After Rigid Interfaces

Investigating Interaction with Deformable Interfaces and the Design of Shape-Changing Interfaces

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Ph.D. Thesis

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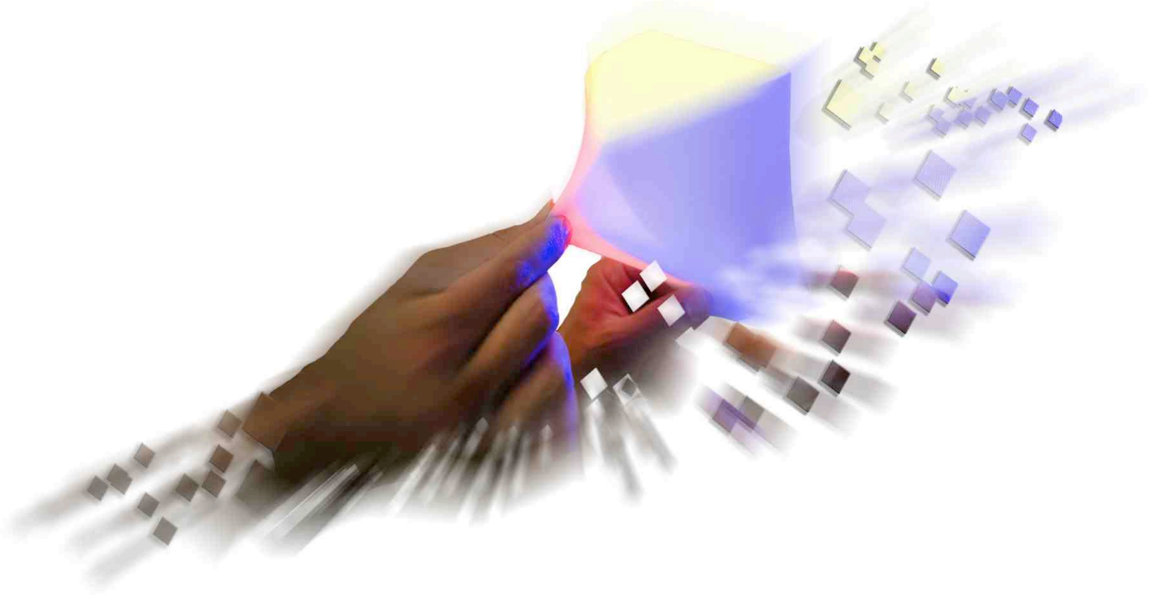

Abstract

Deformable and shape-changing interfaces are rapidly emerging in the field of human-computer interaction (HCI). Deformable interfaces provide users with newer input possibilities such as bending, squeezing, or stretching, which were impossible to achieve with rigid interfaces. Shape-changing interfaces can reconfigure their shape dynamically, providing users with new affordances and output modalities. This thesis contributes to both the field of deformable interfaces and shape-changing interfaces through empirical research.

In the area of deformable interfaces, this thesis presents two studies (1) a user study with a prototype of an elastic, deformable display, and (2) a user study of deformable interfaces for performing music. The first study reports a guessability study with an elastic, deformable display where 17 participants suggested fitting gestures for 29 tasks, including navigation and manipulation of 3D graphical objects. Results from the first study describe a user-defined gestures set for elastic, deformable displays, showing how participants used depth and elasticity of the display to simulate various deformations, rotations, and displacements. The second study investigates how musicians use deformable interfaces to perform electronic music. First, we invited musicians with different backgrounds (e.g., performers, DJs, instrument builders) to three workshops, where we made them explore 10 deformable objects and generate ideas on how to use those to perform music. Then, we implemented sensors in the five preferred objects and programmed them for controlling sounds with computer software. Finally, we ran a performance study where six musicians performed music with deformable interfaces at their studios. Results from the performance study show that musicians systematically map deformations to certain musical parameters and that deformable interfaces are generally used as tools to filter and modulate sounds.

In the area of shape-changing interfaces, this thesis presents two work (1) an analysis of sketches made by 21 participants designing either shape-changing radios and mobile phones, and (2) a large-scale analysis of 340 science fiction (Sci-Fi) movies that analyses behavioral qualities of shape change, and how they support particular functionalities of shape-changing interfaces. The first work presents an analysis of 42 sketches of shape-changing interfaces, specifically radio and mobile phone. The result of this analysis shows a range of interesting design elements, but also a lack of conventions on the use of metaphors with shape change and the need to extend present vocabulary. Also, the analysis shows how metaphors and dynamic affordances in shape change can be used to convey particular information (e.g., big-is-urgent, loud-is-up). The second work presents a large-scale analysis of 340 Sci-Fi movies that identifies instances of shape-changing interfaces. Results from the analysis reveals emergent behavioral patterns of shape change, namely *Reconfiguration*, *Transformation*, *Adaptation* and *Physicalization*.

