Where am I? Investigating Compound Textile User Interfaces for Eyes-Free Use

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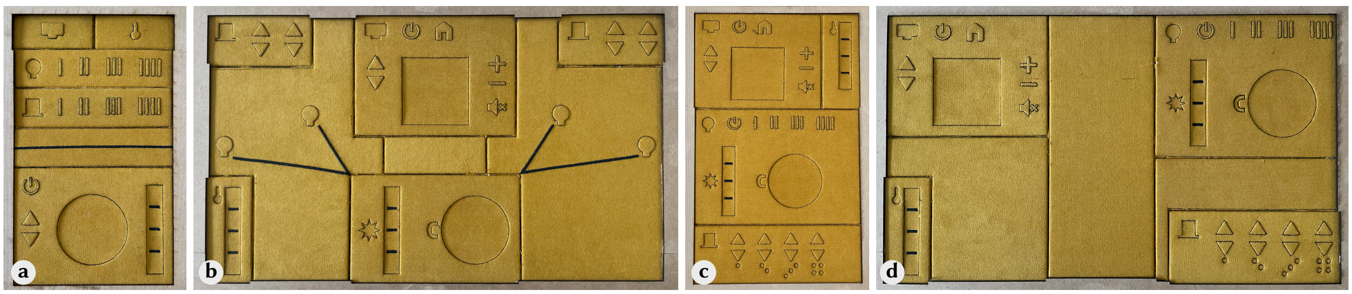

Figure 1: We investigated four textile interfaces implementing three composition concepts: a) *Universal*, b) *Mapping*, c) *Categories*. d) *Sparse* is a variant of *Categories* to investigate the effect of blank space on usability. All interfaces were used to control a virtual 3D living room and included controls for lights, blinds, room temperature, and a TV.

Abstract

The haptic properties of textile interfaces support eyes-free use well. However, user interfaces often require composing many controls, which complicates orientation by palpation. We investigated three composition concepts that combine textile components in different ways, using a sample smart home scenario: One uses the select-and-control flow of universal remotes, one resembles the users' environment, and one divides the interface into application sections. Of the latter, we also created a spacious variant to observe the effect of blank space between interface regions. We first explored how well users understand those composition concepts when first using the interface eyes-free. After familiarization, we measured input performance and preferences. We found task completion times much faster than expected from previous recognition studies. While performance was similar for most interfaces, the select-and-control flow was slower, but participants preferred it after familiarization. From our findings, we derive design recommendations for compound textile UIs and individual components.

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CCS Concepts

• **Human-centered computing → Haptic devices**; *Ubiquitous and mobile devices*; **Empirical studies in HCI**.

Keywords

textile interfaces, smart home, design guidelines, eyes-free interaction

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1 Introduction

Textile interfaces are promising candidates for digitally extending our environment since fabrics are already widely used in objects such as sofas, pillows, or table runners. Unlike touchscreen interfaces, the haptic properties of textile interfaces support eyes-free use so that users can focus on the controlled target instead of the controls. This gets especially handy when the environment is dark, the interface is out of sight (e.g., on the side of an armchair), or when it is covered. While previous haptic recognition studies showed successful and relatively quick eyes-free recognition of single textile elements [29, 36], aspects like finding a path to a target control by palpation have not been investigated in such a scenario.

Also, research into textile input techniques has focused mostly on single interface components [21, 39, e.g.,]. Yet, real-world interfaces often need to integrate large numbers of controls. In smart homes, for example, the numerous devices and features available require more complex user interfaces. While dark scenarios are common when controlling light or media in the home, these UIs should also require as little visual attention as possible when visible.

For product designers, it remains unclear which composition concepts for textile interfaces should be used to make them easy to understand and use by palpation, while still aligning with the visual expectations and aesthetics that users bring from GUI applications. To help establish such guidelines, we compared three different interface composition concepts. We used a smart home setting as a well-known application example. Each of our composition concepts allows users to control several feature-rich smart home applications: *Universal* (Fig. 1a) imitates universal remote controls by letting users first select a target device and then change its parameters. *Mapping* (Fig. 1b) makes use of the spatial information from the users' environment by applying Norman's concept of Natural Mappings between controls and their target devices [25]. *Categories* (Fig. 1c) divides the interface into separate sections, i.e., one section for each device category. Additionally, since it is currently unclear whether distributing controls over a larger surface supports or impedes haptic exploration, we added *Sparse* (Fig. 1d), a variant of *Categories* in which the sections are clearly separated spatially and placed farther away from each other.

To create our interfaces consistently, we propose fabrication rules that use existing guidelines from the literature and our experience from designing the interfaces. To ensure that the interfaces do not suffer due to the design of the single components, we evaluated new variants of textile icons in a pre-study.

In our main study, which involved recognizing and discriminating multiple UI elements, we found that task completion on our compound interfaces took approximately the same amount of time as haptic recognition of single elements in the literature [e.g., 36]. While our interface concepts all performed similarly, participants ranked *Universal* best. Furthermore, we found that blank space creates disorientation and that recessed elements are suited for additional, secondary guidance when haptic orientation using raised elements is not sufficient.

Overall, we thus (1) present four textile user interfaces incorporating three different composition concepts, (2) report the performance and our observations of those interfaces during initial use and after familiarization, (3) derive guidelines for single textile components and their composition.

2 Related Work

Textile interface research often addresses the fabrication of new textiles that enable users to perform touch input, as in Project Jaquard [33] or ZebraSense [37]. Beyond simple touch input, many papers describe how to achieve novel and more expressive input using textiles, such as Parzer et al. [31], who presented their data processing pipeline to recognize 22 gestures, including grasping, shaking, and twisting the fabric, on their SmartSleeve. LoopSense [1] showed a fabrication approach to sense, inter alia, fabric stretches. Karrer et al. [18] utilized fabric folds so that users can roll the fold to input continuous values. Wu et al. [38] showed that even mid-air gestures like pinching two fingers or drawing a checkmark on a finger can be achieved using textile sensors. Researchers also presented artifacts that enable textiles to create output: EmotoCouch [20] and I/O Braid [30] provide output via integrated lights. Albaugh et al. [2] presented a fabrication approach to actuate stuffed machine-knitted objects by pulling dedicated strings, and ClothTiles [24] and Flextiles [9] both use shape memory alloys to create fabric deformation.

While much of this literature puts these interfaces onto clothes and other wearables, there is also research that focuses on non-wearable controls. Rus et al. [35] developed a couch that recognizes people's posture. Ikeda et al. [17] used fluorescent ink to show pictures on soft surfaces like cushions and lampshades. Chamunorwa et al. [6] elicited how participants would perform different smart home tasks on a cushion interface. Brauner et al. [4] presented an armchair that could change the position of the armrest and leg rest by using several types of textile controllers. In their study, they investigated the acceptance of textile remotes. While their participants still found a conventional plastic remote to be more practical, they liked how well the fabric controllers matched the aesthetics of the textile furniture. Looking beyond typical sofas and cushions, Heller et al. [11] presented a curtain that opens and closes using swipe gestures, and Funk et al. [7] demonstrated that even shower curtains could be extended digitally, although external devices were used to make the curtain interactive.

