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Co-Designing Shape-Changing Interface Scenarios in Smart Homes

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Abstract

Shape-changing interfaces (SCIs) are an emerging technology with a variety of possible areas of application, including augmented living. They are interfaces that utilize a physical change of shape or materiality as input or output to convey information, meaning, or affect. The benefits of SCIs can be utilized for smart home devices. Smart homes offer customizable services to users and consist of linked sensors, appliances, and controls. They have shown to have important potential for the design of future homes. However, research so far has not focused on application scenarios for SCIs in smart homes. It is unclear which preferences users have for using SCIs in smart homes.

We therefore asked the following research questions: 1. Which application areas of shape-changing interfaces can users imagine in a Smart Home? 2. Which characteristics of shape changes can users imagine in these scenarios? 3. How do users imagine interacting with shape-changing interfaces in smart homes? To answer these questions, we conducted a co-design user study. Our participants created storyboards that show possible application scenarios for SCIs in smart homes and their context.

We found four scenarios that were frequently imagined across participant groups and a variety of additional ideas. Those common scenarios are *Controlling the Environment through Permeability*, *Preventing Injuries and Damage*, *Adaptable Objects and Rooms*, and *Causing Behavioral Changes through Discomfort*. With these scenarios, we contribute inspiration for the construction of future SCIs in smart homes and recommendations on characteristics of SCIs that fit user preferences. We additionally showed that our methodology can contribute to making smart home and SCI research more user-centric. Our work reveals the potential of using SCIs in smart homes instead of traditional smart home devices.

Überblick

Shape-Changing Interfaces (SCI) sind eine neu aufkommende Technologie mit einer Vielfalt von Anwendungsgebieten, einschließlich erweitertem Wohnen (augmented living). SCIs sind Interfaces, die eine physikalische Veränderung der Form oder Stofflichkeit als Input oder Output benutzen, um eine Information, eine Bedeutung oder einen Affekt mitzuteilen. Ihre Vorteile können für Smart-Home-Geräte genutzt werden. Smart Homes bieten Nutzern personalisierbare Dienste und bestehen aus verbundenen Sensoren, Geräten und Kontrollelementen. Ihre Vielzahl von Vorteilen hat wichtiges Potenzial für das Design des Zuhauses der Zukunft gezeigt. Jedoch hat sich die Forschung bis jetzt nicht mit möglichen Anwendungsszenarien für SCIs in Smart Homes beschäftigt. Es ist unklar, welche Präferenzen Nutzer bezüglich der Verwendung von SCIs in Smart Homes haben.
Wir haben deswegen die folgenden Forschungsfragen gestellt: 1. Welche Anwendungsgebiete von Shape-Changing Interfaces können sich Nutzer in Smart Homes vorstellen? 2. Welche Eingenschaften von Shape-Changing Interfaces können sich Nutzer für diese Szenarien vorstellen? 3. Wie stellen Nutzer sich die Interaktion mit Shape-Changing Interfaces in Smart Homes vor? Um diese Fragen zu beantworten, haben wir eine Co-Design-Nutzerstudie durchgeführt. Unsere Teilnehmenden haben Storyboards entwickelt, die mögliche Anwendungsszenarien für SCIs in Smart Homes und ihren Kontext zeigen.
Wir haben vier Szenarien identifiziert, die in mehreren verschiedenen Teilnehmendengruppen vorkamen und eine Vielfalt an zusätzlichen Ideen. Diese verbreiteten Szenarien sind *Kontrollieren des Umfelds mit Durchlässigkeit*, *Verhindern von Verletzungen und Beschädigungen*, *Anpassungsfähige Objekte und Räume* und *Bewirken einer Verhaltensveränderung durch Ungemütlichkeit*. Mit diesen Szenarien tragen wir Inspiration zur Entwicklung zukünftiger SCIs für Smart Homes bei. Außerdem bieten wir Empfehlungen für Eigenschaften dieser SCIs, die Nutzerpräferenzen entsprechen. Wir haben außerdem gezeigt, dass unsere Methodologie helfen kann, Smart Home und SCI Forschung nutzerzentrischer zu machen. Unsere Arbeit offenbart das Potenzial der Nutzung von SCIs in Smart Homes anstelle traditioneller Interfaces.

Acknowledgments

I would like to thank Prof. Dr. Jan Borchers and Prof. Dr.-Ing. Ulrik Schroeder for advising and examining my thesis.

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Many thanks to everyone who participated in my user study. Without your creativity and helpfulness, this thesis would not have been possible.

Finally, I would like to thank my family and friends for supporting me through this thesis.

Conventions

Throughout this thesis, we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.
- Unidentified third persons are described neutrally.

Categories that were taken from taxonomies or emerged from our findings, as well as names of existing prototypes, are written in *italics*.

Short definitions are set off in green boxes.

> **DEFINITION:**
> Definitions are set off in green boxes.

Where appropriate, paragraphs are summarized by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

Chapter 1

Introduction

Shape-Changing interfaces (SCI) are an emerging technology with a variety of possible areas of application, such as architecture, infrastructure, entertainment, or medical applications [Sturdee et al., 2015]. They make a multitude of futuristic designs and innovative ways of interaction possible and will thus shape our way of living in the future.

1.1 Shape-Changing Interfaces and their Application in Smart Homes

SHAPE-CHANGING INTERFACE:
Alexander et al. [2018] define SCIs as interfaces that utilize a physical change of shape or materiality as input or output. This change is interactive or computationally controlled and either self- or user-actuated. Further, it conveys information, a meaning, or an affect.

Definition: *Shape-Changing Interface*

Research on shape-changing interfaces has focused on different areas. Examples are developing toolkits to facilitate prototyping and fabricating SCIs [Pardomuan, 2022] and building artifacts, such as shape-changing curtains [Coelho and Maes, 2009] or mirrors [Davis et al., 2013]. Additionally, taxonomies for the development and classifica-

Research on SCIs includes the development of toolkits, prototypes, and frameworks.

tion of those artifacts have been developed [Rasmussen et al., 2016, 2012; Sturdee and Alexander, 2018]. How SCIs are perceived and their effect on users has also been investigated [Zhong et al., 2021; Nabil et al., 2018].

User-centric research on SCIs is rare.

However, research so far has not focused on users' preferences for application scenarios [Rasmussen et al., 2012; Sturdee and Alexander, 2018]. As our goal in designing interfaces for human-computer-interaction (HCI) should always be to take users into account as much as possible, this is an important research gap. There are many open questions regarding the user experience and usefulness of SCIs. Specifically, it is unclear when using SCIs has benefits over traditional non-shape-changing interfaces and which aspects of SCIs provide which precise benefits to users [Alexander et al., 2018].

SCIs have many benefits that can be utilized in smart home devices.

Rasmussen et al. [2012] identified many potential benefits of using SCIs. They make communicating information more efficient, utilize dynamic affordances, provide haptic feedback, and can be used to find practical solutions to problems. These benefits can specifically be used for smart home systems, as communicating information about the home environment and customizing users' homes are essential parts of smart home technology [Alam et al., 2012]. Furthermore, Sturdee et al. [2015, 2019] have made an important step towards user-centric research on SCIs. They identified possible application areas for SCIs, including augmented living, which describes the enhancement of homes through technology. This indicates that users also recognize the potential of integrating SCIs into smart home systems.

Definition: *Smart Home*

SMART HOME:
Smart homes are homes that provide tailored services to users. They consist of linked sensors, appliances, and controls, and offer the possibility of remote monitoring and control of homes and their devices [Gram-Hanssen and Darby, 2018].

Smart home systems offer a multitude of benefits, such as efficient energy management, more convenient controllability, and assistance for accessible living and healthcare [Sovacool and Furszyfer Del Rio, 2020]. Thus, they are an important chance to improve daily life in the future. Additionally, many researchers have already developed specific shape-changing artifacts that could be used in our homes. Examples for such SCIs are a shape-changing door [Economidou and Hengeveld, 2021] or vacuum cleaners [Jakobsen et al., 2016]. Some of those attempt to solve specific problems, for example, helping babies sleep in a safer position [Zhao et al., 2021]. Others aim to provide an aesthetic value with shape-changing decoration [Nabil et al., 2018] or find innovative ways to reflect users' emotions, such as stress, with a textile mirror [Davis et al., 2013]. Yet, not only research on SCIs but also on smart homes lacks when it comes to taking user needs into account. For example, women as users are underrepresented [Strengers et al., 2019] and common user needs such as privacy are often neglected [Samancioglu et al., 2024].

There are already examples for SCIs with smart home applications.

We therefore used a user-centric approach to find application scenarios for SCIs in smart homes and formulated the following research questions:

We formulated three research questions.

- *Q1:* Which application areas of shape-changing interfaces can users imagine in a smart home?
- *Q2:* Which characteristics of shape changes can users imagine in these scenarios?
- *Q3:* How do users imagine interacting with shape-changing interfaces in smart homes?

To answer these questions, we conducted a user study utilizing co-design. With this method, the researcher facilitates the ideas of the user by guiding them through the relevant steps of the design process. Co-design is beneficial for user-centric research as it takes user needs and preferences into account and profits from their knowledge about their own specific experiences [Sanders and Stappers, 2008]. Although users have different competencies from designers,

We conducted a user-centric co-design study.

they can still offer valuable insight, depending on their own creativity [Sanders and Stappers, 2008]. Co-design has successfully been applied in research on applications of shape-changing interfaces [Albarrak et al., 2023; Sturdee et al., 2019] and smart homes [Fitton et al., 2018; Yao et al., 2019]. However, it has not been used in this combination and with our specific goals.

Storyboarding is an established method in HCI and co-design.

Storyboards have been used in co-design studies before, as they allow participants to fast and easily sketch interactions between interfaces and users [Hong et al., 2018; Lupton and Leahy, 2019; Young et al., 2022]. They are also an established method in HCI to characterize an interface and the interaction with it. Therefore, we decided to ask participants to create storyboards of scenarios in which they could imagine using shape-changing smart home interfaces.

We found multiple frequent application scenarios for SCIs in smart homes and user-preferred characteristics.

To evaluate the results of our study, we used thematic analysis. We identified application scenarios for SCIs in smart homes and common characteristics of SCIs in these scenarios. We found that users can imagine using SCIs in smart homes for many different application areas. Some of these, like environmental control, have been explored in the literature on smart home interfaces before [Sovacool and Furszyfer Del Rio, 2020]. Others, including multifunctional objects and furniture pieces, show benefits that are specific to shape-changing smart home interfaces and are not included in current smart home application taxonomies. Furthermore, we found differences in popular SCI characteristics between users' preferences and existing artifacts. We constructed scenarios from our results that connect application areas with user-preferred characteristics. Our study showed the extensive potential of using shape-changing interfaces in smart homes to improve users' lives.

1.2 Outline

After the Introduction to this thesis in Chapter 1, we will proceed as described in the following paragraphs.

In Chapter 2 "Related Work", we will talk about the existing research relevant to this thesis. We will discuss shape-changing interfaces with a focus on user-centric work and smart home system benefits and applications. Additionally, we will address co-design studies, especially in the areas of SCIs and smart homes.

Chapter 3 "Co-Design User-Study" will focus on the planning, methodology, and execution of our co-design user study, which aimed to find possible application scenarios for shape-changing interfaces in smart homes.

The results of our study will be evaluated and discussed in Chapter 4 "Evaluation". There, we will apply existing frameworks to the scenarios designed by the participants of our study and also discuss new themes found through inductive thematic analysis. We will construct scenarios that describe the possible applications of SCIs and their characteristics. Finally, the limitations of this thesis will be elaborated upon.

Chapter 5 "Summary and Future Work" contains the summary and contributions of this thesis as well as possible directions for future work on shape-changing interfaces in smart homes.

Chapter 2

Related Work

Much research on shape-changing interfaces has focused on developing toolkits and artifacts. There have also been attempts to categorize SCIs and define design requirements. Additionally, application areas and benefits not only for SCIs but also for smart home systems have been reviewed from different perspectives. In both areas, it has become apparent that user-centric research is still lacking. Therefore, this chapter focuses on the recent work in the mentioned areas. In the following, we will first give an overview of taxonomies to categorize SCIs and open questions regarding user experiences and preferences. We will go over existing shape-changing interfaces for smart homes with various intended benefits. Then we will review current user-centric smart home research and taxonomies, and lastly describe relevant co-design studies in the areas of SCIs and smart homes.

2.1 Shape-Changing Interface Frameworks

Rasmussen et al. [2012] were one of the first to conduct a literature review on shape-changing interfaces. They analyzed different types of shape change, the interaction techniques of SCIs, and the aims of using shape change. The

An early literature review on SCIs identified open questions and benefits, and described the design space.

three open questions they identified are concerned with which purposes shape-changing interfaces manage to fulfill, how to characterize the design space, and how users experience shape-changing interfaces. Notably, they already found the need for research concerned with users and their interaction with SCIs. Additionally, key benefits of shape-changing interfaces were described by Rasmussen et al. [2012]. These include communicating information more intuitively and efficiently, communicating changing possibilities to use the interfaces (dynamic affordances), and providing haptic feedback. Furthermore, SCIs were found to be beneficial in creating practical solutions to problems and making the construction and assembly of different interfaces possible. Not only are the functional benefits of SCIs described, but also hedonic aims, such as aesthetics, inducing emotion, and stimulating engagement with materiality and space.

There are different taxonomies that identify specific types of SCIs.

Multiple different taxonomies have been developed with the aim of characterizing shape-changing interfaces. Rasmussen et al. [2012] themselves identified eight different types of shape change: *volume, form, orientation, texture, viscosity, spatiality, adding/subtracting* and *permeability*. These types of shape change are illustrated in Figure 2.1 and are defined in Appendix C. We used these categories to classify the shape changes described by the participants in our study and to explain the concept of shape change to the participants. A different categorization by Sturdee and Alexander [2018] divides shape-changing interfaces into the categories *enhanced 2D, bendable, paper and cloth, elastic and inflatable, actuated, liquid, malleable* and *hybrid*. These categories focus more on the materiality of the interfaces but have some overlap with the categorization of Rasmussen et al. [2012] (e.g. *bendable* and *orientation*). This literature review again came to the conclusion that application-based and user-centric research is missing.

Another framework describes the levels of control that users have over SCIs.

