Interactive FUrniTURE – Evaluation of Smart Interactive Textile Interfaces for Home Environments

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ABSTRACT

Ubiquitous computing strives to reach the *calm computing* state where sensors and actuators disappear from the foreground of our surroundings into the fabric of everyday objects. Despite the great progress in embedded technology, artificial interfaces, such as remote controls and touch screens, remain the dominant media for interacting with smart everyday objects. Motivated by recent advancements in smart textile technologies, we investigate the usability and acceptance of fabric-based controllers in the smart home environment. In this article we describe the development and evaluation of three textile interfaces for controlling a motorized recliner armchair in a living room setting. The core of this contribution is the empirical study with twenty participants that contrasted the user experience of three textile-based interaction techniques to a standard remote control. Despite the slightly lower reliability of the textile interfaces, their overall acceptance was higher. The study shows that the hedonic quality and attractiveness of textile interfaces have higher impact on user acceptance compared to pragmatic qualities, such as efficiency, fluidity of interaction, and reliability. Attractiveness profits from the direct and nearly invisible integration of the interaction device into textile objects such as furniture.

Author Keywords

Digital Textiles; Smart Interactive Textiles; User Experience; Technology Acceptance; Laphroaig; User Diversity

ACM Classification Keywords

H.5.2 User Interfaces: Input devices and strategies (e.g., mouse, touchscreen)

INTRODUCTION

Human history is inherently linked to the use of textiles. Early traces of their use date back to 30.000 years B.C. [32, 18]. They are often perceived as warm, soft, smooth, or fluffy, come in various different sizes, colors, forms, and structures, and are part of our daily lives, for example, in form of clothes, handbags, furniture, bed linen, and carpets. One the other hand, along with the advent of the microprocessor came the development of ubiquitous sensing and communication technologies that reshape how we use and interact with digital devices. Consequently, over 25 years ago Marc Weiser and his team at Xerox Parc envisioned how work environments will change when information and communication technology gets smaller, smarter, and eventually ubiquitous [39].

Figure 1. A motorized recliner armchair is augmented with a tactile textile interface and evaluated in a user study in a prototypical living room setting.

Today, this once bold vision of Ubiquitous Computing is becoming a reality. In people's habitats, numerous actuators and sensors are increasingly interconnected and orchestrated towards the vision of the *smart home*: Internet-enabled lights shift their hue with the time of day, smart heating no longer follows static schedules, but use presence information and geo-location to balance energy consumption with coziness and comfort, and robotic vacuum cleaners automatically detect and remove dust from our spaces. However, today's smart home gadgets are predominantly made of glass, metal, and plastic interfaces and are thus perceived as impersonal, digital, stiff, and cold objects.

Research on interactive textile aims to combine the power of digital devices with the ubiquity of analog textiles. So far, this line of research has been dominated by wearable systems [7]. The work presented in this paper bridges the gap between impersonal electronic devices and the flexibility and softness of textiles in the home environment.

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We integrate and contextualize interactive textile interfaces in furnitures by taking an adjustable recliner armchair in a living room (Figure 1). We embroidered conductive thread onto the fabric of an armchair, creating two tactile interfaces which support three different interaction techniques. In a user study, we evaluate the usability and acceptance of these techniques compared to a baseline, a conventional remote control, based on the scales of the User Experience Questionnaire [19, 36] and the *intention to use* predictor from the Technology Acceptance Model [1, 8].

The remainder of this paper is structured as follows: First, we provide an overview of the state of the art in smart interactive textiles and technology acceptance research. Second, we present the technical development of the realized textile interfaces and the textile-based interaction techniques. Third, we describe the user study designed to evaluate and compare the textile interfaces. Fourth, we present and discuss the key findings and limitations of the study. Finally, we conclude this paper with a summary and an overview of future research questions that should be addressed for integrating smart textile interfaces into people's habitat.

The main contributions of this work are:

- First, the paper describes briefly the technical implementation of the textile sensors and how embroidery was used to integrate conductive thread into the fabrics of the armchair.
- Second, the paper presents an empirical user study that compares three different textile interaction techniques against the conventional remote control.
- Third, participants quantitative evaluations are supplemented and partly explained by qualitative results in terms of statements and ideas participants expressed.
- Finally, we identify attractiveness and hedonic properties as key determinants for acceptance and projected later use of smart textile interfaces in home environments.

STATE OF THE ART

Interactive Textile Interfaces

In recent years, researchers have been investigating ways to augment and model textiles as interactive surfaces. The concept of integrating conductive textiles, data and power distribution, as well as sensors and actuators into fabrics has been introduced by Post et al. in 1997 [28, 29]. Early work [35, 31] examined the benefits of integrating a capacitive touchpad into clothing. Today, touch enabled textiles are produced commercially. For example, Project Jacquard incorporates conductive thread into fabrics during the weaving process on regular industrial looms [30]. The conductive thread can be integrated as weft as well as warp during weaving. Thus, fabrics with two-dimensional grids can be realized and facilitate multitouch and gesture implementation.

