What's That Shape? Investigating Eyes-Free Recognition of Textile Icons

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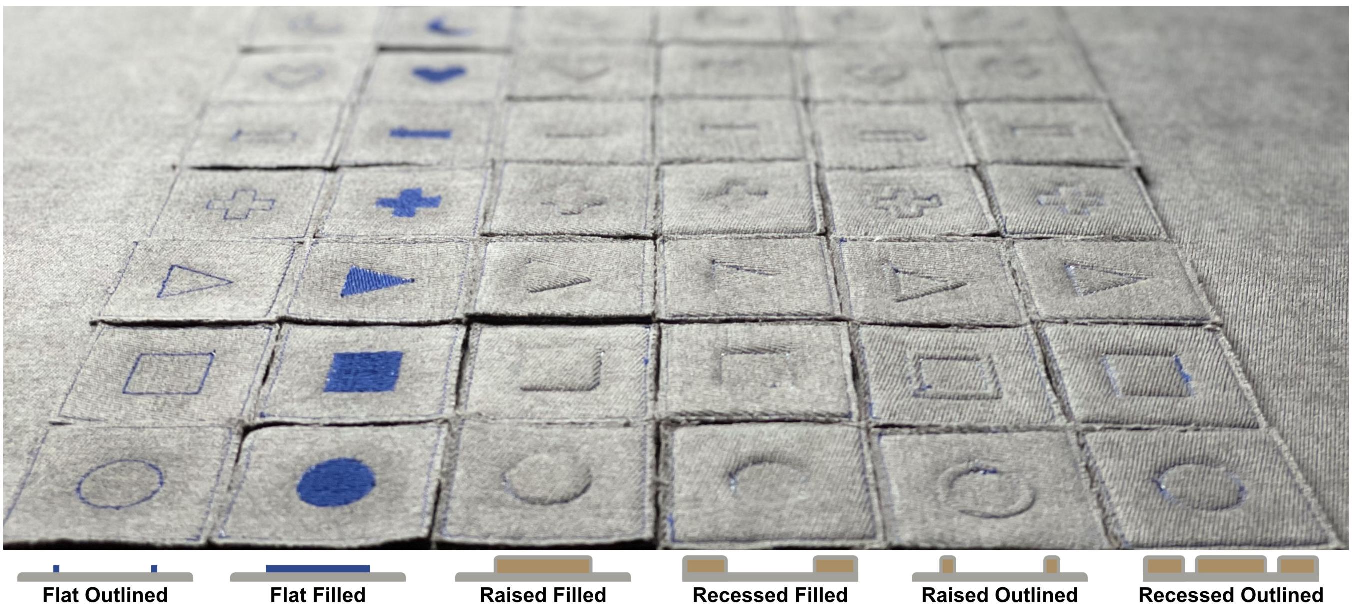

Figure 1: A set of textile icons in six different fabrication variants (from left to right): *Flat Outlined, Flat Filled, Raised Filled, Recessed Filled, Raised Outlined,* and *Recessed Outlined*. Overall, we created 84 textile icons (14 shapes × 6 fabrication variants) for our study to investigate how well they can be recognized and distinguished without looking. Beneath the photo, a schematic shows a cross-sectional view of our icons with their fabric (grey), yarn (blue), and MDF (brown) materials.

ABSTRACT

Textile surfaces, such as on sofas, cushions, and clothes, offer promising alternative locations to place controls for digital devices. Textiles are a natural, even abundant part of living spaces, and support unobtrusive input. While there is solid work on technical implementations of textile interfaces, there is little guidance regarding their design—especially their haptic cues, which are essential for eyes-free use. In particular, *icons* easily communicate information visually in a compact fashion, but it is unclear how to adapt them to the haptics-centric textile interface experience. Therefore, we investigated the recognizability of 84 haptic icons on fabrics. Each combines a shape, height profile (raised, recessed, or flat), and affected area (filled or outline). Our participants clearly preferred raised icons, and identified them with the highest accuracy and at competitive speeds. We also provide insights into icons that look very different, but are hard to distinguish via touch alone.

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CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Haptic devices**; **Empirical studies in HCI**.

KEYWORDS

Textile Interfaces, Textile Icons, Design Recommendations, Eyes-free Interaction, Haptic Recognition

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1 INTRODUCTION

Devices in the home are usually controlled either directly on the device itself, via remote controls, or using voice. However, controls on the target device are impractical when devices are out of reach. For certain devices, such as electrically adjustable chairs, rigid plastic controls also do not match the look and feel of the device. Remote controls address the reachability problem in principle, but they are frequently misplaced or out of reach themselves, and also tend to look alien in home environments. Finally, voice assistants offer no visible interface, making them hard for casual users to explore, and using them can be awkward in social situations.

Since textiles are omnipresent in our environment, from clothes to home furniture, we are used to interacting with them on a daily basis. Therefore, they offer promising surfaces to embed interfaces for controlling devices in our environment. They can be implemented where they are needed, such as on sofas, pillows, or on clothing, and they can be fabricated to match the appearance of those objects.

Textile interfaces have been studied extensively in recent years, with a strong focus on their technical implementation. Examples include work on wearables [11], knitting [17], manufacturing technologies [28], gesture recognition [33], and smart fabrics [6, 26, 32]. Thus far, however, there is little guidance regarding their interface design: Textile interfaces need to communicate that a fabric is interactive, and what it does. This becomes especially important if it is supposed to support eyes-free use, maybe because the user's focus is on a distant target device that is being controlled, or because the interface is somewhere difficult to see, such as on the side of an armchair or on the upper arm of a jacket.

To communicate the interactive qualities of a UI, *icons* are a standard choice. They help users understand an interface while taking up little space. Simple icon shapes are often used to create mappings that are easy to remember, such as a heart to like something, or a star to access favorites or provide a rating. Icons are also less language-dependent than textual labels. However, it is unclear how to adapt the concept of visual icons to *textile icons*, i.e., compact and palpable shapes on fabrics. Plus, even shapes that are easy to distinguish visually may be hard to tell apart by touch alone.

There is only little research on how to design the visual and haptic appearance of textile interfaces, in particular textile icons: Existing guidelines for haptic interfaces cover, e.g., the complexity of shapes used [3], and provide first insights into how physical properties such as size, height, and texture [20] help users recognize and differentiate elements and shapes by palpation.

While the applicability of our work is not limited to the smart home, our research is motivated by this environment in particular, due to the unique fit that textile interfaces offer here: For example, sofas, which are frequent in living rooms, conveniently offer space on top of and on the outside of the armrest for controls to navigate and play back media on a TV. However, this requires numerous buttons with both similar symbols and arrangements. One example are arrow or +/− buttons for common functions like menu navigation, volume, and channel selection that are all arranged in vertical pairs. Such buttons need to be easy to tell apart so users can operate them with confidence. Another example are the feature buttons on TV remotes (e.g., for starting video-on-demand apps) that are often of the same shape, just using different colors or labels. Confidently differentiating these reasonably quickly is crucial to make the textile interface a valid alternative to input via voice or remotes. However, visual indicators may conflict with the aesthetics of the furniture piece, and hinder confident eyes-free input.

Sofas and armchairs are also often located such that they are suitable places from which to control multiple devices such as fans and thermostats in the entire room. In this case, icons can communicate what device each section of controls in an interface belongs to. Here, however, icons may be used both as passive labels, and on buttons that trigger actions. This means designers need manifold possibilities to change the appearance of such icons, so that users do not confuse icons of one type with the other.

Finally, moving beyond furniture for sitting, table runners offer an intriguing place to, e.g., set ambient light scenes while dining, and curtains, while more challenging due to their flexibility, can offer an unobtrusive interface to control themselves or, e.g., the shutters outside.

For our study, we produced a set of textile icons with fourteen different shapes, using six different fabrication variants for each shape: three different height profiles (flat, recessed, and raised), each with two different choices of affected area (filled and outlined). This resulted in 84 unique textile icons; Fig. 1 shows the six variants for several of our icon shapes, along with cross-sections to illustrate the different materials they were created from. We then investigated how well users recognized and differentiated these icons when using them eyes-free.

Overall, our contributions are:

- a description of our fabrication process for raised and recessed icon features,
- six fabrication variants of icons (four created with this process) that work for commonly used icon shapes,
- a study investigating how well users recognize our 84 textile icons created in those fabrication variants, and
- insights regarding haptic similarities of shapes that are visually easy to distinguish.

In the remainder of this paper, we first discuss related work in this field, before introducing the icon shapes and fabrication variants we used in our study. After presenting and discussing our results, we synthesize them into a set of design guidelines for textile icons. We close with limitations of our work and promising avenues for follow-up research.