Another framework by Rasmussen et al. [2016] is concerned with categorizing the levels of control that users have over shape change. *Directly-controlled* refers to the user directly causing the change of shape. *Negotiated* control means that the user influences the shape change, but also reacts to shape changes controlled by the system and

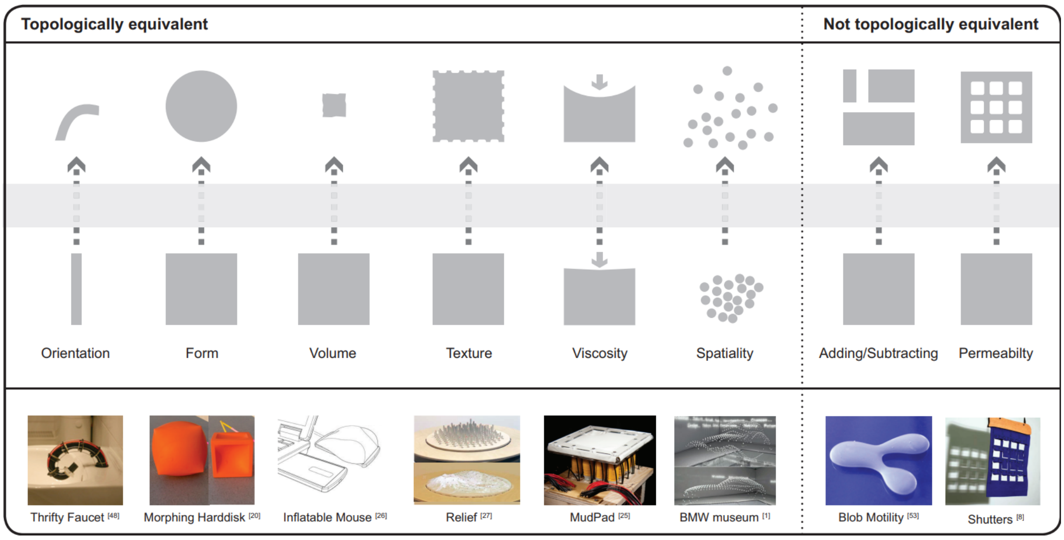


Figure 2.1: The figure shows the taxonomy that categorizes the different types of shape change. Image taken from Rasmussen et al. [2012]. The examples in the figure are from the following sources (from left to right): Togler et al. [2009]; Horev [2006], Kim et al. [2008]; Leithinger and Ishii [2010]; Jansen [2010]; source not available anymore; source not available anymore; Coelho and Maes [2009].

modifies their influence accordingly. When shape change is *indirectly-controlled* by the user, it is not intended by them but indirectly caused by their actions. The least control of the user is found in *system-controlled* interfaces, whose shape change is only controlled by the interface itself.

2.2 Applications Areas for Shape-Changing Interfaces

Multiple studies were concerned with possible application areas of SCIs.

In a public ideation of applications for SCIs, Sturdee et al. [2015] found eleven different application areas. The area that occurred the second most (after *entertainment*) with 12.79% was *augmented living*, which describes the application areas of smart home devices. Other popular application areas found in this study were *medical*, *utensils and tools*, *research*, and *architecture*. This framework was also used to categorize application areas in a participatory

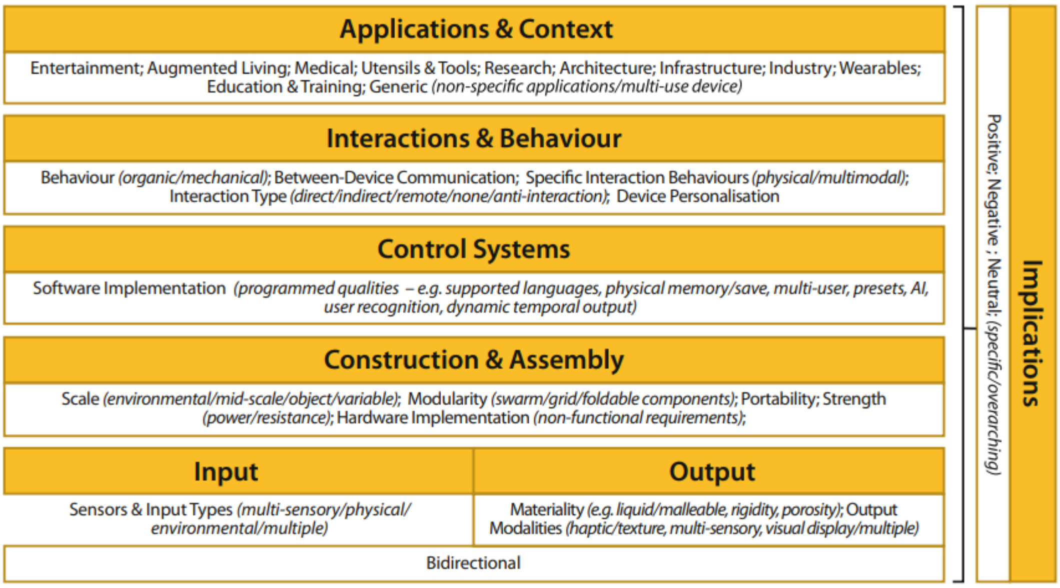


Figure 2.2: The stack model of design requirements that emerged from a participatory design study describes the different areas of the design space of SCIs. It shows the many different layers that are necessary to take into account for designing SCIs. Image taken from Sturdee et al. [2019].

design study, again finding ideas that fit the area of augmented living [Sturdee et al., 2019]. Based on the same study, Sturdee et al. developed a stack model that can be seen in Figure 2.2. It further describes the design requirements of shape-changing interfaces and includes layers for *application, interactions and behavior, control systems, construction & assembly, input, output*, and *implications*. To better describe the scenarios for the use of SCIs in smart homes that participants envisioned in our research, we used this model for orientation.

Speculative scenarios were used to discuss risks and potentials of SCIs.

In their exploration of speculative scenarios for the use of SCIs in an imagined future, Rasmussen and Hemmert [2019] discussed possible challenges and potentials of SCIs. Among others, they mention safety and security risks due to unexpected shape changes, researching how to communicate possible shape changes to users, and the prospects of making mass-produced products customizable and thereby personal. Their exploration is based on a workshop with other researchers familiar with SCIs and, therefore, not user-centric in its methodology. Still, the concerns and benefits of SCIs that are discussed are relevant to creating SCIs that fulfil users' wishes.

Alexander et al. [2018] identified 12 main challenges in SCI research in a literature review, with challenges relevant to user preferences and design of SCIs among them. They found a lack of research on user experience and the usefulness of SCIs, which they consider necessary to determine which values and benefits SCIs offer to users. They also relate this to a lack of structured user evaluations of SCI prototypes, which we will elaborate on in the next section. Therefore, Alexander et al. formulate the goal of predicting user reactions to SCIs and identifying robust scientific claims about their benefits. Other challenges are related to the design of SCIs. These include developing tools to design interactions that are satisfying and understandable to users, and determining the best-suited applications of SCIs. Alexander et al. state, that this remains unclear, although a lot of prototypes for various applications have been developed (also see Section 2.3). Further, they identified that it is necessary to determine when to apply which shape changes. Challenges related to the technological feasibility and implementation of SCIs are also found important, to build SCIs once user preferences and design guidelines have been clarified.

In a more recent literature review, big challenges in SCI research were identified, including user-related ones.

2.3 Existing Shape-Changing Interfaces for Augmented Living

A variety of shape-changing interfaces that would fit into a home have already been developed with different benefits and aims in mind. In the following, we describe a selection of examples.

An early example of a prototype of an SCI is the *Thrifty Faucet* [Togler et al., 2009]. It changes its shape by bending into different directions. The intention of the shape change is making users think about their energy consumption. A textile mirror was built to reflect the emotions of users through texture changes [Davis et al., 2013]. Both of

Some prototypes of SCIs explore shape changes as a novel method of communication of information and emotions.

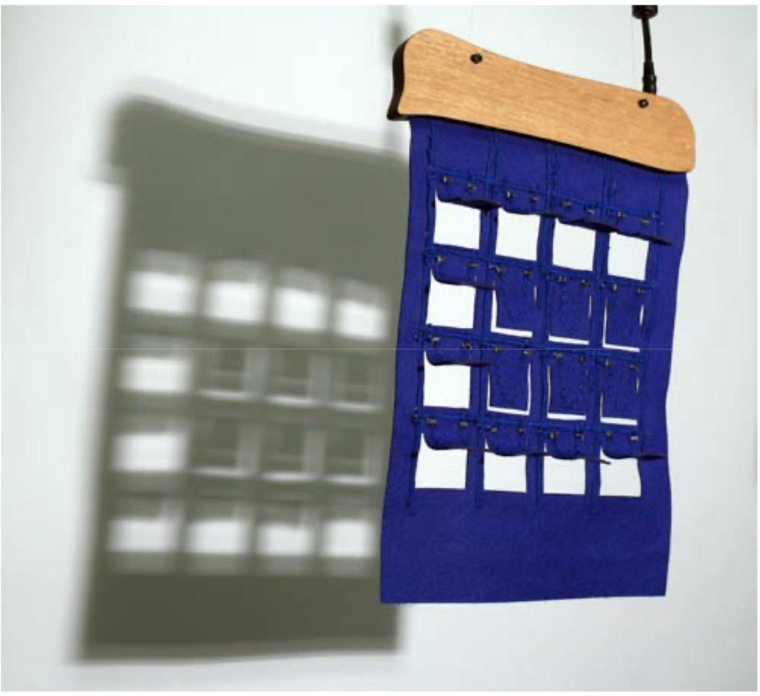


Figure 2.3: The curtain shutters. It shows how shape change can be used to find novel ways of communication. Picture taken from Coelho and Maes [2009].

these are instances of SCIs whose shape change is mainly used to explore novel ways of device-user communication. With the curtain *Shutters*, Coelho and Maes [2009] were also interested in the potential of using the changing permeability of a surface for communication with additional applications in environmental control. The shadows cast by the gaps in the curtain, as seen in Figure 2.3, are used to display information. Users generally reacted positively and with curiosity to the faucet, but neither the textile mirror nor *Shutters* were evaluated with user studies.

Other SCIs prototypes fulfil decorative and exploratory functions.

Zhong et al. [2021, 2023] studied the long-term reaction of users to the growing and shrinking *deformTable* and *coMorphing-stool*. The artifacts were not developed with a specific application in mind, but rather to determine which applications users would come up with. The *deformTable* grows and shrinks depending on how much weight is placed on it. The *coMorphing-stool* grows when its envi-

Figure 2.4: The *ActuEater* in a dinner setting. The participants interact and react to it in various forms. Picture taken from Nabil et al. [2018].

ronment is brighter and shrinks when it is darker. Users described interacting with the *coMorphing Stool* and the *deformTable* first as unfamiliar, but integrated them into their lives seamlessly after some time. They came up with different usages and interpretations, such as a timekeeper or a stand for a flowerpot. Similarly, the effect of an actuated tablecloth called *ActuEater* on social interactions and its decorative benefits was studied [Nabil et al., 2018]. It can be seen in Figure 2.4. In a dinner setting, the participants showed a variety of reactions to the *ActuEater*, including patting it and talking to it.

SCI prototypes with multiple possible functions have also been developed.

Shape-changing interfaces often fulfill multiple functions. *Transform* is a piece of interactive furniture (see Figure 2.5) that uses actuation to hold objects, create dividers, and sculptures to represent audio output, such as music [Vink et al., 2015]. It is based on the *inFORM* prototype and uses dynamic affordances and constraints to convey a variety of interaction possibilities to the user [Follmer et al., 2013]. Another example of multi-functional furniture is the *Funituroid*, which consists of lamps and bars that can be moved and arranged in different ways, forming varying types of

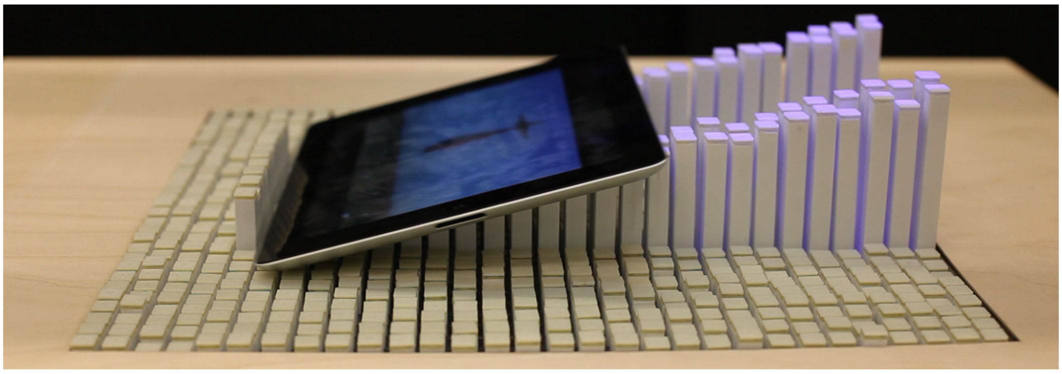


Figure 2.5: The inFORM prototype. It shows how SCIs can be used to fulfill multiple functions. Picture taken from Follmer et al. [2013].

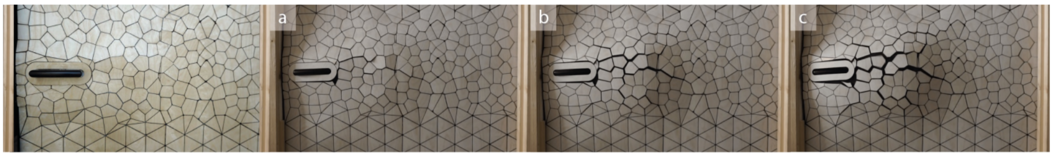


Figure 2.6: The shape-changing door. From left to right, the door becomes less inviting to be opened by obstructing its handle. This shows how SCIs can be used to provide dynamic affordances. Picture taken from Economidou and Hengeveld [2021].

furniture pieces [Nakanishi, 2022]. None of these prototypes was evaluated in a user study.

SCI prototypes utilize natural mappings and dynamic affordances.

Another benefit of SCIs that has been explored is the possibility to allow for more intuitive control and communication, for instance, through natural mappings and dynamic affordances. Economidou and Hengeveld [2021] for example, prototyped a door that warps forward to make its handle unusable when locked. Their user study showed that users can correctly interpret the entry invitation and prohibition as shown in Figure 2.6. Another example of an SCI utilizing natural mappings is the lamp *MoLux* [Sørensen et al., 2022]. The lampshade can be manipulated directly by the user, with a larger lamp leading to an increase in brightness and a more spiky lampshade making the light warmer. Users found the mapping to control the brightness of the lamp easy to understand, but the mapping for the warmness of the light was found to be less intuitive. They preferred negotiated control over the lamp, and some-

Figure 2.7: The PneuMat from different perspectives. It shows how shape-changing interfaces can solve specific, relevant problems. Pictures taken from Zhao et al. [2021]

times interacted with it as if it were a living being. Legaard et al. [2016] built three prototypes of parts of a typical vacuum cleaner, which also uses natural mappings to improve communication between the device and the user: a power button that only appears when the cord is rolled out, a handle that communicates dust intake with shape changes, and a corpus that retracts its wheels when the device is treated poorly. In an exposition, users understood the functionality of the prototypes and were curious about them.

Some prototypes of SCIs were developed to fix a specific problem.

