Smart Textiles as Intuitive and Ubiquitous User Interfaces for Smart Homes

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Abstract. Textile user interfaces for smart homes offer novel intuitive input gestures and may lower acceptance barrier for technophobic or elderly people. To understand the users' requirements of smart textile input devices, an Adaptive Conjoint Analysis with the attributes wearability, functionality, haptic, location, and components was carried out with 100 participants. The attributes were rated with different importances. Users request non-wearable textile input devices with no noticeable electronics for the living room. Gender, but no age effects were identified, as women prefer health applications, whereas men prefer media control. In summary, the device needs to be individually tailored to the user's requirements to achieve high acceptance.

Keywords: Smart textiles · Technology acceptance · Design space · User centered design · Conjoint · Smart home

1 Introduction

Marc Weiser's vision of Ubiquitous Computing [1] is slowly becoming a reality. As early as in 1991, Weiser envisioned the appearance of different smart input devices in form of walls (table-size displays), pads (tablets), and tabs (smart phones) and smart appliances that can be controlled via a network. The envisioned input devices already penetrated the market and smart appliances currently spread in domestic, commercial, and industrial environments. Television and other media, lights, or smart heating control, washing machines and refrigerators are just some of many devices that are increasingly connected to the "Internet of Things" and that are accessible via tablets or smart phones, or by other smart appliances nearby.

While the road to the future may seem straight ahead, one should not forget about our past. In human history textiles have been used for over 30.000 years [2, 3] and accompany us every day since then [4]. Textiles are typically perceived as warm, fashionable, and pleasurable and come in uncountable forms, materials, functionalities, sizes, and colors. Still, textiles have rarely been used as input or output devices for computing machinery, leaving the field to inflexible and cold devices of plastic, metal, or glass.

Using textiles as input devices is an innovative research field [5, 6], at least out of two reasons. One reason is methodological by nature: Creating a novel input device or even a set of input devices that combine smart sensors and actuators can be seemingly

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integrated in textiles surfaces, such as in pillows, blankets, or in couches. Contrary to currently available computing technology, these devices ought to be soft and smooth, and may be cuddled – technology characteristics that could open out into a completely positive connoted devices. The second reason refers to novel application contexts, which go much beyond he traditional field of applications of input devices. Also, new user groups currently not interested in computing technology could be addressed [7]. In particular, smart textile user interfaces may be a way for reaching social inclusion of elderly and technophobic people and allow them to handle technology with a well-known material (fabrics) in their personal home environment [8, 9].

1.1 Smart Textiles as Input Devices

Textiles are defined as smart, if they have intrinsic properties that are not normally associated with traditional textiles and can respond to environmentally stimuli. In contrast to that, the term functional textile refers to textiles that have specific functions added by specific materials or coatings. Distinguish characteristic is the integration of electronics in the textile architecture. There are three distinct hierarchical categories of smart textiles depending on the closure between fabrics and electronics: Textiles made of fibers and yarns to reach wearable computing, textiles with woven or embroidered fabrics and yarns to: The first category contains textiles that are made of fibers and yarns that build a single functionality in combination with conventional components (e.g., wearable computing). With textiles of the second category functions are achieved by the use of the textile itself resulting from a closer connection (embroidery and weaving) between fabric and electronic components. Third categories textiles are developed to offer functions on the fiber level by implementing the electronic device deep into textiles fabrics. Current challenges are mechanical flexibility, washability, power supplies and product development and commercialization [10]. Due to flexibility, closeness to human body and the possibility of very discreetness, smart textiles can apply to a very wide range of tasks like health, security and smart homes [11].

Karrer et al. [12] created PinStripe, a poloshirt with electric sensors in a sleeve for measuring a continuous value based on grasping and deforming. Possible applications were seen in controlling mobile devices or music, but also in safety-critical contexts. From a technical and or electronic point of view, the development of smart textiles is at an advanced stage [13, 14]. Current research discussions are directed to the integration of novel sensors into smart clothing [15] and wearables [16]. Also, [12, 17] are focusing on novel interaction technologies.