2 RELATED WORK

Tactile icons on textile interfaces (textile icons) involve multiple areas of Human-Computer Interaction, mainly *textile interfaces*, *tactile interaction*, and *shape recognition via touch*.

Textile interfaces enable interactions on or around textile surfaces and therefore allow for versatile interaction methods. Resistive and capacitive sensing allow touch input on textiles comparable to common interactions on touch surfaces [8, 11, 25, 28, 30, 32, 34]. Other approaches also support attaching [35] or embedding [7] mechanically movable parts into textiles. Furthermore, textile interfaces provide additional interaction techniques that exploit their characteristics to allow input by, for example, pinching, rolling, folding, or twisting the fabric [9, 13, 26].

Most of this work focuses on questions of technical implementation and feasibility demonstrations. When using such artifacts, however, the question arises how to convey the *semantics* of the interface, and this is, by the nature of such contributions, rarely covered. When designers can expect users to be able to look at the interface, information about the semantics of possible interactions is mainly conveyed visually. Eyes-free situations, however, require haptic cues to indicate possible areas of interaction and to communicate semantics about how to use the interface. Unlike graphical user interfaces, textile interfaces can readily provide such cues.

Research in the field of *tactile interfaces*—i.e., interfaces that convey information via tactile cues such as roughness and are designed around touch interactions [1]—is often conducted in the context of visually impaired or blind people (see [21] for an overview). Since these users employ their touch sense more often than sighted people, study results cannot simply be transferred between these two demographics. To investigate the recognizability of non-textile tactile icons for elderly visually impaired people, Macik et al. [18] created a cross in a *filled* and *outlined* condition and combined it with three height profiles (0.5 mm, 1.0 mm, and 1.5 mm). In a follow-up recognition study, five of six evaluated shapes had recognition rates above 95%. Overall, all variants were distinguishable, and the authors state that for their participants, 1.0 mm height and filled shapes would be a good choice. Bridging several demographics, Leo et al. [16] investigated the recognition of tactile pin-array symbols for blind, visually impaired, and sighted people. The symbols were simple shapes like X or T created by 3×3 and 4×4 pin matrices. The authors found that, while recognition rates varied little between blind and sighted users (around 90%), the latter needed about 3 times as long (47–55 seconds vs. about 17 seconds) for the task. In another design exploration, Challis and Edwards [3] created a tactile cover for a commercial touch pad to provide blind people with a better overview of musical notes and to facilitate related conversations with sighted people. Their resulting guidelines suggest, e.g., that tactile elements should work in their visual and tactile representation, that direct mapping from visual to tactile can be problematic, and that tactile elements should aim to be as simple as possible.

To operate (textile) interfaces eyes-free, the interface should make it clear what inputs are possible and what their effect will be. For this, Norman [22] differentiates *knowledge in the head* from *knowledge in the world*. In the literature, which mainly focuses on new fabrication and sensing techniques, application examples for textile interfaces that rather use *knowledge in the head*, requiring users to learn how the controller works, are easy to find. Examples include *Project Jaquard* [28], *SmartSleeve* [26], and the *Textile Interface Swatchbook* [5]. This raises the question of how to enable novice, untrained users to intuitively use those devices by adding *knowledge in the world*. One approach is the use of icons that convey interface semantics at a glance without added text.

Haptic shapes on textiles have already been the focus of recent research to enable eyes-free use of textile controls. When creating haptic textile icons—i.e., compact and palpable shapes on fabrics—, designers can adjust haptic properties like height or texture of such elements. Mlakar and Haller [20] investigated how properties of embroidered elements on a textile surface affect their distinguishability. They found that a height difference of 1.6 mm creates a reliably identifiable contrast between two elements. Furthermore, height differences are easier to perceive than shape or texture differences [20]. Regarding size, the authors found that simple shapes like squares, circles, and triangles should have a minimum size of 13 mm—about the size of a fingertip—to be recognized reliably. In a related experiment, Chen et al. [4] found that non-textile tactile icons of this size are also a good choice for blind people. At our lab, Nowak et al. [23] previously investigated haptic form factors of textile sliders, and found that raised and recessed forms facilitate recognition. Especially recessed forms provide useful haptic cues for sliders since they create a natural path for the finger to follow. Raised forms, on the other hand, help to recognize the overall shape, but it is easier to 'fall off' the shape [23].

Both Mlakar and Haller [20] and Nowak et al. [23] also found that shape recognition via touch on textiles suffers if only their outline is stitched on the fabric while the fabric inside the shape remains unchanged. Numerous research has investigated the recognizability of simple raised-line drawings of common objects as addressed by Picard and Lebaz [27]. Among others, Lebaz et al. [15] have shown that these are hard to recognize for sighted people. 46% of their participants were able to correctly name the respective shapes, which were raised by about 0.5 mm above the surface, with an average recognition time of approximately 86 seconds. For raised-line drawings, researchers found that visual imagery supports the recognition of haptic shapes: Wijntjes et al. [31] found that when allowing participants to sketch what they felt after exploring the drawing, a certain amount of haptically unrecognized drawings could yet be named, but only by actually looking at the sketch (30.8% vs. 2.2% without looking). Cecchetto and Lawson [2] also found that sketching and looking at the sketch during haptic exploration makes identification even easier, likely by either unloading working memory or guiding subsequent exploration.

Identifying 3D objects, on the other hand, is easier and faster. Klatzky et al. [14] reported 94% correct recognitions within a 5-second time interval when tasking their participants to recognize 3D objects via touch while being blindfolded. Harrison and Hudson [10] compared buttons created via pneumatic actuation to flat acrylic regular physical buttons. They found that raised and recessed designs increased user performance compared to flat counterparts. Holleis et al. [11] looked at different textile buttons on an apron: *Visible buttons* embroidered on the fabric, *ornament buttons* consisting of an ornament surrounded by four dots, and nearly *invisible buttons* in the color and texture of the apron. While users found *invisible buttons* visually more pleasing, they disliked them in eyes-free situations as they were less tangible than the other designs.

Overall, the related work shows that haptic 3D cues improve the recognizability of shapes and objects. Because of this, we strive to improve the haptic recognizability of icons on textile interfaces by investigating different fabrication methods that mainly affect height profiles.

3 USER STUDY

For our user study, we fabricated different textile icons varying the shape, whether the icon consisted of a filled area or only an outline, and whether the filled area or outline was flat, recessed, or raised. For those properties, we investigated how well and how fast our participants could recognize all shapes by palpation.

3.1 Shapes

Overall, the following 14 different *shapes* were used in our user study—marked shapes (*) were used for familiarization trials in the user study:

- *Circle*
- *Triangle*
- *Square*
- *Plus*
- *Minus*
- *Heart*
- *Star*
- *Bookmark*
- *Arrow*
- *Moon*
- *Lightning*
- *Raindrop*
- *Bell*
- *Telephone*
- *Fish**
- *Crown**

Similarly to Mlakar and Haller [20], we decided to use well-known shapes that are used frequently in user interfaces: *Triangle*, *Square*, and *Circle* are fundamental building blocks for more complex icons (such as an 'i' for getting more information), but are also often used standalone e.g., in media controls ('play', 'stop', 'record') or navigation buttons on Android smartphones (going back, or to the home screen). *Plus*, *Minus*, and *Arrows* are frequently used to adjust values, and to determine directions, like brightness of lights, volume, or the direction shutters should move. *Heart*, *Star*, and *Bookmark* are commonly used to express likes, ratings, or favorites in media content. *Bookmark* may also be used to continue audio books or TV shows from where one left off. *Moon* is suitable for activating lighting scenes or a do-not-disturb mode, *Lightning* to indicate control of power sockets or extension cords, *Bell* to ask for notifications, *Telephone* to call someone or start an announcement, and the *Raindrop* to get the weather report, or for actions involving water, such as getting cold water from a dispenser in a fridge, or extending and retracting a rain awning when it rains.

We paid special attention to ensure that our shape set included different numbers of convex and concave curves (e.g., *Circle* vs. *Moon*), edges (e.g., *Triangle* vs. *Bookmark*), and combinations of both (e.g., *Raindrop* vs. *Telephone*).

3.2 Fabrication Variants

For all *shapes*, we created two versions with different *affected areas* that create different haptic sensations: a version that only consisted of the shape's *outline*, and a version with a *filled* inner area. To investigate whether recognition varies if icons are either embroidered 'flatly' onto the fabric, stand out, or are recessed into the base surface, we created outlined and filled icons in each of those three *height profiles*. For our user study, we combined height profiles and affected area into six *fabrication variants*: *Raised Filled*, *Recessed Filled*, *Flat Filled*, *Raised Outlined*, *Recessed Outlined*, and *Flat Outlined* icons. Each *shape* was then fabricated in every *fabrication variant* (Fig. 1).