There are also instances of shape-changing interfaces that were built to solve a specific problem. *DogPulse*, for example, is a lamp that changes its form and starts pulsing to remind people of walking their dog [Skovgaard et al., 2015]. It uses a timer connected to the collar to automatically reset the lamp after the dog is taken outside. Thereby, it is meant to reduce the mental load of having to remember and coordinate regular walks. In a preliminary evaluation, users liked the design of the lamp and appreciated that it produced an ambient awareness that was not irritating. However, they criticized the noise of its motor. Zhao et al. [2021] developed a prototype for a surface with inflatable chambers that babies can sleep on, which can be seen in Figure 2.7. The mat inflates the chambers according to the baby's position to redirect it into a safer sleeping position. The system was not tested on real babies but showed potential in tests with dolls. Another prototype for a vacuum cleaner by Jakobsen et al. [2016] was built with a "mouth" that can shrink and grow to fit into differently sized spaces. Therefore, its users would not need to exchange the attachment anymore. This prototype was not evaluated with a user study.

In summary, current research on SCI prototypes is not always user-evaluated.

It is apparent that in-depth user studies on shape-changing artifacts for at-home use are not always conducted. Additionally, only some SCIs are developed to fix a specific problem or with a specific usage scenario in mind. This makes it difficult to determine how well the artifacts fit user preferences and in which areas they can be improved. However, when the artifacts are evaluated by users, they consistently react positively and with curiosity to them. Some of this reaction might be caused by novelty bias [Nabil et al., 2018], but it still shows that users are generally accepting of shape-changing interfaces used in their homes. This underlines the potential of combining smart home devices with SCI technology. Furthermore, users have been shown to understand the natural mappings used to control some of the interfaces.

2.4 User-Centric Smart Home Research

Taxonomies for Smart Home Devices describe application areas and benefits.

Not only SCIs but also smart home systems have been sorted into different taxonomies. One such taxonomy identified thirteen different types of benefits of smart home devices through expert interviews, thereby expanding on existing reviews on smart home benefits [Sovacool and Furszyfer Del Rio, 2020]. The most mentioned areas (80,65%) were *energy savings* and *convenience and controllability*, followed by *financial benefits* and *system benefits*. Another home-related taxonomy is the framework of application areas for smart home devices, as identified through a literature review by Taiwo et al. [2020]. Those five areas are *environment*, *safety and security*, *healthcare*, *energy management*, and *entertainment*, which overlap with the identified benefits from Sovacool and Furszyfer Del Rio [2020]. To see whether these taxonomies capture the user-expected benefits and applications of specifically using shape-changing smart home interfaces, we applied both to our findings.

Multiple studies have determined preferences and expectations of smart home users.

Coskun et al. [2018] conducted interviews with early adopters and early majority smart home users on their preferences. Among other findings, they determined that users especially value the ability to remotely control their devices and autonomously functioning devices. However, they were also unsure whether complete autonomy would be achievable due to the complexity of household tasks and structures. Additionally, they only wanted the smart home devices to take over chores, not tasks they enjoyed, such as cooking. The participants also expressed that they wanted to stay in control of their appliances and be able to override decisions made by them. In another user study, Jensen et al. [2018] interviewed Australian households on user preferences and needs for smart homes. They identified that users desire smart home devices to be omnipresent and "intelligent" and to have a modern aesthetic. They also want to have remote control over the house, to be more sustainable, and to be able to personalize their devices. Samancioglu et al. [2024] found that the needs and preferences of users, such as privacy or ethical and environmental considerations, are often neglected in smart home research. They based their findings on a literature review and therefore recommend starting with user needs when designing new smart home interfaces.

User-centric research on smart homes is not reflecting the wishes of diverse user groups.

Smart home research tends to be focused on middle-class single-family homes and therefore leaves out large user groups [Kozubaev et al., 2019]. Participants of a participatory design workshop who live in public housing have specifically shown skepticism about data being collected and potentially being shared with outsiders, such as housing companies [Kozubaev et al., 2019]. Women are another neglected user-group, whose differing needs and expectations for smart homes are currently not met [Strengers et al., 2019]. For example, they are worried about threats through increased surveillance and security, and are concerned with being expected to take care of digital housekeeping. Both of these examples highlight the importance of including diverse user groups in smart home research to make smart home devices accessible and desirable for all users in the future.

Although some of the mentioned research gaps are being filled, there is still the necessity for more user-centric smart home research

In a literature review of 55 papers Yao et al. [2023] analyzed trends in human-centered smart home research. They found five popular areas of research, namely *interaction design*, *user behaviors*, *smart devices*, *design exploration*, and *data privacy and security*. The area of design exploration also includes co-design studies. These areas already show that user-centric smart home research is becoming more common. They further found that target groups have become more diverse, although 40% of research still focuses on users who are already experienced with smart products. While these findings indicate that smart home research is improving by taking users' diverse preferences into account, Yao et al. also state that studies are still limited to specific features and services provided by smart homes. Additionally, sample sizes of studies are often small.

The presented studies show that there is already more user-centric research on smart homes than on SCIs. However, some research gaps remain, and further focus on diverse user groups and specific user preferences is necessary. Therefore, a user-centric approach is often recommended, which we pursue in this thesis.

2.5 Co-Design and Participatory Design Studies

Co-design is a method that heavily involves users in the design process as the researcher guides them through it and facilitates their ideas [Sanders and Stappers, 2008]. It can take different forms, depending on the user's creativity and expertise. In some cases, users even become designers themselves. Co-design has been used in both SCI and smart home research, as described in the following sections.

Co-design has successfully been applied in smart home research, including by using storyboards.

Albarrak et al. [2023] applied co-design to study users' ideas regarding applications of shape-changing walls. They used virtual reality to show users different types of shape-changing walls that would have been too complicated to build, and then conducted co-design sessions with each participant individually. The participants were able to come up with designs of SCIs with a variety of different purposes and utilized all the demonstrated types of shape change. The aforementioned participartory design study by Sturdee et al. [2019] evaluated the potential of using sketching and storyboarding to identify requirements for the design of SCIs. They introduced their participants to SCIs using white box prototypes representing different materialities and videos of existing shape-changing interfaces. After that, the participants generated ideas for shape-changing interfaces and then sketched storyboards for one idea each. Sturdee et al. [2019] found that their method worked well in explaining shape-changing interfaces to users and recommend it for further research on the topic, for example, for more concrete application areas.

Co-design has been used in smart home research, sometimes showing limitations caused by bias.

In smart home research, co-design has also successfully been applied. To find out about the wishes of teenagers regarding possible engagement with voice interfaces in smart homes, Fitton et al. [2018] conducted a co-design study. They gave teenagers examples of commands they could use to interact with the voice interfaces and then asked them to design dialogs. Although the prompts given to the teenagers helped them come up with ideas, they also biased these ideas a lot. Therefore, most of the ideas of the teenagers were very similar to each other and to the prompts. Another study that focused on privacy protection in smart homes also used co-design [Yao et al., 2019]. They first discussed the advantages and disadvantages of smart homes, and showed scenarios with privacy issues to participants, and then asked participants to develop their own usage scenarios as well as create prototypes of their designs and present them. Bourazeri and Stumpf [2018] found that co-designing for smart homes also works with user groups that have cognitive restrictions, in their case, dementia. In another paper, Berger et al. [2023] analyzed questionable values such as privacy, autonomy, and trust violations that became apparent through a co-design study using an IoT (Internet of Things) toolkit for smart home devices. Instead of designing specific artifacts, Xue et al. [2024] co-designed Trigger-Action-Programs in a user study to specify the ways smart home interfaces are controlled. They used cards with smart home devices and environmental information, as well as stickers of operators

(“IF”,“THE”,“AND”, “OR”) to connect cards and a floor plan of a home.

All these examples show the applicability of the method of co-design for smart home and SCI research with multiple different approaches. However, the limitations that are created by biasing the participants also become apparent, which we therefore considered in our study design.

Chapter 3

Co-Design User Study

Our goal was to work towards closing the research gap in user-centric research on application scenarios for shape-changing interfaces in smart homes. We therefore conducted a user study utilizing the method of co-design to find such scenarios. In the study, we introduced the participants to SCIs and smart homes and then asked them to create storyboards for application scenarios.

In this chapter, we will first describe our set-up and general procedure in Section 3.1.1. Then we will elaborate on the introduction to the topic, tasks, and concluding interview in detail in Section 3.1.2. In Section 3.2, we will report on the demographics of our participants. We tested our approach in a pilot study and made a few changes, which will be mentioned when relevant.

3.1 Method

In this section, we describe our set-up and procedure, as well as elaborate on our decisions regarding our study design.

3.1.1 Set-Up

We conducted the study in groups with creative materials.

Our study was conducted in groups of two to three participants at a time (6 groups of 2 and one group of three) to allow for discussion and creative exchange while making sure that everybody could voice their own ideas. The participants were seated opposite each other at a table, with the creative materials placed in the middle (see Section 3.1.2). A phone for video recording was placed to capture the table, but not the participants' faces, to make them feel as comfortable with the recording as possible. The participants were not compensated for taking part in the study, but they were provided with snacks and water throughout it. A smart TV was used to show animations and the timer during the tasks, although more time was given to participants if they needed it. The study conductor sat at another table to take notes and guide the participants through the study, but not to interfere with the creative process. The whole study took between an hour and one and a half hours. We conducted the study in German or English, depending on the language in which the participants felt more comfortable.

3.1.2 Procedure

We gave out the declaration of consent and a demographic questionnaire to the participants.

Firstly, the participants of the study were given the declaration of consent. There were no known risks to our study, but we informed them that they could always take a break or stop the study, for example, if they became fatigued. We also obtained their consent for the audio and video recording and notified them during the study when we started and stopped the recordings. Furthermore, we explained the aim and procedure of the study to them. They then filled in a demographic questionnaire to collect data about their age, gender, job or field of study, and prior knowledge related to SCIs and smart homes. To find out about their prior knowledge, we first asked whether they had heard the terms "smart home" and "shape-changing interface" before. If they did, we also asked them to define those terms, to get an impression of the extent of their knowledge. The evaluation of this questionnaire is provided in Section 3.2.

The declaration of consent and demographic questionnaire can be found in the Appendices A and B.

The main part of the study was divided into four parts: an introduction to SCIs and smart homes, a first task to generate ideas independently, a second task for the creation of storyboards in groups, and finally a semi-structured interview. The individual parts of our study and their methodology are described in the following paragraphs.

Our study was structured into four parts.

Introduction to SCIs and Smart Homes

To make sure that all of our participants had the same level of knowledge about SCIs and smart homes available to them, we started by introducing them to both concepts. This introduction took ten to fifteen minutes. As other co-design studies have reported that giving examples introduced a heavy bias into their results, we were careful to avoid it [Fitton et al., 2018]. We therefore kept our explanations abstract and unrelated to specific areas of application in the smart home.

We explained the concepts of SCIs and smart homes to our participants

First, we explained that interfaces offer ways to interact with a device. Further, we described that they have an input and an output. We defined shape-changing interfaces using the definition that can be found in Chapter 1. To convey the benefits of using SCIs, we gave the following information to the participants, which is adapted from the functional and hedonic aims of SCIs as described by Rasmussen et al. [2012]:

We defined SCIs and explained their benefits.

- When the shape of an interface changes, new interaction possibilities can be signaled to the user.
- Shape change can communicate data or other information to the user.
- Shape change can be intuitive, as users already have specific associations with certain shapes.
- Shape-Changing interfaces can integrate well into the environment or have an aesthetic benefit.

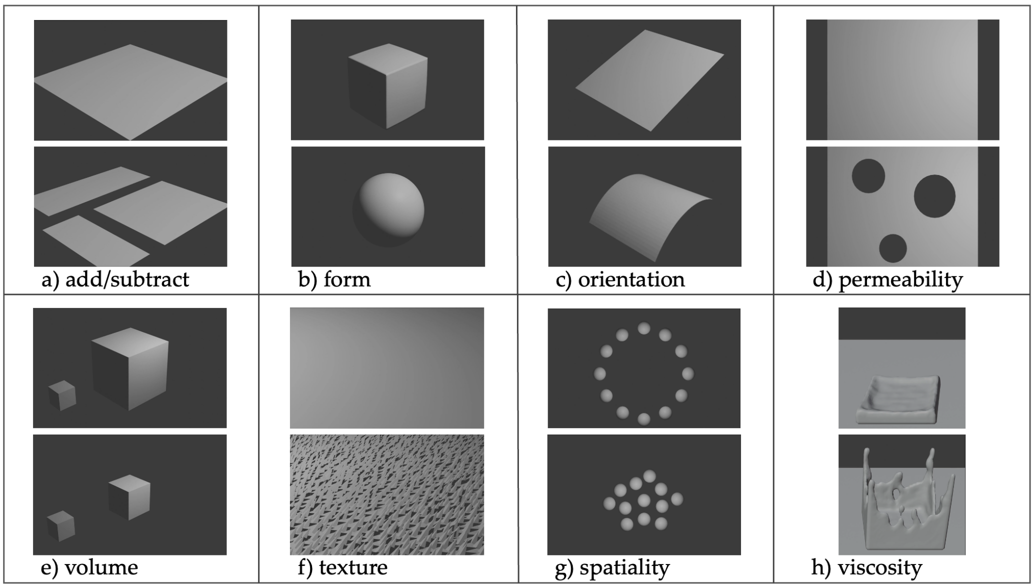


Figure 3.1: The animations that were shown to our participants during the introduction to the topic of SCIs. They demonstrate the various ways in which SCIs can be used.

We defined smart homes to the participants.

To inform the participants about smart homes, we also defined them as we did in Chapter 1. To motivate new ideas that are not related to existing smart home devices, we additionally told participants to imagine that every object in their homes could be turned into a smart home device. A more in-depth introduction to smart homes was not necessary, as smart home devices are already more widespread than shape-changing interfaces. This was also confirmed for our specific group of participants by the results of the demographic questionnaire (see Section 3.2).

We used animations to introduce the participants to shape changes.

We used animations of the eight different types of shape change identified by Rasmussen et al. [2012] to clarify what shape change can mean specifically. We made the animations using Blender[1] . We decided to leave them very bare to avoid biasing the participants regarding an interpretation of a type of shape change. As bias has been found to have a large effect on the results of co-design studies [Fitton et al., 2018], limiting it was an important consideration for us. Thus, the animations are all in grayscale and made

[1] `https://www.blender.org/`, *last accessed 09.27.2025*

up of simple shapes such as cubes and spheres. Still, this bias could not be eliminated completely, as we had to, for example, choose textures to animate the texture change. As it was difficult to animate a change of viscosity, we decided to animate two fluids with different viscosities next to each other and explained this depiction to our participants. All shape changes apart from viscosity were shown in both directions, meaning that, for instance, a sphere would first grow and then shrink again. This was done to limit bias towards the direction of the shape changes. Stills of the two states of each animation can be seen in Figure 3.1.

We also considered different ways to introduce shape change to our participants, such as hardware prototypes.