Leveraging the textile nature of many of the objects that surround us enables natural interaction with and seamless integration into our environment [26]. For example, Lee et al. [20] defined a gesture alphabet of possible fold, bend, and distort gestures for paper, plastic, and stretchable fabric. Natural interaction with fabric (e.g., pinch, stretch, squeeze, drape, etc.) has recently been motivated as an interaction metaphor for deformable user interfaces [27, 21, 37].

Karrer et al.'s Pinstripe [17] is an augmented t-shirt sleeve with parallel stripes of conductive thread stitched onto the fabric to detect when the user grabs the fabric as well as the size and displacement of the rolling grip. The grip activates the textile sensor, and the rolling gesture manipulates a continuous, one-dimensional input value. Gioberto et al. [10] use a different approach by integrating stretch sensors into fabrics.

Hamdan et al. [12, 11] used embroidery to stitch a two-dimensional pattern of textile sensors. They propose using the unique affordances of textiles, folding the fabric at different angles, as eyes-free interaction technique for, e.g., menu selection. They argue that avoiding simple touch gestures and leveraging the flexibility of textile materials for input could minimize accidental activation in everyday settings.

Besides wearable textile sensors, domestic environments are increasingly regarded as an application field for smart textiles. The ability to embed textile sensors ubiquitously into existing textile objects has the advantage of providing simple control interfaces that are less intrusive than other approaches. The flexibility and versatility of textile materials allows us to easily manipulate the fabric to provide mappings, visual, and tactile affordances that relate directly to the object they control.

Heller et al. [13] embroidered conductive thread into a curtain cloth to realize an interactive curtain. The curtain detects changes in the electric field of the conductive thread when the user swipes her hand along the curtain's fabric and triggers an actuator to open or close the curtain. By embroidering different patterns onto the cloth, the interactive curtain can provide adequate visual affordances and reveal its functions to the users.

Rus et al. [34] integrated capacitive sensing into a couch to demonstrate the integration of smart textiles into furniture. Several patches with conductive fabric at different places on the couch enable an automatic and reliable posture detection.

Besides the development of those textile innovations and with regard to their success or failure in the market, it is important to investigate whether, and to which extent, people accept such novel textile interfaces.

Technology Acceptance

The goal of technology acceptance research is to understand if, why, and by whom a product or service is or will be adopted [33, 8]. Many empirical models are based on the Theory of Reasoned Action [9] and the Theory of Planned Behavior [1]. Both theories state that the observable behavior of an individual is closely linked to the individual's intention towards that behavior (behavioral intention). This intention is governed by the individual's attitudes, subjective believes, and self-efficacy towards the specific behavior. On this basis, Davis [8] formulated the Technology Acceptance Model (TAM), which uses perceived usefulness and ease of use as predictors for the *intention to use* a technology and found that

74% of the variance in the *intention to use* predictor and later actual *use* can be predicted months in advance.

Davis' TAM has been validated, refined, and extended in many studies and was applied in many different domains. For example, Venkatesh et al.'s Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) model incorporates additional evaluation scales, such as the hedonic value of a product [38]. But none of these models were specifically tailored towards smart interactive textiles in the home environment.

Other metrics to evaluate interactive systems include the User Experience Questionnaire (UEQ) [19, 36], which evaluates a systems based on pragmatic quality, hedonic quality and overall attractiveness. But it omits the *intention to use* predictor of TAM. And it remains unclear which scales of the UEQ are more decisive of the overall acceptance of a product. Furthermore, it is unclear if this model is applicable for evaluating the acceptance of interactive textiles.

Several studies examined the acceptance of interactive textiles using scenario-based approaches. Ziefle et al. [40] conducted a survey to analyzed possible usage scenarios for interactive textiles in the home environment. The study with 72 participants found that the aesthetics, (perceived) durability, and the tactile sensation of the textiles are some of the important characteristics of textile interfaces. The participants identified table cloths and armchairs as good candidates for textile augmentation, while carpets and curtains were rated as less suitable. Regarding the desired functionality, media control (e.g., changing the volume or the current song), as well as the control of the interior light and the window blinds were attributed a high usefulness rating. On the other hand, the control of smart locks or controlling the heating were not perceived as useful functions to control with a textile interface. The most preferred location for interactive textile surfaces in people's habitat was the living room, whereas rather personal spaces, such as the bathroom, bedroom, and the children's rooms, were not considered as suitable.