3.2.1 Fabrication. We used an automated sewing machine to fabricate our icons. For this experiment, we chose a fabric that fits in a home setting. Therefore, we selected a 100% polyester fabric that is made particularly for upholstery of furniture such as sofas. Following the recommendation of Nowak et al. [23], we paid attention that the fabric was rough enough for fingers not to slip, but smooth enough to avoid friction burn, and that the fabric texture did not guide the finger.

We included flat icons in our study to represent a common and simple way of adding decorations to textiles by embroidering yarn patterns directly onto the fabric. Thus, those fabrication variants were not perfectly flat, but instead the *affected area* was lifted slightly from the base fabric, and had a recognizable texture. While flat icons have been studied previously, inter alia, by Holleis et al. [11] and Mlakar and Haller [20], those investigations were either purely qualitative [11] or of a rather small scope [20]. It is thus currently still unclear how quickly and reliably users can recognize textile icons from larger icon sets. We also set out to determine the performance of different fabrication variants to allow designers to make an informed decision for their interfaces. While there have been studies regarding success rates (e.g., [20]), recognition performance studies for textile icons have not been performed yet.

For the *Flat Outlined* icons, we used a triple stitch to create easily recognized lines. We used a step fill for *Flat Filled* icons, since this pattern ensured that the embroidered surface did not guide the finger into a particular direction. Both embroidery approaches also avoided irregular haptic sensations in corners and curves due to dense stitching.

For raised and recessed icons, we used medium-density fiberboard (MDF) cutouts 1.6 mm thick to create a noticeable contrast to the base surface, and following related work [20]. The MDF cutouts allowed for sharp height contrasts on their boundaries to establish each icon's features. For fabricating *Raised Outlined* icons, we set the width of the outline to 1 mm. To not sew into the MDF, we always added a 1 mm gap from the MDF to the stitch. With this, the stitches on the inside are 3 mm apart from those on the outside of the outline (1 mm MDF + 1 mm sewing gap on each side). This represents the smallest perceivable thickness we were able to fabricate with consistent quality for *Raised Outlined* icons. For *Recessed Outlined*, the gap between the MDF plates was set to 3 mm with a 1 mm gap between the stitches. Since our fabric is soft and compressible, we estimate the perceived thickness of both the recessed and the raised outlines to be approximately 2 mm. To fabricate raised and recessed icons, we used the following fabrication workflow:

(1) Cut the wanted shapes and a frame from MDF using a laser cutter.
(2) Embroider alignment marks for the frame on the fabric (cf. Fig. 2a,b).
(3) Glue the frame onto the fabric (cf. Fig. 2c).
(4) Glue the parts of the icon onto the fabric.

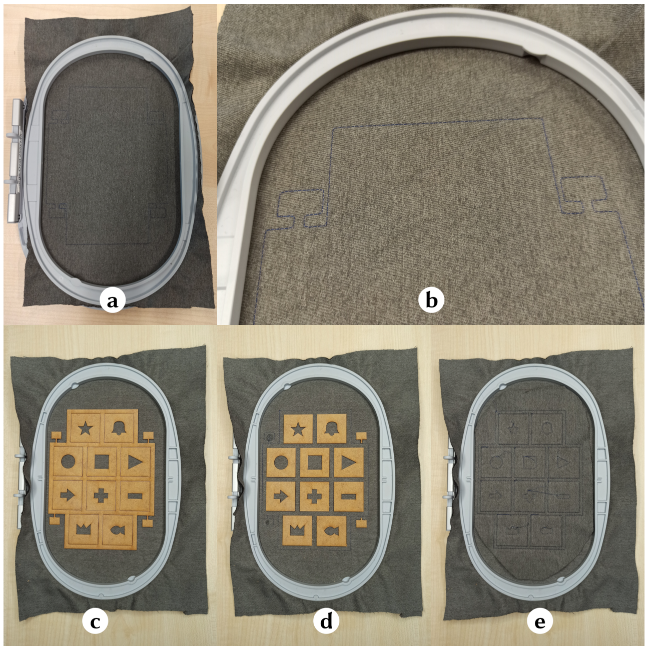

Figure 2: Production steps for creating raised and recessed textile icons. First, we embroidered alignment marks for the frame (a,b), and glued the frame at its rectangular connectors onto the fabric (c). Then, we glued the icons onto the fabric and removed the frame (d). Finally, we embroidered the shapes with a layer of fabric that was placed over the wooden shapes (e).

(5) Break the frame at its connectors and remove it (cf. Fig. 2d).
(6) Cover the MDF with another layer of fabric, and embroider the shapes using 1 mm offsets directed away from the MDF to not sew into it (cf. Fig. 2e).

Independent of the fabrication variant, icon sizes were chosen such that either their width or height, measured in the center of the raised or recessed outlines, was 18 mm (similarly to the recognition experiment by Mlakar and Haller [20]). For the user study, each icon was placed at the center of a 46 × 46 mm patch of fabric.

3.3 Study Setup

The overall task was to recognize different textile icons eyes-free. For this, we seated our participants next to a sight protection wall (Fig. 3). The patches with textile icons were fixated with Velcro on padding foam near the wall to ensure that they were comfortable to reach without seeing them. A homing button for measuring the time was placed near the icon, to minimize time variances due to the homing movement of the participant's arm. During the trials, we filmed the participant's hand. In front of the participant, a monitor displayed the complete set of icons during the study when necessary. The displayed icons always had a gray filling with a black border (cf. Section 3.1) and functioned as a simple memory aid for participants without representing the exact fabrication variant. We mirrored our setup for left-handed participants.

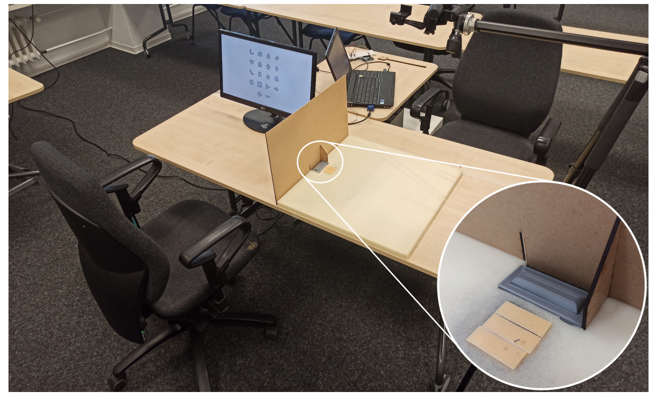

Figure 3: The setup from our user study: A monitor was placed in front of the participant to show digital versions of the tested shapes. Behind a sight protection, Velcro was placed on the padding foam to fix the icon's location during the task. The button was used for time measurements and the participant's hand was video recorded during the trials.

3.4 Procedure and Task

When starting the user study, we presented all shapes one by one to participants on the screen to let them familiarize themselves with the icons. Doing this, we also asked participants to name each shape to ensure that they and the conductor agreed on the same name. For the recognition trials, the conductor placed an icon on the Velcro. We did not alter position or orientation of the icons. Since the homing button was close to the tested icon, we covered the icon to ensure that the user had no accidental contact prior to the trial.

Before we tested the 14 different icons of one variant, participants could familiarize themselves with the fabrication variant by completing the study task with two test icons (*Fish* and *Crown*). Participants were not introduced to any fabrication variant prior to the respective familiarization. We made sure participants understood the current fabrication variant before starting the measurements.

For the task, participants had to place their hand on the other side of the sight protection wall, and when they were ready, they were asked to press the button to start the time measurement. With this, the cover was removed from the icon by the conductor and the participants should start recognizing the shape. The displayed shapes on the monitor disappeared during each trial to avoid pattern matching between the visual and haptic shapes. As soon as participants thought that they could identify the shape, they had to press the button again and name the shape of the icon. We did not state whether participants were correct to ensure that they could not use this information to recognize a later shape. Each trial was limited to 30 seconds to reduce the length of a study session, and since we did not consider longer recognition times for a shape as user-friendly in a real-world scenario. After those 30 seconds, participants got alerted by an acoustic signal, and the monitor turned from white to black to indicate that a timeout occurred. If participants got in contact with the cover after they pressed the homing button the first time, the trial was repeated. This was done for every *shape* within each *fabrication variant*. After participants performed the task with all icons of one fabrication variant, they filled out a questionnaire. Since some questions referred to the shapes, an overview containing all shapes was shown on the monitor during this time. In the end, participants filled out a final questionnaire to also rank the different fabrication variants, and to specify the shapes they found especially easy or difficult to recognize overall.

