2:** Study setup of the first study from different perspectives: Presents the setup from the side (a), from above for the icon recognition phase (b), and from above for the trackpad recognition phase (c). Also, in each image is shown the sensorplate for the icons (i), the mount for the trackpads (ii), the sight protection wall with curtain (iii), and the homing position (iv) for the icon recognition phase.

the right. A hole in the sight-protection screen was covered by a curtain so that participants could stretch their hands through but could not see through it. A homing position is in front of the icon holder, which ensures that users have an area where they can return after feeling an icon, and they do not touch icons too early. The trackpad holder was covered with plastic as the icons were to be felt first. Once the participant had reviewed all the icons, the sight protection wall was moved to the right so that the free area on the wall was at the same height as the trackpad holder. Markings on the table were used to ensure the sight protection wall was in the same position for all participants.

## 3.4 Task

The task was divided into three phases: visual identification of the icons, haptic recognition of the icons trackpad experiment.

The task of the study was to identify the textile icons haptically and to explore the textile trackpads. The haptic recognition of the icons was divided into three parts. First, the users were randomly shown all the icons on an iPad screen and asked to name them visually to see how users recognize them visually. In the second part, users were asked to place their hands on the homing position and then to feel each icon haptically. As soon as an icon has been recognized, the participants should move their hand back to the homing position and name the icon. This was then repeated for all icons in random order. In the trackpad phase, the conductor asked the participant to feel and interact with the rectangular or round trackpad (without calling it a trackpad). The following three questions were asked one by one to understand how the participants understood the textile trackpad and which additional aids were needed:

1. "You are about to receive textile icons to feel. What can you imagine using these, and what would you be able to control with them?"
2. "How would you use this object to control or manage your smart home devices?"
3. "Imagine you have several lamps to control. Now, you want to select a specific lamp, turn it on, and change the color. How do you think the control can help you with which step?"

## 3.5 Study Procedure

At the beginning of the study, the conductor explained the purpose of the study, what textile controls are in general, which form factors are used in the study (recessed, raised), what context we are in (smart home), and what the tasks look like. In addition, the conductor explained that recessed icons signal applications/functionalities and that something can be controlled with raised icons. It was also explained that several icons can have the same meaning and that some icons have a border to indicate that they consist of several components.
First, the participants randomly named each icon on the iPad screen. Then, all the icons were looked at again, and, if necessary, the participants changed the names of the icons. Once this was done, the video recording was started, and the icons were placed on the sensor plate one by one. The

participants placed their hands on the homing position and started to feel the corresponding icon as soon as they were ready. The participants had 30 seconds to feel each icon. The measurement started when an icon was touched for the first time. After recognizing an icon, the conductor noted the answer and asked the participants to complete a questionnaire. Meanwhile, the next round was prepared by replacing the icon on the sensor plate. This order was determined randomly, and care was taken to ensure that it differed from the vocabulary question. After all 39 icons had been conducted, the participants were asked to complete a final questionnaire. Meanwhile, the conductor moved the sight-protection screen to the right and placed the round or rectangular trackpad in the holder to continue the trackpad experiment. The conductor again mentioned the smart home context and asked the participants to explore the trackpad.

## 3.6 Measurements

Measured were *success rate*, *confusion rate*, *timeout rate*, *recognition time*, *mental demand*, *ease of recognition*, and *confidence*.

As a result of the first part of the task, we compared the visually named *icon names* with the icon meanings we chose. In the second part of the task, we evaluated the responses for each icon and calculated *success rate*, *confusion rate*, and *timeout rate*. *Recognition time* was automatically calculated for each icon using the sensor plate. A timeout was measured if a participant recognized an icon for more than 30 seconds. If an icon was recognized but confused with another icon, this was counted as confused. In addition to the recognition time, we determined the *touched* and *not touched* time per icon. Appendix A shows the questionnaires participants answered after each icon, along with the final questionnaire for icon recognition. *Mental demand*, *perceived ease of rough shape recognition*, *perceived ease of shape features recognition*, and *confidence in answers* were recorded for each icon. In the final questionnaire given, the participants were asked to *rank* the icons per icon group, and questions were asked about *comfort raised*, *comfort recessed*, *recognition of grouped icons with borders*, and *recognition of grouped icons without borders*.

In the last part of the task, the conductor wrote down what the participants said and if they recognized the shape and possible functionalities of the trackpad.

## 3.7 Results

The results of our study are presented below, with a detailed descriptive description of the data collected provided in the following subsections.

### 3.7.1 Visual Recognition

There were no significant differences in the visual recognition of the icons.

This subsection shows the results of the visual naming of the icons, illustrated in Figure 3.3. We performed a statistical analysis for each icon group. Using a Shapiro-Wilk test, we calculated that the icon groups 'Robot Vaccuum Cleaner', 'Cold', 'Home', and 'Forward/Backward Arrow' are normally distributed and the others are not. We performed a paired t-test for the normally distributed icon groups and a Wilcoxon signed-rank test for the non-normally distributed ones. No significant difference in visual recognition was found within the groups.

*Toggle* Material Icon from the Toggle icon group was named 100% as 'On/Off' and, therefore, 100% correctly. The Alternative variant was named 78.5% as 'On/Off', 14.5% as 'Circle with stick on top', and 7% as 'Rotated Q' and was 78.57% correctly named.

*Brightness* The Material icon from the Brightness icon group was named 'Sun' by 86% and as 'Brightness/Light' by 14%. The Alternative variant was 92.8% correctly named 'Star' and 7.2% 'Spike'; therefore, 92.86% correctly named.

*Light* Material of Light was named as 'Bulb' by 85.7%, 'Sunset' by 7.15%, and 'Ball that is strange at the bottom' by 7.15% and was therefore 85.7% correctly named. The alternative variant was named 'Bulb' by 42.8%, 'Keyhole' by 21.6%, 'Balloon' by 14%, as 'Light', 'Pinhead', and 'Circle

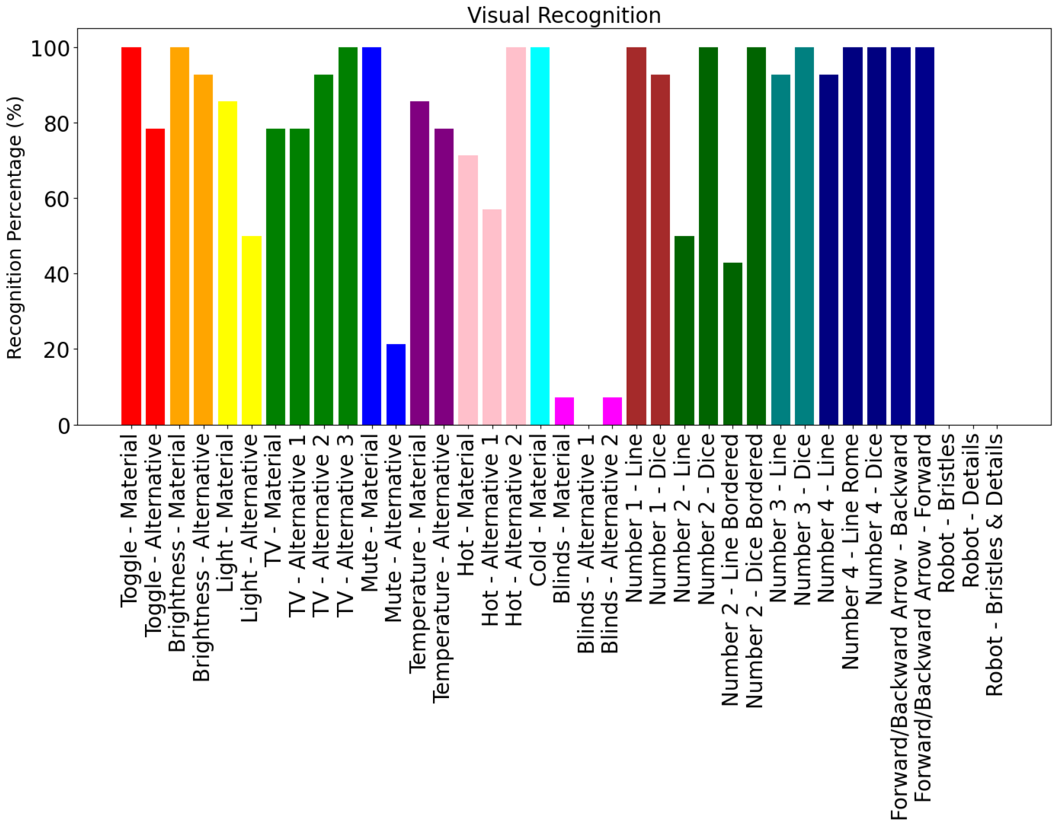



**Figure 3.3:** Visual recognition results study 1: Presented in different colors per icon group. Most icons were visually recognized very well, only blinds and robot icons very poorly.

with pin' by 7.2% each. Thus, there is a correct recognition rate of 50%.

*TV* The Material variant of TV was named 78.5% as 'TV/Screen', and 4.3% each as 'Lego brick', 'Sign', 'Window frame', and 'Recessed briefcase', giving a 78.5% correct recognition rate. The alternative 1 variant was named 78.5% as 'TV/Screen', and 7.16% each as a 'Scoreboard', 'Bordered briefcase', and 'Raclette pan'. This gives a correct recognition rate of 78.5% for this variant. Alternative 2 and 3 variants were 100% correctly recognized as 'TV'.

*Mute* For the mute icon, Material was 100% recognized as 'Mute', and the Alterantive 1 variant was 78.5% recognized as 'Speaker/Sound' and 21.5% as 'Mute', resulting in a correct recognition rate of 21.5%.

*Home* With Home, both variants were 100% recognized as this.

*Temperature*. The Material variant of the temperature icon was recognized at 85.7% as a 'Thermometer/Temperature' and 7.15% as a 'Kettlebell and Ball with a rod on top with a bump'. The recognition rate is therefore 85.71%. The Alterantive 1 variant was also 85.7% recognized as 'Thermometer/Temperature' and 7.15% each as 'Ball with a rod on top and inverted lock' and therefore also has a correct recognition rate of 85.7%.

*Hot*. Hot Material was labeled 71.4% as 'Flame/Fire', 21.6% as a 'Water Droplet', and 7% as 'Ribeye' and, therefore, has a correct recognition rate of 71.4%. Alternative 1 was labeled 57.1% as 'Flame/Fire', 35.9% as water droplet, and 7% as leaf green. This results in a correct recognition rate of 57.1%. Alternative 2 was visually recognized as 'Flame/Fire' 100% of the time.

*Cold*. The Material variant of the cold icon was named 'Snowflake' by 86% and 'Cold' by 14% and, therefore, has a correct recognition rate of 100%.

*Blinds*. Blinds material was labeled 28.4% as a 'Hat', 14.6% as a '3D printer', 14.6% as a 'House', 14% as a 'Computer' and 7.1% each as 'Blind', 'Machine', 'Volleyball net', and 'Coffee machine'. This results in a correct recognition rate of 7.1%. Blinds Alternative 1 was named 58% as a 'Hat' and 7% each as an 'Open window', 'Toaster', 'Oven', 'Street sign', 'Stamp', and 'Upside down trash can' and was not recognized correctly once. Blinds Alternative 2 has a correct recognition rate of 7.1%, which results from the names 'Hat' (63.5%), 'Toaster' (7.1%), 'Window closed' (7.1%), 'Stamp' (7.1%), 'Wall' (7.1%) and 'Oven' (7.1%).

*Number 1*. Number 1 Line was recognized here by 78.5% as 'Stroke/Stick' and 21.5% as one and thus had a recognition rate of 100%. Number 1 Dice, on the other hand, was named 64.8% as 'Circle/Sphere', 21% as 'Dice 1', and 7% each as a 'Switch', and one with a recognition rate of 92.8%.

*Number 2*. Number 2 Line icon was labeled 50% as 'Pause', 43% as two 'Strokes/Sticks', and 7% as 'Two', with a recognition rate of 50%. Number 2 Dice was named 50% as 'Two circles/spheres', 43% as 'Two dice', and 7% as 'Two', with a correct recognition rate of 100%. Number 2 Line Bordered was labeled 57.2% as 'Pause', 21.4% as 'Two bars/II', and 21.4% as 'Two'. This results in a recognition rate of 42.8%. Number 2 Dice Bordered were named 64% as 'Dice 2' and 36% as 'Two circles/spheres', thus with a 100% recognition rate.

*Number 3*. In the number 3 icon, 64.2% of the Number 3 Line was named 'Three bars', 28.8% 'Three', and 7% 'Heating 3 bars' with a recognition rate of 92.8%. Number 3 Dice was named 50% as 'Three circles/spheres', 43% as 'Three dice', and 7% as 'Three', with a recognition rate of 100%.

*Number 4*. Number 4 Line was named 64.2% as 'Four bars', 28.8% as 'Four', and 7% as 'Heating 4 bars'. Number 4 Line Roman was named 64% as 'IV', 21% as 'Four', and 15% as 'Roman four'. Thus, Number 4 Line has 92.8%, and Number 4 Line Roman has a 100% recognition rate. The Number 4 Dice variant was named 50% as 'Four circles/spheres', 43% as 'Four dice', and 7% as 'Four', with a 100% recognition rate.

*Forward/Backward*. The forward icon was labeled 43% 'Forward/redo', 21.5% 'Repeat right', 21.5% 'Clockwise/right', and 14% 'Arrow (right)'. The backward icon was labeled 64% 'Repeat/reset', 29% 'Counterclockwise/left', and 7% 'Arrow left'. Both icons, therefore, have a recognition rate of 100%.

*Robot*. All three variants were not recognized at all. The robot with only bristles was named 29% as a 'Circle with dashes', 21% as an 'Alien head', and 7.14% each as 'Spikes without Pokeball', 'Empty eye', 'Stopwatch', 'Bomb', 'Beetle head', 'Pokemon shell', and 'Fennel'. The second variant with only inner details was named 'Pokeball' by 86% and 'Eye and donut' by 7% each. The variant with bristles and

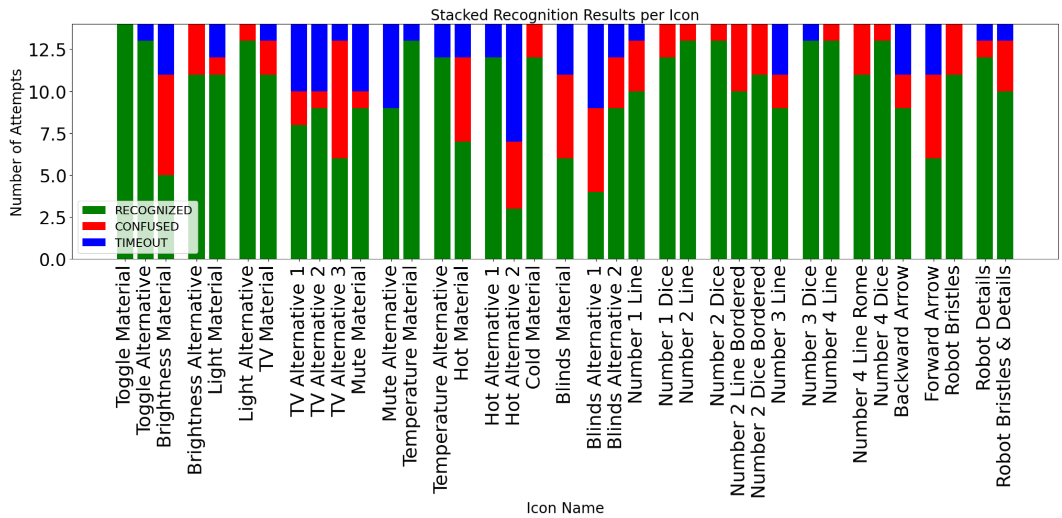



**Figure 3.4:** Haptic recognition results study 1: Separated per icon group shown per icon in green (*recognized*), red (*confused*), and blue (*timeout*).

inner details was named 'Pokeball (with spikes)' by 50%, 'Eye' by 14%, and 'Donut' and 'Alien' by 7% each.

### 3.7.2 Haptic Recognition

There were significant differences in haptic recognition for the icon groups 'Brightness', 'Temperature', 'Hot' and 'Number'.

This subsection presents the results of the haptic recognition of the icons, illustrated in Figure 3.4. Here, we present how often icons were correctly recognized (*recognized*), how often they were confused (*confused*), and how often there was a *timeout*. Based on this, we performed a statistical analysis per icon group to see if there was a significant difference in the correct recognition of icons within an icon group.