These findings are further backed by a trade-off analysis weighting the criteria that shape people's willingness to use smart textiles in home environments [15]. The study shows that the most decisive acceptance criterion is the absence of noticeable electronic components. The second most important aspect is the location of the interactive device. People preferred the interactive technology to reside in the living room rather than in the kitchen or the bedroom. No clear preference towards the actual functionality of the interactive textile was identified, and people were undecided if the interaction surface should be used for media control or for controlling other functions in the smart home.

A further study adapted the UTAUT2 model to capture the acceptance of smart interactive textiles, taking a cushion as an example [4]. The study with 136 participants identified three key predictors for the *intention to use*: First, the perception whether using the device can be part of the daily routine. Second, the hedonic properties and the attractiveness of the interactive cushion were identified as crucial for acceptance. Third, the perceived benefits and usefulness of using the novel textile interaction surface were considered as important. In combination, these three factors explained 86% of the variance in usage intention. However, the study also found attitudes towards novel technologies shape usage intention and that the sample was clearly divided into technology adverse and technology enthusiastic people.

The three presented studies used scenarios-based approaches to identify user requirements and acceptance. However, it remain unclear if similar acceptance patterns and user requirements emerge in the evaluation of tangible textile prototypes.

REALIZED DEMONSTRATORS

To understand how textile interfaces for controlling furniture in the home environment are perceived, we designed textile demonstrators that vary along two orthogonal dimensions (Figure 2): The first dimension, *tactile design*, describes the physical affordances the interactive textile offers for controlling the armchair. The presented demonstrator includes either a tangible fold or noticeable stitches. The second dimension, *interaction principle*, refers to the way interactions are performed on the textile surface. The demonstrators can either be controlled by touching or by bending the fabric interface.

The combination of an interactive textile surface of noticeable stitches and the bending interaction principle is not feasible. Hence, only three of the four possible interaction techniques were developed and evaluated.

The armchair used in this experiment was a commercial chair provided to us by one of the market leaders. In the study, we used the original motors that were either controlled by the original plastic remote control, or one of the three textile interfaces. The textile interfaces were connected to the motors through the same interface as the original remote control. Input latency was the same for all four input techniques.

Technical Construction

The sensing patterns of our demonstrators are embroidered onto two swatches of the armchair fabric using AMANN Silver-tech 120 conductive thread. In the first demonstrator (Figure 2a), we created a textile fold using the armchair fabric (dimensions: $100mm \times 2mm \times 8mm$, $L \times W \times H$). On the sides and the base of the fold a total of four sensing lines (electrodes) are stitched (dimensions: $95mm \times 4mm \times 1mm$). In the second demonstrator (Figure 2c), four sensing lines are stitched directly onto the fabric. The lines have similar dimensions to the first demonstrator. Each two lines are laid out parallel to each other with $7mm$ spacing.

In both demonstrators, the sensing lines are spatially arranged to resemble the shape of the armchair—the backrest and footrest—to provide a more natural mapping for control as suggested by, e.g., Norman [25].

All sensing lines are connected to a TI MSP430 microcontroller, which performs resistive sensing to detect when the user connects two parallel sensing lines in the fold demonstrator, and capacitive sensing to detect the user's touches on individual lines. It then controls the armchair's four (servo) motors, while the back- and footrest are each controlled by two motors to lift them up or push them down.

Technique 1: Touch the fold

Figure 2a demonstrates one way of interacting with the textile fold. By positioning the finger between one side of the fold and the base of the fold, the user makes contact between two sensing lines. In this example, the user is interacting with the textile fold that controls the footrest. When touching the upper side of the fold the micro-controller senses the electrical contact and lifts the chair's footrest upwards. The chair reacts to user input by continuously adjusting the position of the chair as long as the user maintains contact with the interface or until the chair reaches its end position.

Technique 2: Bend the fold

Alternatively, Figure 2b depicts how the user interacts with the textile fold by bending it along its axis towards one of its sides. In this example, the user is bending the fold that maps to the backrest of the armchair upwards. The chair reacts to the user input by lifting the backrest to an upward position.

One consequence of textile interfaces is involuntary activation [11, 12, 17], e.g., by accidentally pressing on the side of the armchair, the micro-controller might detect a false positive touch and adjust the recliner undesirably. Interacting with the fold is a more explicit gesture compared to a simple touch (Technique 3), which could decrease the chances of accidental activation. Additionally, the fold leverages the affordance of pressing and folding textiles and provides a pronounced tactile cue for supporting eyes-free interaction.

Technique 3: Touch the stitches

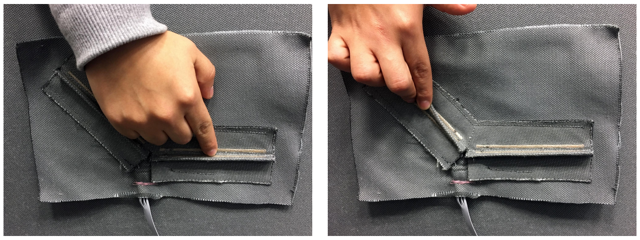
Figure 2c shows a direct way to interact with the armchair. This metaphor is very familiar to the users since it is carried from the way we interact with flat touch screens. Here, the user is touching the upper sensing line which is responsible for lifting the footrest upwards. To support eyes-free interaction, we manipulated the stitches of the sensing lines to have high density and build-up so they can be perceived tactilely.