Because of their closeness to human body, smart textiles can also react to implicit input like temperature and breathing frequency. Najafi [18] created SmartSox, a pair of socks that can measure temperature, pressure and hallux range of motion to avoid diabetic feet. All patients perceived the socks as comfortable and had no problems while walking with them.

Smart textiles are increasingly used for different application scenarios, as e.g. motion sensing [19] or sports [20] or even within the education context [21], in which efforts were made to tailor teaching anatomy and physiology to children with smart wearables. Stark [22] developed SnapToTrace, a textile component kit that can be used to learn computational systematics and coherences for youths by rearranging textile input- and output components on a base mat. Also, smart textiles find their way into caring and health monitoring contexts ([5, 23, 24]).

1.2 The Missing Keystone: Usability, User Diversity and Acceptance

While the potential of textiles in different application domains is widely acknowledged still the research and technology development is mostly technology driven. Yet, the impact of user requirements and the general acceptance of devices in close distance to persons did not adequately receive attention. Sparse knowledge is known about the impact of user diversity on acceptance of textiles [5, 25, 26]. However, the integration of users in the technology development is indispensable for the success of textile input devices and therefore a mandatory requirement for sustainable solutions.

Recent research directed to personal medical devices revealed that user diversity – in terms of gender, technology generation and technical self-confidence – is impacting not only the ease of using devices but also the degree to which users are willing to use technology in their home environment. Especially the perceived barriers when confronted with novel technologies and the prevailing aloofness towards consequences when using technology in the close environment is much higher in women compared to men [27, 28]. Age and technology generation is especially sensible to the perception of the usefulness of the novel technology and the susceptibility to stigmatizing by device design, as elderly feel being marked as old and ill [29]. Another meaningful outcome in this context is that devices implemented at home are very differently accepted depending on the respective location and the room [30].

Another critical issue is the way of how technology acceptance is assessed [7, 31]. To gain knowledge about users preferences and the acceptance of the technology, conventional methods like conceptualization of dimensions like “importance of placement on the human body” or compositional traditional technology acceptance models [32, 33], reach their limits due to functional dependencies within a possible design space of textile input devices. What is needed for the question regarding the acceptance of smart textiles in the home environment is a holistic evaluation of ecologically more valid decision scenarios, in which different single factors are weighed against each other, and the possibility of direct simulations. That’s why we took usage of an adaptive conjoint analysis, a methodology where incompletely described concepts are compared with each other to calculate part-worth utilities of every possible attribute. As far as we know, this is the first approach to evaluate technology acceptance using ACA using technology decomposing attributes and levels (in comparison see [34]).

2 Method

2.1 Measuring Technology Acceptance via Conjoint-Analysis

Conjoint analysis in general is a multivariate analysis method for measuring customer’s preferences in a decompositional way: well-defined concepts of products are compared against each other to decompose their part-worth utilities for every *level* and relative importances for every *attribute* of a product or service. In this context, *attribute* is a property of a product or service and *level* is a concrete manifestation of an attribute, i.e. green would be a level of the attribute color. Because of the similarity to a real buying situation Conjoint Analysis is very widespread in marketing disciplines to perform trade-off analysis and market simulations.

The Adaptive Conjoint Analysis (ACA) method used in this study consists of several steps. In contrast to other conjoint methods, ACA is a hybrid method consisting of a compositional part also. The ACA is made up of four steps, the first two being compositional, the third being decompositional and the forth being for calibration. In the first step, called ACA Rating, every level of an attribute is rated from desirable to undesirable. In the second step, called ACA Importance, the importance of these ratings is measured by rating the importance of the difference between the most desired level and the least desired level from ACA Rating. During these steps, relative importance are created and updated with every given answer. In the third step, called ACA Pairs a comparison between two products takes place on a 9-Point rating-scale, while the amount of levels starts at two and increases to an upper limit. During this step, part-worth utilities and are created and updated with every given answer. The concepts presented to the participant are assumed to have nearly equal desirability. In the last step, called ACA Calibration, fully described concepts are rated from 0 to 100 to calculate the predictive value of the method [35].