While many researchers provide application examples in their work, research on concrete design principles and guidelines specific to textile interfaces is still too sparse to create practical interfaces. However, initial design guidelines have been explored recently: Holleis et al. [12] investigated, inter alia, the appearance of textile controls similar to a directional pad on an apron: a clearly visible one, one using an ornamental design, and one nearly invisible. In a semi-public setting, they had participants do some media-related tasks and observed that the directional understanding of people is inconsistent, that locating controls should be possible without looking, that participants preferred smart clothes over phone use, and that the visual appearance of the controls mattered to their participants. Mlakar and Haller [23] derived design guidelines through brainstorming sessions with experts of different domains and additional experiments on how to create haptic contrast on textile elements. They found that raising elements above the environmental surface creates the most contrast, followed by the UI element shape. They found more ambiguous results on different textures. Furthermore, they elicited affordances from recessed buttons and other shapes where the outline was made recessed on the textile. Nowak et al. [28] investigated different designs for textile sliders, finding that straight, recessed sliders with varying tick mark designs helped their participants best orient themselves on the sliders. To add semantics to the interfaces, Schäfer et al. [36] investigated how textile icons should be fabricated to achieve confident recognition. Nowak et al. could not observe that placing icons next to each other influences recognition performance of the single ones [29], and that their participants preferred larger icons for recognition than usually used [27].

Those guidelines, however, mostly focus on single elements. When artifact contributions for textile interfaces also include application examples with combined controls [e.g., 12, 16, 19, 32], the design rationale—except for technical considerations—is often not the focus of the work. However, textile UI designers can adapt guidelines from non-textile interfaces: For people who are blind or have low vision (BLV), swell paper is often used to create tactile graphics [34] and maps [13, 14]. Race et al. [34] presented guidelines to create novice-friendly, readable tactile schematic drawings focusing on labeling, symbol sizes, space, and creating contrast. Holloway et al. [13, 14] developed guidelines for 3D-printed objects used with swell paper graphics. They found that pathways on such maps should be the size of a finger and icons to be at least 1 cm apart. For exploring music notations, Challis and Edwards [5] presented an interface that uses plastic sheets on top of a touchscreen and derived several design guidelines that include avoiding empty space, not making people move out of a comfortable area to find controls, and that visual-to-tactile mapping probably does not lead to the most efficient design. For blind participants, Arnim et al. [3] suggested adding ridges forming a path to controls and framing the interface to avoid overshooting [3]. Huang et al. [15] developed haptic interactive elements for interfaces on paper and identified design guidelines for those, such as highlighting starting points, using simple structures, and reducing hand travel. Nowak et al. [26] also investigated for plastic controls how to target devices in 3D space using a 2D controller that mostly shows a room from the top. They found that introducing a haptic language by framing several buttons is an effective approach for smart home device selection.

While those works might be adapted for textile interfaces and provide initial guidance on facilitating the use of textile interfaces by palpation, it still remains unclear which interface paradigms best guide users through an interface eyes-free.

3 Pre-Study: Individual Textile UI Elements

In this pre-study, we evaluate the single textile UI elements that we plan to use in our interfaces. We found a smart home interface to be a perfect fit for investigating our compound textile interfaces, as smart homes include multiple device classes with numerous devices that each support several features. This enabled us to test a scenario in which many controls were present that could be easily grouped semantically, and we could expect our participants to understand this setting easily and be more familiar with the icons we use.

Although textile interfaces offer many more input actions than binary touch (e.g., twisting the fabric like in [31]), we decided to keep the focus in the main study on the pathfinding on the interface and therefore test familiar touch controls such as buttons, sliders, and trackpads in this pre-study. To build those controls, we fabricated our components according to the guidelines found in the literature [28, 36]. The proposed icons from Schäfer et al. [36] match user expectations from graphical user interfaces and have also been shown to be haptically recognizable. However, as those authors found that icon recognition varies even between relatively simple shapes [29, 36], we decided to test the recognizability of shapes for our interfaces first. More precisely, we evaluate whether our participants are able to recognize a symbol by palpation when they already know that it exists. For this, we fabricated several variants of the shapes we planned to use in our user interfaces and asked users to identify them in a pre-study. Fig. 2 shows the icons we investigated. In our main study, we planned to use recessed and raised shapes, depending on whether they trigger actions or not (see Section 3.1). As testing all shapes in both variants would not have been suitable time-wise in our user study, we only tested the icons in the form they should have on the final interfaces. In addition to the icons, we planned to use round and rectangular touchpads, e.g., for color selection vs. menu control in our main study. For this, we gathered data on how people perceive trackpads of those shapes.

3.1 UI Element Form Factor

We defined the form of our UI elements depending on their purpose. For this, we used the form factors that achieved the best results in the literature:

- Since **buttons** are primary actionable targets that should set themselves apart from each other and other elements, we fabricated them as shapes raised above the surface, which leads to the best recognition rates [36].
- For **signifiers** [25], which are non-interactive labels, we used recessed shapes since these differ from raised elements yet are still easy to recognize [36].
- For **sliders**, we followed existing guidelines [28] and used recessed versions. These guide the finger without the danger of slipping off the control and activating other elements.
- Since **touchpads** are closely related to sliders, we used the same fabrication method.

As a starting point for our designs, we used Material Icons[1] where matching icons existed (Fig. 2, top row). We thereby aimed to achieve a certain level of familiarity with the symbols due to their extensive use in mobile and web applications. Furthermore, the symbols also seem recognizable to people who are not technology-savvy. Many Material Icons are already rather detailed, which we expected to be too challenging to explore haptically. In those cases, we designed simpler or entirely new versions. However, we also added variants if we believed that further details increase recognition (e.g, a TV with screen, or a house with door). If we found no way to simplify or improve the haptic recognition of the original icon, we did not add alternatives. Where we informally observed that users did not perceive parts of an element as clearly belonging together, we also tested variants with a border added around the icon. As representative examples, we added framed variants for *TV* and the dotted and line version of the number *'2'*. *Skip* was also included in a mirrored variant to test whether this causes confusion.

Since *TV*, *Light*, *Blinds*, *Temperature*, and *Vacuum* were planned only to indicate the device categories, and *Brightness*, *Hot*, *Cold* and the *Numbers* should accompany other, active UI elements, we fabricated all of them as signifiers. The remaining icons were intended to be actionable and were therefore designed as raised shapes.

Fabrication. We fabricated all icons according to [36] and used 1.6 mm high 3D-printed plates in the icons or the environment to create raised or recessed icons. This fabrication approach was also used for our sliders and trackpads. For the framed icons, we ensured that the frame would feel different by embroidering it with a multi-layer satin stitch. Following the recommendations in [36], we created our elements from furniture fabric. Our fabric was 100%

[1] https://fonts.google.com/icons *(accessed August 2025)*

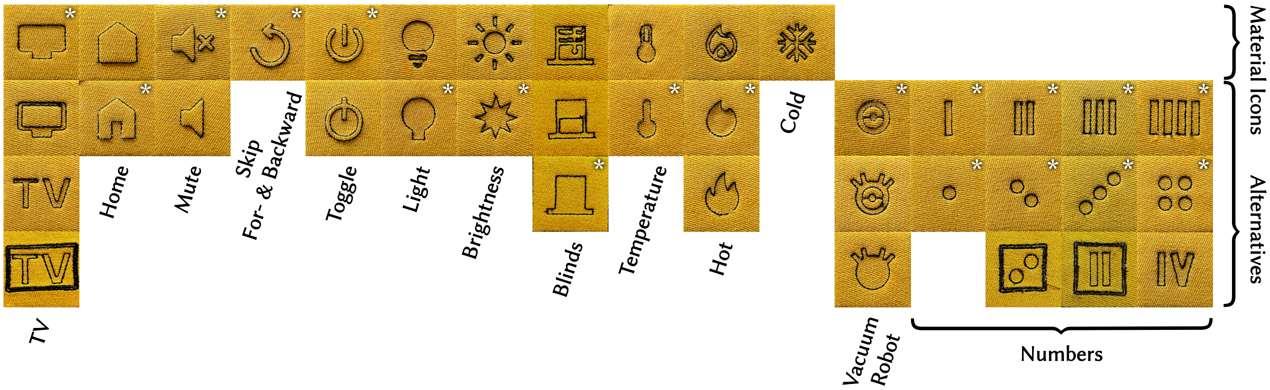

Figure 2: Icon variants that were palpated in our pre-study. The fabrication style follows our design language and corresponds to the intended use in the main study. We tested Material Icons (top row) and our own designs. Where we informally observed that users did not perceive parts of an element as clearly belonging together, we also tested variants with a border added around the element. Icons marked with '*' were considered for the final interfaces after evaluating the pre-study.

polyester with a fine texture and a weight of 270 g/m^2. We designed all icons to have approximately the same size of 18×18 mm^2. For the trackpad, we followed the size recommendations of 80×80 mm^2 in [10] for simple touch gestures.