The icon groups for *recognized* are not normally distributed. For the icon groups consisting of two icons, we performed a Wilcoxon signed-rank test. For groups of three, a Friedman test with Wilcoxon signed-rank test with Holm correction was used, and for groups of four, a Friedman test with Wilcoxon signed-rank test with Holm correction was also used.
The following significant differences were found in the haptic recognition of the icons within the respective groups:

- *Brightness Alternative* was recognized significantly more often than *Brigthness Material* (W=25, p<0.05).
- *Temperature Alternative* was recognized significantly more often than *Temperature Material* (W=30, p<0.05).
- *Hot Alternative 1* was recognized significantly more often by touch than *Hot Alternative 2* and then *Hot Material* (21%) (Friedman $\chi^2(2) = 14$, $p < 0.001$; Wilcoxon post-hoc tests with Holm correction: Hot Alternative 1 vs. Hot Material, p = 0.008; Hot Alternative 1 vs. Hot Alternative 2, p = 0.028).
- *Number 2 Line* was recognized significantly more often than *Numbver 2 Line Bordered* (Friedman $\chi^2(3) = 11.91$, $p < 0.01$; Wilcoxon post-hoc test with Holm correction: Number 2 Line vs. Number 2 Line Bordered, p = 0.049).

### 3.7.3 User Preferences

User preferences and rankings of the icons were investigated, and significant differences were found in the icon groups 'Blinds', 'Heat', 'Number 2' and 'Number 4'.

This subsection describes our statistical analysis of user preferences regarding individual icons. In addition, a ranking per icon group was carried out, in which users could decide which icon they liked best per group. For the statistical analysis, we converted the Likert Scale, which goes from 1 to 7, to -3 to 3, centering around zero, in order to be able to recognize better negative or positive tendencies. Due to the many results, we will only describe the icon groups with significant differences in detail below, as these provide insights for selecting our icon set. A complete presentation of all results would exceed the scope of this paper. Using a Shapiro-Wilk test, we checked the data for normal distribution. The results for the rough shape questions in the icon group mute were normally distributed, the rest were not. For groups of two, which are not normally distributed, we performed a Wilcoxon signed-rank test, and for groups of two, which are normally distributed, we performed a paired t-test. In addition, for groups three and four, which are all not normally distributed, we carried out a Friedman test with Wilcoxon signed-rank test with Holm correction. The following significant differences were identified.

- *Blinds* The study participants found it significantly easier to recognize the rough shape of the Blinds Alternative 2 icon (Mean: 1.92, SD: 0.95) than Blinds Material (Mean: -0.3, SD: 2.18) (Friedman $\chi^2(2) = 9.22$, p = 0.00995; post-hoc: Blinds Alternative 2 vs. Blinds Material, p = 0.0219). In addition, recognizing the shape details of the Blinds Alternative 2 icon (Mean: 0.69, SD: 0.95) was perceived as significantly easier than with Blinds Material (Mean: 0.69, SD: 1.27) (Friedman $\chi^2(2) = 10.09$, p = 0.00643; post-hoc: Blinds Simple 2 vs. Blinds Material, p = 0.0339). In contrast, recognizing the shape details was perceived to be significantly easier with Blinds Material (Mean: 0.69, SD: 0.95) than with Blinds Alternative 1 (Mean: 0.77, SD: 1.54) (post-hoc: Blinds Alternative 1 vs. Blinds Material, p = 0.0450).

- *Heat* In the Hot icon group, Hot Material performed significantly worse than Hot Alternative 1 regarding mental demand (Mean: 1.92, SD: 0.95) (Friedman $\chi^2(2) = 10.60$, p = 0.00498; post-hoc: Hote Alternative 1 vs. Hot Material, p = 0.0167). However, Hot Material was significantly better at recognizing the rough shape (Mean: 2.08, SD: 0.95) and the details of the shape (Mean: 2.08, SD: 0.95) than Hot Alternative 1, which scored lower on the rough shape (Mean: 0.77, SD: 1.59) (Friedman $\chi^2(2) = 9.67$, p = 0.00793; post-hoc: Hot Alternative 1 vs. Hot Material, p = 0.0467) and the details of the shape (Mean: 0.77, SD: 1.59) (Friedman $\chi^2(2) = 8.32$, p = 0.0156; post-hoc: Hot Alternative 1 vs. Hot Material, p = 0.0333).

- *Number 2* The rankings for Number 2 Line are as follows: it was ranked second five times, third three times, and fourth three times. Number 2 Dice ranked second seven times, third five times, and fourth twice, without ever being ranked first. On the other hand, Number 2 Line Bordered never ranked first or second but did rank third three times and fourth three times while not being ranked at all eight times. Number 2 Dice Bordered, meanwhile, was not ranked first, ranked second three times, third twice, and fourth six times, and was not ranked at all three times. Based on these results, Number 2 Dice significantly outperformed Number 2 Line Bordered ($\chi^2(2) = 12.58$, $p = 0.0103$).

- *Number 4* Number 4 Line was ranked in first place once, second place once, third place eight times, and fourth place four times. Number 4 Line Roman was also ranked in first place once, second place, third place three times, and fourth place nine times. In contrast, Number 4 Dice was ranked once at number 1, eleven times at number 2, and twice at number 3, without ever reaching number 4. Enum 4 Simple 2 performed significantly better than Number 4 Line and Number 4 Line Roman ($\chi^2(2) = 14.92$, $p = 0.0064$).

About the rankings of the icons within the icon groups, we carried out a Wilcoxon signed-rank test for groups of two and a Friedman test with Wilcoxon signed-rank test with Holm correction for groups of three and four.
Significant differences were found in the four icon groups illustrated in Figure 3.5.

- *Blinds* Blinds Material was ranked once at number 1, once at number 2, three times at number 3, and nine times at number 4. Blinds Alternative 2 was also ranked in first place once, but six times in second place, six times in third place, and only once in fourth place. Blinds Alternative 2 performed significantly better than Blinds Material ($\chi^2(2) = 7.54$, p = 0.0292).

- *Hot* Hot Material was not ranked 1st, second, or third once but was ranked 4th all 14 times. In contrast, Fire Alternative 1 and Fire Alternative 2 were each ranked 2nd seven times and 3rd seven times without being ranked first or fourth. Fire Alternative 1, and Fire Alternative 2 performed significantly better than Fire Material ($\chi^2(2) = 21.0$, p < 0.001).

- *Number 2* The rankings for Number 2 Line are as follows: it was ranked second five times, third three times, and fourth three times. Number 2 Dice ranked second seven times, third five times, and fourth twice,

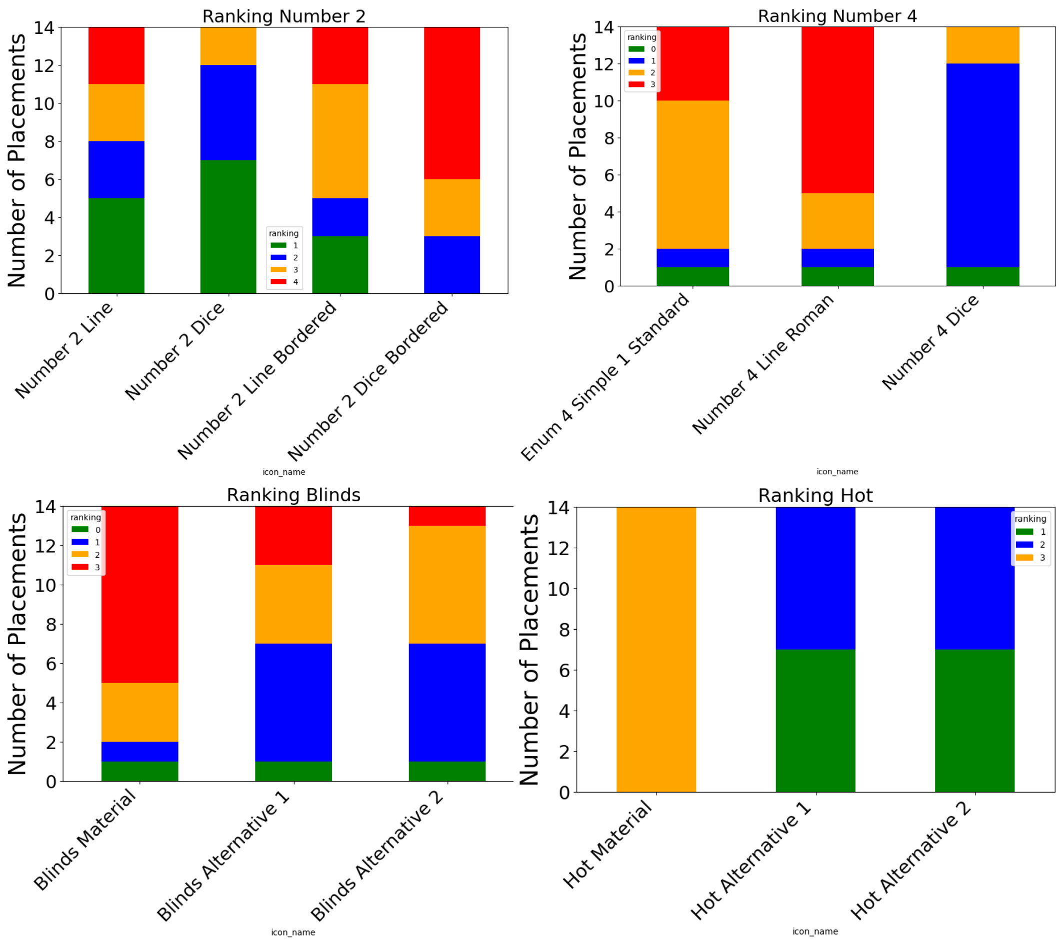



**Figure 3.5:** Distribution of user ranking for the icons in the four groups in which significant differences were found: Blinds, Number 4, Hot, and Number 2.

without ever being ranked first. On the other hand, Number 2 Line Bordered never ranked first or second but did rank third three times and fourth three times while not being ranked at all eight times. Number 2 Dice Bordered, meanwhile, was not ranked first, ranked second three times, third twice, and fourth six times, and was not ranked at all three times. Based on these results, Number 2 Dice significantly outperformed Number 2 Line Bordered.

- *Number 4* Number 4 Line was ranked in first place once, second place once, third place eight times, and fourth place four times. Number 4 Line Roman was also ranked in first place once, second place, third place three times, and fourth place nine times. In contrast, Number 4 Dice was ranked once at number 1, eleven times at number 2, and twice at number 3, without ever reaching number 4. Number 4 Dice performed significantly better than Number 4 Line and Number 4 Line Roman.

### 3.7.4 Trackpad Experiment

When investigating the two textile trackpad shapes (rectangular, round), we asked three questions and thus divided this into three phases. We wanted to determine whether the rectangular or the round trackpad is recognized as such and, for our later lighting application, whether these are also associated with the possible association of a color selection. The results of the individual phases are illustrated in Table 3.6.

The rectangular trackpad performed better in all phases regarding recognition as a trackpad, while the round trackpad was recognized better in phase 2 regarding color selection.

For the rectangular prototype, 71.43% of participants recognized this as a trackpad in phase 1 and 100% in phases 2 and 3. The color selection functionality was not recognized by any participant in phase 1 or 2, only in phase 3 to 85.71%. For the round prototype, 85.71% of users recognized the trackpad in both phase 1 and phase 2, with recognition increasing to 100% in phase 3. The color selection function, on the other hand, was not recognized in phase 1 but was identified by 42.86% of users in phase 2, with recognition rising to 85.71% in phase 3.

| | **Phase 1** | **Phase 2** | **Phase 3** |
|---|---|---|---|
| **Trackpad (Rectangle)** | 71.43% | 100.00% | 100.00% |
| **Color Selection (Rectangle)** | 0.00% | 0.00% | 85.71% |
| **Trackpad (Circle)** | 85.71% | 85.71% | 100.00% |
| **Color Selection (Circle)** | 0.00% | 42.86% | 85.71% |

**Table 3.6:** Results of Trackpad and Color Selection recognition across three phases for both prototypes (rectangle, circle). The values represent the percentage of users who recognized the prototype as a trackpad and as a possilbe color selector.

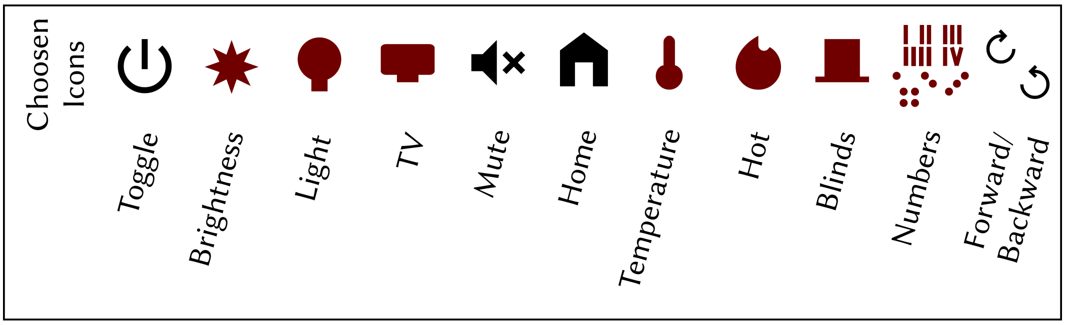



**Figure 3.7:** Selected icons derived from study 1 results: We choose *Toggle Material*, *Brightness Alternative*, *Light Alternative*, *Mute Material*, *Home Material*, *Temperature Alternative*, *Hot Alternative 1*, *Blinds Alternative 2*, *Number (1-4) Line (Without borders and roman variant)*, *Number (1-4) Dice (without borders)* and *Forward/Backward Arrow Material*

## 3.8 Discussion

Based on the study results, we now present which icons we have selected as suitable for our textile icon set for larger textile interfaces. The decision was made based on *haptic recognition* (> 60%), *user preferences* (significant differences), and *visual recognition* in that order.

- *Toggle* We chose the Toggle Material Icon because it had a very good recognition rate and was significantly better than Toggle Alternative at recognizing the rough shape and the shape details.
- *Brightness* The Brightness Alternative 1 icon was selected because it was recognized significantly more often than Brigthness Material.
- *Light* We chose Light Alternative 1 because it had a high recognition rate and a simpler shape than Light Material, making it more consistent for the interface.
- *TV* The TV Material icon was selected due to its good recognition rate and significantly better rough shape recognition than the alternatives.

- *Mute* We chose Mute Material because it was well-recognized and visually better identified as a mute icon than the Mute Alternative.
- *Home* Home Material was chosen because it had a very good recognition rate and was significantly better than Home Alternative in recognizing shape details and confidence. In addition, the studies showed that the house door is an important feature for participants to recognize.
- *Temperature* We chose Temperature Alternative because it had a better recognition rate and required less mental effort than Temperature Material.
- *Hot* Hot Alternative 1 was selected due to its better detection rate than Hot Material and Hot Alternative 2.
- *Cold* Cold Material was not selected for the next study due to its low recognition rate.
- *Blinds* We chose Blinds Alternative 2 because it showed a better recognition rate and significantly better results in recognizing the rough shape and shape details than Blinds Material.
- *Number 1* Both Number 1 Line and Number 1 Dice were evaluated as suitable, as both had high recognition rates.
- *Number 2* Number 2 Line and Number 2 Dice were selected as suitable due to their high recognition rates.
- *Number 3* Number 3 Dice was preferred due to the better results in recognizing shape details and confidence compared to Number 3 Line. However, Number 3 Line is also suitable and was therefore also selected.
- *Number 4* We selected Number 4 Dice because it showed the highest recognition rate and significantly better results in recognizing the rough shape and the shape details. Number 4 Line is also suitable here and was therefore also selected as we want to use two different types of enumeration (line shape, dice shape) in the larger textile interfaces.

- *Forward/Backward Arrow* We selected both Back and Forward Arrow Material as suitable because both icons had good recognition rates, and no significant differences were found.
- *Robot Vaccuum Cleaner* For the robot group, all three icons (Robot Bristles, Robot Details, Robot Bristles Details) were evaluated as suitable, as no significant differences in recognition were found. However, since the icons were not visually recognized at all, we decided not to select them for the later larger textile interfaces.

Finally, it is interesting to mention that bordered icons did not perform well in our study. This was unexpected for us and should be re-examined in a future study, examining additionally different shapes with and without borders.

# Chapter 4

# Design Decisions for Larger Textile Interfaces

This chapter discusses our design choices for larger textile interfaces in the context of smart home. We focused on four interface concepts and selected three basic metaphors.