Besides marketing analysis, Conjoint Analysis can be used to provide decision criteria or concrete practical guidelines for designers of technical systems [36]. ACA was chosen for this study to avoid cognitive or creative overload that could occur in a comparison of fully defined concepts. In addition to that underestimation of pricing and bad mimicry of buying situations does not matter in this context, indeed we assume that a gradually decision between two concepts fits better in this context of technology acceptance [34].

2.2 Characteristics of the Sample

Overall 100 people aged 18 to 73 years (M = 31.8; SD = 11.5) participated in the study (41 % of female, 59 % male).

Self-efficacy in Interacting with Technology (SET): Participants reported an average SET of M = 3.8/6 points max (SD = 1.2). A two-way analysis of variance with *age* and *gender* as independent variables and *SET* as dependent variable yielded in a significant effect of gender on SET ($F_{1,99} = 16.7$, $p < .001$) with men reporting considerable higher technical self-efficacy (M = 5.3, SD = .9) than women (M = 4.4, SD = 1.2). No age effects on technical self-efficacy were found.

Liking of Textiles: The index for assessing the linking of textiles achieved a moderate internal reliability of α *(100, 4 items) = .635*. On average, participants reported an affinity of M = 3.27 (SD = 0.94). Again, a two-way ANOVA with *age* and *gender* as independent variables and the *textile index* as dependent variables revealed a significant effect of gender ($F_{1,99} = 8.3$ $p < .05$, $\eta^2 = .079$), but no effect of age ($F_{1,99} = .417$, $p = .520 > .05$, ns.) on liking of textiles. Specifically, women reported a higher affinity towards textiles (M = 4.5, SD = .8) than men (M = 3.9, SD = 1.0).

Experience with textiles: 73 % of participants had heard or read about smart textiles and 15 % had actual experiences in any form with smart textiles. Interestingly, there is a significant relationship between persons with smart textiles experience and technical self-efficacy ($F_{1,98} = 7.4$, $p < .05$,), with experienced persons having higher self-efficacy scores also having more experience with smart textiles.

2.3 Study Design

The study was realized in an online survey with an average completion time of 15 min. The survey started with a brief motivation of the research. Next, demographic information was recorded (age, gender, educational level, (last) occupation). In addition, participants were surveyed regarding individual factors that are known to impact the interaction with and evaluation of technology.

Self-efficacy in interacting with technology (SET) on a Beier's scale [37]. SET has been identified as an pivotal psychological construct that explains the users' effectiveness, efficiency [38], learnability [39], user satisfaction, and acceptance in interacting with electronically devices. Also, participants' inclination towards textile surfaces was surveyed, in order to control for individual differences in the liking of textiles. These aspects were captured using 6-point Likert scales (0 to 5, 5 max.).

Table 1. Attributes and Levels

Attribute	**Level**
Wearability	Wearable
	Non-wearable
Functionality	Health function
	Media controlling
	Smart home controlling
Components	Box
	Smartphone
	Textile
Haptic	Soft
	Medium
	Hard
Room	Bedroom
	Kitchen
	Living room

Attributes and dimension of the Conjoint Analysis were taken from prior research [26], in which a design space of possible factors (spatial context, users, tasks, application scenarios) were explored (see Table 1). The five factors with the highest impact on further prototyping decisions were chosen: *Wearability* (wearable/non-wearable), *Functionality* (remote controlling of media /smart home technology /health technology), *Components* (textile only /communication with smartphone needed /box of hardware needed). The other two attributes are *Haptic* of the textile (hard /medium / soft) and *Room* of usage (bedroom /kitchen /living room).

In ACA Rating and ACA Importance the evaluations were measured on a scale from 0 to 5. The upper limit for the number of attributes in ACA pairs was set to three, there were six questions with two and three attributes each. ACA Calibration consisted of five concepts. Addressing the fact that there are no functional dependencies none of the 162 possible products were excluded from the study. An exemplary question set is shown in Fig. 1.