3.2 Task & Procedure

After participants were introduced to the study and had signed an informed consent form, we began the study by randomly showing images of all 39 icons on a screen and asking participants to verbally name or describe each one. Participants did not palpate the icons during this description phase to see whether they could later recognize the icons haptically if all they knew before palpation was that a certain functionality existed. Next, we asked participants to recognize the shapes in random order by palpation only. For this, they should verbally name the shape. To ensure eyes-free use, they put their hand through a sight-protection wall similar to the one in Fig. 6. After each recognition, participants filled out a Likert scale questionnaire on a tablet computer. In accordance with Schäfer et al. [36], participants could look at a list of all icons between recognition trials to help them remember the shapes they might encounter. This matched our scenario, as familiarized users should already know what they encounter on their smart home interface. This list was not available when palpating to avoid pattern matching between the haptic and visual shapes.

After all icons had been tested, participants palpated either a squared or a circular trackpad behind the sight-protection wall without having any information about the object they palpated. Next, we asked participants how they would use the object to control something in the home and what they assumed the object's purpose in a smart home context to be. We then introduced the following scenario: *"Assume you can control multiple lamps. You want to select one, turn it on, and change its color. How do you think this control can help you with which step?"*.

One complete study session took about 40 minutes.

3.3 Measurements

To measure *recognition time*, we built a small frame with an embedded conductive plate connected to an MPR121 capacitance sensor, allowing us to detect touch on top of the icon inserted in the frame. If a recognition took more than 30 seconds, we stopped the trial in accordance with [29, 36] to keep the experiment duration manageable. We expected this to be sufficient, as participants in their studies needed about 10 seconds to recognize a single shape. Additionally, we measured participants' *recognition success*. After all trials, we asked participants to rank the different icon variants. We did not constrain which criteria they used for this. The questionnaire after each trial included Likert scale questions for the *mental demand*, *recognition confidence*, *ease of rough shape recognition*, and *ease of shape detail recognition*.

3.4 Results

Fourteen people aged 22 to 27 participated (M=24.6 years, SD=2.03 years). Nine identified as male, four as female, and one did not provide an answer. One participant was left-handed. Twelve were computer science students, one a chemistry student, and one a software developer.

When the icons were shown to participants visually, they recognized our icons well. The only ones that participants misidentified noticeably often were our variant of *Light* (50% correct associations), the two-spike version of *Hot* (Fig. 2, row 2, 57% correct associations), any version of *Blinds* (max. 7% correct associations), and *Vacuum* (no correct associations).

For eyes-free *recognition success*, we tested the effect of the icon variants on recognition using a Friedman test and Wilcoxon Signed-Rank tests with Holm correction for post-hoc analysis. We found significant effects for *Brightness* ($\chi^2(1) = 4.5$, p<0.05), *Temperature* ($\chi^2(1) = 5$, p<0.05), *Hot* ($\chi^2(2) = 14$, p<0.001) and the variants of *'2'* ($\chi^2(3) = 11.91$, p<0.01—no effects in the post-hoc analysis).

For *recognition time*, we used the same statistical tests as for *recognition success*, as our data was not normally distributed. We found significant effects when comparing the groups of *Light* ($\chi^2(1) =$

10.29, p<0.01), *TV* ($\chi^2(3) = 11.36$, p<0.01), *Home* ($\chi^2(1) = 6.23$, p<0.05), *Hot* ($\chi^2(2) = 7.84$, p<0.05), and the variants of *'1'* ($\chi^2(1) = 4.57$, p<0.05), *'2'* ($\chi^2(3) = 13.84$, p<0.01), and *'4'* ($\chi^2(2) = 7$, p<0.05). Fig. 3 shows *recognition success*, *recognition time*, and the significant effects of the post-hoc analysis for both measurements.

We analyzed all our *questionnaire ratings* using Friedman tests and Wilcoxon Signed-Rank tests for post-hoc analysis. Since most ratings confirmed the findings from the time and success measurements, we briefly summarize the most important significant results (each at p<0.05): Overall, the recognition of all framed *'2's* was significantly more mentally demanding than their unframed variants. Furthermore, it impeded the recognition of the shape details. For the *'4's*, *IV recognition confidence*, *ease of rough shape recognition*, and *ease of shape detail recognition* were significantly worse than for *4 dots* and *IIII*. We found that inner shape details made the recognition more mentally demanding when comparing *hot (2 spikes)* and *hot (Material)*. For *Blinds*, the inner shape details also led to worse *rough shape* and *shape detail recognition*. Interestingly, the gaps in the outlines of *home (door)* and *On/Off (Material)* facilitated our *rough shape* and *shape detail recognition* ratings. Participants were also more confident recognizing *home (door)*.

In the second phase of the user study, 5 of 7 people recognized the recessed *rectangle* and *circle* as surfaces for swiping gestures. When naming the device's purpose, three participants mentioned color change for the *circle*, while none did so for the *rectangle*. When the task description got more precise with the last question asked, however, 6 of 7 participants named color selection for both variants.

3.5 Pre-Study Conclusions

For most icons, our pre-study delivered a clear winner for the icon groups: *brightness*, *light*, *tv (material)*, *home (door)*, *temperature (material)*, and *hot (2 spikes)* were chosen due to their significantly better performances and ratings. We found the tendency that the fewer inner details an icon had, the better either *recognition time* or *recognition success* tended to be. However, since we did not find sufficiently significant effects and our icon variations varied a lot between icon groups, further investigation on this is necessary.

Surprisingly, framed icons generally performed worse. We expected that the frames would help users better understand where the multi-component symbols end, thereby providing a clearer picture of the symbol. Instead, it seemed to make recognition more difficult without any significant influence on the recognition confidence. Therefore, we discarded framed icons for our main study.

Letters—at least where we used two or more—performed relatively poorly in our study. While we did not find any significant effects for *TV*, the results for the *'4's* surprised us as we did not expect that counting the bars from *IIII* would be better than recognizing the two very distinct letters of *IV*. Eventually, we considered icons marked with '*' in Fig. 2 for our final interfaces.

4 Designing the Composite Interfaces

Our preliminary user study gave us designs for individual components. For our main study, we now needed to build four interfaces to represent our different composition concepts from these individual UI components. For consistency, we used the same design rules for all four prototypes:

- If a signifier describes the meaning of a control element, like the *brightness* for our brightness sliders, we call it a **control signifier** and place it only 5 mm apart from adjacent components.
- If a signifier describes the functionality of a region, like the *Light* signifier in *Categories*, we call it an **application signifier** and place it in the top left corner of the corresponding region with a margin of ≈10 mm.
- For **button pairs** that form a group, such as *plus* and *minus*, we also use a spacing of 5 mm.
- Otherwise, a regular distance of 20 mm is used.
- **Separation or guidance lines** are embroidered using a 3 mm wide multi-layer satin stitch to create a clearly distinguishable haptic experience.
- **Interface regions** are created by recessed gaps ≈2 mm wide.

The distances of 5 mm and 20 mm are based on whether a finger touches both elements or not when placed in between them, and were determined iteratively through informal experiments. Region lines were recessed due to fabrication constraints, and since they are never directly connected to an action. Fig. 4 shows how these rules are applied for *Mapping*.