While we were planning the user study, we also considered using hardware prototypes to demonstrate the possible types of shape changes, as Sturdee et al. [2019] and Kwak et al. [2014] have successfully done. However, this would have taken up too much time to be commensurate with this thesis. The effort needed to build high-quality prototypes of SCIs has been found by other researchers, such as Alexander et al. [2018]. We also decided against showing videos of existing toolkits or artifacts since finding video material for each type of shape change in consistent quality and specificity was very difficult. This was confirmed by Sturdee et al. [2019]. High-quality videos would have stood out, and more specific applications shown in videos would have been easier to interpret regarding our task. Therefore, using such videos would again have introduced unwanted bias.

We offered additional explanations on our animations.

After showing the animations to our participants, we gave some additional explanations. We told our participants that the different types of shape changes could also be combined. We also clarified that the shape changes did not have to look exactly like they are shown in the animations, but rather that the animations are examples. Lastly, we made sure that our participants understood that the animations just show shape changes, not finished interfaces.

Task 1: Independent Idea-Generation

The first task involved our participants independently thinking of ideas for the use of SCIs in smart homes.

The first task given to our participants was to write down all their ideas for scenarios for the use of shape-changing interfaces in smart homes. They were told to additionally think about how the change is controlled and what type of change they want to use. However, we did not ask them to elaborate on their ideas in detail, but instead to write down as many rough ideas as possible. To give each participant the possibility to come up with their own ideas without influence from other group members, this task was to be worked on individually. The time limit to complete the task was five minutes. In our pilot study, we originally allotted ten minutes for it, but noticed that the participants struggled with overthinking their ideas. As research has shown that time pressure can have positive effects on productivity and lead to higher rates of performance, shortening the initial time for fast idea generation was helpful to combat this issue [Kelly and Karau, 1993; Liikkanen et al., 2009]. This task was neither audio nor video recorded. To give the participants a starting point for their idea generation without giving examples, we gave each group the following inspiration:

We gave inspiration to our participants without biasing them towards specific applications.

- I1: Think about movies that you have seen or books that you have read, maybe you can find some examples of SCIs there.
- I2: Think of Smart Home devices that you already know or own and about how shape-change could improve the interaction with those devices.
- I3: Think of the types of shape changes that I just showed you. Which ones could you imagine in a home, and how could they be incorporated?
- I4: Go through your home and consider how you might turn objects into shape-changing interfaces.
- I5: Go through your daily routine and consider objects that you interact with. How could they be turned into shape-changing interfaces?

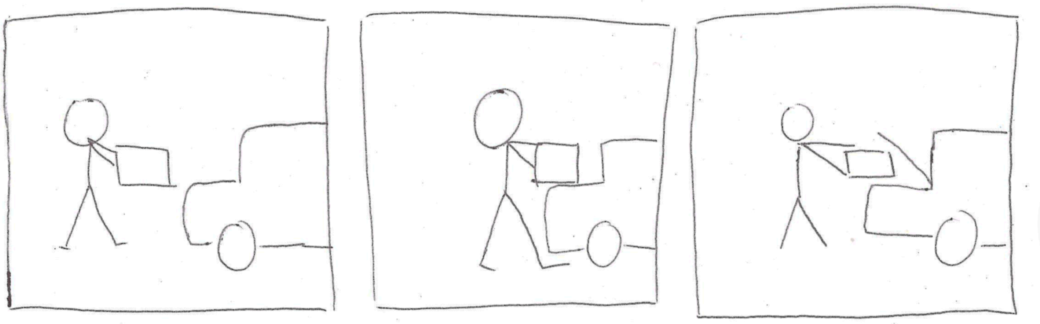


Figure 3.2: A sketch of the storyboard that was used to introduce the participants of the study to storyboarding. It demonstrated how storyboards show the interaction with an interface and its context.

To remind them of the possible types of shape changes we also provided a handout with the stills from our animations (see Appendix C). This was another improvement that we implemented after feedback from our pilot study, as the participants mentioned that it was difficult to remember everything they had seen in the animations. If the participants told us that they had issues coming up with ideas, we further told them to think of problems at home and how they could use a shape-changing interface to solve them. We did, however, not give any examples for shape-changing interfaces even if participants specifically asked for them, as we wanted to limit bias.

We provided a handout, but no examples of SCIs to our participants.

Task 2: Storyboard Creation in Groups

For the second task, we asked our participants to first discuss the ideas that they came up with and then create storyboards based on them. There was no expected number or limit to the number of storyboards they created. Storyboards are well-suited to show scenarios of interaction between users and interfaces and therefore an established method in HCI design processes [Truong et al., 2006]. Especially rough storyboarding is very accessible and allows for quick communication of scenarios and their context [Van der Lelie, 2006]. Other co-design studies in the area of smart home applications also used different techniques,

The second task involved the groups of participants creating storyboards of scenarios for the use of SCIs in smart homes.

such as Trigger-Action-Programs, but those did not fit our goal of finding application scenarios.

We explained the method of storyboarding with a live example.

We explained the concept of storyboarding by sketching an example, which can be seen in Figure 3.2. The first panel of this storyboard shows a person holding their groceries in their hands and is therefore unable to use them to open the trunk of their car. In the second panel, the person interacts with the car by moving their foot underneath it, which opens the trunk. This can be seen in the last panel. The chosen example contains neither a shape-changing interface nor is it a smart home application, and would therefore not bias the participants. Using this example, we explained that storyboards usually show the problem or initial situation of the scenario, then the interaction with the interface, and finally the solution or situation after the interaction. We also asserted that storyboards do not have to look perfect, but rather quickly sketch an interaction and its context. This in-depth explanation of storyboarding was necessary to make sure that the participants would sketch the whole interaction scenario, instead of just an interface. Since this has happened in other co-design studies using storyboarding before, we were careful to avoid it [Young et al., 2022].

We provided crafting materials for creating depictions of SCIs.

Additionally, to the paper and pencils that were intended for sketching, we also provided the participants with simple crafting materials. These included sticky notes, colored pencils and paper, modeling clay, scissors, and glue. The participants were told that they could use these materials if they helped them depict the SCIs in their scenarios better, but they did not have to use them. This task was given a time limit of thirty minutes to allow for enough time to first discuss and then create. If more time was needed, we also allowed for small extensions, and if participants finished long before the time was up, they were encouraged to think of more ideas and scenarios together. This task was video and audio recorded.

Semi-Structured Interview

In our semi-structured interview, our main goal was to make sure we understood the storyboards that were created by the participants correctly. Therefore, we started each interview by asking them to explain the storyboards to us. Depending on the detail of their explanations, we asked follow-up questions such as the following:

We conducted a semi-structured interview to understand the scenarios in the storyboards.

Q1: Which benefits does your shape-changing interface have over other interfaces?

Q2: Why did you decide on this particular type of shape change?

Q3: How is your interface controlled and why?

Q4: Which kind of inputs and outputs did you decide to use and why?

Q5: Which problem is solved by this interface?/ Which goal did you have when you came up with this interface?

We also asked participants which of the presented interfaces they would actually like to use if they existed. For the ones that they would not want to use, we were interested in the underlying concerns. In the end, we gave participants the chance to add any thoughts that they had not mentioned before and considered relevant. The audio of the interview was recorded for easier transcription, and the whole interview took about ten minutes.

3.2 Participants

We recruited 15 participants through convenience recruitment. We neither made sure that the participants in each group knew each other nor that they did not. Their ages ranged from 21 to 29 (M = 23.8, SD = 2.79). Five of the

15 participants who were mostly computer science students took part in our study.

participants were female and ten were male. All participants had a technical background, with eleven of them being Bachelor's or Master's students in computer science. All of the participants knew what a smart home is. Eleven of the participants had also heard of shape-changing interfaces before.

All participants had at least a basic understanding of smart homes.

When defining smart homes, all participants showed a basic understanding. Ten participants mentioned automation as a characteristic feature, and five participants used the words "smart" or"intelligent" to describe devices in homes. Sensors, control via the internet, and control via apps or smartphones came up three times, respectively. The most mentioned benefit was convenience, with a total of four times. Two participants could not define smart homes directly, but instead gave multiple fitting examples. Other participants also gave examples in addition to their definition.

Only ten participants could at least roughly define SCIs.

Of the eleven people who had heard of shape-changing interfaces before, eight paraphrased shape change in their definition. Another two described a change of function of an interface. Additionally, three people described that such interfaces communicate information. Input or output, interactivity, and change as a response to a specific context were mentioned two times, respectively. One person stated that they had heard of the term before but did not know what it meant exactly. Notably, no one gave any examples for SCIs.

Chapter 4

Evaluation

We analyzed our results using thematic analysis. In the following, we will present frequent themes that could be found in the storyboards created by participants. In one section, we apply existing taxonomies that were described in Chapter 2 to our results. Additional themes that were not covered by the taxonomies are presented in the next section. We describe common scenarios and their characteristics. The last part of our thematic analysis is about the concerns about using SCIs in smart homes that were often mentioned by the participants. Finally, we will discuss our findings and the limitations of our study.

4.1 Thematic Analysis

We used a deductive and an inductive approach to thematic analysis.

We used a deductive and an inductive approach for our thematic analysis. For our deductive analysis, we used taxonomies and frameworks that already exist in the literature. We aimed to find out if they can be applied to findings from a user-centric approach. This is especially interesting when the frameworks were derived from reviewing existing artifact papers, because we will thereby get an insight into the overlap between the preferences of users and current research practices. Therefore, we also analyzed whether SCIs that were designed by our participants have similarities with already existing artifacts. For this approach, we used codes that described the categories of the taxonomies. For example, Rasmussen et al. [2016] used the terms *directly-controlled*, *negotiated*, *indirectly-controlled*, and *system-controlled* to describe the influence of the user on the shape change. These terms became codes for our analysis.

For our inductive analysis, we used the six steps from Braun and Clarke [2006].

Our process for the inductive analysis was modeled after the six steps of thematic analysis adapted by Ahmed et al. [2025] from Braun and Clarke [2006]. These six steps consist of the following:

1: Familiarizing yourself with the data.

2: Generating initial codes.

3: Searching for themes.

4: Reviewing potential themes.

5: Defining and naming themes.

6: Writing up.

We constructed themes that describe scenarios for the use of SCIs in smart homes.

We first transcribed the interviews and audio data from the videos from our study with the help of a locally hosted AI transcription tool[1] . Then we checked and corrected those transcriptions. To evaluate the transcriptions, we used MAXQDA[2] , which is a program for qualitative analysis that offers a customizable overview of themes, codes, and their frequency as well as helpful visualization tools. We focused on finding codes for benefits and application areas of SCIs that were not covered by existing smart home application categories. Then we constructed themes from both the codes of the inductive and the deductive analysis, which described scenarios for the use of SCIs in smart homes. We first only used the interviews on the storyboards with our participants, as these show the scenarios that the participants liked best. We only included the prior discussions in our analysis later, as those were the ideas that were ultimately not preferred by them, and we will mention when findings are based on them.

[1] `https://git.rwth-aachen.de/i10/research/local-research-transcriber-python/`, *last accessed 09.27.2025*

[2] `https://www.maxqda.com/de/`, *last accessed 09.27.2025*

4.2 Results

A total of 41 storyboards were created by our participants. This is an average of 5.85 storyboards per group. One storyboard was not drawn but instead used clay and sticky notes. We noticed that even if participants were unsure and had difficulties coming up with ideas, they ended up still creating storyboards and contributing to their group's discussion. The additional crafting materials were only rarely used for the storyboard creation. Some participants used the colored pencils, and the clay was used twice; however, only once to depict a shape change. Our results are described in this section. We translated all quotes into English if necessary, and overlaid German text with English text in some example storyboards.

Our participants created 41 storyboards in total, with everyone having ideas to contribute.

4.2.1 Existing Taxonomies and Artifacts

In this section, we apply existing SCI and smart home frameworks to our results. This later enables us to discuss the overlaps and discrepancies between our findings and the existing literature. We start with frameworks concerned with the characteristics of SCIs and then proceed with taxonomies of smart home application areas and benefits.

Type of Shape Change

To classify the different types of shape changes, we used the framework of Rasmussen et al. [2012]. The exact numbers of occurrences of each category can be seen in Table 4.1. The most popular types of shape changes were *form* and *texture*, while *orientation*, *volume*, and *permeability* were also frequently mentioned. When a change of *texture* was described, it was often a roughening of a surface or the appearance of spikes. We also classified changes of color as *texture* changes, as the color of an object is dependent on its surface. As the definition of a change of *texture* by Rasmussen et al. [2012] refers to small visual properties of a surface, we found this category most accurate. A change

Participants used all types of shape changes with differing popularity, apart from *viscosity*.

Category	Number of Occurrences
volume	6
form	12
orientation	6
texture	11
viscosity	0
add/subtract	4
permeability	8
spatiality	1

Table 4.1: The table shows the types of shape changes and their occurrences in the storyboards of our study. *Form* and *texture* were the most frequent types of shape changes, while *spatiality* and *viscosity* barely occured at all. The categories were defined by Rasmussen et al. [2012].

of *viscosity* was not used in the storyboards at all. In the discussions before the creation of the storyboards, it was mentioned twice, but the participants were unclear about its benefits, as the following quote shows.

> *"Somehow you need a certain viscosity [of a liquid], [...] and then it mixes it for you [...]. I don't know when I would need that."*
>
> ***—P7***

Some shape changes were difficult to classify.

We also only described one shape change as a change of *spatiality*. This shape change was a rearrangement of furniture, which was difficult to fit into the existing categories. Rasmussen et al. [2012] define that a change of *spatiality* only occurs when the repositioning of an object in space changes the perception of a structure that the object is part of (see Appendix C). In this case, the layout of the furniture and thereby the design of the room can be seen as this structure. Another shape change that did not neatly fit into the existing categories was *elevation*. It occurred a total of six times, and we categorized it as a change of *form*, but it could also be described as a change of *volume*. An example of this shape change was the actuated elements of the surface of a desk, which could elevate or descend.

Category	Number of Occurrences
directly-controlled	18
negotiated	0
indirectly-controlled	6
system-controlled	27

Table 4.2: The table shows the levels of user-control over shape change and their occurrences in the storyboards in our study. System-controlled shape changes occurred the most often, while negotiated control was not described at all. The categories were defined by Rasmussen et al. [2016].

User-Control

Participants mostly used *system-controlled* and *directly controlled* interfaces in their storyboards.

We used the framework from Rasmussen et al. [2016] to analyze how users imagine controlling SCIs in smart homes. *System-controlled* shape change occurred the most in the storyboards of our participants and covers, for example, interfaces that make use of sensors or are controlled by a timer. Notably, *system control* was the most popular type of control by a very large margin. This category is followed by *directly controlled* shape change. This was achieved by the user through actions such as pressing buttons or interacting with an app. There were no instances of *negotiated control* and only a few instances of *indirect control*. These include interfaces that automatically react to the user's voice, without them using targeted commands. The exact numbers of occurrences of each level of control can be seen in Table 4.2.