3.5 Experimental Design

We chose a within-subjects design for our study. The order of the *fabrication variants* was counterbalanced using a Latin square, and the *shapes* within each fabrication variant were randomized. Overall, there were *14 shapes × 6 fabrication variants*, resulting in 84 trials per participant and 3,528 trials overall.

3.6 Measurements

For each trial, we recorded each participant's answer regarding the recognized shape, and measured their *recognition time* using an Arduino Uno microcontroller board. The *recognition time* describes the time between the two home button presses during each task. From the participants' answers, we calculated the *success rate*, *confusion rate*, and *timeout rate* for each fabrication variant based on the outcome of the trial:

- *Success*: The correct shape was identified within 30 seconds.
- *Confused*: A wrong shape was recognized within 30 seconds.
- *Timeout*: No answer was given within 30 seconds.

If participants gave an ambiguous answer, we asked for a clear answer based on the agreed names.

In the questionnaire, participants rated, inter alia, for each fabrication variant the perceived *mental demand*, the perceived ease of recognition (*rough shape recognition*, *shape detail recognition*, and *distinguishability from the underlying fabric*), how comfortable the recognition felt (*comfort*), and how confident they felt about their answers (*confidence*). All ratings were given as 7-point Likert items.

At the end of the study, participants ranked the six fabrication variants regarding their haptic and visual appearance and their overall impression of the variant. For the latter two rankings, participants were allowed to look at the actual textile icons.

3.7 Results

Overall, 42 people participated in our study, age 18 to 42 (M=24.73 years, SD=4.48 years, 14 women, 22 men, 5 non-binary and 1 n/a). Recognition times were analyzed using a repeated measures ANOVA and paired t-tests with a Holm correction as post-hoc tests. Likert scales, *success rate*, *confusion rate*, and *timeout rate* were all analyzed using Friedman tests. Post-hoc tests were performed using Wilcoxon signed-rank tests with a Holm correction, as well. We summarized the *success rate*, the *confusion rate*, and the *timeout rate* for all *fabrication variants* in Table 1. The respective *recognition time* for each *fabrication variant* is shown in Table 2.

3.7.1 Recognition. A Friedman test revealed significant effects of *fabrication variant* on *success rate* (χ^2(5)=153.47, p<0.001), *confusion rate* (χ^2(5)=68.43, p<0.001) and *timeout rate* (χ^2(5)=137.39, p<0.001).

Success rate. Wilcoxon signed-rank tests revealed significant effects between nearly every pair of *fabrication variants*. Only the comparisons *Raised Filled* vs. *Raised Outlined* and *Raised Filled* vs. *Recessed Filled* showed no significant differences. *Raised Outlined* had the highest *success rate* among all fabrication variants with 93.71%, followed by *Raised Filled* (92.86%) and *Recessed Filled* (90.65%). *Flat Outlined* had the lowest *success rate* with 46.43%.

Confusion rate. Wilcoxon signed-rank tests revealed significant effects between *flat* fabrication variants in combination with any other fabrication variant, except of *Flat Filled* vs. *Flat Outlined*. Additionally, *Raised Outlined* lead to significantly less confusions than *Recessed Outlined*. *Raised Outlined* had the least confusions with approximately 2.21%, followed by *Recessed Filled* (3.57%) and *Raised Filled* (4.42%). *Flat* fabrication variants had the most confusions with more than 14% over all trials.

Timeout rate. Wilcoxon signed-rank tests revealed significant effects between nearly every pair of *fabrication variants*. Only three conditions were not significant: *Raised Filled* vs. *Raised Outlined*, *Raised Filled* vs. *Recessed Filled* and *Raised Outlined* vs. *Recessed Filled*. *Raised Filled* had the least timeouts with 2.72%. *Raised Outlined* and *Recessed Filled* had slightly more timeouts: 4.08% and 5.78% respectively. *Flat* fabrication variants had significantly more timeouts than any other fabrication variant with 27.04% (*Flat Filled*) and 38.77% (*Flat Outlined*).

3.7.2 Recognition time. For the time analysis, we excluded all trials that caused a timeout. Therefore, we only considered trials where participants were certain enough to name a shape. Since our time data was distributed log-normally, we performed the ANOVA on log-transformed time data that was averaged per participant. The test revealed a significant effect of *fabrication variant* on *recognition time* (F(5,205)=219.3, p<0.001). Medians and 95% CIs of the *recognition time* are shown in Table 2. We calculated the median for each *fabrication variant* based on the geometric means of each participant in the respective variant. For small sets of data points (≤ 25) the geometric mean is a better center estimate compared to the median and the arithmetical mean regarding task time data [29].

Raised Filled icons were recognized in 6.82 seconds on average. *Recessed Outlined* and *Raised Filled* took slightly longer with 7.31 and 7.41 seconds. *Recessed Outlined* needed 9.83 seconds. *Flat* icons took the longest—14.89 seconds for *Flat Filled* and 15.61 seconds for *Flat Outlined* (Table 2). Post-hoc tests revealed significant differences between nearly every pair of fabrication variants. Only for three comparisons, the tests did not indicate significant differences: *Raised Filled* vs. *Recessed Filled*, *Raised Outlined* vs. *Recessed Filled*, and *Flat Filled* vs. *Flat Outlined*.

Since the number of timeouts varied over the different fabrication variants (see Table 1), shapes performing 'badly' were underrepresented in some variants such as *Flat Outlined*. To see how our findings would change if this data was kept, we repeated the statistical tests setting those trials to 30 seconds, the time at which we stopped the trials. The data was still log-normally distributed. Consequently, we performed the analysis analogously to the significance test without the timeout data. The ANOVA revealed a significant effect (F(5,205)=266, p<0.001), and the post-hoc tests deviated only in one instance from the post-hoc tests without the timeout data, adding a significant difference between *Flat Filled* and *Flat Outlined*.

Raised Filled	*Raised Outlined*	*Recessed Filled*	*Recessed Outlined*	*Flat Filled*	*Flat Outlined*	Success
○ (42, 0, 0)	○ (42, 0, 0)	○ (42, 0, 0)	▭ (41, 0, 1)	▭ (39, 1, 2)	□ (37, 0, 5)	>95%
▷ (42, 0, 0)	▷ (42, 0, 0)	▷ (42, 0, 0)	▷ (40, 0, 2)	☾ (39, 1, 2)	▷ (32, 2, 8)	>90%
□ (42, 0, 0)	□ (42, 0, 0)	□ (42, 0, 0)	□ (40, 0, 2)	☏ (36, 1, 5)	▭ (25, 5,12)	>75%
▭ (42, 0, 0)	☾ (42, 0, 0)	💧 (42, 0, 0)	○ (40, 2, 0)	□ (29, 2,11)	💧 (25, 2,15)	>50%
🔖 (42, 0, 0)	☆ (41, 0, 1)	☾ (41, 0, 1)	☾ (39, 2, 1)	ϟ (29, 3,10)	🔖 (24, 4,14)	>25%
♡ (41, 0, 1)	▭ (41, 1, 0)	☏ (41, 0, 1)	💧 (38, 2, 2)	☆ (29, 3,10)	☾ (22, 9,11)	>10%
☾ (41, 0, 1)	🔔 (40, 0, 2)	🔔 (40, 0, 2)	🔖 (37, 0, 5)	✙ (26,11, 5)	ϟ (20, 9,13)	<=10%
☆ (41, 0, 1)	♡ (40, 0, 2)	▭ (40, 2, 0)	♡ (36, 1, 5)	🔔 (20, 9,13)	○ (20,10,12)	
💧 (40, 2, 0)	💧 (40, 2, 0)	🔖 (39, 1, 2)	🔔 (31, 4, 7)	💧 (20, 9,13)	☏ (17, 7,18)	
☏ (38, 3, 1)	🔖 (39, 0, 3)	♡ (39, 1, 2)	☏ (30, 7, 6)	♡ (19,10,13)	♡ (15, 5,22)	
ϟ (35, 3, 4)	ϟ (39, 0, 3)	☆ (37, 2, 3)	☆ (29, 3,10)	🔖 (17, 9,16)	⇨ (14, 8,20)	
🔔 (35, 5, 2)	☏ (38, 2, 2)	✙ (31, 4, 7)	ϟ (24, 6,12)	▷ (16, 3,23)	☆ (9, 7,26)	
⇨ (34, 3, 5)	✙ (34, 4, 4)	ϟ (29, 6, 7)	✙ (21,10,11)	⇨ (15,12,15)	🔔 (9,11,22)	
✙ (31,10, 1)	⇨ (31, 4, 7)	⇨ (28, 5, 9)	⇨ (20, 7,15)	○ (12, 9,21)	✙ (3, 8,31)	
92.86% A B	93.71% A	90.65% B	79.25% C	58.84% D	46.43% E	*Success rate*
4.42% A B	2.21% A	3.57% A C	7.48% B C	14.12% D	14.80% D	*Confusion rate*
2.72% A B	4.08% A C	5.78% B C	13.27% D	27.04% E	38.77% F	*Timeout rate*

Table 1: Number of successful recognitions, confusions, and timeouts per *shape* and their respective average rates for each *fabrication variant*. Notation: *(success, confused, timeout)*. The shapes are sorted according to their individual recognition, confusion, and timeout rate. Columns sharing the same letter in the same row are not significantly different regarding the corresponding measurement. Apart from *Recessed Filled*, *raised* icons clearly outperformed other *fabrication variants* in every category.