Using those design rules, we designed our composite interfaces to support controlling the color and brightness of four lamps, lowering and raising four blinds, increasing and decreasing the room temperature, and controlling a TV. For the TV, users can open and navigate a grid-based menu, change and mute sound, switch channels, and turn it on and off. For this functionality, we built the interfaces to represent our composition concepts as follows:

Universal (Fig. 1a). This composition concept follows the select-and-control flow of universal remotes: The upper rows let you specify the target device. The lower area offers very generic interface components to change device parameters. If multiple devices of one category can be addressed in the top area, number buttons in combination with an application signifier were used.

Mapping (Fig. 1b). This composition concept implements the principle of Natural Mappings by Norman [25] in that the spatial distribution of the targets in the real world is imitated in the interface. In our scenario, we created a room layout from a top-down perspective similar to Nowak et al. [26]. To avoid the interface getting too large or cluttered, we created only a single control area for the lights and used guidance lines to navigate the user to this area once a *Light* button was selected. For closely located controls of the same application (i.e., blinds), we created an application region with only one application signifier to keep the interface clear.

Categories (Fig. 1c). This composition concept divides the UI into areas for each application type by keeping the UI as small as possible. While a small and clear layout was easily possible for the blinds using four enumerated up and down arrows next to each other, we had to use a row of number buttons for the lamp selection.

Sparse (Fig. 1d). This variant of *Categories* explores whether people benefit from or are hindered by more space between control areas in our setting. For this, we adapted and extended *Categories* horizontally, putting each of its application sections into one corner.

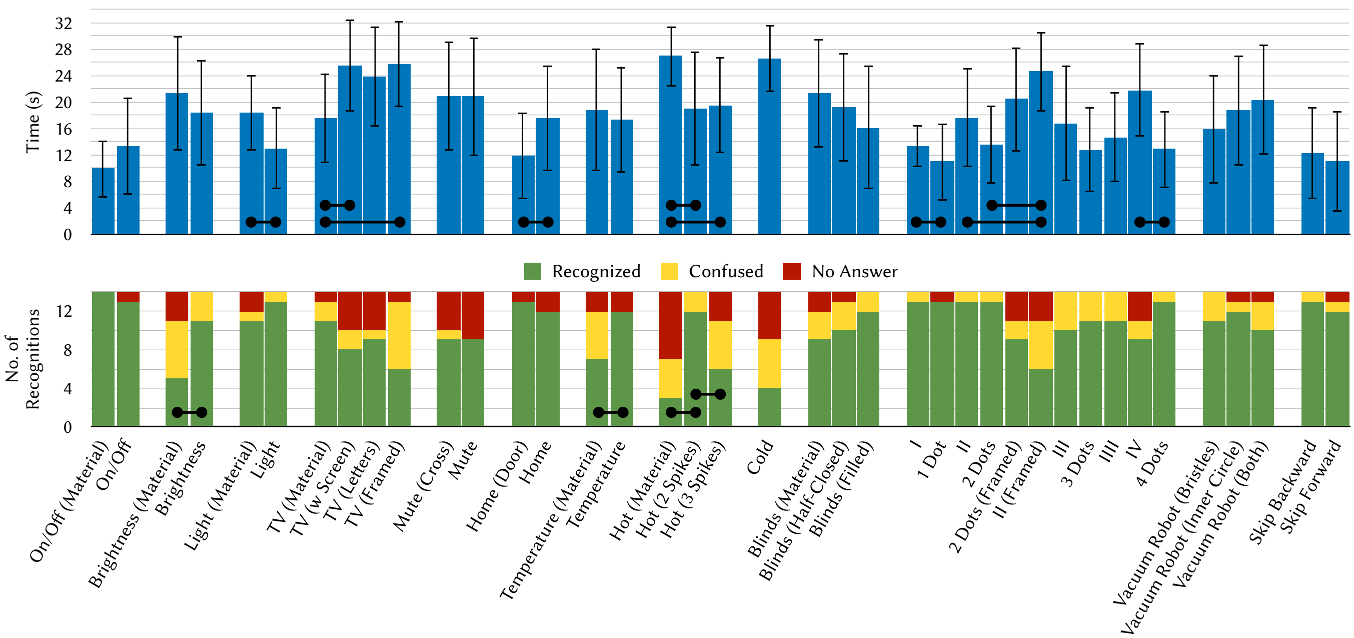

Figure 3: Haptic recognition count and recognition time of the icons grouped by their associated action or meaning. Often, icons with fewer details were recognized more frequently or quickly. Framing icons seems to hinder recognition. Horizontal lines show significant differences, and whiskers denote standard deviation.

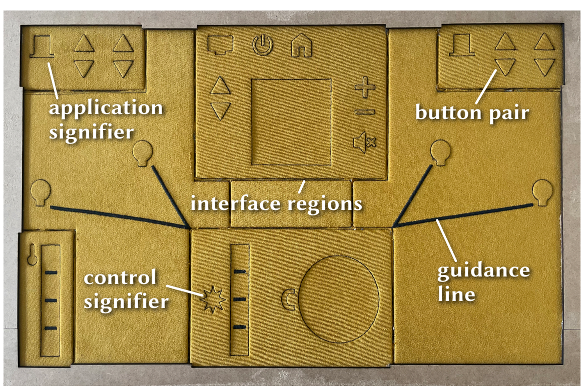

Figure 4: Types of UI elements to which our consistency design rules are applied. Except for *control signifier* and *button pairs*, elements are at least 2 cm apart. *Interface regions* are created using recessed gaps. *Application signifiers* are top left in such regions. Helping *lines* are embroidered.

All interfaces were fabricated similarly by first producing the application regions and then mounting the modules in a frame. To create the application regions, we first fabricated each region by embroidering medium-density fibreboard (MDF) between two layers of fabric, as proposed by Schäfer et al. [36]. However, to be able to create recessed and raised elements in one module, all elements were initially created to be recessed. To create the raised buttons, we then laser-cut slightly higher button shapes from acrylic glass and glued them onto the base fabric (Fig. 5, top left) before embroidering the top fabric (Fig. 5, bottom left). After mounting the modules in the frame (Fig. 5, center), we removed unnecessary fabric and added copper tape underneath each UI component. The tape was connected to the same capacitance sensors from the preliminary study to make our prototypes functional. To avoid accidental input when users initiate touches on the wires, we shielded them using copper tape. The resulting sensors are shown in Fig. 5 (right). The interfaces have a size of 52×31 cm^2 for *Mapping* and *Sparse*, 18×31 cm^2 for *Universal*, and 24×40 cm^2 for *Categories*. We designed the smaller controllers to fit on a sofa with large armrests, and the large ones to fit the size of a typical table runner.

5 Main User Study: Evaluating Composition Concepts

Our main user study consisted of two phases. First, participants explored one interface without any prior knowledge. In this *exploration phase*, we investigated whether people could discover all features of our textile interfaces and whether we could rely on people's haptic perception to understand and use them when they are not visible, for example, when it is dark or placed on a side. Then, in the *task phase*, we investigated which compound concept works best for eyes-free use of our interfaces by measuring user performance and ratings after they had familiarized themselves with the interfaces.