Application Areas and Benefits of Smart Homes

The most common application areas for SCIs were *environment* and *safety and security*.

To compare application areas of SCIs in smart homes to smart home application areas, we used the taxonomy created by Taiwo et al. [2020]. The categories *environment* and *safety and security* occurred the most. Applications in the area of *environment* were, for example, walls that changed their permeability for easy ventilation or parasols that adapted to the position of the sun. *Healthcare* and *entertainment* were also represented in the storyboards but *energy management* was not, as can bee seen in Table 4.3. It

Category	Number of Occurrences
entertainment	2
healthcare	3
safety and security	8
environment	12
energy management	0

Table 4.3: The table shows the application categories of smart home devices and their occurrences in the storyboards of our study. *Environment* was the most frequent application area, but *energy management* was not mentioned by our participants. The categories were defined by Taiwo et al. [2020].

only occurred once during discussions between the participants. *Safety and security* and *healthcare* as application areas overlap with the benefits of SCIs that are discussed in the next section, and will be elaborated upon there (see Section 4.2.1). An example of an SCI in the application area of *entertainment* is a TV that changes its orientation depending on where the user is sitting. The storyboards that did not fit into the application areas could instead be described using the taxonomy of smart home benefits that is applied in the next paragraph.

The benefits *convenience and controllability* and *safety and security* were the most commonly mentioned benefits

To classify the benefits of SCIs in smart homes, we started with the categories found by Sovacool and Furszyfer Del Rio [2020]. However, it became apparent that the categories *safety and security* and *controllability and convenience* described a broad selection of more specific benefits. We therefore split up *safety and security* into *avoidance of damage*, *avoidance of injuries*, and *home security*. An overview of all categories of benefits can be seen in Table 4.4. *Avoidance of injuries* includes interfaces such as surfaces that change their texture to become less slippery or sharp edges that are turned round. *Avoidance of damage* and *home security* both describe the protection of material objects, the first regarding mid-size objects like furniture and the second regarding the whole house or flat. *Convenience and controllability* was split up into *effort reduction*, *saving space* and *controllability*. *Effort reduction* remains a large category, containing examples such as a filter for food waste in the sink that automatically changes its openings appropriately or actuated

Category	Number of Occurrences
social benefits	4
entertainment	2
educational and learning	1
aesthetics	6
safety and security	
avoidance of damage	2
avoidance of injuries	5
home security	4
health and assisted living	7
convenience and controllability	
effort reduction	22
saving space	5
controllability	9

Table 4.4: The table shows categories of benefits of smart home devices and their occurrences in the storyboards of our study. The most frequently mentioned benefit was *convenience and controllability.* The categories were defined by Sovacool and Furszyfer Del Rio [2020].

surfaces that remind users of taking their keys. *Controllability* refers to interfaces with easier-to-operate controls, such as buttons embedded into sofas. These benefits also overlap sometimes, for example, as embedded buttons also reduce effort because users do not have to move to use them. *Saving space* was, for instance, mentioned as a benefit of furniture that can grow or shrink depending on whether it is used.

Other benefits include *social*, *educational*, *aes-thetic*,*entertainment*, and *health*.

The other categories from Sovacool and Furszyfer Del Rio [2020] that also occurred in our results are *social benefits*, *educational and learning*, *aesthetics*, *entertainment*, and *health and assisted living*. *Social benefits* were, for example, achieved through flexibly dividing space to be used by multiple parties at the same time, and educational benefits by using walls to separate learning areas. *Aesthetic* benefits often co-occur with other benefits, as seen with the embedded buttons in Figure 4.5 that only show up when they are needed. Benefits for *health and assisted living* came up with interfaces such as elevating desk surfaces to reduce neck pain or automatically moving furniture for elderly people with less physical strength. An example of an *entertainment*

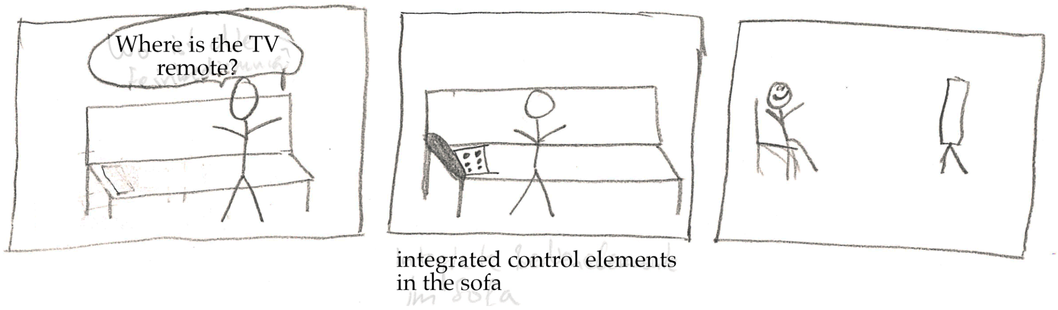


Figure 4.5

benefit is a TV that can change the size and orientation of its screen based on voice input or spatial perception.

Occurrences of Existing Artifacts

Some SCIs from our study have already been prototyped in research papers.

Some of the imagined SCIs in our study have already been built as prototypes by researchers. A lamp that changes its brightness when a user extends its shade was described in one storyboard. This kind of lamp resembles the *MoLux* prototype developed by Sørensen et al. [2022]. In the follow-up interview, the group also reported the benefit of this lamp to be more intuitive control, as the following quote illustrates. This is the same benefit as was intended by *MoLux*'s developers.

> *"If you extend something, you mostly think that it becomes more and then you automatically have the association with the lamp[...]"*
>
> —***P6***

Multiple groups had the idea of integrating a remote control into a sofa, which is similar to current research on textile interfaces.

The idea of a remote control that is integrated into a sofa and emerges when needed was mentioned a total of three times. In two instances, the idea was incorporated into a storyboard, such as the one in Figure 4.5. The first panel shows a person who is searching for their TV remote. In the second panel, there are control elements for the TV embedded into their sofa, so that the protagonist can happily watch TV in the last panel. This idea shows similarities to current research on textile interfaces [Mlakar and Haller, 2020]. In one case, the participant admitted that they had "stolen" this idea.

Other examples of existing SCIs in our storyboards include vacuum cleaners and actuated tabletops.

Furthermore, an actuated desk with elevating surfaces that can serve multiple applications was mentioned and shows similarities with the *inFORM* [Follmer et al., 2013] and *Transform* [Vink et al., 2015] prototypes. Two designs for shape-changing vacuum cleaners were not turned into storyboards but only discussed by participants. These have comparable benefits to the prototypes of Legaard et al. [2016] and Jakobsen et al. [2016], including not having to exchange attachments due to the "mouth" changing its size or changes in texture to signal that the vacuum cleaner is full. Multiple participants also described using changes of permeability for environmental control (see section 4.2.3). Their described interfaces do not exactly exist yet, but the prototype *Shutters* is based on a similar idea. One participant brought up the idea of doorknobs that point downwards when the door is locked. However, they were not confident in this idea, as the following quote shows.

> *"I thought of, well, doorknobs that point downwards, when the door is locked.[...]This is really shit."*
>
> *—P9*

As the group did not further discuss this idea or turn it into a storyboard, it did not become clear why the participant did not like it. It is, however, similar to the shape-changing door created by Economidou and Hengeveld [2021], although it uses a different type of shape change (*orientation*).

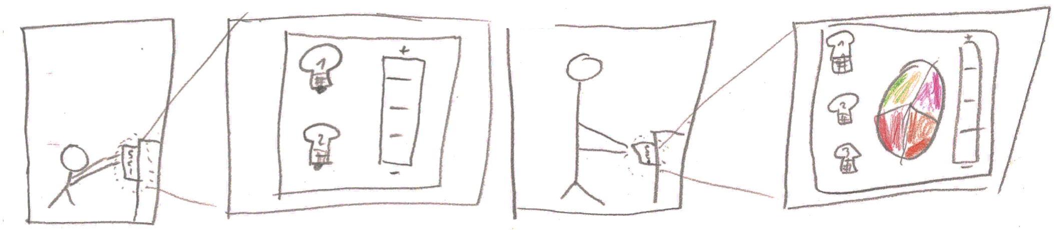


Figure 4.6: An example of the storyboards created by our participants. It shows how SCIs can incorporate the benefit of multi-functionality.

4.2.2 Additional Benefits

Some benefits that we found in our results could not be categorized using existing smart home frameworks and occurred so often that they are worth mentioning explicitly. We will define the benefits of *Multi-Functionality* and *Intuitiveness* and give examples for them in the following sections.

Multi-Functionality

Multi-functionality is a benefit that was not represented in smart home taxonomies, but in our results.

The idea of objects or furniture that can change their functionality by changing their shape was very popular. This benefit includes SCIs such as a fork that can turn into a spoon, seating furniture with variable levels of comfort, and rooms that are dividable to be used for different purposes. Generally, this benefit refers to the possibility of having your home and its devices always fit your current needs. The different functionalities were not arbitrary but related, as seen with the example of seating furniture. Sometimes, this co-occurred with the benefit of *saving space*. It also co-occurred with *safety and security* benefits, for instance, a control panel that changes its interface based on who uses it. This example can be seen in Figure 4.6. In the first two panels, a child is using smart home controls. In the second two panels, an adult is using the controls, which is why there are more options to choose from than before.

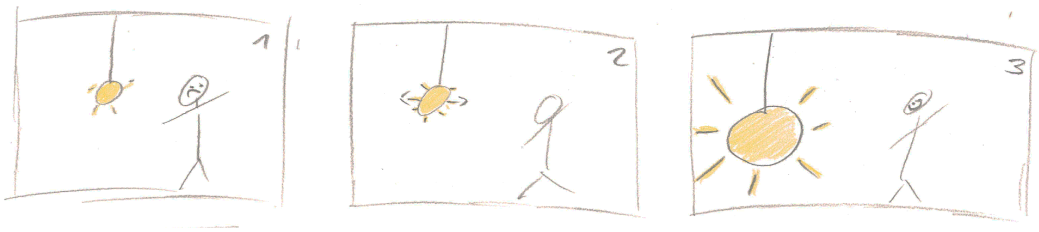


Figure 4.7: An example of the storyboards created by our participants. It shows how SCIs provide the benefit of intuitive control.

Intuitiveness

Higher *intuitiveness* as a benefit is specific to shape-changing interfaces in smart homes.

Many of the imagined SCIs utilized natural mappings to increase the intuitiveness of controlling them. An example would be the lamp in Figure 4.7, whose brightness is controlled by extending and collapsing its shade. In the first panel, the user is unhappy because the lamp is not providing enough light. In the second panel, they extend the lamp manually. Therefore, the lamp is bigger and its brightness has increased in the third panel. In this case, the brightness is mapped to the volume of the shade. Instances of perceptual analogies[3] also occurred. Participants suggested controlling the extension of curtains or shutters using a little model of them or rearranging the furniture in a room by using a model of the room. One could argue that this benefit can be grouped into controllability. However, as it is not only concerned with making something controllable but increasing the intuitiveness of controlling it, it is important to examine it separately.

PERCEPTUAL ANALOGIES: Perceptual analogies are a type of mapping. Using them, the design of UI (User Interface) elements imitates the devices they control. Mappings describe the relationship between devices and their controls.

4.2.3 Scenarios

From our codes, we constructed themes that describe scenarios for using SCIs in smart homes. To further define those scenarios, we looked for descriptions of the parameters of the design requirements model that was developed by Sturdee et al. [2019] (see Figure 2.2). In the following,

[3] `https://hci.rwth-aachen.de/public/Lectures/DIS1/2023_24_ws/DIS1%20WS23%20L03%20Mappings,%20Constraints,%20Seven%20Stages%20Of%20Action.pdf`, *last accessed 09.30.2025*

Figure 4.8: An example storyboard created by our participants. It shows how *permeability* can be used to control the environment.

we describe the scenarios along the parameters of the design requirements model, when applicable. We focused on the frequent scenarios that showed recurring characteristics. However, as described in Section 4.2.1, there are generally a lot more application scenarios for SCIs in smart homes.

Controlling the Environment through Permeability

Controlling the environment with SCIs utilizing a change of permeability is a common scenario in our results.

A commonly occurring scenario in our results is the wish to control different environmental parameters through a change of permeability. Such parameters could be temperature, sun, or whether mosquitoes are let into the room. The user was described as interacting with the system by setting a parameter that they wanted to achieve (e.g., temperature). In other cases, the shape change would be entirely controlled by the system, for example, for automatic ventilation based on air quality. Further, it was mentioned that a window that uses permeability to block the sun would be controlled via the time of day, indicating a clock as a control system. The objects affected by the shape change in this scenario were windows, walls, or curtains. An example in Figure 4.8 illustrates this scenario. In the first panel, there is a person at a desk who is trying to play video games on their computer. However, they are blinded by the sun coming through the window. In the second panel, dark spots

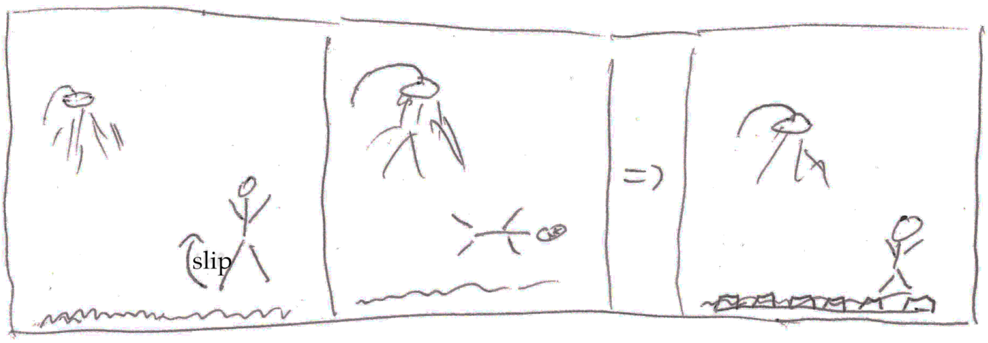


Figure 4.9: An example of a storyboard created by our participants. It shows how SCIs can be utilized in smart homes to prevent injuries.

have appeared on the window, which block the sun's rays in certain spots.

Preventing Injuries and Damage

Another application scenario for SCIs is system-controlled avoidance of injuries and damage.

To avoid injuries and damage to objects and their houses, users nearly exclusively imagine system-controlled SCIs. For injury prevention, the scenarios either use a change of texture or a change of form. Especially often, the idea of using a change of texture to make a wet surface less slippery came up, an example of which can be seen in Figure 4.9. The first panel shows a person slipping in the shower. In the second panel, this person is lying on the ground. The third panel shows a different outcome of the scenario, in which the surface of the floor has changed its texture, and the protagonist has not fallen. This scenario was sometimes mentioned in combination with *health and assisted living* benefits, as it was imagined to be beneficial to elderly people. In this case, a sensor would notice the wetness of the surface and cause the shape change.