We developed four interface designs based on three metaphors: *Universal*, *Room*, and *Dense*, with an additional *Sparse* design incorporating white space.

The first metaphor, *Universal*, is based on a universal remote control. Here, the applications share the controls by first selecting the application and then controlling it using the unviersal controls. The second metaphor, *Room*, is based on Norman's research on natural mappings. The spatial metaphor creates a natural association by placing the controls on the interface, based on the placement of the associated devices in the room. The third metaphor, *Dense*, organizes the interface into narrow but clearly defined areas, similar to Apple Home[1]. In addition to the *Dense* interface, we have developed a *Sparse* interface. This interface is based on the same modular design as the *Dense* interface, but contains additional white space between the modules. We wanted to find out whether white space generally makes the haptic exploration of larger textile interfaces more difficult, even though Challis and Edwards emphasized minimizing white space in tactile interfaces.

Figure 4.1 shows the four larger textile interfaces intended to be integrated into sofa armrests and table runners based

[1] https://www.apple.com/de/home-app/ (access: August 2024)

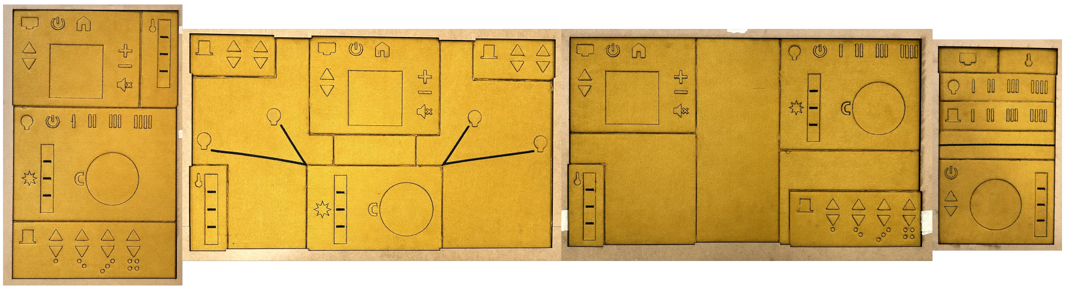


**Figure 4.1:** The four designed interfaces for the main study, presented in their correct size relation from left to right: *Dense*, *Room*, *Sparse*, and *Universal*.

The interface sizes are based on the typical dimensions of sofa armrests and table runners.

on their dimensions. The *Dense* and *Universal* dimensions are based on the size of typical sofa armrests, with a maximum width of 24 cm and height of 45 cm, based on IKEA sofa models[1][2][3][4]. We have made *Dense* 24 cm wide and 39 cm long and *Universal* 18 cm wide and 29 cm long. This difference in size is due to the number of controls on the interfaces; since *Universal* controls several applications with shared controls, there are also fewer on the interface than in comparison to *Dense*.
*Sparse* and *Room* are based on the dimensions of a table runner[5][6] , so we specified a maximum size of 40 cm x 70 cm. Both interfaces were set to an identical size of 52 cm

1 https://www.ikea.com/de/de/p/kivik-2er-sofa-tibbleby-beige-grau-s09440599/ (access: August 2024)

2 https://www.ikea.com/en/en/p/vimle-2er-sofa-with-wide-armrests-gunnared-beige-s69400543/ (access: August 2024)

3 https://www.ikea.com/de/de/p/jaettebo-2er-sitzelement-samsala-dunkelgelbgruen-s29471405/ (access: August 2024)

4 https://www.ikea.com/de/de/p/jaettebo-2er-sitzelement-mit-nackenkissen-tonerud-grau-s19510412/ (access: August 2024)

5 https://de.erwinmueller.com/Erwin-Mueller-fleckabweisender-Tischlaeufer-Krefeld-74327-107069-460498?wid=qi77izmy&gad_source=1&gclid=CjwKCAjwxY-3BhAuEiwAu7Y6sz4K6HCRr_vdHpSR2xQ9LNSRCU_KBSfpQhR9Y6_WUGu_6tW-reGqpBoCQu8QAvD_BwE&wmn=SG21805&ext_channel=Adwords&ext_category=dooshop%2BPLA%2BCSS&ext_subcategory=zu%2BHause&ext_name=Google%2BShopping&subid=SG21805&cw=shop(access:September2024)

6 https://www.urbanara.de/products/tischlaeufer-hellgrau-leinen-miral?variant=13195493572674&campaignid=20406627565&adgroupid=157381578848&gad_source=1&gbraid=0AAAAADvrSR7fes_VOH2RAtUkG1sBVi7g0&gclid=CjwKCAjwxY-3BhAuEiwAu7Y6s1wwHi3UAR7Ez2wrWfgSbcWr7aPq2IJEf8-_yUO_qLSy8hH8NeRcshoCougQAvD_BwE (access: September 2024)

wide and 31 cm high for consistency.

We decided to use raised icons for buttons (controllable icon) and recessed icons for signifiers intended to signal an action or application to the user. Based on the study results of Nowak et al., in which recessed sliders performed best, we also designed the sliders and trackpads as recessed, even if this includes a slight inconsistency in the design. Two types of signifiers were used: *Control Signifiers* and *Application Signifiers*. *Application Signifiers* are always placed in the top left corner of an application and show the user what type of application it is. These signifiers have a consistent distance of 1 cm from the edge in all interfaces. *Control Signifiers*, on the other hand, are located near the corresponding controls, at a distance of 0.5 cm, to indicate which control they are intended to signal clearly. This is based on the Law of Proximity [Norman, 2013] to ensure that the *Control Signifiers* are assigned to the respective control. Since both line and dice icons performed well as enumerators in Study 3 and we needed enumerations as both signifiers and buttons, we used dice icons as signifiers and line icons as buttons to create a clear haptic distinction between them. Across all interfaces, we set the distance between icons that belong together as a group (e.g., Volume Up, Volume Down, and Mute) to 1 cm. Icons that belong to the same application but do not belong together as a control group (e.g., On/Off TV and Home TV) have a distance of 2 cm between them.

We used raised icons for buttons, recessed icons for signifiers, and designed sliders and the trackpad as recessed based on prior study results.

Due to the technical limitations in producing the interfaces, explained in more detail in Chapter 5, and considering the Law of Common Region [Norman, 2013], we have decided to design each application modular. As a result, each application is represented as a box surrounded by haptically perceptible section boundaries.

We decided on four typical smart home applications for our prototypes. In the beginning, we wanted to study five applications. However, due to the poor recognizability of the robot vacuum cleaner icon in the first study and the limited space on the interfaces, we decided on TV control, light control, temperature control, and blinds control. The TV control makes it possible to switch the TV on and off (on/off button), discreetly increase or decrease

We selected TV control, light control, temperature control, and blinds control as the applications for the prototypes.

the volume (plus and minus buttons) and mute/unmute (mute button), change the channel (triangle up, triangle down), switch to home (house button) and control a mouse in the home menu using the trackpad. The TV control modules are identical for the *Dense*, *Sparse*, and *Room* interfaces. Only in *Universal*, where an application is selected in the upper area and controlled in the lower area, has the home functionality been omitted, and the volume control has been moved to a slider, as the triangles have already been used to change channels. The light control works with all interfaces in such a way that a user first selects which light is to be controlled (Line Buttons 1 to 4) and can then either turn the selected light on or off (On/Off button), increase/decrease the brightness (Slider) or change the light color (Trackpad). *Universal* activates the trackpad, the on/off button, and the slider when selecting a lamp. The up/down triangles have no function in this case. With *Room*, a user also selects a lamp, but instead of enumeration buttons, four bulb buttons correspond to the actual positions of the lamps in the room. These were additionally connected to the control area of the lamps with embroidered lines to signal a clear association. When selected, a lamp could be switched on using the slider, which is different from the other interface designs. The temperature control is represented by a slider with which the temperature can continuously increase or decrease. With *Universal*, a user selects the temperature by pressing the thermostat button before the slider can be operated. Meanwhile, the other controls (trackpad, up/down, on/off buttons) are deactivated. There are four button groups for controlling the blinds, each consisting of an up and a down triangle. *Dense* and *Sparse* also have *Control Signifiers* that indicate which blind is involved. This has been omitted for *Room*, as the spatial arrangement of the groups already indicates the respective blind. With *Universal*, the blinds must first be selected in the upper area before they can be controlled with the up and down triangles. The on/off button, the trackpad, and the slider are not functional. The TV signifier and temperature signifier icons were displayed here as raised buttons in the selection area to allow users to select these applications directly. The button itself serves as its signifier. Due to the universal operating concept, we have dispensed color and sun signifiers for the trackpad and slider, as these also offer other control options. The selection and control areas are separated by an embroidered dividing line to signal the transition between the two areas and make orientation easier.

With the development and selection of the four interface designs, we have created a basis for our main study. Each design was conceptualized to explore different aspects of user interaction with larger textile interfaces in a smart home context. Before presenting the study, the next chapter explains how we technically implemented and produced the interfaces.

The development of the four interface designs forms the basis for our main study.

# Chapter 5

# A Fabrication Process for Larger Textile Interfaces

When designing and producing the four larger textile interface designs (*Dense*, *Universal*, *Sparse*, *Room*), our focus was on already existing guidelines for textile icons, sliders, and trackpads together with the results of our first study and combining standard visual design guidelines. We also wanted to make our interfaces functional by combining laser cutting with embroidery and capacitive sensors. For this we used a Bernina 880 embroidery machine[1] with a Large Oval hoop[2], which measures 145 x 255 mm. We chose furniture fabric[3] as the surface fabric, as it represents a sofa's tactile and visual properties. Since our interfaces are meant to be integrated into a sofa, this fabric offers a realistic representation and an authentic user experience.

Design and fabrication of four textile interfaces using laser cutting, embroidery, and capacitive sensors, integrating existing design guidelines.

In the following subsection, we describe the general fabrication method for our interfaces, which is presented using the *Dense* interface as an example. The design

1 https://www.bernina.com/de-DE/Maschinen-DE/Serien-Ubersicht/BERNINA-8er-Serie/BERNINA-880 (access: August 2024)

2 https://www.bernina.com/de-DE/Zubehor-DE/Zubehor-fur-Stickmaschinen/Stickrahmen-und-Adapter-de/Stickrahmen-gross-oval (access: August 2024)

3 https://www.stoffe-hemmers.de/moebelstoff-rolando-senfgelb (access: August 2024)

decision for the design of the interfaces has already been explained in more detail in chapter 6, which is why we will concentrate on pure production here.

## 5.1 Component Structure and Layered Design

Modular design with recessed signifiers and raised functional controls for clear differentiation.

We designed our larger textile interfaces to be modular, as we were limited in size by the embroidery hoop. In other words, we designed applications and application selection and control as individual modules. We used recessed icons, raised buttons, recessed sliders, recessed trackpads, section boundaries, and helper lines for the interfaces. We decided on a height and depth of the raised/recessed icons of 2 mm, based on Mlakar and Haller's results.

Three-layer design ensures tactile differentiation with recessed and raised elements.

Maintain a 2 mm height difference for both raised and recessed elements after embroidery.

We have achieved the combination of recessed and raised icons on an interface by dividing the interface into three layers, which is illustrated in 5.1. A bottom, middle, and top layer. The bottom layer consists of the bottom fabric. The middle layer consists of a 3 mm thick MDF board, whereby MDF is robust and has clearly defined edges, which supports the feeling of recessed icons. The top layer consists of the top fabric, which is stitched to the bottom fabric. Recessed icons must maintain a minimum depth of 2 mm after embroidery, as the bottom fabric can be pulled upwards by up to 1 mm when joined to the top fabric. For this reason, the raised icons were cut 5 mm high from an acrylic sheet using a laser cutter. This creates tactile edges and, together with the middle panel, ensures a minimum height of 2 mm. However, other materials such as MDF boards or PLA (3D printing) could also be used. However, especially in terms of 3D printing, this would significantly increase the production time compared to a laser cutter.

Recessed sliders and trackpad follow guidelines for optimal gesture support, with precise tick marks for accuracy.

The textile slider design is based on the work of Nowak et al.. We decided to use recessed sliders because they support sliding gestures well and performed best in the study. In addition, we used three tick marks per slider, placed at 25%, 50%, and 75%. A slider is 10 cm long and 2

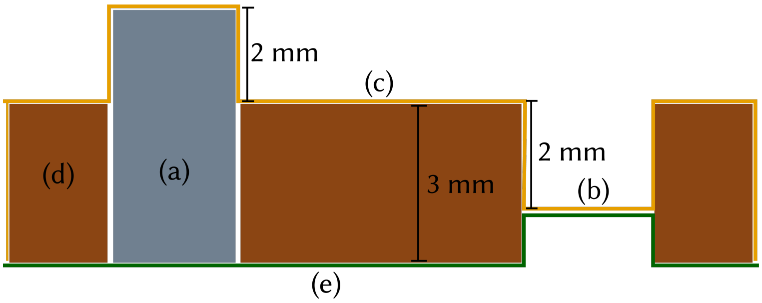



**Figure 5.1:** Cross-section of a Textile Interface with 3 Layers: (a) Raised Button (Acryl), (b) Recessed Icon, (c) Top Fabric, (d) MDF Board and (e) Backing Fabric. Layer 1 is at the height of the raised buttons, Layer 2 at the height of the top fabric, and layer 3 at the height of the recessed icons.

cm wide. The textile trackpad is based on the size guideline from Heller et al., with a recommended size of 80 x 80mm. Since the interaction of the sliders and trackpads is similar, we also designed the trackpad recessed.

## 5.2 Preparation of Required Files

In this subchapter, we explain how to prepare the files required for the embroidery machine and laser cutter based on the design of an interface.

First, we created the interface designs using a vector program. We used Figma[1] for this. The designed interfaces were then divided into modules, depending on our limiting factor. Figure 5.2 illustrates this as an example, with different colors representing the individual modules. The individual modules were then exported from Figma as an SVG file (*interfacetype_modulex.svg*).

Figma was chosen for designing the interfaces, especially because it supports the modular approach needed for this project

The SVG module files were then imported into a CAD program. For this, we used Autodesk Fusion360[2], as it offers an easy-to-use sketch function, which allowed

1 www.figma.com (access: August 2024)
2 https://www.autodesk.com/fusion-360 (access: August 2024)

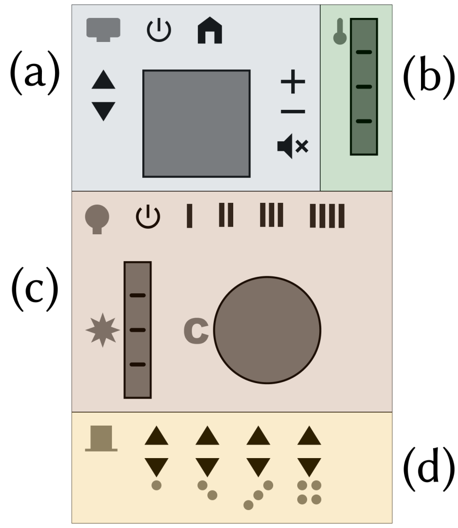



**Figure 5.2:** Dense interface Figma design divided into four modules: (a) TV control, (b) temperature control, (c) light control and (d) blinds control. Gray elements represent recessed elements and black elements represent raised elements.

Fusion 360 is used to prepare designs for each module, creating files for both the laser cutter and embroidery machine.

us to customize the SVG files according to the production quickly. First, we created the base design for the individual modules. The vector paths were changed according to the interface elements to do this. The paths for raised buttons and recessed icons were enlarged 1 mm outwards and 0.5 mm outwards, respectively. This is because recessed icons use the original path as a stickline, and the size of recessed and raised icons should remain the same as those in Figma. The same was done for the recessed slider and recessed trackpads. After that, we created the template for the embroidery by moving the paths 1mm and 0.5 mm back inwards, respectively, starting from the base design, once for raised and once for recessed elements. These paths represent the subsequent embroidery paths. If an interface design also required an additional auxiliary line embroidered on the surface, we created an additional 2 mm wide path at this point, starting from the base design. Finally, we needed the raised buttons and the base plate of the modules, which were to be cut out later. We drew additional paths 1 mm inwards from the original paths to do this. The designs created

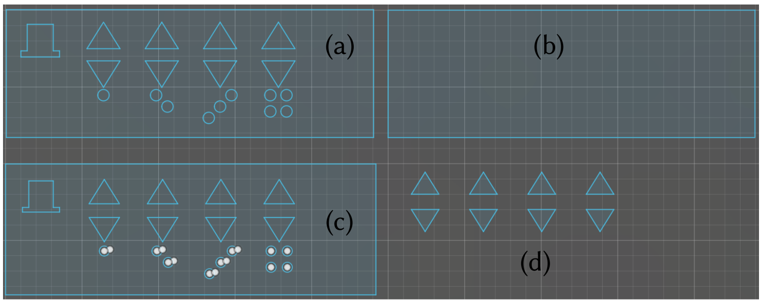



**Figure 5.3:** Blind module designs created in Fusion360: (a) basic design, (b) template design, (c) embroidery design and (d) button design.

are illustrated in Figure 5.3 using the *Dense* interface as an example. These are then exported as DXF files (*interfacetype_modulex_base.dxf*, *interfacetype_modulex_template.dxf*, *interfacetype_modulex_embroidery.dxf*, *interfacetype_modulex_buttons.dxf*).