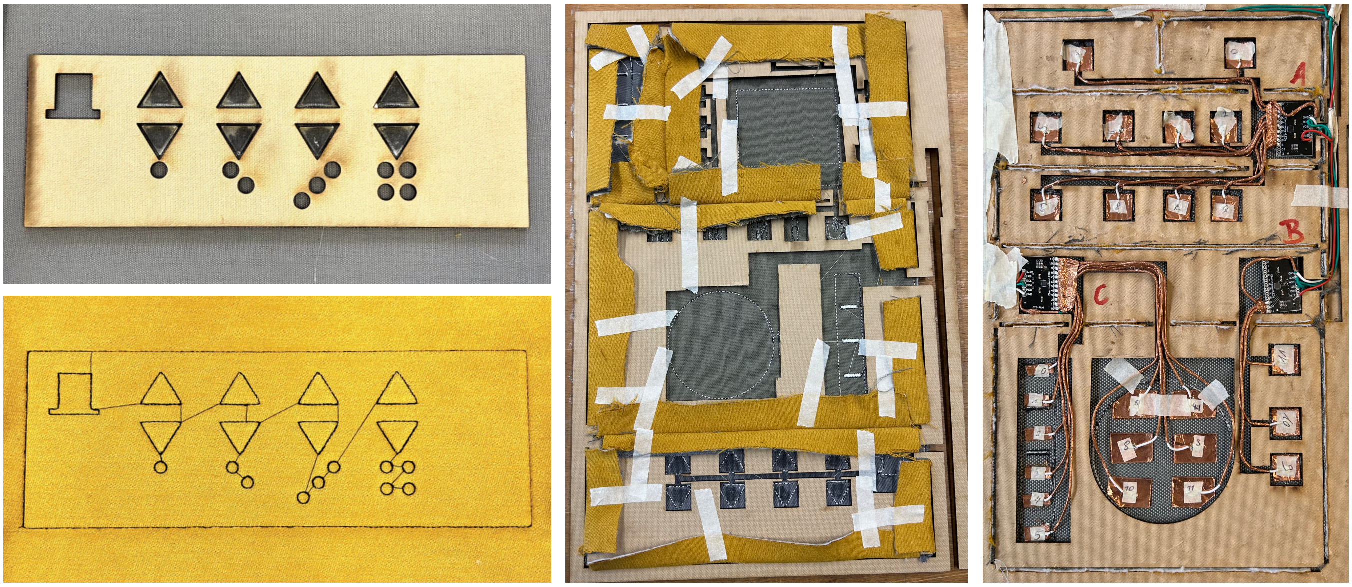

Figure 5: Processing steps of our prototypes. Different application modules were fabricated by gluing interface cutouts onto a piece of fabric and adding thicker acrylic glass for raised elements (top left). After sewing another fabric on top (bottom left), the modules were mounted inside a frame (center). Copper tape connected to capacitance sensors was placed under each interactive element of our UI (right).

5.1 Setup

Like in our preliminary user study, our participants sat in front of a sight protection wall. This time, a display was placed to the side of their non-dominant hand, showing a virtual representation of a living room that fit the scenarios of our controllers. The interfaces were placed behind the sight protection and covered before the study tasks started. The setup is shown in Fig. 6.

5.2 Tasks & Procedure

We informed participants about the purpose of the user study and explicitly mentioned the smart home use case. Then, they signed an informed consent form. To familiarize our participants with our textile fabrication, they palpated a row of Heart and Plus symbols in raised, recessed, and embroidered form factors before the *exploration phase* started. They could look at the hearts and pluses while doing so. Then, the ***exploration phase*** started, in which the participants explored one interface while verbalizing their impressions. While exploring, they observed the effects of their touches on the virtual living room. Participants ended this exploration on their own when they found no further interface functionality. Since most of the functionality of our smart home scenario would have already been discovered after the first exploration, the *exploration phase* was only performed with one of the four interfaces. Thus, we employed a between-groups design in this phase, where every fourth participant began with the same interface.

In the ***task phase***, we followed a within-groups design in which all participants encountered all four interfaces. Here, we asked participants to perform typical smart home tasks, such as setting the left ceiling light to green, lowering the blind next to the TV, or adjusting the room temperature to approximately 20% (for simplicity, a scale from 0–100% was used instead of concrete °C values). Before they performed the tasks, we explained the interface to them and let them familiarize themselves with the UIs by exploring them and receiving feedback on the virtual room display. Participants could see the interfaces and practice the tasks in this setting. We answered all questions regarding the interfaces and did not limit the time spent on familiarization. Afterward, the measured trials began, in which participants performed the required smart home tasks behind the sight protection. For this, the conductor named each task verbally, while participants were asked to press a homing button to the left of the interface. They then had to perform the task as quickly as possible and finally press the homing button again. We did not emphasize the accuracy of their input to avoid biasing their intuitive pathfinding on the interface.

Overall, participants performed three tasks per application, resulting in 12 tasks. The tasks were to turn on devices, adjust temperature, TV volume, brightness, or blind level, switch TV channels, and set light colors. For lights and blinds, another target device was used for each task of an application. Participants repeated this procedure using another controller when they completed all tasks. In both phases, participants were asked to fill out a questionnaire after using each interface.

The order of the interfaces was determined using a Latin Square where the interface used in the *exploration phase* was also the first one used in the *task phase*. The *task phase* tasks and their target devices were randomized. The exploration took about 10–15 minutes, while the task phase for each interface required about 5 minutes. Between each treatment, a break was taken to switch between interfaces.

Figure 6: Setup of our main user study. Participants palpated the yellow interface concepts behind a sight protection wall. The black button at the corner of the interface was used to start and end a trial. A virtual living room (right) was displayed on the monitor to the left of the participant.

5.3 Measurements

During both phases, participants filled out questionnaires including 7-point Likert Scales about, inter alia, *concept comprehension*, *mental demand while exploring*, whether people could connect elements to their device category (*identify UI element belonging*), *ease of use*, and whether they could distinguish the elements of our design language (*UI type identification effort*).

During the *task phase*, we measured the time our participants needed to perform our tasks. Time started after participants released the homing button, and ended when they touched the last element necessary for the task for the first time. Thus, time measurements did not include the processing time of the last element, which could vary between touchpads, sliders, and buttons. Furthermore, we collected the number of unnecessary elements touched by the participants. We call this measurement *additional input*. This can include intentionally palpated elements, but also accidental touches created with the palm or the arm while reaching out to other elements. Using this metric, we wanted to quantify our participants' palpation effort and provide a value for the risk of unintended activation of other elements. To get the time and touch data in case of sensor noise, we recorded each participant's hand from the top with a camera resolution of 2160×3840 px^2 and 60 frames per second and measured the data manually.

5.4 Participants

Overall, 16 new people participated in our user study between the age of 20 and 60 (median=25.5, mean=30.75, sd=13.59, 3 participants were older than 54). 7 identified as male, 9 as female. One person was left-handed. 13 participants were STEM students; the others worked in non-scientific jobs. 9 people had already participated in prior experiments involving our fabrication techniques. However, they were not exposed to any UI elements or interface concepts used in this study or the pre-study.

5.5 Results

5.5.1 Time and Additional input. Since our *time* measurements were log-normally distributed, we transformed our time data accordingly before analyzing it using repeated measures ANOVA. For the post-hoc tests, we used paired t-tests with a Holm correction. We analyzed the data once for each device category and once for the overall interface performance. The ANOVA revealed significant results of the interface on *time* for the *blinds* (F(3,45)=30.03, p<0.001), *temperature* (F(3,45)=59.39, p<0.001), *TV* (F(3,45)=43.95, p<0.001), and the complete interface (F(3,45)=23.89, p<0.001). The post-hoc tests did not reveal any significant effects for the *Light* and *TV* device categories. We assume that this is the case for *Light*, since it required the same number of interaction steps on each interface. For *TV*, we assume that this is due to the far location of its controls in all interfaces and the more complex icons this device category uses. The post-hoc tests revealed significantly worse results of *Universal* on the *time* for every other scenario. *Categories* was significantly faster than *Sparse* and *Mapping* for *temperature* controls and significantly faster than *Sparse* for the *blinds*. While we assume that *Categories* simply performs better because it is small, for *Universal*, we assume it performed worse due to the additional action steps and recognitions that have to be taken. The results of our measurements are shown in Table 1.