In synthesis, the work presented in this thesis shows (1) implications of usefulness for deformable interfaces and how their new input modalities can redefine the way users interact with computers, and (2) how a systematic understanding of conventional design elements and behavioral qualities of shape change can help the design of shape-changing interfaces in the future.

Dansk resumé

Deformerbare og form-skiftende grænsefalder er et hurtigt voksende område indenfor menneske-maskine interaktion. Deformerbare grænseflader giver brugere nye input muligheder såsom bøjning, presning og strækning, hvilke ikke er mulige med faste grænseflader. Form-skiftende grænseflader kan dynamisk ændre form hvilket giver brugere nye muligheder og output modaliteter. Denne afhandling bidrager til begge områder gennem empirisk forskning.

Den første halvdel af denne afhandling præsenterer to studier indenfor deformerbare grænseflader: (1) et brugerstudie af en elastisk, deformerbar skærm og (2) et brugerstudie af deformerbare skærme til at spille musik. I det første studie interagerede 17 brugere med en elastisk og deformerbar skærm gennem 29 opgaver, og forslog forskellige håndbevægelser til f.eks. navigering og manipulering af grafiske 3D objekter. Resultatet er et bruger-defineret sæt af håndbevægelser for elastiske og deformerbare skærme, der viser hvordan deltagerne brugte skærmens dybde og elasticitet til at simulere forskellige deformationer, rotationer og forskydninger. Det andet studie undersøger hvordan musikere bruger deformerbare grænsefalder til at spille elektronisk musik. I den første del af studiet, inviterede vi musikere med forskellige baggrunde (kunstnere, DJs, instrument byggere) til tre workshops, hvor de udforskede 10 deformerbare objekter og blev bedt om at komme med forslag til hvordan disse objekter kunne bruges til at spille musik. Vi satte herefter sensorer i de 5 fortrukne deformerbare objekter og programmerede dem til at kontrollere lyd. Slutteligt bad vi seks musikere om at bruge de deformerbare grænseflader til at spille musik i deres lydstudie. Vores resultater viser at musikerne systematisk associerede deformeringer til specifikke musikalske parametre og at deformerbare grænseflader primært bruges til at filtrere og modulere lyd.

Den anden halvdel af afhandlingen præsenterer to studier indenfor form-skiftende grænseflader: (1) en analyse af skitser af enten form-skiftende radioer eller mobiltelefoner udfærdiget af 21 deltagere, og (2) en analyse af 340 science fiction (Sci-Fi) film der analyserer de adfærdsmæssige kvaliteter af form-skiftende grænsefalder og hvordan de støtter særlige funktionaliteter af form-skiftende grænsefalder. I det første studie blev 42 skitser af form-skiftende grænseflader af radioer og mobiltelefoner analyseret. Resultatet viser en række interessante design elementer, men også en mangel på konventioner om bruge af metaforer for form skiftning og behovet for at udvide den nuværende nomenklatur. Derudover viste analysen hvordan metaforer og de dynamiske muligheder i form-skiftning kan bruges til at overbringe særlig information (f.eks. 'big-is-urgent', 'loud-is-up'). Det andet studie præsenterer en analyses af 340 Sci-Fi film der identificerer instanser af form-skiftende grænseflader. Resultatet af denne analyse viser at *Reconfiguration*, *Transformation*, *Adaptation* og *Physicalization* er emergente adfærdsmæssige mønstre ved form-skiftning.

Ialt demonstrerer denne afhandling (1) implikationerne for anvendeligheden af deformerbare græseflader og hvordan deres nye input modaliteter kan omdefinere måden hvorpå brugere interagerer med computere, og (2) hvordan en systematisk forståelse af konventionelle design elementer og adfærdsmæssige kvaliteter af form-skift kan hjælpe med designet af form-skiftende grænseflader i fremtiden.

Preface

This thesis is submitted to obtain the PhD degree at the Department of Computer Science, Faculty of Science, University of Copenhagen. The work described in the thesis was carried out between January 2013 and June 2016.

The thesis consists of two parts. The first part of the thesis (page 2 – 25) positions the work, discusses and summarizes its contributions, and points to possible directions for future work. The second part consists of four papers, which are listed on page 1 and can be found from page 35 and on.