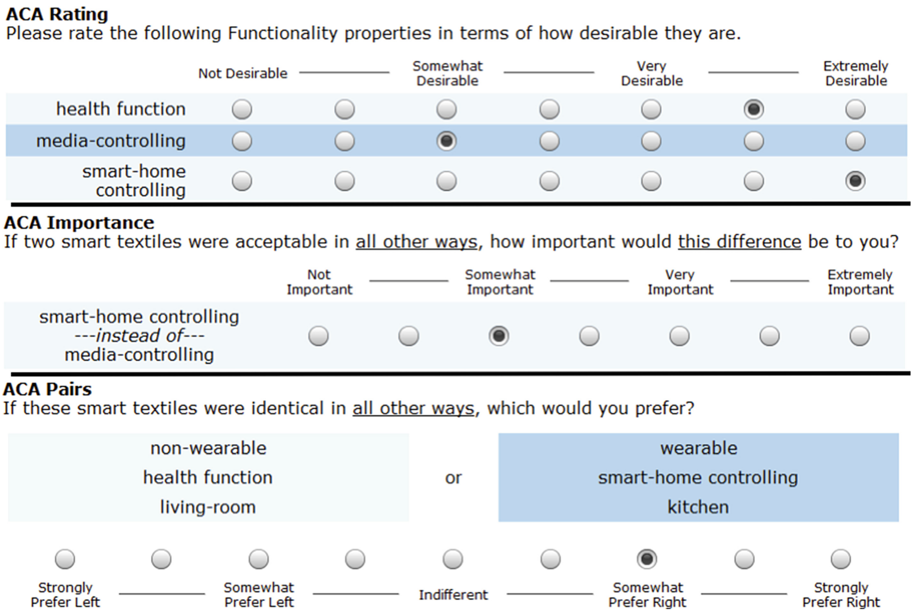

Fig. 1. Illustration of exemplary ACA questions

3 Results

First, the relative importance of the five dimensions is shown. Finally, for each of the five dimensions the rating of the individual levels is presented and gender differences will be discussed.

3.1 Relative Importance and Part-Worth Utilities

The participants of attach different importance to the five considered dimensions of a textile input device. Specifically, *Components* is rated as the most important attribute (24.6 %), followed by *Room* (22.5 %) and *Functionality* (22.0 %). *Haptic* (18.7 %) and

Wearability (12.2 %) were found to be least important to the subjects. What is noteworthy in this context is that the order of importance across criteria is not affected by user diversity (neither age nor gender). Figure 2 shows the relative importance of the five attributes.

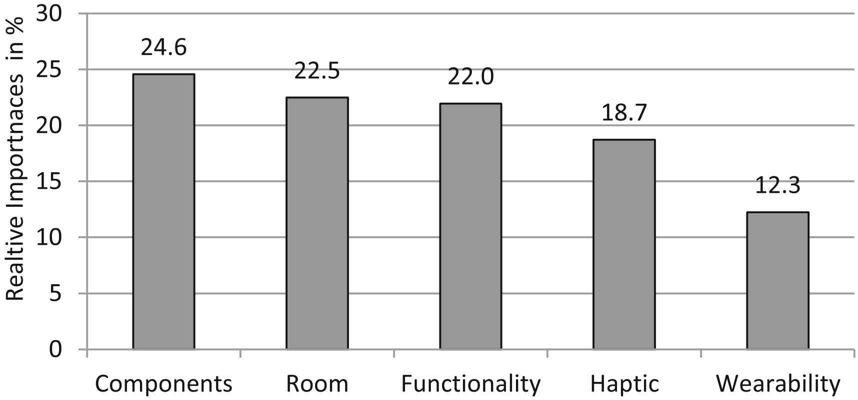

Fig. 2. Relative importance of smart textile attributes

3.2 The Impact of User Characteristics on the Evaluation of Textiles.

In the following sections the preferences for the individual levels for each attribute are discussed in order of relative importance. Figure 3 illustrates the part-worth utilities separated by gender.