For the *additional input*, we used a Friedman test in combination with Wilcoxon Signed-Rank tests with Holm corrections for the analysis. As our sensor output occasionally flickered, resulting in a clearly recognizable frequency of touches, we decided to remove such outliers if they deviated by more than three times the standard deviation of the particular task. The Friedman test revealed significant effects for *blinds* ($\chi^2(3)$=18.35, p<0.001), *temperature* ($\chi^2(3)$=18.66, p<0.001), and *TV* ($\chi^2(3)$=17.77, p<0.001). No significant effects were found in the post-hoc analysis for the overall interface performance and the *Light* tasks. However, *Universal* caused significantly more additional input for *Blinds* and *Temperature* due to the additional input required. The clear structure and small size of *Universal* and *Categories* might have contributed to their significantly better performance for the *TV* controls compared to the other large interfaces. Fig. 7 shows the average number of *additional inputs* and the results of the post-hoc tests.

5.5.2 Ratings. We used Kruskal-Wallis tests to analyze the questionnaire data in the exploration phase, if the question was evaluated only for one phase, and non-parametric analysis of variance based on the Aligned Rank Transform if Phase–Interface interactions were analyzed. For both variants, Mann-Whitney U tests with Holm corrections were used for post-hoc tests.

Interface	Blinds M	Blinds SD		Light M	Light SD		Temperature M	Temperature SD		TV M	TV SD		Overall M	Overall SD	
Mapping	4.61*s*	2.98*s*	B C	11.09*s*	5.03*s*	A	0.88*s*	0.37*s*	C	7.48*s*	5.75*s*	A	6.01*s*	5.51*s*	A
Sparse	5.32*s*	3.24*s*	C	11.54*s*	7.11*s*	A	1.46*s*	1.13*s*	C	5.71*s*	4.07*s*	A	6.01*s*	5.65*s*	A
Categories	3.18*s*	2.55*s*	B	13.43*s*	5.05*s*	A	3.01*s*	2.28*s*	B	7.34*s*	5.48*s*	A	6.74*s*	5.85*s*	A
Universal	14.40*s*	7.43*s*	A	16.75*s*	11.45*s*	A	6.97*s*	3.01*s*	A	7.15*s*	3.17*s*	A	11.31*s*	8.25*s*	

Table 1: Average *time* and standard deviation per device category and overall. Rows are significantly different from each other unless connected by a shared letter. In most cases, *Universal* took significantly longer to use.

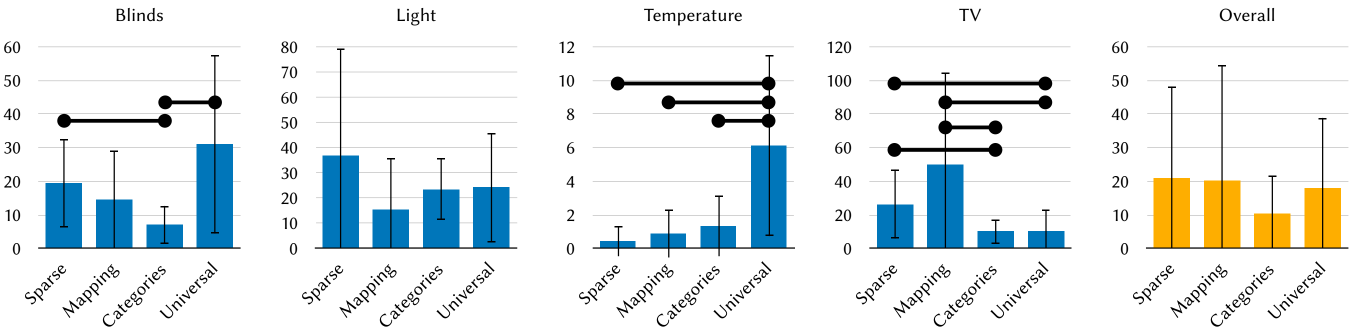

Figure 7: Average number of unnecessary control touches per device category (blue) and overall (orange). Bars that are connected with a horizontal line performed significantly differently. Whiskers denote standard deviation. Overall, the amount of *additional input* did not vary significantly between our interfaces.

The results of our questionnaire are shown in Fig. 8. Overall, the Kruskal-Wallis test indicated only a significant effect of the interface on *concept comprehension* ($\chi^2(3)=8.91$, $p<0.05$). The post-hoc test, however, did not indicate any significant effects.

When analyzing the effects of the different *phases* and *interfaces* on participants' ratings, we only found effects of the phase on *identify UI element belonging* ($F(1,24)=4.83$, $p<0.05$) and *ease of use* ($F(1,24)=9.8$, $p<0.01$). We found no other variable or interaction effects. Fig. 9 shows the results of those questions.

As the *task phase* followed a within-subject design, we analyzed ratings for this phase using a Friedman test. However, those tests did not reveal significant effects, as shown in Fig. 10.

5.5.3 Observations & Rankings. Overall, most participants identified all four device categories in the exploration phase. Only for *Universal*, we observed a remarkably more difficult exploration, as not every button directly caused an effect. Nonetheless, two of four participants found all the functionality of our prototype. In the *task phase*, participants often mentioned that they did not use the recessed borders in our interface. Instead, they moved their hand roughly in the direction they remembered the application was located and then used the elements there to identify where they were. For this, we observed that particularly the touchpads served as anchor points for the orientation. Still, the signifiers were mentioned as helpful, too, although those also earned critique for being more challenging to recognize than raised symbols. For *Sparse*, we found that our participants were mostly confused about the blank space they encountered and critiqued it as not supporting orientation. Instead, the space even hindered them from remembering the layout easily. This is also reflected in the user rankings (cf. Fig. 11), where *Sparse* performed remarkably worse and *Universal* was ranked best.

6 Discussion

From all interfaces, we could derive design recommendations for compound textile user interfaces. For this, we first discuss the interface performance and then describe new guidelines in Section 6.2.

6.1 Interfaces

The results of our user studies have shown a clear tendency for one interface throughout all measurements:

While *Universal* offers a bad discoverability of features and needs more time to perform the actions, once the mechanic of this interface is understood, our participants appreciated its clear structure and flexibility. The average user ratings after familiarization indicate that this controller is appreciated for its ability to identify elements and regions, as well as for orienting on the interface. We assume that the separation of selection and control improved error handling because if a wrong element was touched, the correct button was always very close, and the user was not required to palpate the entire interface. This ease of correcting navigation errors may be the reason why the controller was ranked so well, although we measured higher task completion times. However, the significant difference between the *exploration phase* and the *task phase* in the *ease of use* ratings clearly shows that such an interface should not be used when one can expect people to be unfamiliar with the systems (e.g., in hotels). Furthermore, the *additional input* measurements show that participants did not encounter more accidental activations, although the task completion time is nearly doubled.

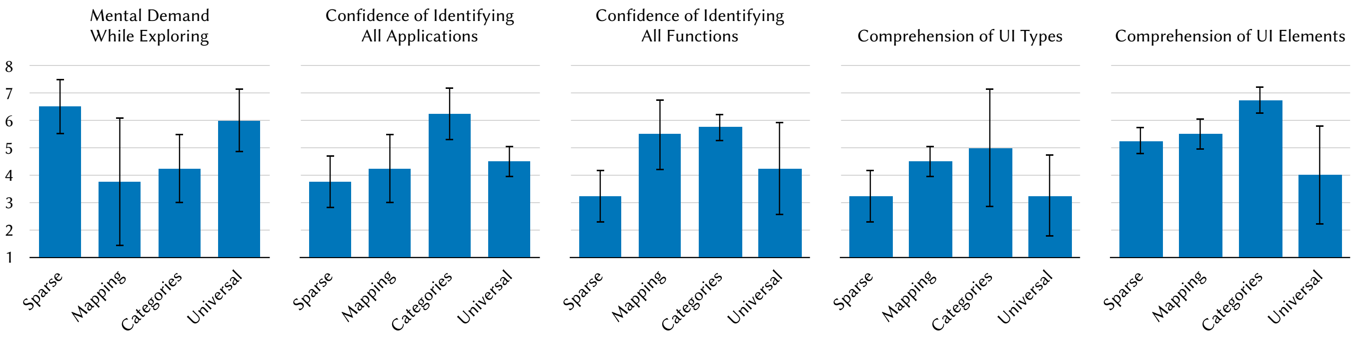

Figure 8: Average user ratings by our participants when exploring the user interfaces for the first time. While no significant effects occur, the diagrams show a tendency of *Sparse* and *Universal* being worse in our measurements. Whiskers denote standard deviations.