In the next step, we prepared the DXF files for the embroidery machine and the laser cutter. As the embroidery machine software is best at handling PNG files and the laser cutter is best at handling PDF files, we converted the modules of our designs accordingly using InkScape[1]. The base and button designs were converted to PDF, and the embroidery templates to png (*interfacetype_modulex_base.pdf*, *interfacetype_modulex_template.png*, *interfacetype_modulex_embroidery.png*, *interfacetype_modulex_buttons.pdf*).

The DXF files from Fusion 360 are then converted into PDF files for the laser cutter and PNG files for the embroidery machine using Inkscape.

## 5.3 Module Fabrication

To produce the individual modules, we first cut out the base and the buttons using the laser cutter. We then mounted the backing fabric in the embroidery hoop and embroidered the template onto it using the embroidery machine.
Using the template as orientation, we then glued the cut-

1 https://inkscape.org

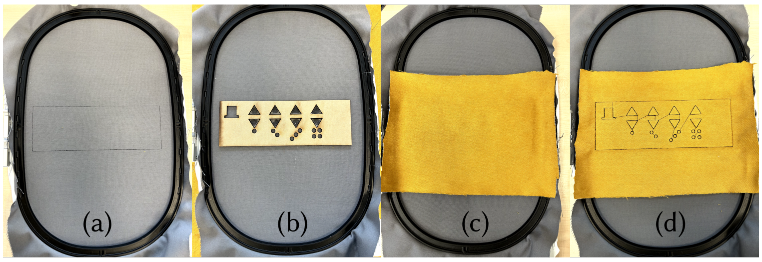



**Figure 5.4:** Production process of a textile interface module: Example for blinds module with (a) the template for correct placement of the base plate embroidered onto the bottom fabric, (b) the base plate and buttons glued onto the template, (c) the top fabric placed over it, and (d) the finished embroidered module.

out base and buttons to the underlying fabric using superglue so that it would not slip during further embroidery, thus ensuring high precision of the interface.
Finally, we placed the top fabric on the base, the buttons, and the bottom fabric and attached them with embroidery. We only embroidered where we left extra gaps in our base design for the embroidery needle. This joins the top and bottom fabric and attaches the base and buttons. This process is illustrated in Figure 5.4.

## 5.4 Frame Construction

Modules are secured using a 3 mm MDF frame with layers for mounting, cable management, and stabilization, ensuring accurate capacitance detection and firm assembly.

The created modules can now be connected using a frame cut out by the laser cutter, which consists of several MDF panels. We need a lower base surface, a middle mounting surface, and an upper surface. We opted for a panel thickness of 3 mm in each case, as this allows cables and sensors to be accommodated under the interface and prevents the interface from becoming too thick.
The top surface fixes the edges of the modules and is attached to the middle surface using wood glue.
The middle plate is there to fix the modules and to provide cable channels for the cables, copper plates, and sensors. To fix the modules, the center plate has special fabric channels, shown in Figure 5.5, in which the protruding fabric at the

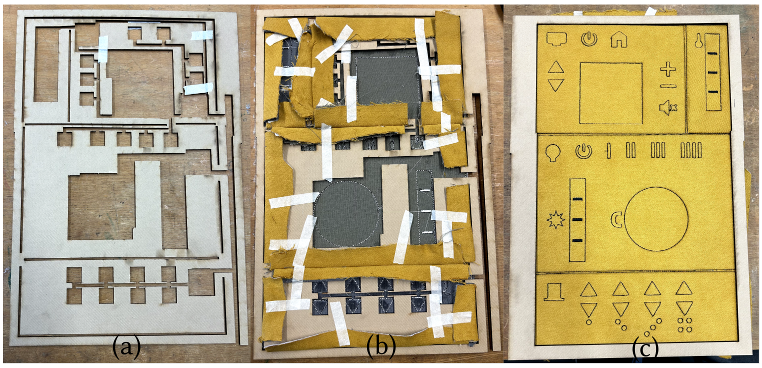



**Figure 5.5:** Dense module attachment with frame: (a) middle surface without modules attached, (b) middle frame with modules attached, and (c) dense interface with lower, middle, and upper frames.

edges of the modules is pulled in and fixed with wood glue. This makes it possible to create larger textile interfaces by connecting modules without wobbling. When placing the cable ducts and sensor positions in the design, keeping the cable length as short as possible is important to obtain more accurate capacitance measurements. We also left areas under textile controls where we placed the copper plates for the capacitance measurements. We then used templates to place them in the same places under the controls.
The lower surface serves as a base and is attached to the middle surface to stabilize the interface.

## 5.5 Integration of Functionality

We have integrated capacitive touch sensors to make our larger textile interfaces functional. For this we used a MPR121 capacitive touch sensor[1], which can monitor 12 inputs simultaneously via I2C connection. In addition, four MPR121s can be controlled simultaneously by one microcontroller, giving us 48 possible inputs per interface. This was sufficient for our interfaces. First, we used an Arduino

Capacitive touch sensors were integrated using the ESP32 for its enhanced computing power and real-time data processing capabilities.

[1] https://www.berrybase.de/mpr121-kapazitiver-touch-sensor-controller-mit-breakout-board (access: August 2024

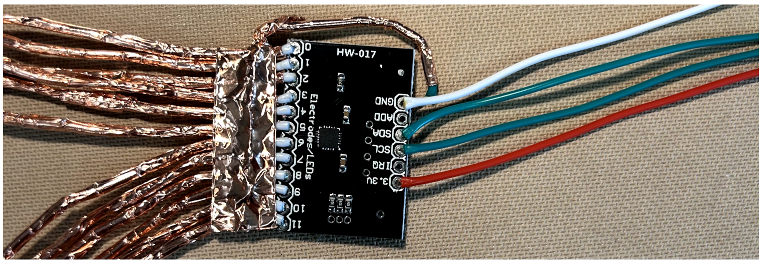



**Figure 5.6:** MPR121 sensor with 12 connected shielded cables. The cables are shielded with copper foil and grounded to the sensor to prevent signal interference.

Nano[1] to read out the sensor data. However, with four sensors we exceeded the computing power and memory resources of the Arduino Nano, which led to data loss on the serial connection. Therefore, we switched to an ESP32[2] microcontroller, which offered higher computing power, larger memory and a faster serial interface. This change has greatly improved the stability and performance of the measurements. Figure 5.6 shows an MPR121 with 12 assigned inputs using shielded cables. To shield a cable, we covered it with copper foil and then grounded it. This is important to counteract interference, which can lead to unwanted changes in capacitance and thus cause errors in the measurement. An unshielded cable would mean a loss of capacitance when touched or when a finger comes close, although we only want to measure this under the control of the copper plates. The shielded cables were individually soldered onto copper plates with a thickness of 5 mm. The copper plates were 2 x 2 cm for raised buttons, 3 x 3 cm for recessed trackpads, and 1 x 2 cm for recessed sliders. We then attached templates to the correct positions precisely below the corresponding controls. This ensures that the measuring points are identical to the positions of the corresponding control elements and that this is consistent across all four interfaces.

Shielding with copper foil prevents interference and unwanted capacitance changes, ensuring accurate signal detection on the interface.

[1] https://store.arduino.cc/en-de/products/arduino-nano (access: August 2024)

[2] https://www.espressif.com/en/products/socs/esp32 (access: August 2024)

# Chapter 6

# Study 2: Investigating User Behaviour When Interacting with Larger Textile Interfaces

In this chapter, we describe our main study, which we conducted to understand how users interact with and understand larger textile interfaces created by placing multiple textile control elements in a limited area in the context of a smart home. Due to the time constraints of this work, the study was conducted with a small number of participants to gain initial insights.

## 6.1 Experimental Design

The study consists of three phases in total.

The study is divided into three phases to investigate how users interact with larger textile interfaces.

The first phase called *Exploration without Feedback*, began with the participants having no prior knowledge of the interfaces. In this phase, they explored the different interfaces eyes-free without any feedback to observe their approach to using them. The first and second phases were designed as a between-group design to compare the influence of feedback and to limit the study length to a maximum of 1 1/2

hours to counteract fatigue effects. The order of the interface designs in Phase 1 and Phase 2 was counterbalanced across participant groups using latin square to minimize order effects.
The second phase is identical to the first but includes feedback, visualized in a simulated smart home living room in Blender[1]. These two exploratory phases were followed by interface familiarization, in which the participants learned about the interface structure and functions. After that, in the *Task Phase*, the participants performed specific tasks with all interfaces to obtain additional quantitative results. The order of the interfaces was determined using latin square, and the order of the tasks was presented randomly to avoid possible order effects.
This study aimed to identify the challenges when multiple textile control elements are placed in a limited space and operated by users in the context of a smart home.

## 6.2 Participants

We conducted the study with five participants. The participants were between 22 and 28 years old (mean: 24.6 years, standard deviation: 2.28 years). All participants were male and right-handed, studying subjects from the STEM fields (mathematics, computer science, natural sciences, and technology).

## 6.3 Apparatus

We used the larger textile interfaces described in chapter 4 for the study. In addition, an 'iPhone 14' was used to capture the interfaces with user interaction and comments.

[1] https://www.blender.org (access: August 2024)

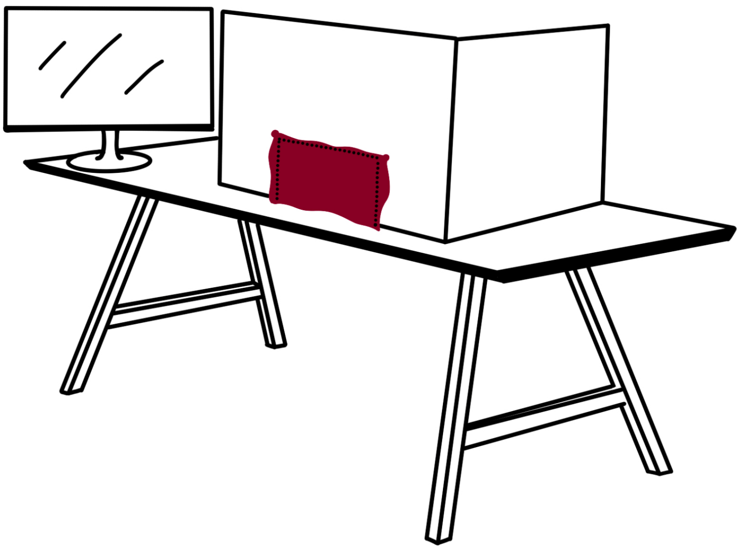


**Figure 6.1:** Study setup study 2: Participants sat in front of the table. The monitor was placed to the left (for right-handers) and right (for left-handers) of the participant. Two sight-protection screens were used to cover the view of the interfaces. There is a hole in the front sight-protection screen (dotted rectangle), which is covered by a curtain (red rectangle).

### 6.3.1 Study Setup

In the study setup, participants were seated in front of a privacy screen with an opening and a curtain to block views of the interfaces, described in Figure 6.1, and an additional privacy screen on the right. A monitor on the left showcased a simulated room in Blender, seen in Figure 6.2. For left-handed participants, this setup would be mirrored to ease use. A homing position was placed behind the curtain for uniform task measurement, with interfaces positioned behind it, taped down for accessibility and to prevent shifting during the study.

Participants sat in front of a screen with a hidden interface and a monitor showing a simulated room, with the setup mirrored for left-handed users.

**Figure 6.2:** Virtual smart living room designed in Blender: Featuring temperature display, two wall-mounted and two ceiling lamps, blinds, and a TV, all controllable via textile interfaces.

## 6.4 Task

Participants explored an interface haptically without time limits and shared their thoughts in the first two phases. After each phase, they completed likert scale questions from -3 to 3 about the interface. After that, the interfaces were shown and explained to the participants, who were then asked if they wanted to try them out to get familiar with them. Participants confirmed their understanding of the interfaces before starting the tasks. Layout and functionalities were visually shown and explained again before the tasks began. The participants completed 12 atomic tasks with each interface in Blender, with no time limit per task. The tasks can be found in Table 6.3 and were designed to be performed with each interface without containing task chains. After using each interface, participants completed a questionnaire about their experience with that interface.

| Task | Description |
|---|---|
| 1 | Turn on left ceiling light |
| 2 | Set right wall light color to green |
| 3 | Dim left wall light to about 20% |
| 4 | Shut down the right blind completely |
| 5 | Open left blind completely |
| 6 | Shut down blind right next to TV completely |
| 7 | Set temperature to 80% |
| 8 | Set temperature to 0% |
| 9 | Set temperature to 20% |
| 10 | Turn on TV |
| 11 | Set Volume to 8 |
| 12 | Go to Channel 03 |

**Table 6.3:** Tasks for study 2: Seperated with three tasks per application. Light tasks, blind tasks, temperature tasks and TV tasks.

## 6.5 Study Procedure

At the beginning of the study, the participants were explained the study procedure and asked to sign a consent form before the video recording started. They were told they would operate large textile interfaces with their preferred hand to control smart home applications. Participants were reminded not to look over the sight protection screen. Before each phase, the task was explained again to ensure understanding. Each phase lasted approximately 30 minutes.

In the first and second phase, the conductor had a log in front of him to quickly check off which shapes, functions and applications the participants recognized on the interfaces. After phase 1 and phase 2 were completed, participants were asked to complete a questionnaire (see Appendix B). Participants were told in the task phase not to correct mistakes made, but to focus on completing the task. The time measurement for each task started as soon as the virtual space changed visually. Before each task, the room was prepared accordingly, with other applications adjusted to signal readiness. Participants were also instructed to keep their hand on the homing position before each task and not start until the room was fully prepared. After completing 12 tasks on one interface, participants completed a questionnaire (Appendix B) as the conductor switched interfaces, repeated for all four. In the task phase, the conductor logged possible errors, and at the end, participants rated the interfaces from 1 to 4 based on personal preference. They were allowed to review all the interfaces.

## 6.6 Measurements

In phase 1, *recognition of the elements*, *haptic strategies*, and *user preferences* were measured.

In phase 1, we took several measurements to understand the participants' exploration and understanding of the larger textile interfaces. First, a protocol and questionnaire were used to measure which interface elements were recognized in which phase. In addition, whether the form, possible functionality, and affiliation to an application of the individual elements were recognized. During the first two phases, it was measured when participants touched which control element in order to identify possible haptic exploration strategies. The questionnaire in phase 1 also asked about the mental demand of exploring the interface, how easy it was to distinguish between different application areas and functionalities, and how confident the participants were in understanding and using them. The participant's ability to haptically recognize UI elements and understand their shapes and purposes was also tested. A particular focus was placed on recording the exploration strategy used by the participants, as well as their first impressions of the interface and how these impressions changed over time.

In addition to the questions from Phase 1, the questionnaire in Phase 2 contained specific questions on feedback. These questions assessed whether the feedback was understandable, whether it helped to understand the UI elements and their functionalities better, and whether it improved the ability to distinguish between the areas of the different smart home applications. It was also recorded whether the feedback influenced the exploration strategy of the participants and whether it helped them to identify and understand the haptic elements better. In contrast to the first phase, in Phase 2, the participants were no longer asked about their first impressions, as they were already familiar with the interface from the previous phase.

In the third phase, *Task Time*, *Intentional Errors*, *Unintentional Errors*, *mental demand*, *distinguishability of the areas*, *haptic recognition*, *clarity of the layout* and a *ranking* of the interfaces were recorded.

The *Task Time* was initially meant to be measured automatically, but video analysis was used retrospectively instead due to hardware issues. This video analysis also enabled us to divide the recorded errors into two categories: *Intentional Errors* and *Unintentional Errors*. An intentional error was a deliberately pressed interface control that did not contribute to completing the task. An unintentional error occurred when the participant accidentally touched a control, for example, with the wrist. In addition to the task times and errors, the participants completed a questionnaire relating to each interface after completing the tasks. Among other things, this questionnaire recorded how mentally challenging it was to operate the interface, how easy it was to distinguish between the areas of the various smart home applications, and how confident the participants were in haptically recognizing the supported functionalities and the shapes of the UI elements. Participants were also asked whether the section boundaries helped them to distinguish between the different smart home applications and how clear the overall layout of the interface appeared. After completing tasks, participants ranked the interfaces based on their experiences.