In the *Component* attribute the level *textile* was strictly preferred by men (43.10) and women (40.69) over the other levels *smartphone* (men 15.08; women 9.41) and *box*, which was strictly disliked by men and women (men −58.18; women −50.10).

Regarding *Room*, a strong preference for using the technology in the *living room* was reported by both genders (47.14 men; 42.79 women). A contrasting gender effect in the evaluation of *bedroom* and *kitchen* was found: women disliked a device the *kitchen* (−11.31) less than the *bedroom* (−31.48) as a location for use of smart textiles; men in contrast disliked the *bedroom* (−16.34) less than the *kitchen* (−30.81).

Evaluation of the attribute *Functionality* revealed gender preferences: men favored smart textiles to control *media* (11.8), while women favored *health functionalities* (10.0). In contrast to that, men disliked *health functions* (−14.6) and women disliked *media functionalities* (-12.7). *Smart home* controlling was tendentially rated positively by both men (3.8) and women (2.7).

As regards *Haptic* of the device, *medium hard* was favored most by men (23.1) and women (20.8), but women liked *soft* textiles (19.4) just marginally less. The *hard* option was disliked by both genders, with women's rating (−40.2) being more negative than men's (−31.0).

Regarding *Wearability* women reported a stronger preference for *non-wearables* (15.9) than men (5.2).

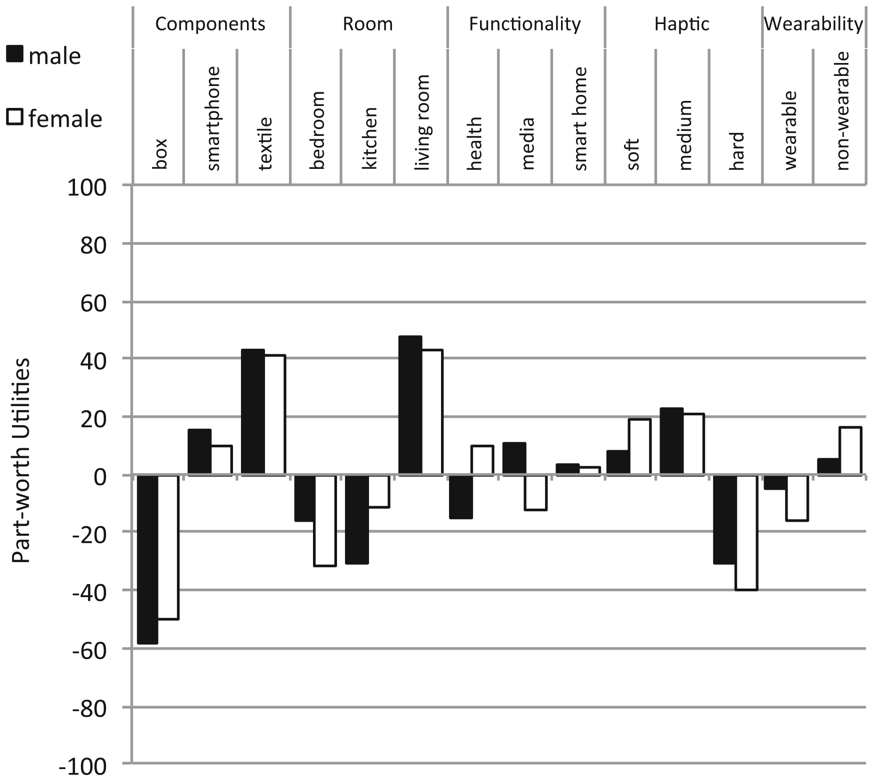

Fig. 3. Part-worth utilities for every level, separated by gender

4 Discussion

The study investigated the users' requirements of the different aspects of a textile input device. The research motivation was to contribute to the undeveloped knowledge about the usefulness of a textile input device that can be implemented in the home context. Different from other social science approaches, in which acceptance for or against a specific technology is assessed by using single factors approach, we simulated the decision process in real world scenarios by using conjoint analysis. Methodologically, the main objective is to simulate decision processes and to decompose the preference of a product or scenario as a combined set of attributes into separate utilities of the attributes and respective attribute levels. From a theoretical point of view this approach mimics the real procedure: Characteristically, acceptance is a "product" out of perceived benefits and at the same time barriers and they weigh those factors depending on their individual situation and perspective.