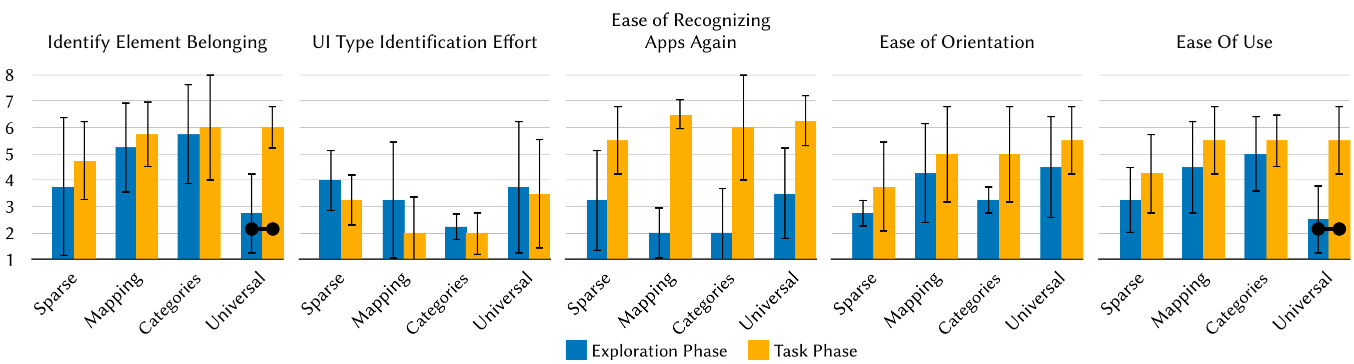

Figure 9: Average user ratings of our participants for questions asked in both study phases. Especially remarkable is the improvement of *Universal* for *ease of use* when people get to know the interface. Whiskers denote standard deviations.

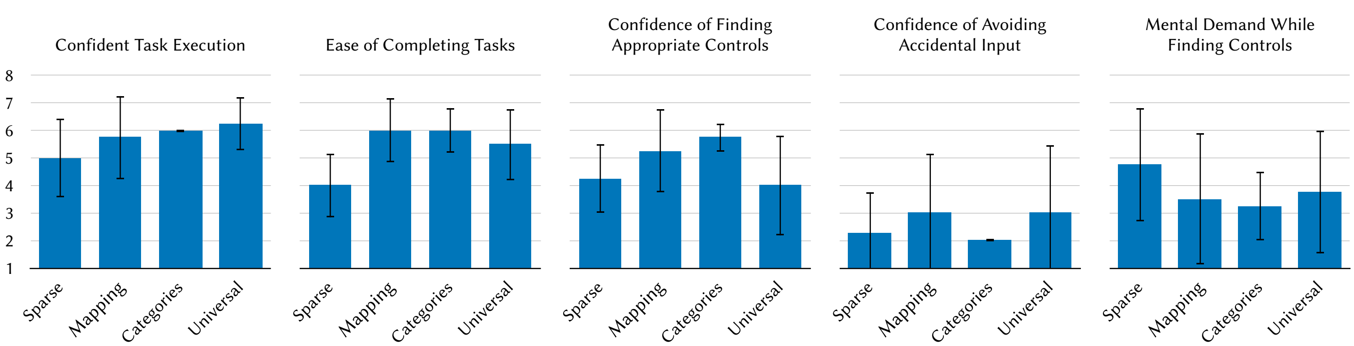

Figure 10: Average user ratings of our participants from the *task phase*. No significant differences were found, although there is a tendency of participants not preferring the distributed layout of *Sparse*. Whiskers denote standard deviation.

Since 1-step interactions were often faster for the other controllers, future interface designers should consider using shortcuts on device selection buttons to trigger the most relevant features. Since 12 of 16 participants already ranked *Universal* best or second best in this version, we can recommend implementing textile interfaces using this composition concept.

Mapping was ranked second best by our participants. Although this controller did not perform remarkably better in any of our measurements, it performed acceptably well throughout our study. When participants rated this controller highly, they liked the natural mapping it provides, although comments also made it clear that our solution of putting the light controls together was unpopular. Thus,

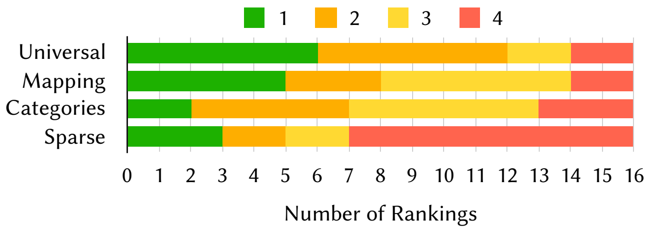

Figure 11: Participants' ranking of our four controllers with 1 being the best controller and 4 being the worst. Participants ranked *Universal* best remarkably often.

a mix of *Mapping* and *Universal* may be a good solution: Users first select devices on a map (similar to [26]), then use more generic controls to change parameters. This way, the map could include fewer elements. Overall, participants often commented that having fewer elements on the interface was highly preferable, and this was also often mentioned as an advantage of *Universal*.

Sparse was least preferred by our participants. While most participants seemed to prefer the more logical concept behind *Mapping* and *Universal*, the remaining participants liked that each device category was clearly located in one corner. We initially expected that participants would be less afraid of accidentally touching the wrong elements, as they could always start in the blank center and approach the correct controls carefully from there. However, due to the size of this interface, participants rather jumped to the corners with their hands instead of touching the surface while exploring the interface. Therefore, we assume that the rating for *confidence of avoiding accidental input* was on the same level as for the other interfaces. In general, our measurements support the guidelines about avoiding blank space by Challis and Edwards [5]. Participants clearly did not like the distance between device areas, which was often commented on and is indicated by our ratings for *ease of use* and *ease of completing tasks*. Some participants also reported that the size actually made it difficult to create a clear mental image of the controller. Although our ratings did not show significant differences in this regard, the ratings for *mental demand while exploring*, *ease of orientation*, *confident task execution*, *confidence of finding appropriate controls*, and *mental demand while finding controls* support those comments. Furthermore, participants were often unsure whether they had overlooked device regions, so they spent some effort to scan the blank space, especially in the *exploration phase*.

Performance of *Categories* was acceptable overall. We expected that the dense placement of UI elements would lead to significantly more *additional input*. However, we were surprised to find that this condition had the lowest average number of touches. Especially when reaching out to the TV controls on the top, users performed significantly better than with its larger competitors.

Overall, we assumed significantly higher task completion times for all our interfaces, as the tasks involved recognizing at least one icon and finding those controls. In previous work, the recognition of single elements was reported to already take about 6–7*s* on average for raised icons and even longer when using other form factors [36]. However, we measured an overall average execution time in the range of 6–12*s* per task, which already includes navigation, using multiple elements, and possible error corrections. From this, we assume that full haptic recognition is not necessary to identify that an element is *not* the one you are looking for. This makes us confident that haptic exploration in real-world scenarios must not be an unfortunate necessity when one cannot or does not want to look at the controls, but can improve the overall user experience when using interfaces embedded in the environment.