Baseline: Plastic remote control

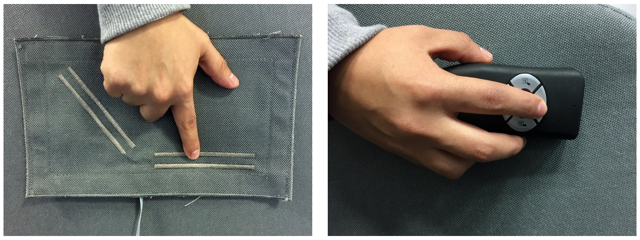
As a baseline, we included the original plastic remote control which comes with the recliner armchair. There are alternative interfaces on the market that feature embedded buttons on the armrests, but we used the remote control that was provided by the manufacturer. As Figure 2d shows, it has four buttons with clear tactile and auditory (mechanical "click" sound) feedback for adjusting the armchair position. It is connected to the chair's motors by a spiral cable with a length of approx. $1m$. In contrast to the other interfaces, the remote control was not attached to the chair's surfaces and freely moveable.

EXPERIMENTAL DESIGN

We conducted a user study to evaluate the user experience and acceptance of an armchair augmented with interactive textile sensors. The study consisted of three parts: an introductory survey, a hands-on evaluation of the INTERACTION TECHNIQUES, and a summative evaluation of the interactive armchair as a whole. We used UEQ's scales: *efficiency*, *perspicuity*, *dependability* (pragmatic quality); *novelty*, *stimulation* (hedonic quality); and *attractiveness* to determine the decisive scales for accepting the augmented armchair. We used TAM's *intention to use* as the main predictor of the overall acceptance of the armchair [1, 8].



(a) Touch the fold **(b) Bend the fold**



(c) Touch the stitches **(d) Plastic remote control**

Figure 2. Four investigated interaction techniques.

Experimental Setup

To increase the realism of our study, we created a simulacrum of a typical living room at our lab using a large monitor wall to display a crackling fire in a fireplace. Cables and other equipment necessary for the experiment were reduced to a minimum and covered by carpets or blankets when possible (see Figure 1). The study was video recorded, and the on-site investigator took notes throughout the user study. The participants' evaluations were captured on paper.

Survey

The introductory survey captured participants' demographics, their *attitude towards textiles* (using five items with a very good internal consistency of Cronbach's $\alpha = .821$), and their *attitude towards technology* on a scale based on Karrer et al. [16] (four items, $\alpha = .798$). *Attitude towards technology* is closely related to perceived *usefulness*, *ease of use*, and *self-efficacy* constructs of the TAM and is often a reliable predictor for users' efficiency, effectiveness, and satisfaction with interactive systems [6, 2, 22].

Measurement of Interaction Techniques

In the hands-on evaluation, participants were involved in four experimental sessions. In each session, participants sat in the armchair and performed a set of tasks to adjust the armchair using one INTERACTION TECHNIQUE (BEND THE FOLD, TOUCH THE FOLD, TOUCH THE STITCHES, PLASTIC REMOTE CONTROL) in random order (within-subject). At the end of each session, participants ranked their experience based on pragmatic quality scales (*efficiency*, *perspicuity*, *dependability*). Each scale is measured using 4-6 items on a semantic differential with two opposing pairs with six levels each (e.g., fast — slow). Additionally, participants indicated their *intention to use* each INTERACTION TECHNIQUE.

Measurement of Interactive Armchair

After the hands-on evaluation, participants ranked their overall experience with the interactive armchair based on hedonic quality scales (*novelty*, *stimulation*), *attractiveness*, and *intention to use* predictor. Finally, they chose their preferred INTERACTION TECHNIQUE.

Experimental Procedure

After welcoming participants, the purpose of the study was explained to them, and they were asked to complete the introductory survey. The participants were asked to sit on the recliner armchair and imagine that they had just arrived home after a stressful work day. A textile interface was attached using Velcro tape to the side panel of the armchair. The investigator prompted participants to adjust the position of the textile interface to their liking. Then, participants were asked to discover and explore the textile interface and figure out how to adjust the backrest and footrest of the armchair. Participants were made aware that the interface with the textile fold can respond to user input using two different techniques. When a participant was unable to discover the handling of an interface, the researcher provided some hints until all interaction techniques were recognized. The participants were asked to perform a set of tasks (e.g., lower the backrest, raise the footrest, put the chair back to initial position) and express their thoughts aloud throughout the study. After interacting with all four interaction techniques, participants completed the summative evaluation. The study lasted 40 minutes.