## 6.7 Results

Due to the small sample size of five participants, we did not conduct any significance tests on the results, but present the results descreptively and interpret possible insights from them. In the first and second phases, the *Dense* interface was tested by two participants, and the other interfaces were each tested by one participant.

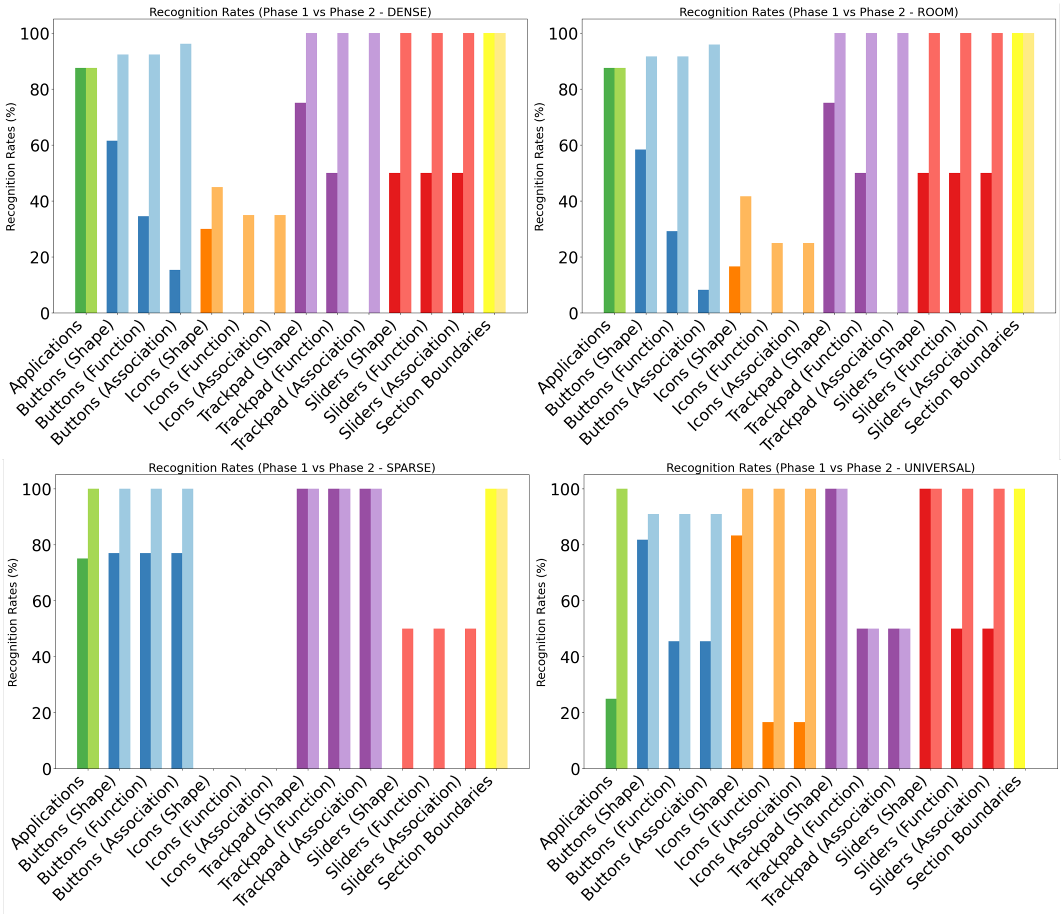



**Figure 6.4:** Interface recognition rates comparison between the first and second phases of the respective interfaces. It is divided by color into groups (Applications, Buttons, Icons, Trackpad, Slider, Section Boundaries). Darker colors represent the 1st phase, and lighter tones represent the 2nd phase.

### 6.7.1 Interface Recognition

The recognition rates of all interfaces improved significantly from phase 1 to phase 2, with the *Dense*, *Room* and *Universal* interface performing particularly well, while the *Sparse* interface remained slightly lower.

In the following, we present the recognition rates of the different interfaces, which are illustrated in Figure 6.4.

*Applications*
In phase 1, the recognition rate for applications in the *Dense* and *Room* interfaces was 87.50%, and it remained the same in phase 2. However, the recognition rate for the *Universal* interface increased from 25.00% in Phase 1 to 100.00% in phase 2, and the *Sparse* interface increased from 75.00% to

100.00%.

*Raised Icons (Buttons)*
In the *Dense* interface, shape recognition of the buttons increased from 61.54% to 92.31% in phase 2, while function recognition improved from 34.62% to 92.31%. Association recognition also improved from 15.38% to 96.15%. The *Room* interface showed a similar pattern with improved shape, function, and association recognition. The *Universal* and *Sparse* interfaces also showed improvements in button recognition.

*Recessed Icons (Signifier)*
For the *Dense* interface, shape recognition increased from 30% to 45%, function recognition from 0% to 35%, and association from 0% to 35%. The *Room* interface showed improvements in shape recognition from 16.67% to 41.67%, function from 0% to 25%, and association from 0% to 25%. The *Universal* interface demonstrated significant increases, with shape recognition going from 83.33% to 100%, function from 16.67% to 100%, and association from 16.67% to 100%. The *Sparse* interface remained at 0% across all categories and phases.

*Slider*
For the *Dense* and *Universal* interfaces, shape, function, and association recognition metrics all saw increases from 50.00% to 100.00% from phase 1 to phase 2, with the *Universal* interface achieving 100.00% in shape recognition from the start. However, the *Sparse* interface initially had 0.00% recognition rates for shape, function, and association in phase 1, which then improved to 50.00% across all categories in phase 2.

*Trackpads*
In the *Dense* interface, phase 1 had shape recognition at 75%, function recognition at 50%, and association recognition at 0%, with all metrics reaching 100% in Phase 2. The *Room* interface showed similar outcomes. Shape recognition started and remained 100% in the *Universal* interface, while Function and Association Recognition were constant at 50% across both phases. The *Sparse* interface maintained 100% in shape, function, and association recognition from

phase 1 into phase 2.

*Section Boundaries*
In both *Dense* and *Room* interfaces, section boundaries were recognized at 100.00% in phases 1 and 2. The *Universal* interface detected boundaries at 100.00% in phase 1 but not in phase 2, resulting in a 0.00% detection rate. The *Sparse* interface maintained a 100.00% detection rate in both phases.

*Light Helper Lines (Room)*
In the *Room* interface, the guidelines indicating that the Bulb buttons belong to the lower middle control area were recognized in both phases.

*Seperator Line (Universal)*
With the *Universal* interface, the dividing line between the selection and control areas was recognized in both phases, but not what this could be for.

For the general recognition rate of the interfaces, we calculated the average recognition rate of all interfaces. In phase 1, the recognition rate was as follows: The *Dense* interface was recognized at 43.15%, the *Room* interface at 41.07%, the *Universal* interface at 58.7%, and the *Sparse* interface at 50.41%. By Phase 2, these rates increased to 84.52% for the *Dense* interface, 82.74% for the *Room* interface, 83.77% for the *Universal* interface, and 67.86% for the *Sparse* interface.

### 6.7.2 User Preferences (1. and 2. Phase)

In phase 1, *Sparse* performed the best and *Room* the worst; in phase 2, all interfaces improved, with *Sparse* still in the lead and *Universal* showing the greatest improvement.

In the first phase, *Dense* and *Room* had a mental effort rating for exploration of 1.5, *Sparse* had 0.5, and *Universal* was highest at 2.0. *Room* and *Dense* had 1.0 rating for haptic identification and *Sparse* and *Universal* both had 0.5. In the second phase, the mental demand of *Dense* decreased to 0.5, of *Room* to -0.5, while *Sparse* and *Universal* remained at 0.5. Haptic load for *Room* and *Dense* decreased to -0.5, and *Sparse* and *Universal* stayed at 0.5.

Initially, the *Sparse* interface was perceived as the most structured (2.0), ahead of the *Universal* interface with 1.5. *Dense* and *Room* had the worst performance with 1.0. In the second phase, the clarity score was improved for all interfaces. *Dense* and *Room* increased to 2.5 and *Dense* also increased by 1.5 for orientation. *Sparse* scored best with 3.0 for layout structuring and 2.0 for orientation, while *Universal* increased to 2.5 for structuring but remained at 1.5 for orientation.

In the first phase, *Sparse* was the easiest to distinguish between the smart home applications (3.0), while *Universal* and *Room* received a rating of 2.0. *Dense* was perceived as the most difficult with 1.5. In the recognition of already perceived application areas, *Sparse* reached 3.0, *Universal* 2.5, *Room* 2.0, and *Dense* 1.5. In the second phase, recognition improved across the interfaces; *Room* and *Universal* went up to 2.5, *Dense* to 2.0, while *Sparse* remained at a stable 3.0 for differentiation. This led to revisiting scores at 2.5, with *Room*, *Universal*, and *Dense* all at 2.0.

*Room* was rated highest for understanding the smart home functions in the first phase (2.0). In contrast, *Sparse* scored best for haptic recognition of UI shapes (2.0) and understanding of UI element's purposes (1.5). *Dense* received the lowest score for understanding functions (-0.5). Smart home areas were recognized as best on the *Sparse* interface (1.0), with the *Room* interface at the bottom (0.0). Improvements were seen across all interfaces in the second phase. The *Sparse* interface led with a 2.0 in function understanding and peaked in haptic shape recognition (2.5) and purpose understanding (2.5). All interfaces saw better recognition of smart home areas, with the *Sparse* at 2.5 and the others at 2.0.

The *Sparse* interface scored highest overall in the first phase, while the *Room* interface had the lowest ratings. In the second phase, all interfaces showed improvement, with the *Sparse* interface remaining the top-rated, followed by the *Dense* interface. The *Room* and *Universal* interfaces also improved, with *Universal* showing the most improvement.

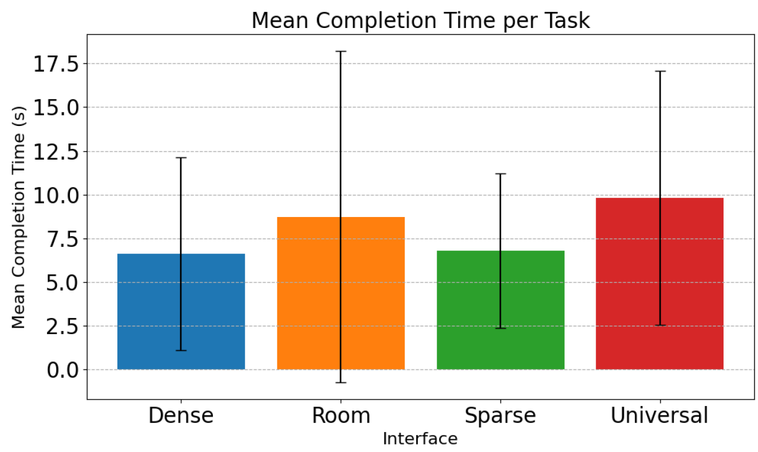



**Figure 6.5:** Task completion times study 2 task phase: Mean completion time per task and interface with standard derivation.

### 6.7.3 Task Results

The *Dense* interface had the shortest task processing time, while *Universal* took the longest. *Sparse* had the most intentional errors, while *Room* had the fewest unintentional errors.

*Dense* showed the shortest task completion time (6.6 seconds) for the interfaces in the task phase. The worst result was achieved by *Universal* with 9.79 seconds. There is a high variation in the results between the users, especially for *Room* and *Universal*. These results are illustrated in Figure 6.5.

In terms of intentional errors, *Sparse* had the highest average number of intentional errors per task with 1.29 (SD 1.38), followed by *Dense* with 1.20 (SD 1.31), *Universal* with 0.97 (SD 1.26) and *Room* with 0.83 (SD 1.13). Counting errors are specific types of errors occurring on all interfaces. This type of unintentional error occurs when a user wants to select an element of an application by pressing a line number (for example, the right ceiling light). Then, from left to right or right to left, the other line numbers are counted haptically until the desired line number is reached. *Dense* had 0.2 (SD 0.68) unintentional errors per task, including six wrist-triggered and five counting errors. *Room* had 0.05 (SD 0.29) unintentional errors, with two errors due to wrist activation. *Sparse* had an average of 0.09 (SD 0.29) unintentional errors per task, with ten wrist and

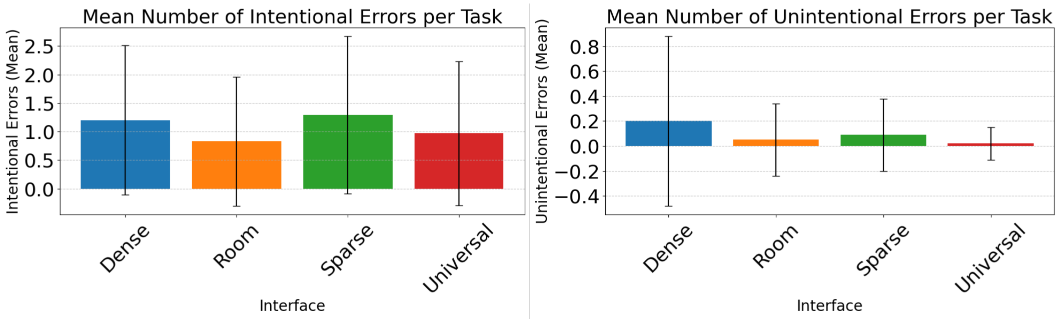



**Figure 6.6:** Errors study 2 task phase: Intentional (left) and unintentional (right) errors per task and interface with standard derivation.

counting errors. In contrast, *Universal* had 0.02 (SD 0.13) unintentional errors per task—also ten wrist and counting errors in total. These results are illustrated in Figure 6.6.

### 6.7.4 User Preferences (Task Phase)

The *Universal* interface performed best in the user preferences questions. In the ranking, *Universal* was also ranked 1st most frequently.

The layout and structure results show different patterns regarding clarity, orientation, and the differentiation of application areas. The *Dense* interface had positive ratings for layout clarity and orientation (mean: 1.4; sd: 2.07), and section boundaries were helpful. The *Room* interface received high ratings for layout clarity (mean: 1.6; sd: 1.67) and orientation (mean: 1.8; sd: 1.64). The *Sparse* interface's layout clarity was rated positively (mean: 2.0; sd: 1.22), but application area differentiation was lower (mean: -0.2; sd: 2.17). The *Universal* interface scored the highest in clarity and orientation (both mean: 2.0), with the latter having the lowest sd (0.71), making it the best-rated layout overall in this category.

The results of the questions on the interface elements showed differences in mental effort and haptic recognition. For *Dense*, recessed icons (mean: -1.6; sd: 2.07) and trackpads (mean: -1.8; sd: 2.17) were perceived as less mentally demanding, while raised icons (mean: 1.4; SD: 2.07) and sliders (mean: 1.2; SD: 2.05) were perceived as more demanding. For *Room*, sliders (mean: 1.4; sd: 1.82), trackpads (mean: 1.6; sd: 1.52), and recessed icons (mean:

-0.8; sd: 2.59) were perceived as less mentally demanding. *Sparse* shows a similar pattern, with sliders (mean: 1.2; sd: 2.49) and raised icons (mean: 1.2; sd: 1.48) as less demanding but recessed icons and trackpads as harder (mean: -1.8; sd: 1.10). The *Universal* interface found nearly all elements like sliders (mean: 2.2; sd: 1.79) and section boundaries (mean: 1.4; sd: 2.19) easier, except for recessed icons (mean: -2.2; sd: 1.10). Overall, raised icons and sliders were consistently seen as less mentally demanding. In contrast, recessed icons and touchpads were viewed as more difficult across interfaces, particularly in the *Sparse* interface.

The results of the task performance questions highlighted differences in the interfaces. *Dense* had a task completion ease of 2.2 (sd: 1.3), but finding the right controls for the tasks was not perceived as very easy (mean: -1.6, sd: 1.67). *Room* had a task completion ease of 1.8 (sd: 0.84), whereby finding the controls was perceived as easier (mean: -0.2, sd: 2.17). For the *Sparse* interface, task completion was easiest (mean: 2.6, sd: 0.55), yet control finding was slightly challenging (mean: -0.4, sd: 2.17). The *Universal* interface had a task completion score of mean: 2.2, sd: 1.1, and the easiest control finding (mean: 0.0, sd: 2.0).