Raised Filled	*Raised Outlined*	*Recessed Filled*	*Recessed Outlined*	*Flat Filled*	*Flat Outlined*	
6.82	7.31	7.41	9.83	14.89	15.61	Median in s
[5.92, 7.47]	[6.60, 7.93]	[6.40, 8.15]	[9.00, 10.51]	[13.43, 16.55]	[14.64, 17.11]	95% CI in s
A	B	A B	C	D	D	Significance

Table 2: Medians and 95% confidence intervals of all *fabrication variants* for *recognition time*. Columns sharing the same letter in the last row are not significantly different. Icons that are either *Raised Filled*, *Raised Outlined*, or *Recessed Filled* were recognized significantly faster.

3.7.3 Likert Scales. We analyzed the Likert scale ratings using Friedman tests. These tests revealed significant effects of *fabrication variant* on *mental demand* (χ^2(5)=132.25, p<0.001), *confidence* (χ^2(5)=149.47, p<0.001), *rough shape recognition* (χ^2(5)=152.08, p<0.001), and *shape detail recognition* (χ^2(5)=130.91, p<0.001). Fig. 4 shows the results of the post-hoc tests, the means and standard deviations for the Likert scales. Overall, *raised* fabrication variants were less mentally demanding and made participants feel more confident when identifying icons compared to other variants. *Recessed Filled* is the closest competitor to the *raised* fabrication variants. Still, it was significantly more mentally demanding compared to *Raised Outlined* and made it significantly harder for participants to recognize shape details compared to the raised fabrication variants.

Additional Friedman tests revealed significant effects of *fabrication variant* on *comfort* (χ^2(5)=115.31, p<0.001) and *distinguishability from the underlying fabric* (χ^2(5)=150.97, p<0.001). The interaction with raised fabrication variants was perceived to be more comfortable. *Raised Filled* was significantly more comfortable than any other fabrication variant (M=2.19, SD=0.77), except for *Raised Outlined* (M=1.81, SD=0.99). *Flat Filled* (M=-0.36, SD=1.73) and *Flat Outlined* (M=-0.67, SD=1.66) were significantly less comfortable than all other fabrication variants.

Like in the other scales, *distinguishability from the underlying fabric* had similar orders regarding the *fabrication variants. Raised Filled* (M=2.60, SD=0.86) and *Raised Outlined* (M=2.43, SD=0.97) out-scored the other fabrication variants, except of *Recessed Filled* (M=2.12, SD=1.38). *Flat Filled* (M=-1.04, SD=1.72) and *Flat Outlined* (M=-2.10, SD=1.33) were significantly harder to distinguish from the background than all other fabrication variants and were also significantly different from each other.

Throughout all Likert scales, participants preferred *Raised Filled*, *Raised Outlined*, and *Recessed Filled* with an overall clear tendency towards *raised* fabrication variants.

3.7.4 Rankings. Results of the rankings are shown in Fig. 5. Regarding the haptics, participants clearly preferred *raised* icons, while *flat* icons were nearly always ranked on 5^{th} and 6^{th} place. Visually, however, flat icons were preferred, with more than half of all

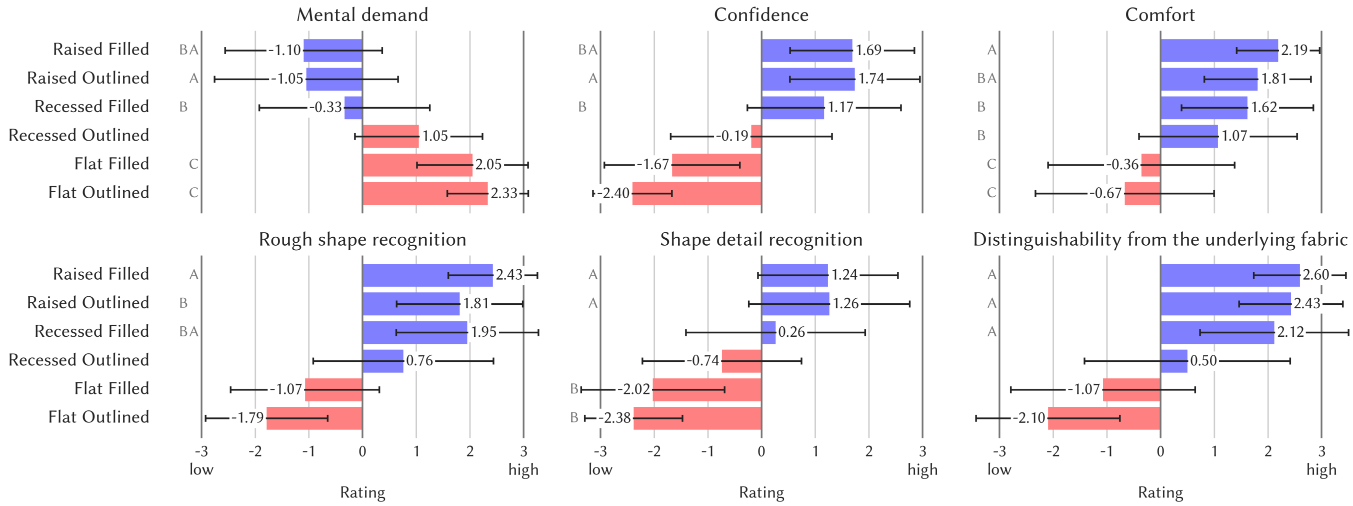

Figure 4: Participants' average ratings for *mental demand, confidence, comfort, rough shape recognition, shape detail recognition,* and *distinguishability from the underlying fabric* on a 7-point Likert scale. The scale ranges from -3 (worst) to 3 (best) except for *mental demand* where smaller values indicate better ratings. Whiskers denote the standard deviation. Fabrication variants sharing the same letter are not significantly different. Overall, the *raised* variants performed best.

participants ranking *Flat Filled* 1^{st} or 2^{nd} and almost half of all participants ranking *Flat Outlined* 1^{st} or 2^{nd}. *Flat Filled* was ranked 1^{st} most often. In the overall ranking, *raised* icons were preferred. While flat icons still received the lowest ranks here, they did so less clearly than in the haptic ranking.

3.7.5 Easy and Hard Shapes. In addition to the final rankings, participants could name shapes that they felt were particularly easy or hard to recognize. For the easy shapes, participants often named shapes with a simple form: *Square* (30x), *Circle* (29x), *Triangle* (19x), *Minus* (16x), and *Moon* (10x). The following shapes were considered to be hard to recognize: *Lightning* (31x), *Arrow* (21x), *Star* (15x) and *Telephone* (15x), and *Bell* (11x).

3.7.6 Confusable Shapes. Overall, we recorded many *directional confusions* where one shape was often mistaken for another shape, but the opposite direction did not occur. The most outstanding cases are that *Plus* was mistaken for *Star* 9 times for *Raised Filled* and 8 times for *Recessed Outlined*, and that *Heart* was mistaken for *Arrow* 9 times for *Flat Filled*. However, the opposite direction did not occur for any of these three cases. Table 3 shows the most common mistakes where one shape was confused for another shape at least three times. For more detailed information about the shape confusions, see the confusion matrices and their visualizations in the supplementary material.

4 DISCUSSION

The results from our study clearly indicate that *flat* icons are not recognized reliably enough to be used for eyes-free interactions on textile interfaces. This finding aligns with Mlakar and Haller [20] whose participants were only able to correctly deduce the shape of *Flat Outlined* icons in 50% of the cases at best. Especially regarding *recognition time*, flat variants would perform worse in a real-world scenario than indicated in Table 2, because the time was calculated on trials where participants felt confident naming a shape. This emphasizes the performance of particularly our *raised* icons, which led to significantly fewer timeouts than *flat* variants. While we expected that flat icons would perform worse, it was surprising to see how much better raised and recessed icons performed, with a noticeable difference of at least 5 seconds for the *recognition time* and 20% in the *success rate* compared to the flat variants. Especially raised icons are promising icon candidates with their overall good performance and approximately 65% of the shapes being recognized successfully with more than 95% accuracy. While our experiment did not test pairwise shape discrimination, our results indicate that those fabrication variants are promising candidates for interfaces using a larger set of icons. Regarding the recessed fabrication variants, we would also not recommend using *Recessed Outlined* due to its rather low *success rate* of approximately 80%. Designers can now pick subsets from our tested icon set which were recognized reliably and between which no confusions appeared. For example, *Plus* was recognized as *Star* nine times, and removing it from our set will minimize such errors.