Description of the Sample

Twenty ($n = 20$) participants took part in the study. Of these, there were 10 males and 10 females, 16 right handed, 2 left handed and 2 ambidextrous. The mean age was 33.0 years (23–60 years, SD=9.7). All participants were highly educated (90% bachelors' degree or higher). On average, participants' *attitude towards technology* was positive ($M = 80.0\%$; $SD = 15.0\%$) and their *attitude towards textiles* was rather neutral (M = 56.7%; SD = 21.7%).

RESULTS

We analyzed the data using parametric and non-parametric methods, such as bivariate correlations (Pearson's r or Spearman's ρ), single and repeated univariate analyses of variance (ANOVA), and step-wise multiple linear regressions. We set the type I error rate (level of significance) to $\alpha = .05$ (findings $.05 < p < .1$ are reported as marginally significant). Effect sizes are reported as η^2, and models with high variance inflation factors are excluded ($VIF \gg 1$). The whiskers in diagrams represent the standard error (SE) of the point estimate, arithmetic means are reported with standard deviations (denoted by SD). All user ratings were captured on 6-point Likert scales, recoded if necessary, aggregated into the respective indices, and then rescaled to 0% – 100% for legibility.

Evaluation of Interaction Techniques

Pragmatic Quality

We found a significant main effect of INTERACTION TECHNIQUE on pragmatic quality scales *efficiency* ($F(3, 17) = 4.392$; $p < .05$) and *perspicuity* ($F(3, 17) = 3.981$; $p < .05$) but not on the scale *dependability* ($F(3, 17) = 2.972$; $p = .061$, n.s.) (see Figure 3).

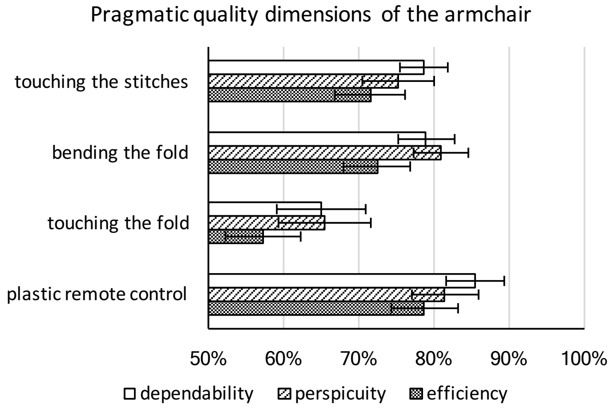


Figure 3. **Evaluation of the pragmatic quality of the interaction techniques: TOUCHING THE FOLD is rated lowest, while the plastic remote control (baseline), TOUCHING THE STITCHES, and BENDING THE FOLD were rated similarly high.**

interaction	**pragmatic scales M% (SD%)**		
technique	**efficiency**	**perspicuity**	**dependability**
plastic remote	78.8 (16.3)	81.5 (16.8)	85.5 (14.2)
bend the fold	72.5 (16.5)	81.0 (13.4)	79.0 (13.9)
touch stitches	71.5 (17.2)	75.3 (17.8)	78.8 (11.8)
touch the fold	57.3 (18.9)	65.5 (22.9)	65.0 (21.8)

Table 1. **Pragmatic ratings of the interaction techniques. The PLASTIC REMOTE CONTROL is evaluated as most pragmatic, whereas TOUCHING THE FOLD is rated lowest.**

Overall, the PLASTIC REMOTE CONTROL received the highest ratings on all pragmatic scales, followed by BEND THE FOLD then TOUCH THE STITCHES. The technique TOUCH THE FOLD received the lowest ratings. Table 1 summarizes the mean and standard deviations of pragmatic scale ratings of each INTERACTION TECHNIQUE.

To identify the most decisive pragmatic scales that explain a person's *intention to use* an INTERACTION TECHNIQUE, we conducted a stepwise multiple linear regression analysis for each INTERACTION TECHNIQUE with the pragmatic scales as independent variables. We found no model to explain the variance in *intention to use* the PLASTIC REMOTE CONTROL based on any of the pragmatic scales. In contrast, a strong regression model (85.1%, $r^2_{adj} = .851$) explained the variance in *intention to use* TOUCH THE FOLD by the scales *efficiency* ($\beta = .502$) and *dependability* ($\beta = .488$). A weaker regression model (69.4%, $r^2_{adj} = .694$) explained the variance in the *intention to use* BEND THE FOLD by the scales *efficiency* ($\beta = .489$) and *dependability* ($\beta = .432$). Finally, a regression model (25.1%, $r^2_{adj} = .251$) explained the variance in the *intention to use* TOUCH THE STITCHES by the scale *perspicuity* ($\beta = .539$).