6.2 Design Recommendations for Compound Textile Interfaces

The design rules we implemented in our user interfaces were well accepted in the user study. From the use of all interfaces, we derived the following design recommendations:

Use recessed elements for secondary information. While buttons, sliders, and trackpads were recognized by almost all participants, many participants overlooked signifiers and the recessed lines separating device regions. We observed participants jumping to the actionable controls, i.e., the raised buttons or the touchpads, from which they then started the exploration. However, they then still used recessed icons as additional help to gain confidence that they were at the correct spot, and they reported the usefulness of those elements after learning of their purpose in the *task phase*. From this, we suggest that recessed symbols and elements should always be used as second-priority interface elements that should guide the users, like tooltips in GUI applications, or provide features that are less frequently used, as Mlakar and Haller [23] presented that recessed elements can also be used to perform actions.

Avoid non-functional segments. Throughout the study, we observed our participants directly jumping to interface regions. However, when they then palpated something that did not trigger an action, this confused them. We observed this in several scenarios: when the manipulation controls in *Universal* did not react, when they surprisingly found the lines connecting the light bulbs with their controls in *Mapping*, and when they did not palpate anything in *Sparse*. Therefore, we suggest extending the guideline of Challis and Edwards [5] to not only avoid empty space, but also reduce *non-functional* space.

Use varying shapes for good orientation. From the insight that raised controls are used especially for orientation, we recommend changing button shapes as often as possible. While this breaks the visual consistency in GUIs, this helps users familiar with the interface to quickly determine where they are. In the study, for example, participants often complained that the device selection buttons for blinds and the lights in *Universal* felt the same, which led to confusion and required finding the application signifier of neighboring interface regions first. Thus, we would change one of those rows with dots in future iterations.

Design large elements to be the starting point of interface exploration. For all interfaces, we observed participants quickly exploring the touchpads and sliders and using them as anchor points for further exploration of the interface. Therefore, we recommend making such user interface elements a central point from which all other application regions are easy to reach.

Increase the input capabilities of each individual component. While the distance to the application areas definitely had an effect on task completion time (see *Categories* vs. *Sparse* for the temperature and blind tasks), what influenced completion times noticeably seems to be the number of elements that are necessary for an operation. While this explains the overall high task completion times of *Universal*, the similarly long times for all interfaces during the light tasks—in which all UIs required using two controls—support this. The distance between the 'device' and 'parameter' controls seems to be of secondary importance, as *Mapping* and *Sparse* performed similarly. While we used binary touch to keep the interface simple in this study, we assume that the overall input efficiency will increase when enabling more input possibilities on one textile element. For example, in our smart home scenario, one could tap the light buttons to toggle the lights on and off, but twist the textile buttons to adjust brightness instead of using separate controls for each functionality.

7 Limitations & Future Work

Our participants appreciated the concepts *Universal* and *Mapping*. Nevertheless, our findings show that our implementations of the concepts could still be improved to increase input efficiency. In the future, we plan to refine our prototypes, for example, by mixing *Mapping* and *Universal*, and to test them in a longitudinal user study, observing how performance improves when people become familiar with the setup. However, following our guidelines, it would be interesting to further evaluate a compressed version of *Mapping* to avoid the non-functional space. For such an interface, one could also observe the effect of natural mappings when proportions are completely ignored and elements only loosely resemble the environment, in order to minimize the blank space. Furthermore, as participants frequently used the touchpads for orientation, designers could consider creating *Universal*-like interfaces with manipulation controls in the center and target selection devices radially around them to facilitate finding the correct devices and reducing accidental input.

In our study, we observed that single-component tasks were remarkably faster. Therefore, we recommend enabling users to change as many parameters as possible with one control element by using specific input gestures that textiles support, such as folding, twisting, or shaking 'buttons' as, for example, presented by Parzer et al. [31]. This would enable, inter alia, more powerful room interfaces, as one control element could be used to support multiple features of a single device. However, this would make discovering functionality more difficult. While recent work by Mlakar et al. [22] already presents how to signify the input capabilities of textile controls, it is currently unexplored how to combine the communication of how an interface should be used with what the input will cause.

Furthermore, we found interesting effects when testing our icon designs. The inner details in our icons, such as in *hot (Material)*, seemed to impede recognition, while the gaps in the boundaries of *home (door)* and *On/Off (Material)* were appreciated by our participants. Surprisingly, we found that letters were less favorable in our limited test set. Future textile interface research should deepen our understanding of how to create easily recognizable signifiers.

We measured how much additional input was created to have a metric for how "chaotically" participants approached the target controls. While it was surprising to see a trend for *Categories* creating the least accidental input, we could not clearly identify what caused the higher amount of additional input for the other interfaces: they may have been caused by intentional palpation of wrong elements to find the correct path, participants may have already expected them to be the correct target initially, or they may simply have been caused by the arm or the lower palm. Future studies could investigate this using qualitative methods to explore how to prevent accidental input, either through algorithmic approaches or new interaction techniques.

Furthermore, the sample scenarios we used to test our interfaces were fairly simple: The number of real devices and target devices on the interface was the same, facilitating the discovery of all devices. We assume that if a room is cluttered with additional devices that cannot be controlled, this will mentally complicate device selection.

We also tested our composition concepts with people who mostly had a technical background. While this worked to our advantage, as they were already familiar with smart homes and we found that most of our icons were already visually familiar to them, changing the application domain or testing with people with different backgrounds, a different sense of touch, or from more varied age groups could at least shift our performance data. Nonetheless, we expect most design recommendations to still hold, as they are mostly based on our participants' usage patterns rather than performance data.

We tested our interfaces in a scenario where participants did not see the interface at all, to investigate the complexity of understanding such interface concepts through palpation alone. When people use such interfaces in the real world, however, they would, especially in the beginning, look at the interface to avoid incorrect input. Therefore, we plan to investigate how interface performance changes when people can view the UI but are possibly distracted by a visually demanding main task, similar to the setup used by Harrison and Hudson [8] to evaluate pneumatic buttons. Furthermore, we aim to investigate the long-term adoption of haptic interfaces in a user study where the interface is visible. We assume that input speed and accuracy will improve over time, while the need to look at the interface will decrease. In addition to such a study, further factors are interesting to investigate in order to extend textile design guidelines. For example, Holleis et al. [12] reported the conceptual orientation of the interface to be unclear for an interface on an apron. This has also been confirmed in a small-scale study for symbols on a vertical surface on the side of the user [27]. As textiles often cover non-planar and non-horizontal surfaces, we plan to further investigate the effect of interface orientation on users.

Finally, one disadvantage of our prototypes is their static nature. While *Universal* offers the most flexibility to room changes, exploring the interface was impeded by buttons that did not seem to work, as no device was selected. For our *Mapping* concept, moving the target devices would require building an entirely new interface. For the latter, we consider creating a tile-based version of *Mapping* in which tiles can be exchanged when the room decor does. Alternatively, inspired by the work of Haynes and Steimle [9], we envision shape-changing displays to solve this problem on an engineering level. This way, temporarily disabled elements simply could disappear in our *Universal* concept—however, this raises new challenges in terms of users' ability to navigate the user interface.

8 Conclusion

In this work, we conducted a user study comparing different composition concepts for textile interfaces, including one that functions similarly to a universal remote, one that resembles the environment, and a concept that separates the interface into application regions. Furthermore, we added one controller that distributes UI elements widely to observe the effect of blank space on usability. Using a consistent fabrication approach, we created interfaces based on each of these composition concepts and included a preliminary user study to identify suitable textile UI element candidates. In our main study, we found the select-and-control flow of *Universal* to be the most promising interface concept according to user ratings. Based on our studies, we developed new guidelines for textile interface design, applicable to both single textile components and composite interfaces. These guidelines include, inter alia, avoiding the use of frames around textile icons, utilizing recessed elements for secondary information, and refraining from non-functional interface regions. Through our work, we aim to assist designers and researchers in creating more efficient and user-friendly textile interfaces.

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