For home security applications, the types of shape changes varied. However, sensors were often used again, this time cameras with facial recognition software or smoke sensors. The systems were also imagined to have different presets depending on the person it would recognize, including strangers or children. This way, the interface could react hostilely to invaders or welcomingly to friends.

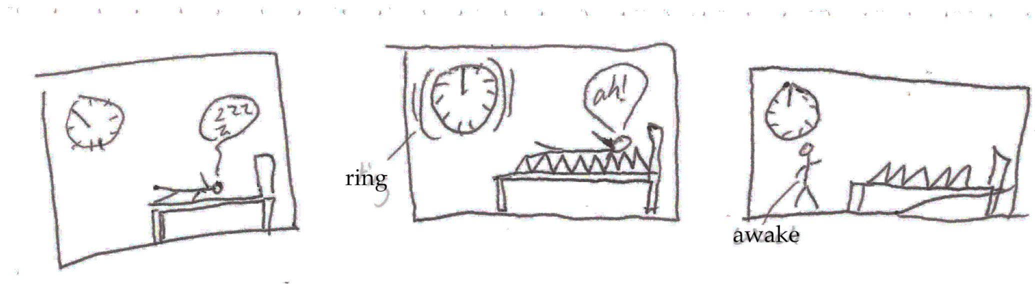


Figure 4.10: An example of a storyboard created by our participants. It shows how SCIs can motivate users to change their behavior.

Causing Behavioral Change through Discomfort

Many storyboards imagined using SCIs with changing levels of comfort to achieve behavioral change of users.

Another scenario that often occurred in our results is SCIs that aim to cause a change in the user's behavior. One example is motivating the user to get out of bed in the morning, which is shown in Figure 4.10. The first panel shows a person sleeping in their bed with a clock on the wall. In the second panel, the clock has moved, and the mattress has become spiky. The clock is ringing, and the person is waking up. In the third picture, they are awake and have left their bed. Another example is motivating the user to leave the sofa and go to sleep in the evening. Some of these behavioral changes caused by the SCIs were described to be beneficial for mental or physical health. These shape changes are exclusively system-controlled and are imagined to be purposefully irritating or uncomfortable, as the following quote describes.

> *"When I was talking about the chair, I was thinking of it like it has to be random [...] and specifically enough to trigger you."*
>
> ***—P12***

The SCIs in this scenario communicate with the user through direct contact. Often, the system controls them based on preset timers. One participant also mentioned that they wanted the system to react to subconscious voice input. The type of shape change that is caused is not consistent across storyboards, but it always affects the comfort

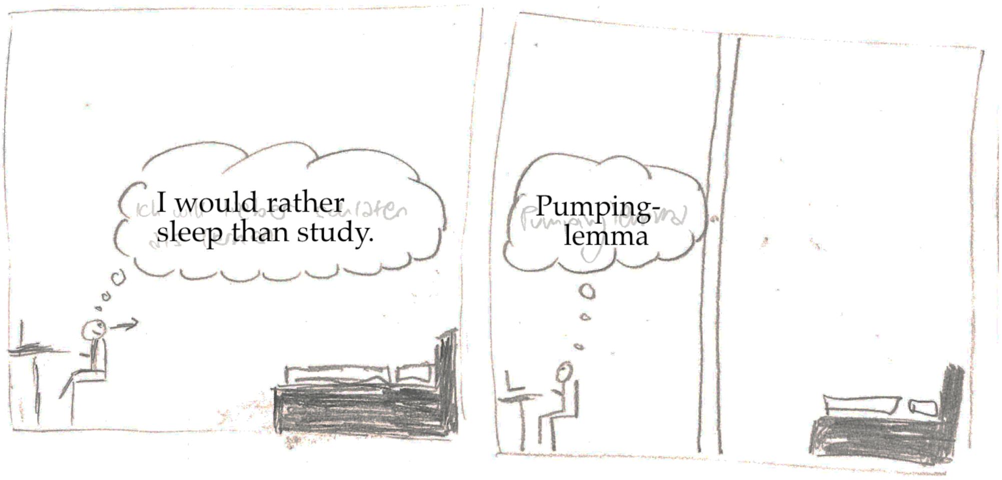


Figure 4.11: An example of a storyboard created by our participants. It shows how SCIs can be used to adapt rooms to the users' wishes.

of the surface. For instance, discomfort was described to be caused by emerging spikes or vanishing pillows.

Adaptable Objects and Rooms

The last common scenario in our results was adapting the function of objects and rooms for different functionalities, mostly with direct control of the user.

As described, a specific benefit of shape-changing interfaces is that different shapes afford different usages of objects. Therefore, a scenario that often occurred was adapting the function of objects, furniture pieces, or rooms. Objects and furniture pieces were described to change into something that had a related function, for example, a mixing bowl changing into a baking tray. The functionality of rooms was often changed through walls that would emerge and divide the room differently. This, for example, can be seen in Figure 4.11. In the first panel, there is a person who is sitting at their desk, trying to study, with their bed behind them. However, a thought bubble says that they would rather sleep. In the second panel, a wall separates the desk and the bed. The protagonist can now focus on studying. Predominantly, the shape changes in this scenario were user-controlled. The exceptions were changes of functions related to who was using the interface, which were described to be system-controlled using sensors or cameras. A benefit that is closely linked to this scenario is *saving space*, as multi-functional objects take up less space than multiple individual objects would.

4.2.4 Concerns

Some participants were concerned with sensors and data security.

We also analyzed which kinds of concerns about using SCIs were mentioned in the discussions of the participants and the interviews. One area of concern was related to the use of sensors in the users' smart homes since participants mentioned that they worried about their privacy and data security. Especially the use of cameras was criticized, while temperature or air quality sensors caused less concern. Some participants even said that they could not imagine having an always-active camera in their houses at all.

Some participants worried that shape-changing furniture would be too convenient.

In one case, concerns were related to SCIs being too convenient. The group was worried that multi-functional chairs would take away the motivation to move and, therefore, lead to health problems caused by sitting too long. In this regard, one participant said the following, highlighting that convenience is not always a benefit.

> *"Furniture that changes to your needs is maybe like eating chocolate. In the moment, it's really good, but in the long run it will ruin you."*
>
> ***—P13***

Participants also had concerns specific to shape change.

Other concerns were related to the use of shape change itself. In some of the scenarios using SCIs to cause behavioral change, the participants said that their imagined shape changes would be too irritating to use in reality. Participants also worried about shape changes causing damage or injuries. For example, they mentioned that growing objects could cause the user to be jammed in between them.

Some participants described using SCIs as unnecessary in cases where they could think of a different solution to their problems and failed to find a specific benefit of SCIs. This concern is exemplified by the following quote.

SCIs were also somtimes seen as unnecessary.

> *"None of this is really necessary. Well, everything is partially nice, and partially a mattress throwing you out of your bed. But everything works like this (meaning without SCIs) as well."*
>
> —***P3***

Finally, some participants imagined SCIs to be easily breakable or to malfunction.

4.3 Discussion

In the following sections, we will comment on our previously described findings. We will first discuss our research questions and compare our findings to work by other researchers. We will also reflect on our methodology and consider possible sources and implications of the concerns of users.

4.3.1 Which application areas for the use of SCIs can users imagine in Smart Homes?

Although we only described the four most commonly occurring scenarios for the application of SCIs in smart homes, many more were thought of by our participants. Out of five possible smart home application areas found by Taiwo et al. [2020], four were represented in our study. The application areas that are not included in the four specific scenarios also show potential for the use of SCIs in smart homes. We were, however, not able to group them into scenarios, as they did not occur often enough. Therefore, we were not able to determine specific characteristics and benefits that co-occurred with the application areas. This

We found four common application scenarios with many more possible.

indicates that more research is necessary to describe other possible scenarios in more detail. The four scenarios *Environmental Control through Permeability*, *Preventing Injuries and Damage*, *Adaptable Objects and Rooms*, and *Motivating Behavioral Changes through Discomfort* were very frequent in our findings. Therefore, they have the potential to be included in the best-suited application scenarios of SCIs, which Alexander et al. [2018] found necessary to identify.

Most SCIs were imagined to solve a specific problem.

In general, most scenarios created by our participants had the goal of solving a specific problem. We only told participants who struggled to come up with ideas to think about the problems they have in their homes. Thus, this finding is only slightly influenced by our methodology. Problem-focused SCI-design is, as described in Chapter 2, not a very common approach with current prototypes of SCIs. Therefore, we infer that users have a preference for SCIs that solve specific problems, which is not yet taken into account in the research on SCIs.

Our participants' demographic background might have resulted in an underrepresentation of energy management as an application area.

Notably, we did not find any application scenarios in the area of energy management, which is the only application area found by Taiwo et al. [2020] that is not represented in our results. This might be due to participants being mostly young students. This user group often either lives with their parents, in student housing, or in shared flats (see Statista[4]), which makes energy management systems less important. Therefore, we cannot definitively conclude that there are no scenarios in which SCIs can be used for energy management, but rather that an application in this area might not be especially attractive to a target group similar to our participants.

We showed that users can imagine using specific benefits of SCIs in smart homes.

The SCIs that were ideated by our participants have benefits that fit into a diverse array of categories, again showing how extensive the potential of SCIs in smart homes is. Notably, *effort reduction* was mentioned as a benefit a lot more frequently than any of the other benefits. This is especially interesting, as it shows that users already see added convenience as an important enough benefit of SCIs. Existing frameworks of application areas or benefits of smart

[4] `https://de.statista.com/infografik/19250/wohnformen-von-studierenden/`, *last accessed 09.27.2025*

home devices do not take shape-changing interfaces into account. This is because shape-changing interfaces offer different benefits to typical smart home interfaces. That became apparent through the thematic analysis, as the benefits *multi-functionality* and *intuitiveness* are not included in the framework by Sovacool and Furszyfer Del Rio [2020] but occur often in our findings. However, they are closely related to the functional aims of SCIs found by Rasmussen et al. [2012]. Therefore, we have not found new benefits of SCIs that have not been considered before, but shown how those benefits can be utilized for smart home applications specifically. Not considering these benefits before is not an oversight in smart home research, but instead shows that the use of SCIs in smart homes has potential beyond the benefits of traditional smart home devices. For example, smart home devices might make controlling environmental conditions in homes easier, but SCIs additionally offer a more intuitive control of those conditions.

Some benefits of smart home devices were not present in our results, possibly because of our user-centric approach.

Some of the benefits of Sovacool and Furszyfer Del Rio [2020] did not appear once in our study. Namely, *energy savings*, *financial benefits and saving money*, *system benefits*, *environmental benefits* (regarding pollution and waste), *free services and promotional gifts*, and *enhanced experiences* (e.g., shopping). As we asked for scenarios in which users could imagine interacting with SCIs in smart homes, it makes sense that system benefits concerning networks and operators or energy and financial benefits would not come up frequently, since they are not very interactive. For other benefits, it is unclear why they were not considered by our participants. One part of the reason could be that some of them are not very common in the research of Sovacool and Furszyfer Del Rio [2020] either. Their framework was also derived using expert interviews, which is a very different approach to our user-centric co-design study. The differences in found benefits can therefore also be interpreted as showing a gap between experts' opinions and users' wishes. This highlights the importance of involving users in further research to determine which benefits and application areas are actually important to them.

Only some user-preferences on characteristics of SCIs in smart homes can be described based on our findings.

When constructing themes that describe specific scenarios, it became apparent that some characteristics were better defined for certain scenarios than for others. For example, for *Controlling the Environment through Permeability*, the shape change was permeability in a majority of storyboards. However, the level of user control over this shape change varied and could therefore not be clearly defined. For the scenario *Preventing Injuries and Damage*, on the other hand, the preferred level of control was clearly system-controlled, while the shape change varied. Thus, for different scenarios, users seem to have preferences regarding different characteristics of SCI's, but not necessarily all of them. We will elaborate on those preferences in the following two subsections(Section 4.3.2 and Section 4.3.3).

4.3.2 Which types of shape changes can users imagine for SCIs in Smart Homes?

Nearly all types of shape changes were represented in our results.

Apart from *viscosity*, all types of shape changes that were defined by Rasmussen et al. [2012] could also be imagined to be used in smart homes by our participants. Although we explicitly told participants that shape changes could also be combined, there were no instances of such combinations. This fits the findings of Sturdee et al. [2015], who also did not find any instances of combinations of shape changes in their public ideation of SCIs. In the following, we will discuss the notably more or less popular types of shape changes.

Form and *texture* were the most commonly occurring shape changes of our participants.

There were clear preferences for certain types of shape changes. *Form* was the most popular one, possibly because it is the most flexible and can describe a variety of objects turning into other objects. This also leads to challenges for the future construction of the described interfaces. The participants were presented with smooth animations between different forms and based their understanding on them. Currently, the construction of such technologies and materials poses unsolved challenges [Alexander et al., 2018]. This means that a construction of the form changes described by participants is not possible and would need to be realized with a different approach. We do not know whether less ideal implementations of shape changes would be just as appealing to users as the SCIs described in their storyboards. The second most popular shape change in the storyboards was *texture*. For both *form* and *texture* Rasmussen et al. [2012] already found a lot of examples in their literature review, meaning that user preferences fit the existing research.

Change of *permeability* was very popular with users, especially in comparison to other work.

Changes of *permeability* were also very popular with our participants, while there are rarely any examples in the literature found by Rasmussen et al. [2012]. Although their paper is not very recent, we also did not find any further examples of SCIs using *permeability*. Of course, we did not conduct a structured literature review on SCI prototypes for augmented living. Still, it is unlikely that we missed a lot of prototypes utilizing *permeability*. This discrepancy might be related to the technical difficulties of creating materials whose permeability can change. It does, however, not negate the potential of investigating possibilities to incorporate permeability in SCIs in the future.

There are multiple possible reasons for *spatiality* and *viscosity* to be less popular with users.

Viscosity and *spatiality*, on the other hand, neither appear much in the literature nor in our study. In general, *viscosity* and *spatiality* as described by Rasmussen et al. [2012] do not deform interfaces and are therefore not typical examples of shape change. Thus, they might not have been obvious choices of shape change for our participants. In the case of *viscosity*, participants had difficulties thinking of benefits, and in one case, mentioned after the creation of the storyboards that they had not really understood it. The issue might therefore lie in making users understand how changing *viscosity* could be used, and not in the fact that there are no applications for it. For *spatiality*, there was no indication of a missing understanding of the shape change or its benefits. We can, therefore, not attribute the lack of storyboards integrating this type of shape change to an insufficient explanation. This type of shape change has thus shown less potential for an application in smart homes in our study.

Users prefer specific shape changes in certain scenarios.

Additionally, users sometimes prefer a type of shape change to be used for a specific scenario (as described in Section 4.2.3). Using *permeability* to control the environment is very logical, as it allows users to control how much sun or air is permitted to enter their surroundings. As a change of *form* describes such a wide area of possible shape changes that can also be very drastic, it makes sense to use it to achieve multi-functionality. These findings take a step in the direction of answering Alexander et al.'s question regarding when to use which shape changes. To conform with the needs of users as best as possible, these scenario-specific preferences should be taken into account in future research.