Subjective Preference

The majority of participants preferred TOUCH THE STITCHES ($n = 8$) or BEND THE FOLD ($n = 8$) whereas TOUCH THE FOLD ($n = 2$) and PLASTIC REMOTE CONTROL ($n = 2$) attracted very few votes. Yet, the distribution is only marginally significantly different from a random choice ($\chi^2(3) = 7.2$, $p = .065 < .1$). Figure 4b graphs the frequencies of the preferred INTERACTION TECHNIQUE.

During the study participants mentioned many qualitative factors that influenced their ratings on the pragmatic scales and subjective preference of each INTERACTION TECHNIQUE. Several participants pointed out that the familiarity of the conventional PLASTIC REMOTE CONTROL played a major role in how they perceived its pragmatic quality and overall usability: *"I am used to the principle of a remote control — I've known it for years and thus, fast and efficient interaction is nothing surprising"*; *"[T]he buttons of the remote control are familiar, clear, and understandable"*; *"[D]ue to the fact that I am familiar with a remote control, I can foresee the functions of buttons and respective interactions"*.

Despite scoring highest on the pragmatic scales, most participants down-rated the PLASTIC REMOTE CONTROL *intention to use* or did not select it as their preferred technique. Some participants mentioned the disruptiveness of the PLASTIC REMOTE CONTROL of their cosy living spaces: *"[It is an] ugly unappealing design"*; and *"[It is a] cold element"*. Many participants shared the annoyance of frequently losing the remote, or having to extend themselves to reach for it when it falls down: *"[T]hen, you have to get up from the chair [. . .] if you imagine older people, this is really a big problem"*.

Participants found the interaction techniques to be easy to learn and use: *"[T]he interaction is comparatively simple, and if you learn it once, you can use it faster"*. The spatial arrangement of the textile interfaces, with an angle separating the backrest from the footrest control surfaces, allowed them to easily identify where to interact on the fabric: *"[T]he shape and arrangement of the stitches imply how to control the chair"*.

Some participants commented on the tactile affordance of the textile fold with BEND THE FOLD: *"I really like that I can feel directly what I have to do — for me, it is obvious that I have to bend the fold up and down in order to operate the chair's footrest and backrest in the respective directions"*. But from the visual design perspective, participants found the fold to be very pronounced, and preferred the subtlety of the bare stitches: *"I think the design is very striking and disruptive. I rather prefer the less visible design using only stitches and not a fold"*.

Most participants found the technique TOUCH THE FOLD to be unintuitive: *"I don't understand what I have to do — should I bend it?"* Even after participants knew how to touch the fold, they still found this technique dissatisfying.

Finally, participants suggested a few improvements on the design of the textile interfaces, such as increasing the distance between the conductive lines or making the lines thicker to speed up the interaction. Several participants suggested adding a third line between each pair of parallel lines as a tactile landmark to guide the user.

evaluation dimensions	**M%**	**SD%**
overall attractiveness	75.0	15.0
hedonic evaluation:		
novelty	71.7	13.3
stimulation	53.3	20.0
pragmatic evaluation:		
efficiency	75.0	10.0
perspicuity	80.0	10.0
dependability	81.7	8.3

Table 2. Evaluation of the interactive armchair on UEQ scales. Overall, the armchair was evaluated positive, but not very stimulating.

Evaluation of Interactive Armchair

In general, participants indicated a high *intention to use* the interactive armchair ($M = 76.7\%; SD = 18.3\%$) (Figure 4a). Table 2 summarizes the ratings of the armchair on each UEQ scale. *Attractiveness* was the highest rated scale ($M = 75.0\%; SD = 15.0\%$).

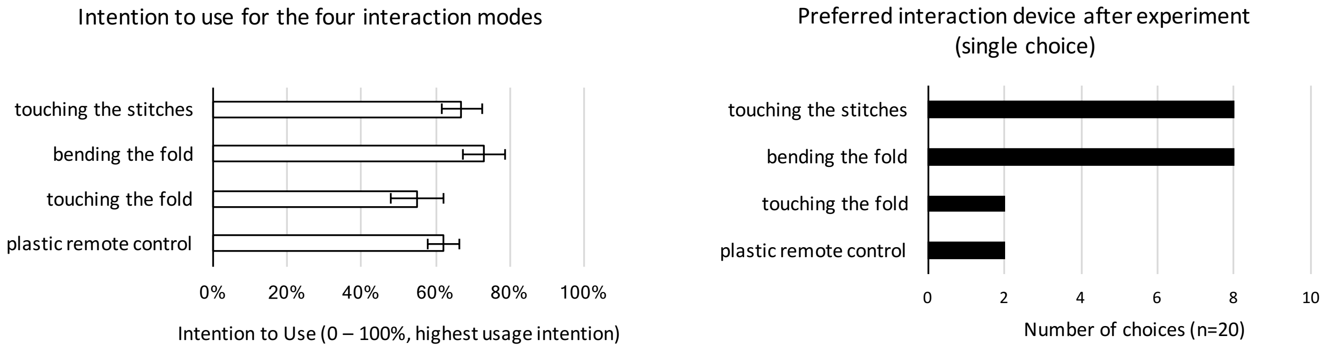
To understand what influences the overall acceptance of the interactive armchair, we calculated a correlation analysis for the explanatory user factors, all UEQ scales, and the overall *intention to use*. Despite the rather small sample size and as Table 3 shows, the correlation analysis reveals four insights:

First, the overall *intention to use* the armchair is not significantly influenced by the user factors AGE, ATTITUDE TOWARDS TEXTILES, or ATTITUDE TOWARDS TECHNOLOGY. However, GENDER influences the *intention to use* predictor—females gave higher ratings.

Second, the influence of user factors on the pragmatic and hedonic evaluation of the armchair on the UEQ scales is rather limited. Within our sample, merely AGE has a negative influence on the perceived *novelty* ($\rho = -.571$, $p < .001$) and perceived *stimulation* ($\rho = -.622$, $p < .001$) of the interactive armchair. Yet, AGE has no influence on the perceived overall *attractiveness* ($\rho = -.082$, $p = .739 > .05$).

Third, the scales of pragmatic quality are closely linked with each other ($\rho \geq .633$, $p < .001$). Surprisingly, the relationship among the hedonic quality scales and overall attractiveness of the chair are only weakly associated.

Fourth, most UEQ scales are positively related to the overall *intention to use* and they appear (although not consistently significant) to be positively associated with each other (which is common for technology acceptance models, e.g. [8, 38]). To untangle this net of interwoven factors, we calculated a stepwise multiple linear regression to identify which of the UEQ scales can be identified as the key predictor of *intention to use*. The regression identified a single scale, *attractiveness*, as the absolute predictor of the *intention to use* the interactive armchair ($r^2_{adj} = .460$; $\beta = .700$). The impact of *dependability* on the *intention to use* (Table 3) diminishes if controlled for the impact of *attractiveness* in the multiple linear regression.



(a) Average usage intentions for the four interaction techniques.

(b) Subjective preference of the interaction techniques.

Figure 4. Acceptance predictors of the interaction techniques: Although intention to use of the PLASTIC REMOTE CONTROL (baseline) and TOUCHING THE FOLD is slightly lower (left), the forced choice reveals a clear preference for TOUCHING THE STITCHES and BENDING THE FOLD (right).

DISCUSSION

Usability and Acceptance

Our findings were in-line with prior (scenario-based) research on interactive textiles in the home environment [4]: results show that the *attractiveness* of the embedded textile interfaces had the highest impact on user experience. In general, the importance of the hedonic quality of products on their acceptance has been highlighted by previous investigations [23, 3, 38]. In the case of interactive furniture, participants valued the seamless integration of textile sensors into the design of the surrounding space.

Our results show that user diversity may have a strong influence on the acceptance of interactive furniture: Female participants reported a more positive attitude towards the chair than males. We observed that females were less critical, especially in regards to the functionality and technical details. Age had a negative influence on the perceived *novelty* and *stimulation* of the armchair: older participants gave more low (more negative) ratings on most scales and seemed to be more critical towards our prototypes than younger participants. The nature of this effect is unclear and we speculate that older participants have higher demands on product quality and design. Therefore, future studies should more closely investigate the influence of age on the acceptance of interactive furniture.

Participants expressed their interest in using an alternative interface, such as textile, for home control. Despite the higher ratings that the conventional remote control scored on the pragmatic scales (*efficiency*, *perspicuity*, *dependability*), participants preferred the textile interfaces and gave them a higher *intention to use* ratings. One can argue that the novelty of the interactive textile controller biased these results, however, participants reported the value of two features in textile interfaces: (a) the spatial and physical closeness of the interaction surface to the target of interest (armchair), and (b) the intimate relation between textile controllers, e.g., the handle, flexibility, and cosiness of fabric, to the environment which they control.

Participants enjoyed and valued the tactile feedback they received when touching the stitches. They rated the FOLD as the superior pragmatic textile interface because it supported a natural affordance—folding—and provided them with a more pronounced yet natural tactile guide, which supports eyes-free interaction. However, they reported that visually, they preferred the subtlety of the STITCHED TEXTILE INTERFACE.