The analysis of the functionalities and interaction issues has revealed differences in the understanding of the application and the differentiation between the areas. *Dense* achieved an average comprehensibility of 1.0 (sd: 1.58) and area distinction of 0.8 (sd: 1.79). *Room* was rated higher, with 1.4 (1.67) for comprehensibility and 1.6 (sd: 1.67) for distinction. *Sparse* scored lower in comprehensibility at 0.8 (sd: 1.64) but higher in distinction at 1.0 (sd: 1.87). The *Universal* interface outperformed all with 2.0 (sd: 1.0) scores for both comprehensibility and area distinction.

The user preferences, based on the user ranking of the interfaces, showed differences between the interfaces. Most participants preferred *Universal*, as it was ranked first most often. *Room* was never placed at rank 1, but most often at rank 2. *Sparse* was ranked 1st and 2nd several times. *Dense* was ranked fourth most often, suggesting that

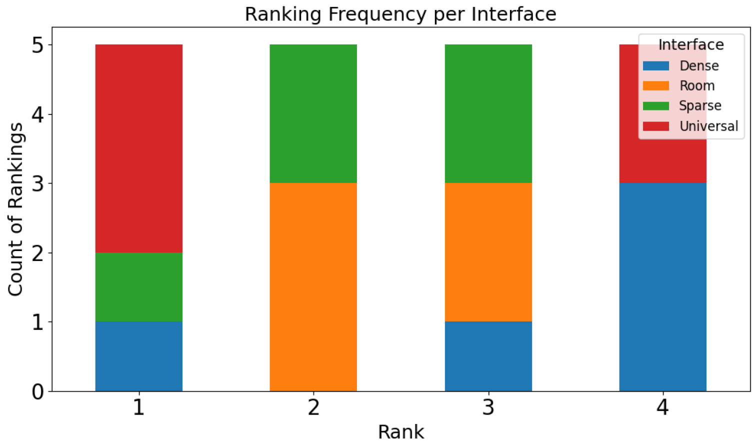



**Figure 6.7:** Interface user ranking study 2: The *Universal* interface was ranked the highest, followed by the *Sparse* and *Room* interfaces, while the *Dense* interface received the lowest rankings.

it was the least favored overall. The ranking is illustrated in Figure 6.7.

### 6.7.5 Exploration Strategies

In this subsection, we will highlight the different exploration strategies used by the participants during the three phases of the study.

The feedback and knowledge about the interfaces changed the exploration strategies of the participants by improving their navigation and understanding of the controls.

In the first phase, participants used different strategies to explore the interfaces haptically. In the *Dense* interface, for example, the surface was slowly felt and the shapes of interface elements were identified using several fingers. Another participant oriented himself using the edges of the interface and then recognized that horizontal lines divide the interface into segments, which made navigation easier for this participant. In the *Sparse* interface, the participant first searched for an anchor point and then the dividing lines to navigate between the modules. In the *Universal* interface, the edges of the interface were first explored to get an impression of the size of the interface before exploring the modules and interface shapes haptically in more detail.

In the second phase, feedback led to an adaptation of the strategies. In the *Dense* interface, one participant realized that lights can be selected using the numbers 1 to 4, and the TV functionalities and light controls became easier to understand. In the *Room* interface, the feedback helped to better understand various controls, such as +/- and the mousepad as part of the TV controls. The participant in the *Sparse* interface started to try out unfamiliar symbols and see which feedback was triggered to better understand them. In the *Universal* interface, the feedback improved the understanding and navigation between the selection of applications and the control of the applications and led to the participant understanding that it was a universal control. Participants continued to change their strategies after learning about the interfaces in the third phase. In the *Dense* interface, they remembered the position of controls such as touchpads, sliders, and circles to find the right segments more quickly. In the *Room* interface, the participant understood better that the physical space corresponded to the layout of the interface, which made navigation easier, even if finding individual light controls was sometimes perceived as difficult. The wider spacing and gaps in the *Sparse* interface helped improve orientation, as the participant was less afraid of accidentally activating the wrong controls. In the *Universal* interface, knowledge of the position of the symbols made navigation considerably easier, as the participant could search for specific elements and less exploration was required.

In addition to the strategies described, the heat maps created from the touch data of the first and second phases provide further insights. These heat maps show which period phase and interface a user touched which elements.

Figure 6.8 shows the heatmap of the 1st phase of the *Dense* interface. Here, you can see that the central trackpad and the central slider are an anchor point for users across all periods. This can also be seen in the other interfaces (Appendix C). As we had technical problems with the *Sparse* interface in the second phase, it was not possible to create a heat map of it. It can also be seen that the more the participant feels the upper part of the interface, the more wrist errors occur, especially with the *Dense* interface. It is also no-

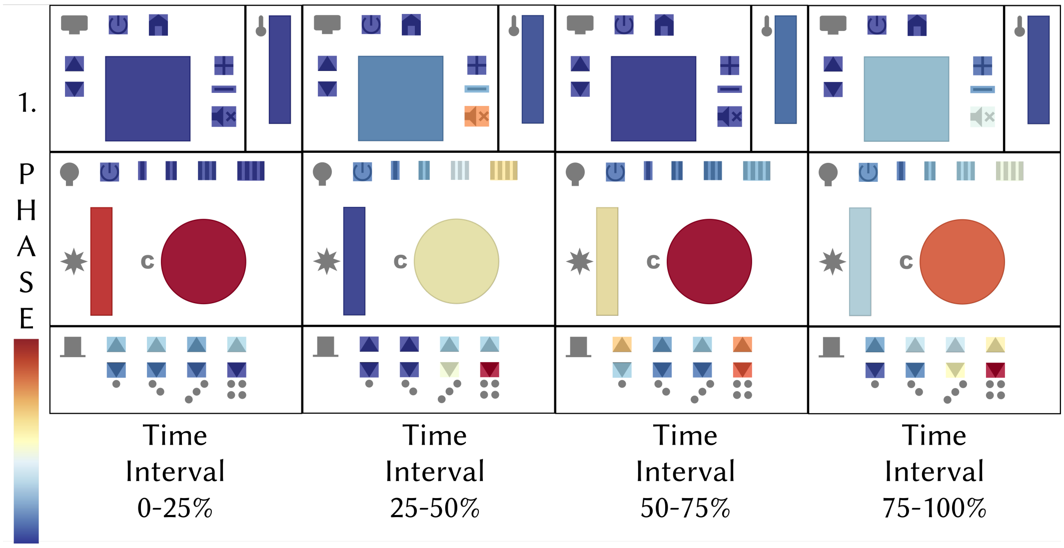



**Figure 6.8:** Interaction heatmap *Dense* 1. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

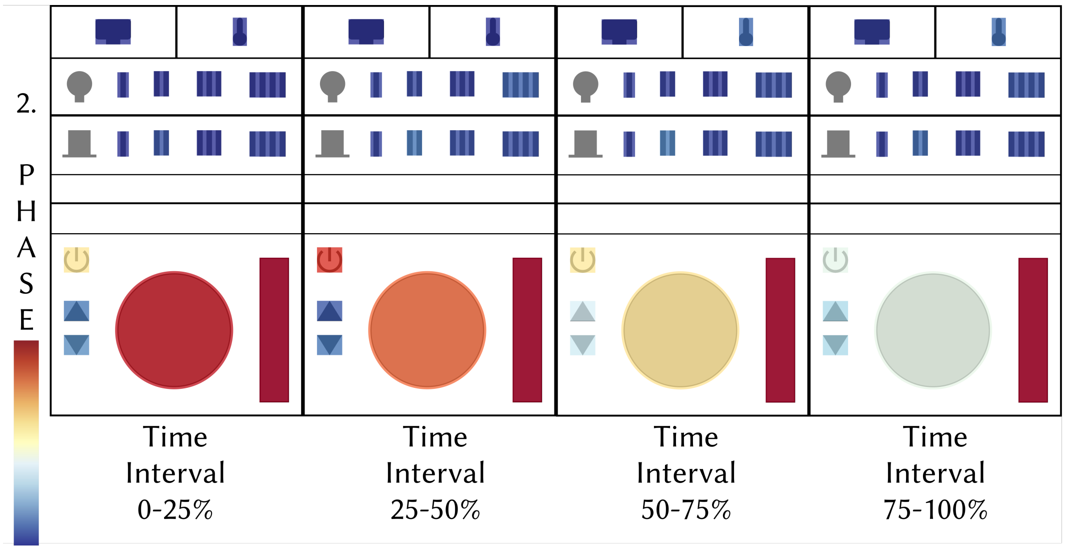



**Figure 6.9:** Interaction heatmap *Universal* 2. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

ticeable that the lower area of the interface is touched more frequently than the upper area with longer interfaces, i.e., with *Dense* and *Universal*. This is particularly interesting for *Universal* (Figure 6.9), as it could be assumed, especially in phase 2, that the touch times for the upper and lower areas are balanced due to the type of operation.

## 6.8 Discussions

Through the study and our four interface designs, we tried to understand how users interact with larger textile interfaces, focusing on haptic interaction. As the number of participants was limited, the interpretations of the results presented here should only be considered as the first possible initial insights. These findings should be further investigated in future studies with a larger sample.

One possible insight from the results is that *Universal* is less intuitive and more difficult to understand without additional help (feedback or knowledge about the interface) than the other interfaces. Application recognition specifically was worst in the first phase, suggesting that users had difficulty understanding the applications and their functions without additional help. However, when feedback was added in the second phase, overall interface recognition was strong, including shape and function recognition of the UI elements. This could be due to the increased complexity of operating *Universal*, caused by the separation of the selection and control areas. This separation may make it more difficult for users to understand the interface's functionality without additional help. The initially high mental load in the first phase, which also decreases in the second phase, could indicate this.

Another aspect is that white space, as used in *Sparse*, could be an orientation aid for larger textile interfaces. Participants could better orient themselves in this interface, as shown by the Likert scale on structure and orientation and by indicating a lower mental load. One participant explicitly mentioned that it was easy to remember in which corner an application was placed, which could be due to the existing white space. Although applications in the corners could also be remembered in denser interfaces, the white space in the middle of the *Sparse* interface could make orientation easier by providing a clearer spatial separation.

Feedback is another aspect that influenced the understanding and usability of the interfaces, which was an important factor in the study. The data indicate that interface recognition was improved for all interfaces through feedback. Especially the recognition of raised icons increased strongly, but not of recessed icons. This could be because the feedback in phase 2 gave raised icons clear functionality, while recessed icons remained without feedback. In addition, the recognition of raised icons in phase 1 was higher than that of recessed icons, similar to Schäfer et al.'s results. This suggests that feedback could also be important in larger textile interfaces.

Another important observation is that section boundaries were more helpful, especially with denser interfaces. Although section boundaries were generally found to be moderately helpful in all interfaces, this was highest for *Dense*. This could indicate that section boundaries could be especially helpful in tighter interfaces to provide clear separations between control areas, which was already done by white space in *Room* and *Sparse*. Interestingly, this was not the case with *Universal*, even though it was designed with minimal white space. One possible reason could be that the application controls are separated in the *Dense* interface, and each application has its controls. The section boundaries could, therefore, additionally support this clear separation by helping users to better distinguish between the different application areas.
It is also noticeable that *Dense* interfaces increase the number of unintentional errors. This is particularly noticeable in the *Dense* interface, where a wrist error occurred more frequently in the lower right area of the blinds control than in the other interfaces. Interestingly, these errors are less common in the *Universal* interface, although this is also *Dense*. This could be due to the separation between the selection and control areas, which means that users may

move their hands directly over the control area to reach the selection area.

# Chapter 7

# Summary and Future Work

## 7.1 Summary and Contributions

In this thesis, we investigated how users interact with larger textile interfaces, i.e., a combination of visual design guidelines and existing single textile control guidelines, in the context of smart homes and how these are understood in an eyes-free interaction. We wanted to understand what potential problems could arise and what the possible causes might be.

Since larger textile interfaces require additional control elements that have not yet been sufficiently researched, we have expanded our textile control set in our first study based on the study by Schäfer et al.. Material design icons, alternative versions, and a round and rectangular trackpad were systematically tested. Four interface designs were created based on this and other visual design guidelines and non-textile and textile haptic design guidelines. The four interfaces are based on a spatial (*Room*), a modular (*Dense*), and a universal (*Universal*) metaphor and additionally (*Sparse*), which extends the modular metaphor. These prototypes were then used in the second study and divided into three phases to investigate user behavior and understanding of these interfaces. In the first phase, participants explored the interfaces without additional feedback, and in the second phase, with feedback using a virtual smart home space. In the third phase, the participants then carried out tasks with the interfaces.

Even though we had little data due to the small number of participants in the second study, we were able to gain possible insights. Interfaces that use white space could improve orientation and reduce mental load without increasing the speed of interaction. In contrast, narrow interfaces could provide fast access to control elements but increase the risk of unintentional activations. The *Room* interface showed potential in terms of the learning curve, as users improved efficiency and accuracy with feedback and knowledge of the interfaces. The *Universal* interface showed potential difficulties for new users who are not yet familiar with it and when there is also no feedback during use. Only through the feedback received and an increasing understanding of how the interface worked was an improvement in interaction and efficiency seen.

Based on this, we have identified first possible recommendations for designing larger textile interfaces:

- When using more complex input mechanics such as the *Universal* interface, it should be ensured that expert users operate them.
- Recessed icons and lines should be used for secondary information, as these are more easily overlooked.
- When selecting different icon designs, choose simple shapes for better recognition.
- Do not use bordered icons to indicate that an icon consists of several components.

However, these recommendations should only be seen as initial possible insights due to the limited data available.

## 7.2 Future Work

Due to the low number of participants in the second study, this study should be conducted with a larger and more diverse number of participants. In particular, participants from outside the STEM sector should also be studied. This would help to examine the possible insights of this work in more detail.

In addition, the prototypes should be further optimized, as the shielded cables for the capacitance measurement are very sensitive and make the study more difficult. An improved technical implementation would possibly lead to more robust results and simplify the subsequent processing and analysis. It should also be considered whether the study should be conducted in a real smart home environment to obtain more realistic results.

Another important aspect for future work is investigating the relationship between recessed and raised icons placed on the same interface. Although previous studies such as Schäfer et al. have shown that raised and recessed icons work in a textile context, it must be clarified whether combining both, especially with recessed icons as signifiers, is helpful. It should also be investigated whether signifiers are necessary for larger textile interfaces focusing on haptic recognition.

It would also be valuable to test what happens if the control elements are not placed on a single textile interface but are positioned directly on each application's devices in the room or, in general, in different areas the user can reach.

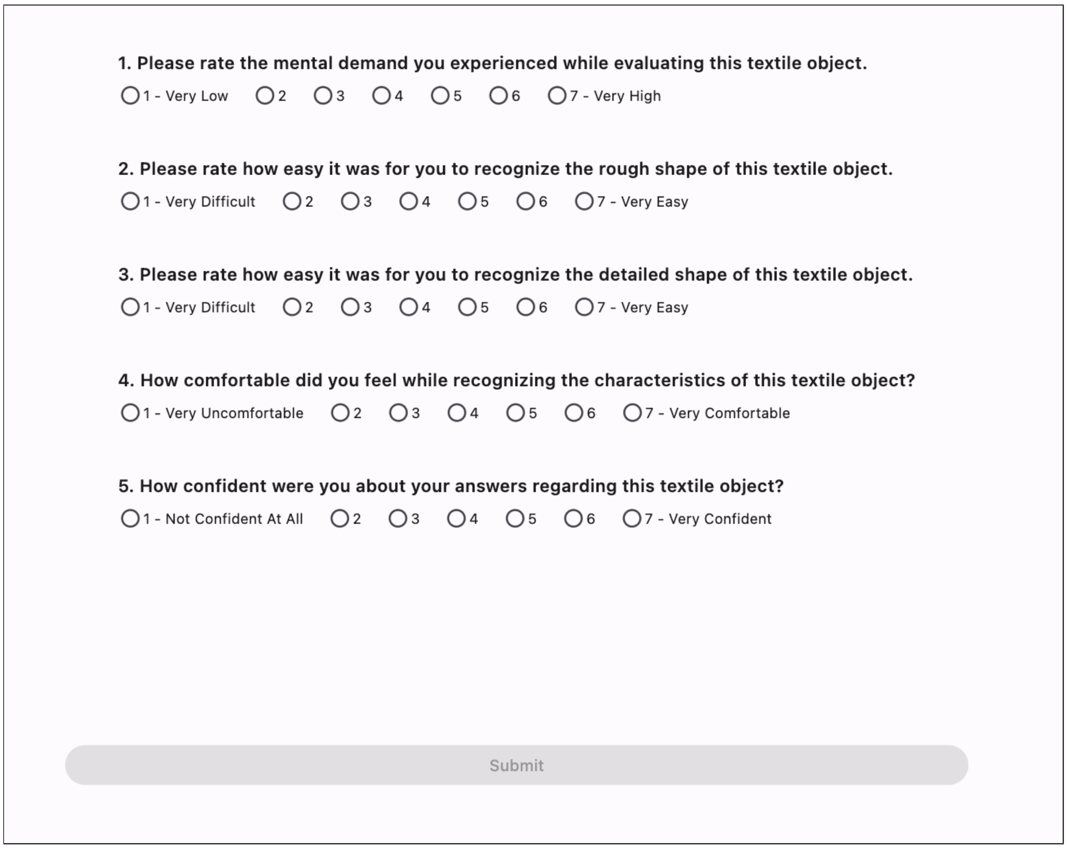
In order to gain deeper insights into user behavior, it would be useful to study larger textile interfaces over longer periods. A long-term study could uncover deeper problems that may not be visible in short-term tests. Users could learn to interact with the interfaces over a longer period, providing new insights into efficiency and usability that become more relevant with repeated use.