Based on our findings, users expect multi-functional SCIs in smart homes to still fulfill a similar purpose after the shape change.

In the case of multi-functionality as a benefit of SCIs in smart homes, it became apparent that users imagine SCIs to still fulfil a similar purpose after the shape change as before. This is interesting, as Rasmussen and Hemmert [2019] discuss finding out which kinds of shape changes users expect from interfaces as a future challenge. Based on our findings, shape changes that lead to a similar functionality are more likely to be expected by users. This can help to design SCIs in the future, whose shape changes feel intuitive to users.

4.3.3 How do users imagine interacting with SCIs in Smart Homes?

The popularity of *system-controlled* shape changes makes sense given the key features of smart homes.

In general users mostly imagined SCIs to be *system-controlled*, as this method of control appears in all scenarios and all application areas. As remote control and systems using linked sensors and appliances are key features of smart home technology (see Chapter 1), it is not very surprising that this level of control was preferred by users for SCIs in smart homes specifically. It is least popular for *Adaptable Objects and Rooms*, and most popular for *Preventing Injuries and Damage*. This makes sense due to safety mechanisms functioning best when they are automatically started when needed. For *Causing Behavioral Change through Discomfort*, the fact that the change is *system-controlled* was even stated as an explicit benefit. Here, giving control to the users would take away the function of the SCI.

Directly controlling the shape change of SCIs was popular for other application scenarios, especially to achieve multi-functionality. Switching between different functions of an object requires knowing which function is suited to the current situation and goal of the user. This is knowledge that only the user has and which thus only they can use to control the shape change. Therefore, users apparently prefer to have the power to personally decide which use case they want the SCI to fit. The specific form of the interaction was highly individual, as apps, buttons, and other physical controls and voice interaction were all mentioned. There were no patterns to be found regarding this, and sometimes group members had different preferences. In one case, they even created two storyboards with the same interface but different methods of controlling it. This shows that there is no one-size-fits-all method of controlling SCIs in smart homes, and future research should take different possibilities into account.

Directly-controlled shape change gives users the power to control which function of an SCI they want to use, and was imagined in many different ways.

In the case of user control over interfaces, Rasmussen et al. [2016] mention that *negotiated* control is the least prominent level of control in their reviewed literature, which matches our findings on user preferences. The fact that *negotiated* control and *indirect* control were less popular might be due to those interactions being more complex and therefore more difficult to design. Since the participants often did not spend a long time on each storyboard, more complex designs might not have been considered.

Our findings on user-control over SCIs match the current literature.

Although we cannot provide the tools that Alexander et al. [2018] found necessary to design interactions between users and SCIs, our findings can help with making decisions on levels of user control when designing future SCIs.

4.3.4 Existing interfaces

As we previously described, some of the imagined SCIs already exist in a similar form. In some cases, this can be explained by the participants possibly being familiar with the corresponding papers or, especially in the case of textile interfaces, with the research at our chair [Nowak et al., 2025].

SCIs that are similar to existing artifacts have positive indications for the state of SCI research.

This does however not apply to all instances and thus shows that existing research on SCIs is already sometimes fulfilling the wishes and preferences of users. This is also supported by the prototype *Shutters*, which offers a simple version of controlling the environment via permeability. It does not function exactly like any of our participants imagined the SCIs in their storyboards, but it is based on the same idea.

Even if there is a bias to some of the imagined SCIs due to existing research, it also means that users like some of the SCIs that have already been developed and can imagine using them. This is also an important finding, which indicates that research on SCIs already fits users' preferences in some cases.

4.3.5 Possible Sources of Concerns

Data security and privacy concerns are not specific to SCIs.

The concerns that were voiced by our participants might stem from multiple sources. Data security and privacy concerns are not caused by the shape-change of the interfaces but by the sensors used in smart home systems. This concern is not new, but has been found by user-centric smart home research before [Samancioglu et al., 2024]. Therefore, it is a concern that needs to be taken into account when integrating SCIs into smart homes and for sensor-controlled shape changes in general, but not necessarily for the design of all SCIs.

Safety and reliability concerns are present in our findings and other current research.

Safety concerns about the shape change, in particular, should be seriously taken into account in future design processes. As there are not many longitudinal studies about interactions with SCIs in smart homes, there is little information about possible safety risks. Unforeseeable shape changes could thus cause damage or injuries, especially when users are not yet used to them. This concern was also described in the speculative scenarios by Rasmussen and Hemmert [2019]. Our findings now prove it to be a relevant concern for users as well. The concerns regarding malfunctions and easy breakability are in line with current technological challenges in SCI construction [Alexander et al., 2018]. Therefore, these challenges need to be addressed and users need to be convinced that SCIs are reliable technological devices.

The importance of clearly communicating benefits of SCIs is still an important challenge.

As some participants also explicitly called the usefulness of SCIs into question, making sure that SCIs bring specific benefits to smart homes, and also communicating those benefits to future users is very important. This concern is consistent with the concerns of researchers in the field of SCIs, as emphasized by the following quote.

> *"Because, even though much progress has been made, the work seems to "forget" to articulate the design aim of the work, i.e., why SCI should be pursued over other types of interfaces."*
>
> *—Legaard et al. [2016]*

As seen specifically in scenarios where cameras were used as input devices and direct contact to furniture that becomes uncomfortable, participants also designed SCIs that they could not actually imagine using. Therefore, with our method, it is important to clarify the actual preferences of the users, independent of their designed scenarios.

4.3.6 Reflections on Methodology

Our methodology has proven to be useful for our specific goals, but also showed limitations.

Our method worked well in highlighting some common characteristics for SCIs in specific scenarios. Based on that, we can also recommend it if one is looking for user preferences on specific problems to be solved using SCIs. However, some categories of the design requirements model by Sturdee et al. [2019] were not represented in the storyboards created by our participants. Such categories are *Control Systems* and *Construction and Assembly*. If researchers are interested in user preferences concerning those categories, a different approach might thus be more well-suited.

Providing additional crafting material did not provide many benefits. Other aspects of our study design, however, proved to be very beneficial.

Interestingly, the additional crafting materials were only seldom used by our participants. We, therefore, can neither recommend nor discourage the use of crafting materials for our approach, as they were not used much, but also did not have any negative effects. We can, however, recommend a phase of individual idea generation for co-design studies in groups, as every participant in our study contributed at least a few ideas to the discussion. Although participants did not always follow the specific structure of storyboards that was explained by us, they succeeded in showing the interaction between the user and the interface. Therefore, we were still able to evaluate storyboards regarding the SCIs' usage scenarios.

4.4 Limitations

Our participant group was not diverse, which limits our findings.

The biggest limitation of our study is our group of participants. As we used convenience recruitment to find participants, our group only consisted of people with a technological background. Additionally, most were students, meaning that there was no representation of older users. This significantly influenced the problems and needs expressed in the study and might have led to possible application areas not being explored, as described in Section 4.2.3. Additionally, two-thirds of our participants were men, which is not ideal as women are already under-represented in smart home research [Strengers et al., 2019]. On the other hand, smart home research does not commonly focus on young students either, as described in Chapter 2. Therefore, we still contributed insights into an overlooked user group.

Although we tried to limit the bias in our study, we could not completely prevent it.

Another challenge we faced was limiting the bias of our participants. Although we kept the animations as basic as possible, we could still notice a bias in our results. Multiple times, a change of *texture* was described as the appearance of spikes, which corresponds to the exemplification in our animation for texture. Changes of *permeability* were also drawn as round holes opening up in a surface, again exactly like in our animation. This shows that our animations influenced our results, meaning other animations would probably have caused the described SCIs to have slightly different characteristics. As mentioned before, participants also showed difficulties in imagining SCIs using *viscosity*, which might be caused by an insufficient explanation. This also limits our study regarding finding potential use cases for a change of *viscosity*. Some participants might also already have been biased before the study due to exposure to research at the Media Computing Group.

We did not identify many user preferences on the more technical side of SCIs.

As discussed before, the creation of storyboards is well-suited to show interactions between users and interfaces and the context around the interactions. However, we struggled to find information about user preferences regarding more technical aspects of SCIs, such as control systems, and can therefore not report many new insights regarding those.

Our study would have profited from more participants

As Yao et al. [2023] found, small sample sizes are a common problem in user-centric smart home research. Our study would also have profited from more co-design sessions with more participants. Although we already found multiple re-occurring scenarios, this number might have grown if we had collected more storyboards.

The imagined SCIs cannot always be built with current technologies.

Lastly, we specifically told the participants in our study not to worry about how an SCI would realistically be built and whether its construction is physically possible. This allowed for more creativity, but also means that some of the SCIs in the storyboards cannot be implemented within current technological restrictions.

Chapter 5

Summary and Future Work

In this chapter, we conclude this thesis by summarizing our findings and contributions. We also elaborate on future work on shape-changing interfaces in smart homes that emerged from our results.

5.1 Summary and Contributions

We conducted a co-design study and found application scenarios for SCIs in smart homes.

We found a lack of user-centric research on shape-changing interfaces for smart homes. Therefore, we conducted a co-design study to find out which scenarios for the use of SCIs in smart homes users can imagine and how those scenarios can be characterized. By using deductive and inductive thematic analysis to evaluate our results, we identified four scenarios that were frequently imagined across participant groups and a variety of additional ideas. Those common scenarios are *Environmental Control through Permeability*, *Preventing Injuries and Damage*, *Adaptable Objects and Rooms*, and *Motivating Behavioral Changes through Discomfort*. With these scenarios, we contribute inspiration for the construction of future SCIs in smart homes and recommendations on characteristics of SCIs that fit user preferences.

We determined user-preferred application areas and characteristics of SCIs in smart homes and compared them to other work.

In general, our findings include examples for the use of SCIs across smart home application areas, except *energy management*. Additionally, we found benefits of specifically using SCIs in smart homes, such as *intuitiveness* and *multi-functionality* that are underexplored in current literature on smart home benefits. We, therefore, showed the potential of using SCIs in smart homes instead of traditional smart home devices. Additionally, currently existing shape-changing interfaces do not utilize some types of shape change that users desire. Moreover, users imagine controlling SCIs in smart homes via system control or direct control, similarly to how existing SCIs are controlled. Some prototypes of already existing SCIs have many similarities to the SCIs described in the scenarios of our participants.

We showed the potential of SCIs in smart homes, but also common user concerns.

Finally, we determined multiple concerns of users regarding the use of SCIs in smart homes, only some of which are specific to the aspect of shape change. They include safety and data security concerns, as well as a missing understanding of the specific benefits of SCIs over other interfaces. We conclude that although research on SCIs sometimes already fits user preferences, research and development of SCIs for smart homes can still benefit from more user-centric approaches. Our work is a step in this direction and can be built upon.

5.2 Future Work

Future work should try expanding on our results and could also apply our method for more specific applications.

We probably only found some of the scenarios in which users can imagine using shape-changing smart home devices. Future work should therefore try to find other application scenarios and further define the ones we found. As our study was limited to a non-representative user group, there is potential in repeating our approach with different user groups to find other scenarios that fit those groups' preferences. This could also help to find scenarios for the use of SCIs in smart homes that our study did not find. Additionally, our method could be improved by changing some of the animations to hopefully better present the possible shape changes. With this approach, one might find application scenarios for changes of *viscosity* and *spatial-*

ity. Since our findings do not describe certain areas of the design requirements for shape-changing interfaces (*control system* and *construction and assembly*) [Sturdee et al., 2019], other methods should be used in the future to gain knowledge about user preferences regarding those areas.

Our results can be used to design SCIs for smart homes in the future.

As we have contributed multiple possible application scenarios for SCIs in smart homes, future research can use that knowledge to design prototypes of SCIs and test them with users. We found specific characteristics of SCIs in those scenarios that can now help with future design decisions. Specifically, the technical feasibility of using permeability for environmental control could be investigated. For the various multi-functional interfaces that were imagined by our participants, the biggest question remaining is also related to their technical implementation. Further, the discussion around deliberate irritation to motivate users to change their behavior was inconclusive on whether users actually desire such interfaces. Future research should investigate this question. To successfully build safety and security systems, the largest challenge for future research is unrelated to SCIs. Instead, it is concerned with data security and privacy issues caused by the use of sensors. This issue has to be taken into account in future work on SCIs, but solved by research on privacy in smart homes.

Appendix A

Demographic Questionnaire

In this appendix, we present the demographic questionnaire of our user study. The English version is followed by the German version.

Demographic Questionnaire

1. Age:
2. Gender:
3. Occupation/ Subject of Study:
4. Have you heard of the term "Shape-Changing Interface" before?

   ☐ Yes ☐ No

5. If yes, please briefly explain the term in your own words.
6. Have you heard of the term "Smart Home" before?

   ☐ Yes ☐ No

7. If yes, please briefly explain the term in your own words.

Fragebogen Demographische Daten

1. Alter:
2. Geschlecht:
3. Beschäftigung/Studienfach:
4. Haben Sie den Begriff “Shape-Changing Interface” schon einmal gehört?

   ☐ Yes ☐ No

5. Wenn ja, bitte erklären Sie ihn kurz in eigenen Worten.
6. Haben Sie den Begriff “Smart Home” schon einmal gehört?

   ☐ Yes ☐ No

7. Wenn ja, bitte erklären Sie ihn kurz in eigenen Worten

Appendix B

Declaration of Consent

In this appendix, we present the declaration of consent of our user study. The English version is followed by the German version.

Consent Form

Study on Shape-Changing Interfaces in Smart Homes

Study Lead: Franca Hübner
Media Computing Group
RWTH Aachen University
Email: franca.huebner@rwth-aachen.de

Goal of the Study: The goal of this study is to understand which scenarios users can envision for the use of shape-changing interfaces in smart homes.

Procedure: During the study, you will consider different scenarios for using shape-changing interfaces and illustrate them graphically. Additionally, you will discuss your ideas and participate in a semi-structured interview.

Risks/Discomforts: There are no physical or psychological risks. If any tasks or the interview become tiring for you, participation can be paused or terminated at any time.

Benefits: The results of the study will be used to gain insights into users' imaginations and scenarios for shape-changing interfaces in smart homes.

Collected Data: During the study, video and audio recordings will be made to document your discussions and ideas and to follow up on them later. Additionally, your responses during the interview will be recorded for post-processing.

The following data will also be collected and recorded: field of study/employment, age, gender, prior experience with smart homes and shape-changing interfaces.

Confidentiality: All information collected during the study will be treated strictly confidentially and anonymized. No personal data can be inferred. The recordings will be stored on RWTH Aachen University servers and can only be accessed by RWTH Aachen University staff.
You may request deletion of the recordings at any time by sending an informal email to franca.huebner@rwth-aachen.de. You may also refuse to provide data or answer questions at any time during the study. Likewise, you may request to stop the video and audio recording at any time.
Personal data will be stored for a maximum of one year.