Except for the flat designs, we observed that simple shapes, such as *Circle* and *Square*, were very easy to recognize by our participants throughout the study. These findings also align with the recommendations and guidelines from related work [3, 20]. While the recognition rates for *Recessed Outlined* icons were worse for more complex shapes than the other non-flat fabrication variants, simple geometric shapes were still identified robustly, and could be used successfully in textile interfaces. Additionally, we want to emphasize that those *Recessed Outlined* icons might also be useful when combined with other fabrication variants to differentiate icons used for different purposes. For example, raised icons could be used for buttons that trigger actions, while recessed ones could be used to label UI sections. Alternatively, different fabrication variants could be used to create contrast between UI sections that

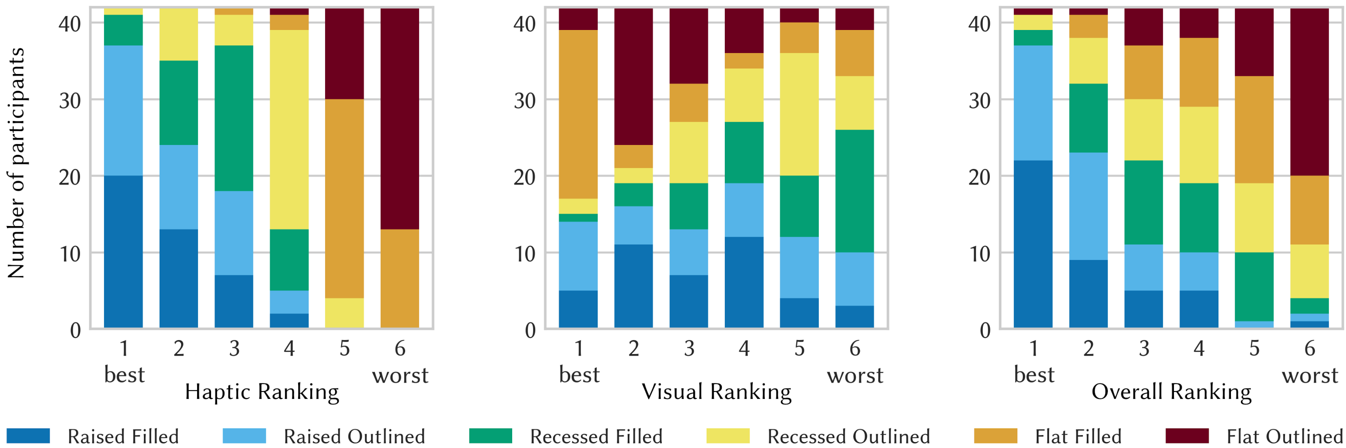

Figure 5: Subjective rankings of the six fabrication variants. Lower ranks correspond to stronger preference by the participants. In the haptic and overall ranking, the *raised* icons received the best rankings, while *flat* variants performed worst. However, *flat* icons were better ranked in the visual ranking.

address different applications, like multimedia vs. lighting control. How exactly using such contrast methods in user interfaces would perform is an intriguing topic for further research.

Regarding the final rankings, participants clearly preferred *raised* icons when only considering haptics. However, when ranking the icons based on their visual appearance, *Flat Filled* was generally preferred more, while *raised* icons were distributed across all ranks regarding this ranking. One possible reason for the good ranking of *Flat Filled* could be that these icons were more colorful since we used blue yarn to fill the area of these icons (cf. Fig. 1). Still, the overall ranking is very similar to the haptic ranking of all *fabrication variants*, indicating that the choice of haptic feedback provided by such interface elements might have a major influence on the participants' preferences. This is supported by the poor recognition performance of the *flat* variants, and by the fact that their perceived mental demand was reported as significantly higher in most cases (cf. Fig. 4). However, we want to emphasize that the study was focused on haptics, which may have influenced the overall ranking.

Looking at the most common confusions in Table 3, we could observe mainly unidirectional confusions in which one shape was mistaken for another, but the other direction did not occur. One shape that many shapes were confused for, is *Star*. Especially *Plus* was often recognized as *Star*. The main reason for this might be that participants were rather uncertain when they felt the corners of *Plus* since they might have overlooked one corner. This is not the case when they had to identify *Star* since they were able to quickly find all haptic cues. It seems that especially 'pointy' shapes with corners on protruding parts can easily be confused with *Star*, possibly because people have difficulties recognizing and differentiating nearby corners and/or their sharpness. Another explanation could be that participants needed to make sure that they did not accidentally miss parts of the shape. Both may also have influenced the recognition time for such shapes.

Two other interesting confusions are *Heart* vs. *Arrow* for *Flat Filled* and *Arrow* vs. *Lightning* for *Recessed Filled*. In both cases, the shapes are easy to tell apart visually. However, they still share some properties, such as sharp corners in similar places, and a diagonal edge from the bottom to the right-hand center of the shape. To make such shapes distinguishable via touch, their 'separating features' have to be made noticeably different. For *Moon* vs. *Telephone*, participants could easily recognize the curved shape that both icons share, but the 'separating features' (in this case the endpoints) could be highlighted more prominently. For example, the tips of *Telephone* could be enlarged to make the flat ends stand out more. Other approaches might be to use a different sewing stitch or to create small yarn bumps in specific areas (e.g., in corners) to highlight discriminating factors of the shapes. The fabrication variant could also influence whether the shapes are easy to distinguish: While the overall *success rate* was lower for *Recessed Filled* compared to raised variants, it is the only variant in which *Telephone* is recognized as well as *Moon*, with zero confusions between the two shapes, and it is the variant with the best recognition of *Telephone* overall.

One shape that did not work well in most fabrication variants was *Lightning*. Overall, it was relatively hard to recognize, and it was part of many confusions. We do not recommend using this shape in its current form.

Our results regarding the recognizability fit the research of haptically salient shape features, i.e. properties whose presence is detected very early during the haptic recognition. One particular example was presented by Panday et al. [24], who found that the presence of (vertical) edges, due to their saliency, can impede the perception of the overall shape, while more curvature information is helpful. This might explain why for shapes with few corners like *Telephone* and *Moon*, their curved shape is still easily identifiable—even though the ambiguous endpoints cause confusion—, while shapes with many corners and no curves are confused often.

With our icon designs, we were able to achieve a reasonable *recognition time* that might already work for real-world use cases without causing frustration among users. Our recognition times for *raised* variants are also close to the reported recognition times of

Fabrication Variant	X	Y	X → Y	Y → X
Raised Filled	✚	☆	9	0
	🔔	🔖	5	0
	📞	☾	3	0
	ϟ	☆	3	0
Raised Outlined	⇨	ϟ	4	0
Recessed Filled	✚	☆	4	1
	ϟ	☆	3	1
Recessed Outlined	✚	☆	8	0
	📞	☾	7	2
	⇨	ϟ	6	1
	ϟ	☆	3	0
Flat Filled	♡	⇨	9	0
	●	🔔	6	0
	✚	ϟ	5	0
	⇨	ϟ	5	0
	✚	☆	4	1
	🔔	🔖	4	1
	🔔	☆	3	1
	🔖	■	3	0
	⇨	☆	3	0
Flat Outlined	●	💧	5	0
	ϟ	☆	4	2
	☾	📞	3	2
	⇨	ϟ	3	2
	●	🔔	3	1
	🔔	🔖	3	1
	🔖	■	3	0
	📞	ϟ	3	0
	♡	☾	3	0
	✚	☆	3	0

Table 3: Relations between icons for which participants confused one shape for another at least three times. X → Y denotes that icon X was mistaken for icon Y, and vice versa for Y → X. Overall, confusions occurred mostly in one direction.

3D objects by Klatzky et al. [14] (94% correct recognitions within 5 seconds). We were surprised to achieve similar performance since 3D objects can provide additional, stronger separating cues, such as material, size, depth, and users can hold and examine such objects from all sides. However, it is noteworthy that both study methods differ. Klatzky et al. [14] investigated the recognition of common 3D objects by blindfolded participants who tried to identify an object while not knowing the set of possible pieces. We, on the other hand, studied shape recognition of textile icons by participants who frequently had access to a visualization of all possible shapes, to achieve a more realistic scenario in which users roughly know the interface they intend to interact with. Wijntjes et al. [31] and Cecchetto and Lawson [2] have emphasized the importance of visual imagery when recognizing haptically. Knowing the set of possible shapes and having preformed mental images of them might have enabled our participants to deduce a given shape also by excluding non-fitting alternatives and focusing more on those parts of the shape that separate it from the rest.