Even if this work could show that feedback for larger textile interfaces is also important for the user experience, it would be interesting to investigate haptic feedback. This could give the user clear signals, such as vibrating the touched surface, as to whether a control has been touched. The combination of visual and haptic feedback could make the operation of larger textile interfaces easier to understand.

Finally, it would be interesting to investigate how users use larger textile interfaces when personalized. Exploring the customizability of larger textile interfaces in that users can customize the layout to their liking could give important insights into the optimal design of larger textile interfaces.

# Appendix A

# Study 1: Questionnaires



1. Please rate the mental demand you experienced while evaluating this textile object.
○ 1 - Very Low ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Very High

2. Please rate how easy it was for you to recognize the rough shape of this textile object.
○ 1 - Very Difficult ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Very Easy

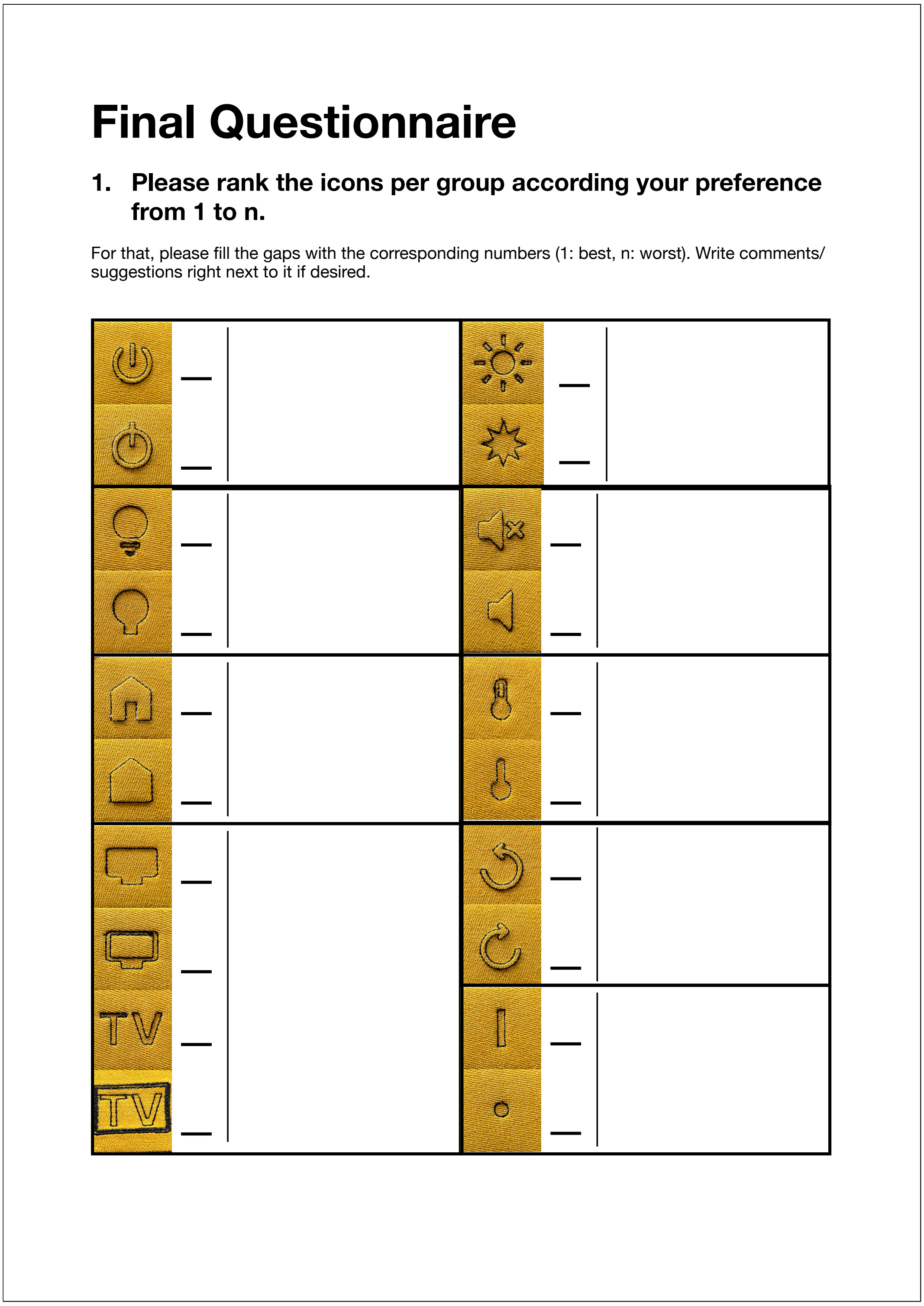
3. Please rate how easy it was for you to recognize the detailed shape of this textile object.
○ 1 - Very Difficult ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Very Easy

4. How comfortable did you feel while recognizing the characteristics of this textile object?
○ 1 - Very Uncomfortable ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Very Comfortable

5. How confident were you about your answers regarding this textile object?
○ 1 - Not Confident At All ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Very Confident

Submit

**Figure A.1:** Questionnaire for study 1 between each icon round: Mental demand, perceived ease of rough shape recognition, perceived ease of shape features recognition and the question about the confidence in answers.



# Final Questionnaire

## 1. Please rank the icons per group according your preference from 1 to n.

For that, please fill the gaps with the corresponding numbers (1: best, n: worst). Write comments/ suggestions right next to it if desired.



**Figure A.2:** First page of the final questionnaire (study 1): Ranking of icon groups *On/Off, Sun, Bulb, Mute, Home, Thermostat, TV, Forward/Backward Arrow, Enumaration 1*

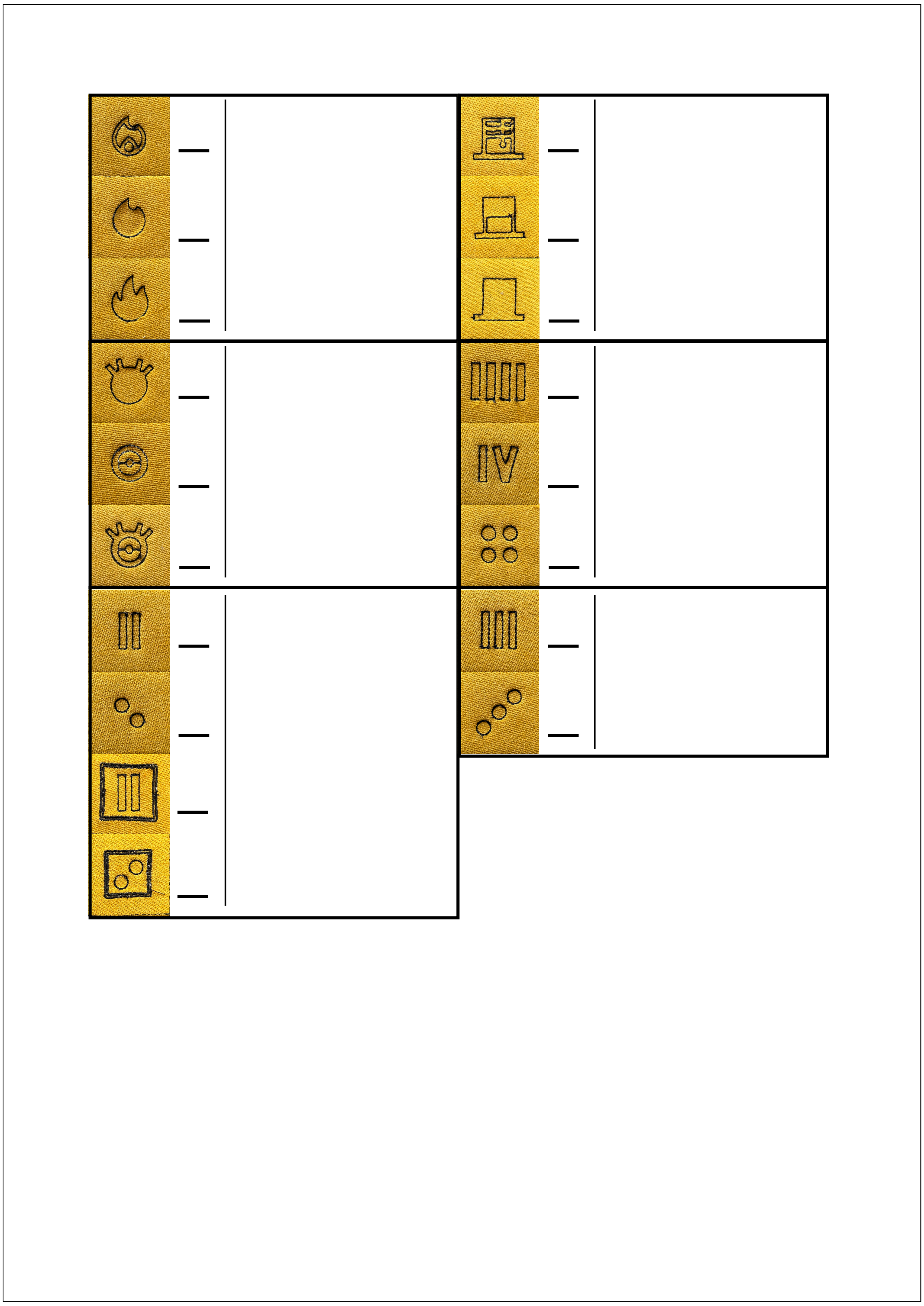


**Figure A.3:** Second page of the final questionnaire (study 1): Ranking of icon groups *Hot*, *Blinds*, *Robot Vacuum Cleaner*, *Enumaration 2*, *Enumaration 3*, *Enumration 4*

**2. I found the Raised Icons comfortable to touch.**

○ 1 - Totally Disagree ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Totally Agree

**3. I found the Recessed Icons comfortable to touch.**

○ 1 - Totally Disagree ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Totally Agree

**4. The borders around certain pairs of shapes helped me recognizing the shapes as belonging together.**

○ 1 - Totally Disagree ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Totally Agree

**5. I could differentiate the Box from the shape well**

○ 1 - Totally Disagree ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Totally Agree

**6. For icons consisting of multiple shapes without borders, I found that the closeness of these shapes aided in recognizing them as belonging together.**

○ 1 - Totally Disagree ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 - Totally Agree

**Figure A.4:** Third page of the final questionnaire (study 1): Questions about comfort raised icons, comfort recessed icons, recognition of grouped icons with border and recognition of grouped icons without border.

# Appendix B

# Study 2: Questionnaires

# 1. Phase: Questionnaire 1

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| Exploring the interface was mentally demanding. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Distinguishing the areas of the different smart home applications was easy. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently distinguish the areas of the smart home applications. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| It was easy to understand the supported functionalities of the different smart home applications. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently understand the supported functionalities of the different smart home applications. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |

Please list recognized smart home applications with their supported functionalities:

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| Identifying the UI elements haptically was mentally demanding. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| It was easy to recognize the shapes of the UI elements haptically. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently recognize the shapes of the UI elements haptically. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| It was easy to understand the purpose of the UI elements. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently understand the purpose of the UI elements. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| It was easy to understand which UI elements belong to which smart home applications. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently identify to which smart home application a UI element belonged. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |

**Figure B.1:** Questionnaire for study 2 after no feedback phase. First page.

Please list the types of UI elements, their possible uses, and the smart home applications to which they may belong you have recognized.

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| The overall layout arrangement of the interface felt clear. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Orientating on the interface was easy. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| If I revisited the area of a smart home application, it was easy to recognize it again. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

## Additional Characteristics

Can you describe the strategy you used to explore the interface and identify different UI elements and applications?

**Figure B.2:** Questionnaire for study 2 after no feedback phase. Second page.

What were your first impressions of the interface, and how did those impressions change as you explored it further?

Were there anything on the interface that you found ambigiuous or confusing? If so, please describe them.

**Figure B.3:** Questionnaire for study 2 after no feedback phase. Third page.

# 1. Phase: Questionnaire 2

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| Exploring the interface was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Distinguishing the areas of the different smart home applications was easy. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently distinguish the areas of the smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to understand the supported functionalities of the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently understand the supported functionalities of the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

Please list recognized smart home applications with their supported functionalities:

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| Identifying the UI elements haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize the shapes of the UI elements haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of the UI elements haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to understand the purpose of the UI elements. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently understand the purpose of the UI elements. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to understand which UI elements belong to which smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently identify to which smart home application a UI element belonged. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

**Figure B.4:** Questionnaire for study 2 after feedback phase. First page.

Please list the types of UI elements, their possible uses, and the smart home applications to which they may belong you have recognized.

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| The overall layout arrangement of the interface felt clear. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Orientating on the interface was easy. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| If I revisited the area of a smart home application, it was easy to recognize it again. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The provided feedback was understandable. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The provided feedback helped improve my understanding of the UI elements. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The provided feedback helped in distinguishing the areas of the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The provided feedback helped improve my understanding of the supported functionalities of the different smart home applications | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

**Figure B.5:** Questionnaire for study 2 after feedback phase. Second page.

## Additional Characteristics

Did the provided feedback change your exploration strategy of the interface and the identification of the UI elements and applications? If yes, please describe how.

Were there anything on the interface that you found ambigiuous or confusing? If so, please describe them.

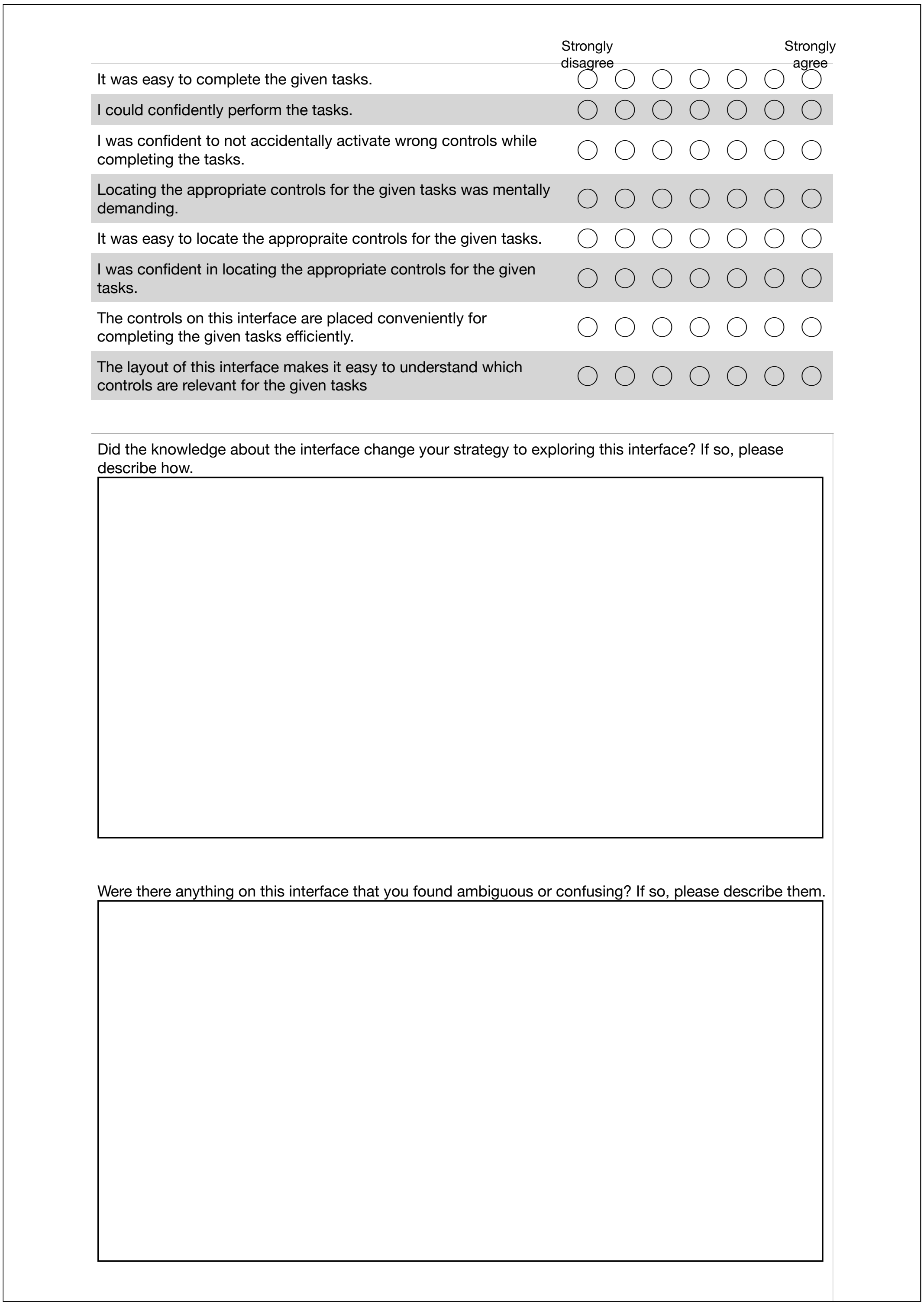
**Figure B.6:** Questionnaire for study 2 after feedback phase. Third page.