___ I have read and understood the information on this form.
___ The information on this form has been explained to me.

Name of participant	Signature of participant	Date
	Lead of Study	Date

If you have any questions regarding this study, please contact Franca Hübner at franca.huebner@rwth-aachen.de

Einverständniserklärung

Studie zu Shape-Changing Interfaces in Smart Homes

Studienleitung: Franca Hübner
Media Computing Group
RWTH Aachen University
Email: franca.huebner@rwth-aachen.de

Ziel der Studie: Das Ziel der Studie ist es, zu verstehen, welche Szenarien sich Nutzer für die Verwendung von Shape-Changing Interfaces in Smart Homes vorstellen können.

Ablauf: Im Verlauf der Studie werden Sie sich verschiedene Szenarien für die Verwendung von Shape-Changing Interfaces überlegen und diese graphisch darstellen. Außerdem werden Sie über Ihre Ideen diskutieren und schließlich wird ein semi-strukturiertes Interview durchgeführt.

Risiken/Beschwerden: Es gibt keine körperlichen oder psychischen Risiken. Sollten die Aufgaben oder das Interview anstrengend für Sie sein, kann die Bearbeitung zu jedem Zeitpunkt pausiert oder abgebrochen werden.

Nutzen: Die Resultate der Studie werden genutzt, um Einblicke in die Vorstellung von Nutzern von Szenarien für Shape-Changing Interfaces in Smart Homes zu bekommen.

Erhobene Daten: Während der Studie wird eine Videoaufnahme und eine Tonaufnahme erstellt. Dies dient dazu, Ihre Diskussionen und Ideen aufzuzeichnen und später nachverfolgen zu können. Außerdem dient dies dazu, Ihre Antworten im Interview aufzuzeichnen um diese später nachzubereiten.

Weiterhin werden folgende Daten abgefragt und aufgezeichnet: Studiengang/Beschäftigung, Alter, Geschlecht, Vorerfahrungen mit Smart Homes und Shape-Changing Interfaces.

Vertraulichkeit: Alle Informationen, die während der Studienphase gesammelt werden, werden streng vertraulich und anonymisiert behandelt. Es können keine Rückschlüsse auf personenbezogene Daten gezogen werden. Die Aufzeichnungen werden auf Servern der RWTH Aachen University gespeichert und sind nur durch Bedienstete der RWTH Aachen University einzusehen. Weiterhin kann zu jeder Zeit eine Löschung der Aufzeichnung durch eine formlose E-Mail an franca.huebner@rwth-aachen.de eingefordert werden. Zusätzlich kann natürlich während der Studie die Angabe von Daten oder die Beantwortung von Fragen verweigert werden. Auch kann zu jeder Zeit ein Stop der Video- und Audioaufzeichnung eingefordert werden. Die personenbezogenen Daten werden maximal ein Jahr lang gespeichert.

_____ Ich habe die Hinweise auf diesem Formular gelesen und verstanden.
_____ Man hat mir die Hinweise auf dem Formular erklärt.

Name der teilnehmenden Person	Unterschrift der teilnehmenden Person	Datum
	Studienleitung	Datum

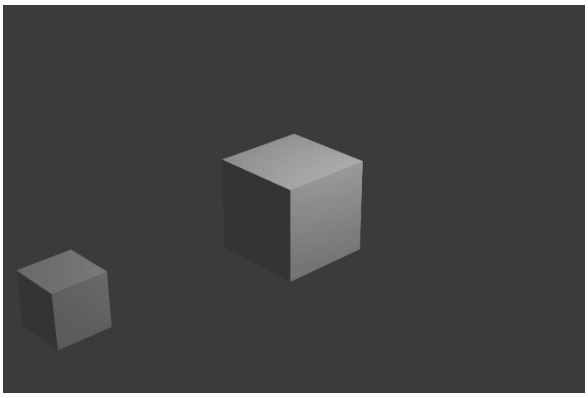
Wenn Sie Fragen zu dieser Studie haben, wenden Sie sich bitte an Franca Hübner unter, Email: franca.huebner@rwth-aachen.de

Appendix C

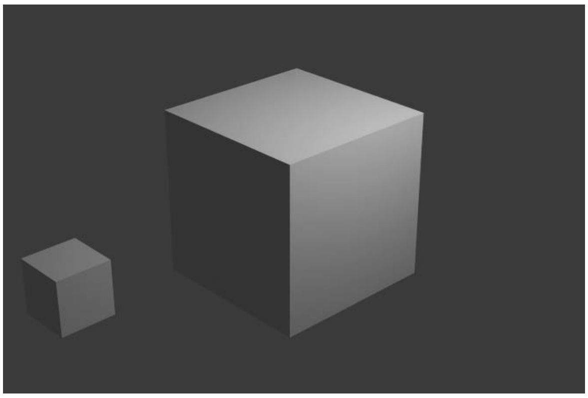
Handout

In this appendix, we present our handout showing the different types of shape changes. The definitions of the types of shape changes, adapted from Rasmussen et al. [2012], are included in Table C.1.

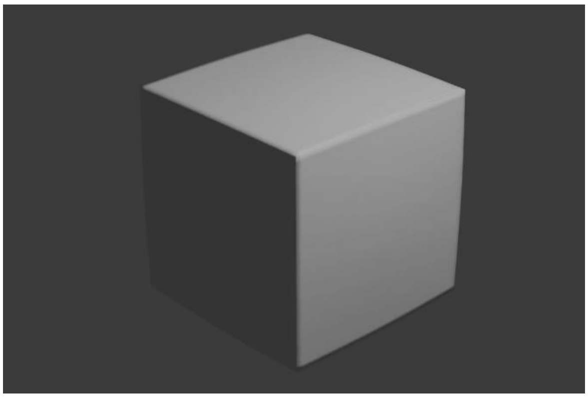
Größe:



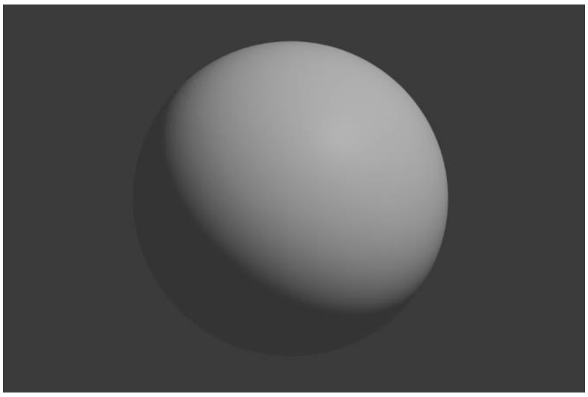
Volume:



Form:

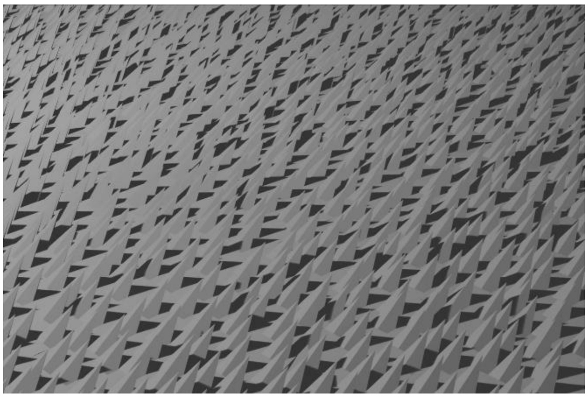


Form:

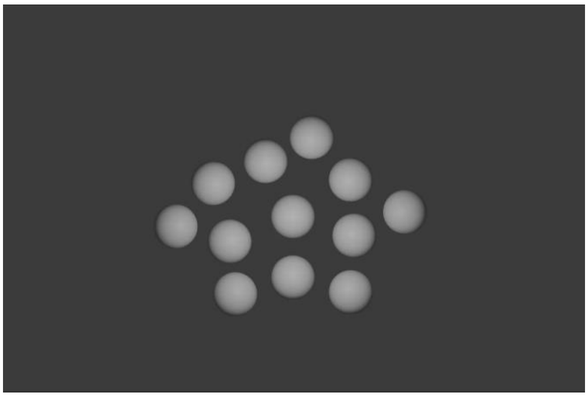


Textur:

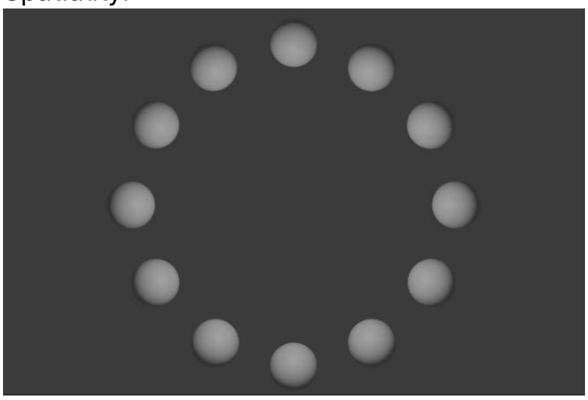
Texture:



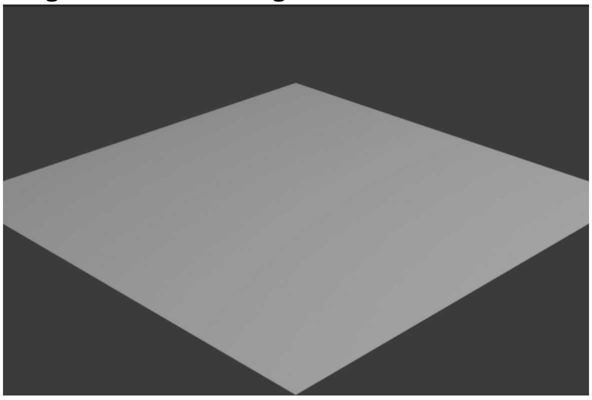
Räumlichkeit:



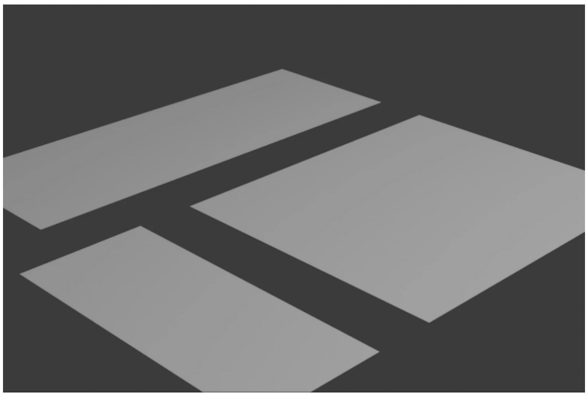
Spatiality:



Wegnehmen/Hinzufügen:

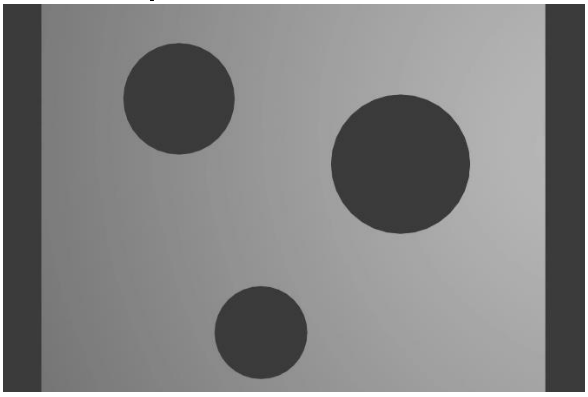


Add/Subtract:

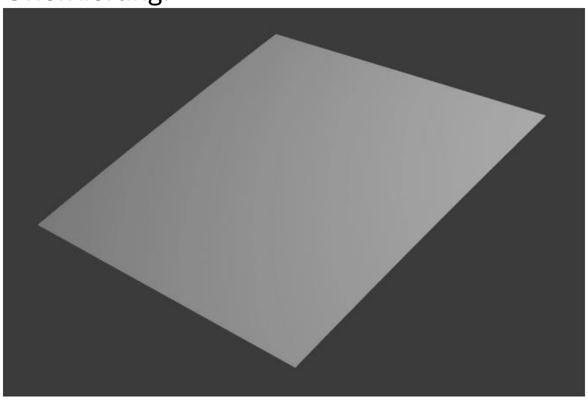


Durchlässigkeit:

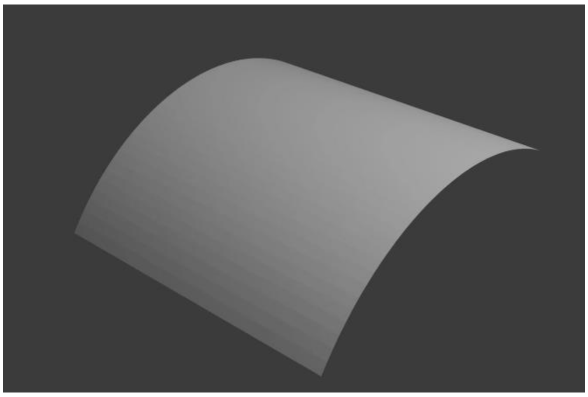
Permeability:



Orientierung:

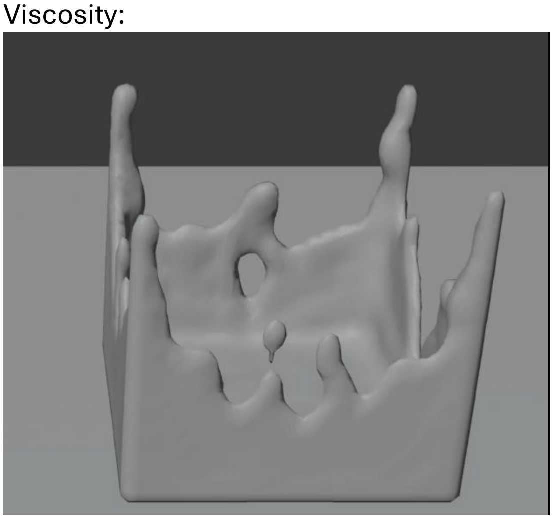


Orientation:



Dickflüssigkeit:

Viscosity:



Category	Definition
volume	Changes of *volume* influence the size of an object while keeping its general form.
form	Changes of *form* influence the overall form of an object.
orientation	Changes of *orientation* influence the shape of an object through changes in rotation or direction.
texture	Changes of *texture* influence the surface of an object without modifying its overall form.
viscosity	Changes of *viscosity* either result in an actual change of shape or in the illusion of a change of shape because the user perceives the softness of the object differently.
spatiality	Changes of *spatiality* depend on the perception of multiple objects as a collective structure. If these objects are repositioned, the structure's shape changes.
adding/subtracting	Changes that are described by the category *adding/subtracting* are achieved by uniting or dividing objects.
permeability	Changes of *permeability* perforate the objects but allow for this transformation to be reversed.

Table C.1: The Table consists of the types of shape changes and their definitions. The categories and their definitions are adapted from Rasmussen et al. [2012].

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