Several additional factors might contribute to the high performance of our *raised* and *recessed* variants, particularly when comparing *Raised Outlined* icons to standard raised-line drawings: Our shapes contain no 3D perspective lines, facilitating recognition according to Lebaz et al. [15]. Kalia and Sinha [12] have shown that recognition generally improves with increased symmetry and decreased complexity of the drawing, and our shapes fall on the beneficial ends of both scales. Based on further study results, they suggest that exploring a drawing gets more confusing if it contains multiple intersecting lines (as is often the case for standard drawings) which was not the case for our shapes that consist of a single outline that never branches. This makes exploration more straightforward. Kalia and Sinha [12] also suggest that a shape is easier to recognize haptically if it would still be visually identifiable after blurring and thresholding its outlines. Since our icons were designed such that no features were lost by the fabrication variants' offsets, this could support the high recognizability of our shapes. The hardness and height of our icons could also explain why our icons performed well as Cecchetto and Lawson [2] have shown that raised-line drawings perform better when using solid and strong height differences compared to typical swellpaper, which has a height of approximately 0.5 mm.

Considering all our findings, raised icons outperformed other *fabrication variants* in almost every single category. This includes the *recognition time*, *mental demand*, *confidence*, *comfort*, *rough shape recognition*, *shape detail recognition* and *distinguishability from the underlying fabric* (cf. Fig. 4 and 5). It is noticeable that the order of the *fabrication variants* stayed nearly the same for most measurements (*recognition time* and Likert scales), suggesting a clear rank order in the choice of a fabrication variant.

From our findings, we derive the following recommendations for using textile icons:

- Use raised icons if possible.
- You can choose between *Raised Filled* and *Raised Outlined* based on the implemented overall design language of your interface, as they perform alike.
- If recessed elements are required, choose *Recessed Filled* as a valid alternative to raised icons.
- You can use very simple geometric shapes as *Recessed Outlined* icons, as they are robustly identifiable.
- Flat icons are only an alternative to be used when the icons should be clearly visible during the interaction and embroidery is chosen for stylistic reasons. For such cases, we recommend testing designs combining embroidery with recessed or raised height profiles.
- For selecting shapes, we gathered the following insights:
  - Pick icon subsets from Table 1 that are easily distinguishable via touch if the interface should be used eyes-free.
  - If shapes that are easy to confuse have to be used close to each other, the 'separating features' of those icons have to be made noticeably different. This can also be influenced by the fabrication variant used.
  - Simple shapes are easy to recognize when using *raised* or *recessed* icons.
  - If you include more complex shapes, users may feel less certain when interacting with simpler shapes.

5 LIMITATIONS AND FUTURE WORK

During our investigations, we identified many aspects that are worth studying in more detail in the future. The icon shapes we included were chosen to cover many application domains while offering an appropriate variance of shape features. However, we found numerous shapes that could also find broad application in environments with textiles, such as *clouds*, *card symbols*, or more complex shapes like *houses*, *twirls*, and *letters*. Additionally, our user study did not focus on the investigation of the recognizability of shape features, but rather on the *affected area* and *height profiles*. Therefore, further studies could be conducted about the recognizability of individual shape features as well as the pairwise shape discrimination in different sets of icons.

In our study, participants were sitting while interacting with the icons that were always fixated on the same place with the same orientation. This allowed for a more stable and predictable interaction than in settings where icon position and orientation may change. The apron by Holleis et al. [11] is a good example of a scenario where icons might be displaced and reoriented depending on the user's posture and how the cloth itself moved. In the end, textile icons can be used in many different positions, orientations, and on different undergrounds, e.g., on the side of armchairs, bags, curtains near a wall, seat belts in a car, and of course on clothes. We expect that recognition can vary significantly when the user's mental model of the interface does not match the icons found due to those factors; this should be investigated further.

Using simple and common shapes in textile interfaces raises the question of whether they can provide cues to the user of what their function is. Especially for eyes-free interactions, interface designers need to negotiate whether they should use simple shapes such as a square for easy recognition or whether they choose more meaningful shapes that can add complexity, and thus make recognition more difficult, to convey the semantics of the interface more adequately. We see that special arrangements of icons can be sufficient for users who are already familiar with a system to orientate on the interface. For example, squared buttons in an arrangement of a keyboard's arrow keys could be understood to be used for going up, down, left, and right. However, using distinctive shapes can increase the confidence to perform the correct action and can function as anchor points in cluttered interface areas. Alternatively, simple shapes allow the creation of more complex icons using compositions of those shapes. For example, an 'i' can be created with a circle and a rectangle. Nevertheless, it is yet unclear how to design such shape compositions on textiles to be understood as one semantic unit. This becomes important when keeping the form factor the same, since the components of the composed icon have to shrink then, and Mlakar and Haller [20] have shown that reducing size beyond 13 mm can complicate the recognition.

Apart from the icon set, we only used a single type of fabric. We chose our fabric such that it supported the recognition task while still being a representative of common textiles in the home. However, one should not expect that the icon recognition is the same on fabrics with different textures, such as *satin* or *cord*. Future work could investigate whether our findings also hold for such fabrics. Regarding our fabrication workflow, we are confident that it will work with various kinds of fabrics for furniture, but it will require adjusting fabrication parameters such as the offset between MDF and sewing lines accordingly. Especially when leaving the domain of furniture, for example when designing icons for clothes, the types of fabric are numerous and factors like fabric elasticity need to be considered.

This work investigated one fundamental design element of many that are used in traditional user interfaces. While in the literature, textile widgets are mainly investigated individually [5, 19, 20, 23], combining them into a larger user interface can lead to different perceptions of these widgets and their affordances. Thus, the design languages for such interfaces are worth investigating.

6 CONCLUSION

In this paper, we introduced 84 different textile icons that combine different *affected areas* with *height profiles* for various shapes. For this, we introduced a simple fabrication process to add raised and recessed icon features to textile surfaces, which is especially useful for prototyping textile interfaces. In our user study, we investigated the haptic recognizability of textile icon variants that were explored by palpation. Our findings agree with previous work [3, 20] that simple shapes should be preferred. Compared to textile sliders [23], where recessed shapes supported the desired action (sliding) better, we found a clear tendency towards raised shapes for textile icons. Raised icons were superior to other fabrication variants regarding recognition time, success rate, and user preference. The closest competitor to raised fabrication variants is our *Recessed Filled* variant. The measured recognition times and successful recognitions for raised textile icons are promising to be investigated further in the future. With our study, we showed significant performance differences between our raised and recessed fabrication variants when compared to conventional flat fabrication variants for a larger icon set. We also found important confusion patterns among different shapes in our icon set. Finally, we distilled our findings into a set of design recommendations for textile icons. Taken together, these findings can help HCI researchers and designers make more informed decisions when creating future textile interfaces. With these contributions, we hope to motivate and support further work in the field of textile interface design.

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REFERENCES

[1] Mohamed Benali-Khoudja, Moustapha Hafez, Jean-Marc Alexandre, and Abderrahmane Kheddar. 2004. Tactile interfaces: a state-of-the-art survey. In *International Symposium on Robotics*, Vol. 35. Citeseer, International Federation of Robotics, Paris-Nord Villepinte, France, 9 pages.

[2] Stefano Cecchetto and Rebecca Lawson. 2015. Simultaneous Sketching Aids the Haptic Identification of Raised Line Drawings. *Perception* 44, 7 (2015), 743–754. https://doi.org/10.1177/0301006615594695

[3] Ben P. Challis and Alistair D.N. Edwards. 2001. Design principles for tactile interaction. In *Haptic Human-Computer Interaction*, Stephen Brewster and Roderick Murray-Smith (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 17–24.

[4] Yu-Cheng Chen, C. H. Chiang, and Huan-Chung Chiu. 2010. The recognition of 3 D basic patterns and tactile icons for the blind. In *Internet Journal of Society*

for Social Management Systems, Vol. 6. Society for Social Management Systems, Kochi, Japan. Issue 1.