## 2. Phase Questionnaire (Dense)

| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| Exploring the interface was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Distinguishing the areas of the different smart home applications was easy. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently distinguish the areas of the smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to understand the supported functionalities of the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently understand the supported functionalities of the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The section borders helped me distinguishing between the different smart home applications. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Recognizing raised icons haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize raised icons haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Recognizing recessed icons haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize recessed icons haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Recognizing sliders haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize sliders haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Recognizing touchpads haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize touchpads haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Recognizing section boundaries haptically was mentally demanding. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| It was easy to recognize section boundaries haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of raised icons haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of recessed icons haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of sliders haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of touchpads haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| I could confidently recognize the shapes of section boundaries haptically. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| The overall layout arrangement of the interface felt clear. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| Orientating on the interface was easy. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| If I revisited the area of a smart home application, it was easy to recognize it again. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| The concept of the interface was easy to understand. | ○ | ○ | ○ | ○ | ○ | ○ | ○ |

**Figure B.7:** Questionnaire for study 2 after every 12 Tasks for one interface design. Examplary shown for Dense interface, questionnaires for the other interface designs sing identical. First page.



| | Strongly disagree | | | | | | Strongly agree |
|---|---|---|---|---|---|---|---|
| It was easy to complete the given tasks. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I could confidently perform the tasks. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I was confident to not accidentally activate wrong controls while completing the tasks. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| Locating the appropriate controls for the given tasks was mentally demanding. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| It was easy to locate the appropraite controls for the given tasks. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| I was confident in locating the appropriate controls for the given tasks. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| The controls on this interface are placed conveniently for completing the given tasks efficiently. | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |
| The layout of this interface makes it easy to understand which controls are relevant for the given tasks | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ |

Did the knowledge about the interface change your strategy to exploring this interface? If so, please describe how.

Were there anything on this interface that you found ambiguous or confusing? If so, please describe them.

**Figure B.8:** Questionnaire for study 2 after every 12 Tasks for one interface design. Examplary shown for Dense interface, questionnaires for the other interface designs sing identical. Second page.

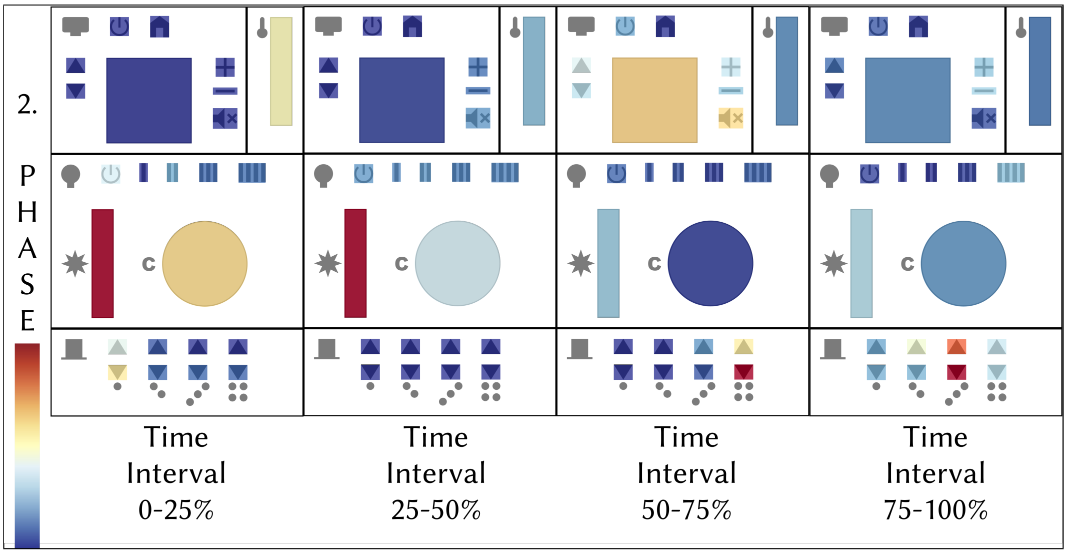



**Figure C.1:** Interaction heatmap *Dense* 2. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

# Appendix C

# Study 2 Interface Heatmaps

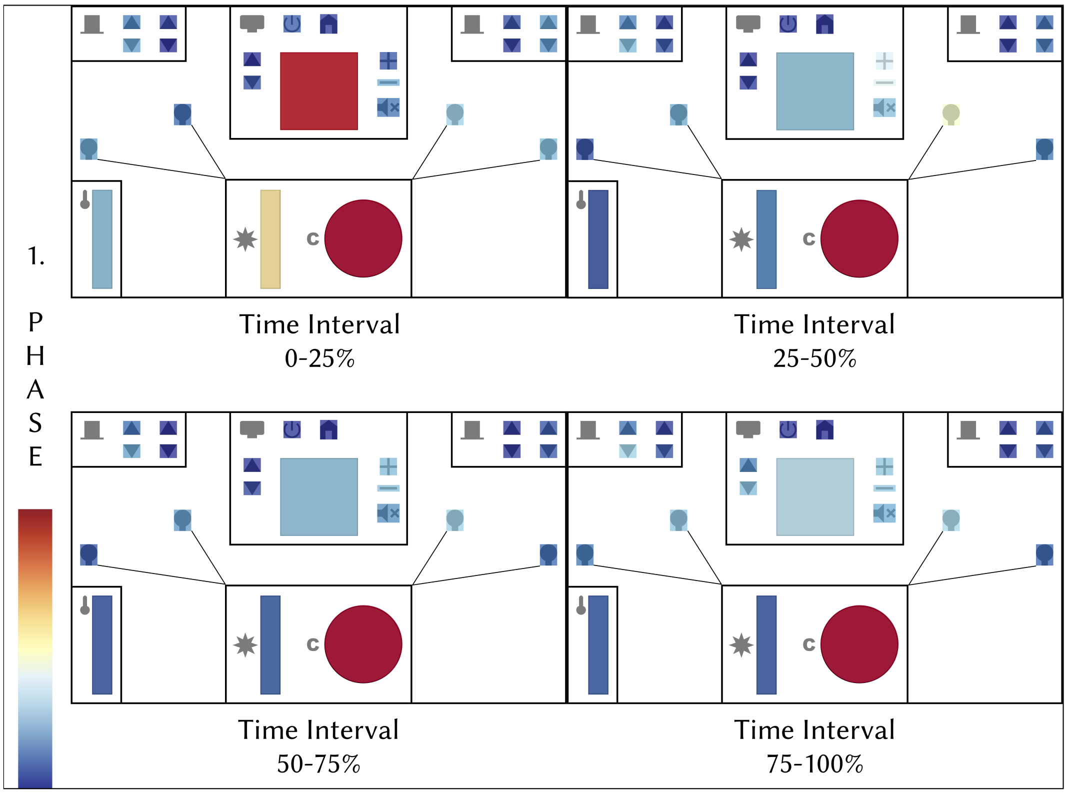



**Figure C.2:** Interaction heatmap *Room* 1. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

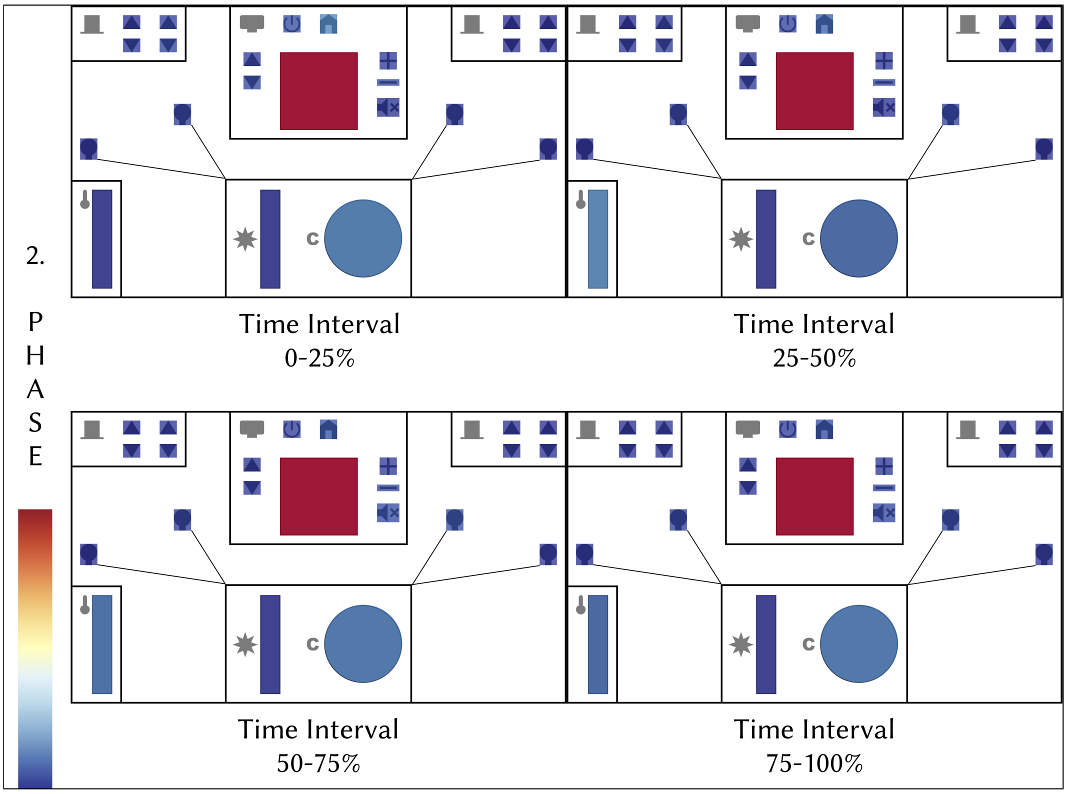



**Figure C.3:** Interaction heatmap *Room* 2. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

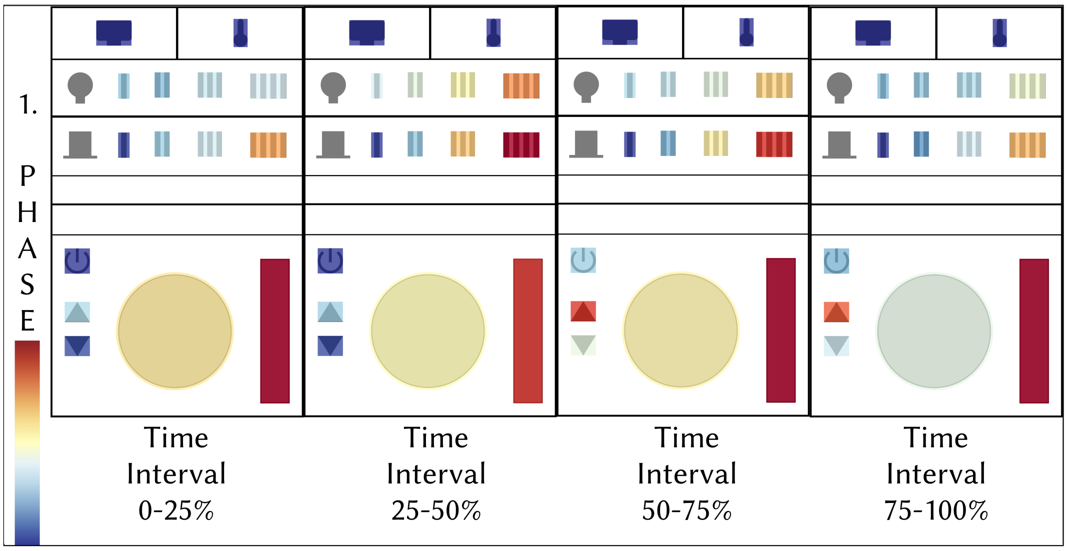



**Figure C.4:** Interaction heatmap *Universal* 1. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

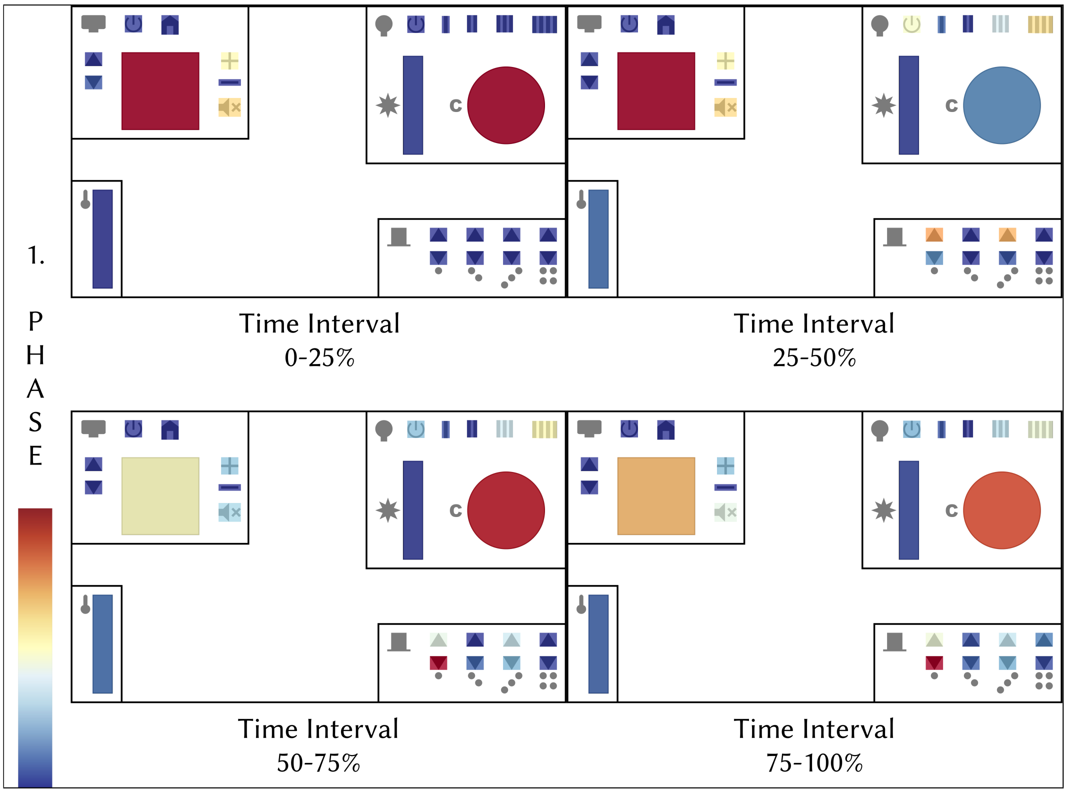



**Figure C.5:** Interaction heatmap *Sparse* 1. phase: The heatmap shows the controllable elements' interaction in four time periods. The colors are about each period. Blue means not touched to little touched, and red means touched a lot.

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