First, I want to thank my principal supervisor Prof. Kasper Hornbæk for his professional guidance and his fundamental support, and my second supervisor Dr. Esben Warming Pedersen for his understanding and professional behavior. If I learned how to do research and had the chance to share my work with other brilliant researchers it's mostly thanks to your teachings.

During the fall of 2015 I have visited the Industrial Design group at KAIST (Korean Advanced Institute of Technology), in Daejeon, South Korea. The collaboration with Korean people has been both fulfilling from the human point of view and fruitful for my professional path. Therefore, I wish to thank Professor Youn-Kyung Lim and her lab for letting me experience a wonderful time in South Korea and for having shared their research perspective with me.

Finally, I want to thank my colleagues from the HCC research group for their respectful behavior and their friendly attitude. I especially want to thank Sebastian Boring for being always fun and positively sarcastic with me, John Tiab for being a friendly and very supportive colleague, and Casper "ABOBS" Petersen for his friendly support.

Giovanni Maria Troiano

Copenhagen, June 2016

To my wife

Rannvá Troiano Glerfoss

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Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2014. User-defined gestures for elastic, deformable displays. In *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces* (AVI 2014). ACM, New York, NY, USA, 1-8.

Paper 2 (page 44)

Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2015. Deformable Interfaces for Performing Music. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI 2015). ACM, New York, NY, USA, 377-386

Paper 3 (page 55)

Majken K. Rasmussen, Giovanni Maria Troiano, Marianne G. Petersen, Jakob G. Simonsen, and Kasper Hornbæk. 2016. Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances (CHI 2016).

Paper 4 (page 69)

Giovanni Maria Troiano, John Tiab, Youn-Kyung Lim. 2016. SCI-FI: Shape-Changing Interfaces, Future Interactions (*Accepted* NordiCHI 2016).

Introduction

Deformable and shape-changing interfaces introduce new input/output possibilities for user interactions. Through the use of soft materials and dynamic actuation, these interfaces make users perceive computers as more "organic" and "alive" in comparison to rigid interfaces. This thesis contributes to both the fields of deformable and shape-changing interfaces by presenting empirical research on how they are used for input and an investigation of their design space.

The work presented in this thesis is also part of the GHOST research project, founded by the EC within the 7th framework programme, through the FET Open scheme under grant agreement no. 309191. The main goal of the GHOST project is to investigate "generically and highly organic shape-changing interfaces". This thesis focuses on two particular aspects of the GHOST project, namely (1) investigating interaction techniques and the usefulness of deformable user interfaces, especially elastic displays and deformable musical interfaces, and (2) investigating the design space of shape-changing interfaces.

Background

Interactive interfaces that can be deformed, or that feature dynamic motion through actuation, have appeared at least 15 years ago in the field of human-computer interaction (HCI). Already in 1997 Iwata et al. developed an interactive display called FEELEX [23], which enhanced graphic contents through haptic and tactile feedback using a flexible display deformed by linear actuators (Figure 1, a). A similar technology has been used later by MIT to develop Relief [37], a scalable shape-changing display that uses an array of 120 motorized pins covered with Lycra to generate and change shapes dynamically, for instance like terrain conformations and landscapes (Figure 1, b).

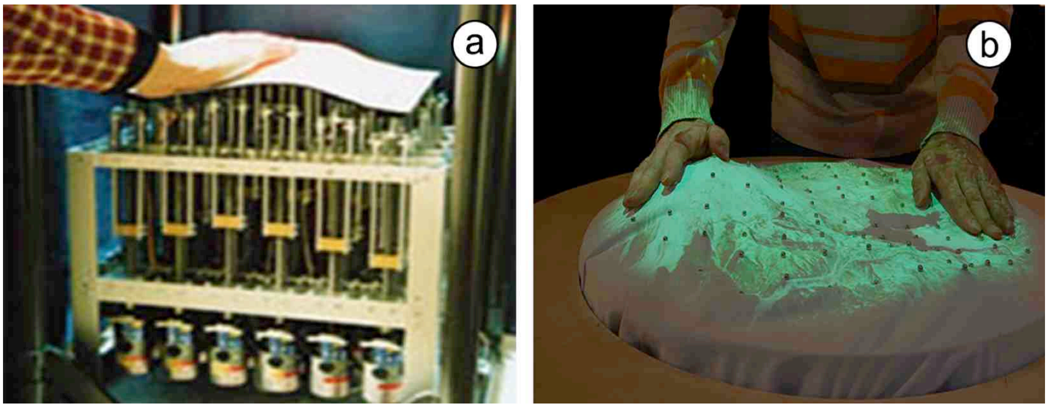

Figure 1: The project FEELEX shows a shape-changing display actuated by an array of motorized pins covered with Lycra (a); the same concept was used by MIT with Relief-Recompose (b)