On the base of previous research, we predefined five aspects of a textile input device that have been identified as important on a single factors level [26].

The conjoint findings corroborate that users assign different levels of importance to the five investigated aspects of the design of a textile input device. Participants evaluate the technical realization as the most important aspect of the device. Here, users clearly oppose a product with a noticeable electronics or a battery pack and they prefer a device with seamlessly integrated electronics or – as a temporary solution – that the computing logic is outsourced into a smartphone wirelessly connected to the device. The second most important criteria for users are the operational area of the device. Users predominantly prefer a device specifically designed for the living room and the two other alternatives, kitchen and bedroom, were disdained by the users. The latter mimics findings according to which rooms at home have different sensibilities and tolerance towards the integration of technology. The third most important criterion is the actual functionality of the device. However, users did not clearly prefer one possible function to the other, meaning that some users want a textile for controlling the smart home, whereas others want to control music or other media. This shows that there is not the tendency for "one function for all" but a tendency for the wish to individually tailor the functionality to own needs and to control the functionality, which is implemented in the device.

What is quite astounding in data outcomes is the fact that user diversity – at least in those facets that were under study here – did not have major impact on acceptance. Beyond the fact, that women dislike smart textiles in the bedroom more than in the kitchen, and vice versa for men, neither age, nor gender nor the level of technical self-competence did modulate the order of importance regarding the evaluation criteria. In addition, age is not related to self-efficacy in interacting with technology, nor does age influence the preferred appearance of a prospective textile input device. This contradicts on a first sight a huge body of research outcomes according to which women are more reluctant to use and like novel technology in their private space [27] or a decreasing openness to novel technology with increasing age [40].

This missing effect of user diversity might be based on three reasons:

The first reason is directed to the textile as input device as a well-known and deeply anchored material. If this assumption is right then the disadvantage of a technical device as a foreign artifact and disliked in the private sphere may be compensated by a highly appreciated technology. More so, this result would then open up a huge success to cope with the challenge developing technical assistance for an aging society: appreciated technology that is not stigmatizing persons with a lower technical competency.

The second reason could lie in the evaluation dimensions, which were under study. To evaluate the functional design space and more or less design aspects of a novel technology might not be sensitive to diversity as such. If so then we have strong arguments to assume that those functions might follow a "design for all" approach, at least in the respective functionalities implemented in the device. Third, a quite simple reason could regard the speculation that this is an effect of the comparably young sample, which might not be representative for the whole group of older and possibly handicapped users. On the base of the present finding we cannot decide which of the reasons might be correct. Future studies could continue in this line of research, addressing many more facets.

In this context, first, we will have to find out whether these devices are accepted at all and if they are preferred over conventional input devices. The concurrently realized focus groups and the previous survey discussed the benefits and barriers of such a device and premises for a successful adoption process.

Second, most participants were recruited via social networks, mostly Facebook or personal emails. This led to a sample askew to younger and more technophile people. A subsequent study must therefore investigate if the presented tradeoffs are comparable with an older and less tech-savvy sample. Furthermore, we have of course to elaborate the range of the design space. So far, only few selected elements were investigated in this study. Subsequent studies must address additional characteristics – such as weight, for a holistic understanding how users balance the pros and cons across these dimensions.

What we can say is that textile input devices offer excellent opportunities for younger and older persons to control the increasingly widespread smart devices in domestic environments. The presented trade-off analysis is one of several important columns of this line of research. In parallel focus groups multiple realizations of possible textile input devices as low fidelity prototypes are investigated. Following the results from this study and earlier work, these prototypes are targeted as a smart remote for home automation and media control for the living room in a smart home. From the technical perspective, the users' requirement that the necessary sensor and actuator technology must be seemingly integrated in the device (i.e., without a noticeable electronic brick and battery pack) is one of the toughest challenges.

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