[5] Scott Gilliland, Nicholas Komor, Thad Starner, and Clint Zeagler. 2010. The Textile Interface Swatchbook: Creating graphical user interface-like widgets with conductive embroidery. In *International Symposium on Wearable Computers (ISWC) 2010*. Institute of Electrical and Electronics Engineers, Seoul, South Korea, 1–8. https://doi.org/10.1109/ISWC.2010.5665876

[6] Jun Gong, Yu Wu, Lei Yan, Teddy Seyed, and Xing-Dong Yang. 2019. Tessutivo: Contextual Interactions on Interactive Fabrics with Inductive Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 29–41. https://doi.org/10.1145/3332165.3347897

[7] Maas Goudswaard, Abel Abraham, Bruna Goveia da Rocha, Kristina Andersen, and Rong-Hao Liang. 2020. FabriClick: Interweaving Pushbuttons into Fabrics Using 3D Printing and Digital Embroidery. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 379–393. https://doi.org/10.1145/3357236.3395569

[8] Bruna Goveia da Rocha, Oscar Tomico, Panos Markopoulos, and Daniel Tetteroo. 2020. Crafting Research Products through Digital Machine Embroidery. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference* (Eindhoven, Netherlands) *(DIS '20)*. Association for Computing Machinery, New York, NY, USA, 341–350. https://doi.org/10.1145/3357236.3395443

[9] Nur Al-huda Hamdan, Jeffrey R. Blum, Florian Heller, Ravi Kanth Kosuru, and Jan Borchers. 2016. Grabbing at an Angle: Menu Selection for Fabric Interfaces. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/2971763.2971786

[10] Chris Harrison and Scott E. Hudson. 2009. Providing Dynamically Changeable Physical Buttons on a Visual Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 299–308. https://doi.org/10.1145/1518701.1518749

[11] Paul Holleis, Albrecht Schmidt, Susanna Paasovaara, Arto Puikkonen, and Jonna Häkkilä. 2008. Evaluating Capacitive Touch Input on Clothes. In *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services* (Amsterdam, The Netherlands) *(MobileHCI '08)*. Association for Computing Machinery, New York, NY, USA, 81–90. https://doi.org/10.1145/1409240.1409250

[12] Amy A. Kalia and Pawan Sinha. 2012. Tactile Picture Recognition: Errors Are in Shape Acquistion or Object Matching? *Seeing and Perceiving* 25, 3-4 (2012), 287–302. https://doi.org/10.1163/187847511X584443

[13] Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: Eyes-Free Continuous Input on Interactive Clothing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 1313–1322. https://doi.org/10.1145/1978942.1979137

[14] Roberta L. Klatzky, Susan J. Lederman, and Victoria A. Metzger. 1985. Identifying objects by touch: An "expert system". *Perception & psychophysics* 37, 4 (1985), 299–302. https://doi.org/10.3758/BF03211351

[15] Samuel Lebaz, Christophe Jouffrais, and Delphine Picard. 2012. Haptic identification of raised-line drawings: high visuospatial imagers outperform low visuospatial imagers. *Psychological research* 76, 5 (2012), 667–675. https://doi.org/10.1007/s00426-011-0351-6

[16] Fabrizio Leo, Caterina Baccelliere, Aleksander Waszkielewicz, Elena Cocchi, and Luca Brayda. 2018. Tactile Symbol Discrimination on a Small Pin-Array Display. In *Proceedings of the 2018 Workshop on Multimedia for Accessible Human Computer Interface* (Seoul, Republic of Korea) *(MAHCI'18)*. Association for Computing Machinery, New York, NY, USA, 9–15. https://doi.org/10.1145/3264856.3264858

[17] Yiyue Luo, Kui Wu, Tomás Palacios, and Wojciech Matusik. 2021. KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 668, 12 pages. https://doi.org/10.1145/3411764.3445780

[18] Miroslav Macik, Vojtech Gintner, Dominika Palivcova, and Ivo Maly. 2018. Tactile symbols for visually impaired older adults. In *9th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. IEEE, Budapest, Hungary, 000105–000110. https://doi.org/10.1109/CogInfoCom.2018.8639872

[19] Sara Mlakar, Mira Alida Haberfellner, Hans-Christian Jetter, and Michael Haller. 2021. Exploring Affordances of Surface Gestures on Textile User Interfaces. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 1159–1170. https://doi.org/10.1145/3461778.3462139

[20] Sara Mlakar and Michael Haller. 2020. Design Investigation of Embroidered Interactive Elements on Non-Wearable Textile Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376692

[21] Mukhriddin Mukhiddinov and Soon-Young Kim. 2021. A Systematic Literature Review on the Automatic Creation of Tactile Graphics for the Blind and Visually Impaired. *Processes* 9, 10 (2021), 17–26. https://doi.org/10.3390/pr9101726

[22] Donald Arthur Norman. 2013. *The Design of Everyday Things: Revised and Expanded Edition* (2nd ed.). Basic Books, New York.

[23] Oliver Nowak, René Schäfer, Anke Brocker, Philipp Wacker, and Jan Borchers. 2022. Shaping Textile Sliders: An Evaluation of Form Factors and Tick Marks for Textile Sliders. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 214, 14 pages. https://doi.org/10.1145/3491102.3517473

[24] Virjanand Panday, Wouter M. Bergmann Tiest, and Astrid M.L. Kappers. 2012. Influence of Local Properties on the Perception of Global Object Orientation. *IEEE Transactions on Haptics* 5, 1 (2012), 58–65. https://doi.org/10.1109/TOH.2011.53

[25] Patrick Parzer, Florian Perteneder, Kathrin Probst, Christian Rendl, Joanne Leong, Sarah Schuetz, Anita Vogl, Reinhard Schwoediauer, Martin Kaltenbrunner, Siegfried Bauer, and Michael Haller. 2018. RESi: A Highly Flexible, Pressure-Sensitive, Imperceptible Textile Interface Based on Resistive Yarns. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 745–756. https://doi.org/10.1145/3242587.3242664

[26] Patrick Parzer, Adwait Sharma, Anita Vogl, Jürgen Steimle, Alex Olwal, and Michael Haller. 2017. SmartSleeve: Real-Time Sensing of Surface and Deformation Gestures on Flexible, Interactive Textiles, Using a Hybrid Gesture Detection Pipeline. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 565–577. https://doi.org/10.1145/3126594.3126652

[27] Delphine Picard and Samuel Lebaz. 2012. Identifying Raised-Line Drawings by Touch: A Hard but Not Impossible Task. *Journal of Visual Impairment & Blindness* 106, 7 (2012), 427–431. https://doi.org/10.1177/0145482X1210600705

[28] Ivan Poupyrev, Nan-Wei Gong, Shiho Fukuhara, Mustafa Emre Karagozler, Carsten Schwesig, and Karen E. Robinson. 2016. Project Jacquard: Interactive Digital Textiles at Scale. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 4216–4227. https://doi.org/10.1145/2858036.2858176

[29] Jeff Sauro and James R. Lewis. 2016. *Quantifying the user experience: Practical statistics for user research.* Morgan Kaufmann, Cambridge.

[30] Stefan Schneegass and Alexandra Voit. 2016. GestureSleeve: Using Touch Sensitive Fabrics for Gestural Input on the Forearm for Controlling Smartwatches. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers* (Heidelberg, Germany) *(ISWC '16)*. Association for Computing Machinery, New York, NY, USA, 108–115. https://doi.org/10.1145/2971763.2971797

[31] Maarten W.A. Wijntjes, Thijs van Lienen, Ilse M. Verstijnen, and Astrid M.L. Kappers. 2008. Look What I Have Felt: Unidentified Haptic Line Drawings Are Identified after Sketching. *Acta Psychologica* 128, 2 (2008), 255–263. https://doi.org/10.1016/j.actpsy.2008.01.006

[32] Tony Wu, Shiho Fukuhara, Nicholas Gillian, Kishore Sundara-Rajan, and Ivan Poupyrev. 2020. ZebraSense: A Double-Sided Textile Touch Sensor for Smart Clothing. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 662–674. https://doi.org/10.1145/3379337.3415886

[33] Te-Yen Wu, Shutong Qi, Junchi Chen, MuJie Shang, Jun Gong, Teddy Seyed, and Xing-Dong Yang. 2020. *Fabriccio: Touchless Gestural Input on Interactive Fabrics.* Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376681

[34] Te-Yen Wu, Zheer Xu, Xing-Dong Yang, Steve Hodges, and Teddy Seyed. 2021. Project Tasca: Enabling Touch and Contextual Interactions with a Pocket-Based Textile Sensor. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 4, 13 pages. https://doi.org/10.1145/3411764.3445712

[35] Clint Zeagler, Scott Gilliland, Halley Profita, and Thad Starner. 2012. Textile Interfaces: Embroidered Jog-Wheel, Beaded Tilt Sensor, Twisted Pair Ribbon, and Sound Sequins. In *2012 16th International Symposium on Wearable Computers*. Institute of Electrical and Electronics Engineers, Newcastle, United Kingdom, 60–63. https://doi.org/10.1109/ISWC.2012.29