	ATT	NOV	STI	EFF	PER	DEP	ItU
ATT	—	.257	.446$^+$	.285	.458*	.455$^+$	.822**
NOV		—	.555*	.253	.237	.476*	.391$^+$
STI			—	−.099	.246	.365	.455$^+$
EFF				—	.700**	.633**	.206
PER					—	.815**	.414$^+$
DEP						—	.478*
Gender	.359	.106	.233	.200	.417$^+$	.200	.489*
Age	−.082	−.571**	−.622**	−.108	−.373	−.350	−.230
TEX	.267	.066	.086	−.003	.044	−.180	.280
TECH	.435$^+$	−.148	−.068	.241	.112	.063	.315

Table 3. Inter-correlations (Spearman's ρ) of user factors (Attitude Towards Technology (TECH), Attitude Towards Textiles (TEX), Gender dummy-coded male=1, female=2); the chair's evaluation on the scales of the UEQ (Attractiveness (ATT), Novelty (NOV), Stimulation (STI), Efficiency (EFF), Perspicuity (PER), Dependability (DEP)); and the overall Intention to Use (ItU). $^+$= $p < .1$, $*$ = $p < .05$, $**$ = $p < .001$

As we discussed previously, our decision to design the textile fold and support BENDING and TOUCHING THE FOLD was motivated by the need to minimize the chance of accidental activation. More designs need to be explored in order to find a balance between a pronounced tactile feedback, natural affordances, visual subtlety and robustness of textile interfaces.

A noteworthy methodological trifle is the limited expressiveness of the *intention to use* construct from Davis' TAM in the comparison of the four different evaluated INTERACTION TECHNIQUES. Obviously, this metric construct has its strengths when the key predictors for increased usage intention ought to be identified using, for example, multiple linear regressions as above. Yet we learned that this metric seems to be insufficient to describe and identify the differences in the overall evaluation of the product. Here, the single choice for one of the four INTERACTION TECHNIQUES provided a much clearer view on the actual preferences of participants.

Technical Aspects

Embroidery is a well developed textile integration technique. One can use embroidery to create and customize two-dimensional shapes on various fabrics. By manipulating the type of thread and stitch, it is possible to create a raised 2.5D tactile effect. We created our textile interfaces in a factory using industrial embroidery machines. The factory owner reported that the production of such interfaces is scalable, reliable, and inexpensive. Except for the textile fold, which required manual intervention.

We connected the electronics to the textile swatches in our lab. This process is still elaborate and not very reliable or scalable. But companies such as Google [30] are working on developing scalable methods to interface soft fabric materials with the hard casings of off-the-shelf electronics.

Limitations

Firstly, the main limitation of this study is the limited generalizability of our findings to other user groups. The sample consistent of mainly younger participants that reported a rather high attitude towards technology. Textile interfaces may have a unique role in the lives of the growing elderly population. Consequently, a thorough investigation with older participants is needed to assess the acceptance of these novel interfaces, and whether they can facilitate the use of technology and bridge the "gray digital divide" [24, 41].

Secondly, many variables in our study were marginally significant. A larger sample is necessary to check the validity of the results. Nevertheless, we were already able to incorporate the results of this study to make informed design decisions for other textile interfaces within our larger research project.

Thirdly, the textile interfaces supported only four functions: raising and lowering the back- and footrest of the armchair. Future studies should consider more complex interfaces: how to design the interface layout, and which input techniques can be overloaded.

Finally, this experiment focused on the evaluation of different manual and eyes-free interaction techniques for controlling a specific furniture with precisely defined actuators. In light of the voice-based assistants (such as Apple's Siri, Amazon's Echo, or Google Home) that are currently emerging in domestic environments, a significantly larger study should contrast which INTERACTION TECHNIQUES are best suited for performing which actions. Voice commands might me more suitable for performing discrete actions (turning lights on/off, music playback), whereas the presented textile interfaces might be preferred for fine-grained control of music's volume, brightness of a lamp, or the position of a backrest.

CONCLUSION AND FUTURE WORK

In summary, this paper shows that interactive textiles are a strong future candidate for smart home control. Users appreciate the integration of controls into the shape and fabric of their surroundings. Our study findings highlight the attractiveness quality of integrated textile interfaces to be the dominant influence on user experience with the interactive armchair compared to the pragmatic qualities of the interfaces. It remains to understand what shapes the overall attractiveness of furniture and how this can be increased. Despite playing a smaller role for the projected acceptance, we need to understand how the *actual and perceived usability* of textile interfaces can be enhanced. In general, participants of the study had a keen interest in the vision of textile interfaces in the home environment. We are interested in validating the usability and long-term acceptance of our textile sensors in a longitudinal study. We will observe what limitations or concerns surface after embedding an interactive armchair in people's living rooms.

From a technical perspective, the paper demonstrated how embroidery can be used to integrate conductive thread into the fabric of everyday objects using industrial machines. We used embroidery to create visual and tactile affordances. We are currently working on a textile toolkit for rapidly prototyping and testing textile interfaces of different shapes, sizes, and layouts (cf. [14]). This would enable us and other researchers to focus on designing and evaluating new textile interfaces for wearable and home uses.

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