In light of the new technological challenges posed by the advent of deformable and shape-changing interfaces, research in the field has recently started to propose several solutions to achieve shape change, for instance by using pneumatic actuation [31,33,45,66,85], or by using mechanical actuation [14,71,73,76], or by using smart materials like shape memory alloys [17,43,55,56]. Also, because deformable interfaces can afford gestures for input that were impossible with rigid interfaces (e.g., stretch, twist, bend), many studies systematically investigated how users give input with interfaces that are flexible and that can be deformed in many ways [2,15,29,34–

36,65,78,79,87,88]. To complement the advances of prototypes and user studies, theoretical research has also contributed to the field of shape-changing interfaces by developing frameworks [57] and models [59] that systematically describe key features and design elements of shape change.

Due to their dynamic motions and their malleable surface, deformable and shape-changing interfaces have often been defined also as *organic* user interfaces [21]. In that respect, the word *organic* defines characteristics of these interfaces that resemble those of organic and living entities, such as the one of expressing emotions through motion [20,52,71], or being physically malleable and deformable [13,31,38,39,62]. These features make deformable and shape-changing interfaces radically different from rigid interfaces, in which they can provide input/output possibilities that could not be achieved before, therefore changing the perception that users have of interactive interfaces. However, despite the rapid scientific advance one fundamental research question remains open:

What are deformable and shape-changing interfaces good for?

Previous work have tried to answer this question in different ways, for instance by investigating the utility of bend gesture with bendable smartphones [1], or by exploring the use of shape-changing actuated displays for data physicalization [14,67]. While research has proposed a broad range of prototypes to investigate potential good application for deformable and shape-changing interfaces, implications of usefulness and their design space remains still underexplored. As part of the GHOST project, this thesis contributes to previous work with systematic explorations of input techniques and use of deformable interfaces, as well as investigating the design space of shape-changing interfaces. Finally, the work contained in this thesis should contribute a better understanding of what deformable and shape-changing interfaces might be good for.

Contributions

This section summarizes the contributions of the thesis divided into two parts (1) on deformable user interfaces (paper 1 and 2) and shape-changing interfaces (paper 3 and 4). Next, the abstracts of the four papers are presented to provide an overview of contributions.

Abstract of Papers

Paper 1. User-Defined Gestures for Elastic, Deformable Displays

Elastic, deformable displays allow users to give input by pinching, pushing, folding, and twisting the display. However, little is known about what gestures users prefer or how they will use elasticity and deformability as input. We report a guessability study where 17 participants performed gestures to solve 29 tasks, including selection, navigation, and 3D modeling. Based on the resulting 493 gestures, we describe a user-defined gesture set for elastic, deformable displays. We show how participants used depth and elasticity of the display to simulate deformation, rotation, and displacement of objects. In addition, we show how the use of desktop computers as well as multi-touch interaction affected users' choice of gestures. Finally, we discuss some unique uses of elasticity and deformability in gestures.

Paper 2. Deformable Interfaces for Performing Music
Deformable interfaces offer new possibilities for gestures, some of which have been shown effective in controlled laboratory studies. Little work, however, has attempted to match deformable interfaces to a demanding domain and evaluate them out of the lab. We investigate how musicians use deformable interfaces to perform electronic music. We invited musicians to three workshops, where they explored 10 deformable objects and generated ideas on how to use these objects to perform music. Based on the results from the workshops, we implemented sensors in the five preferred objects and programmed them for controlling sounds. Next, we ran a performance study where six musicians performed music with these objects at their studios. Our results show that (1) musicians systematically map deformations to certain musical parameters, (2) musicians use deformable interfaces especially to filter and modulate sounds, and (3) musicians think that deformable interfaces embody the parameters that they control. We discuss what these results mean to research in deformable interfaces.

Paper 3. Sketching Shape-Changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances
Shape-changing interfaces allow designers to create user interfaces that physically change shape. However, presently, we lack studies of how such interfaces are designed, as well as what high-level strategies, such as metaphors and affordances, designers use. This paper presents an analysis of sketches made by 21 participants designing either a shape-changing radio or a shape-changing mobile phone. The results exhibit a range of interesting design elements, and the analysis points to a need to further develop or revise existing vocabularies for sketching and analyzing movement. The sketches show a prevalent use of metaphors, say, for communicating volume though big-is-on and small-is-off, as well as a lack of conventions. Furthermore, the affordances used were curiously asymmetrical compared to those offered by non-shape-changing interfaces. We conclude by offering implications on how our results can influence future research on shape-changing interfaces.

Paper 4. SCI-FI: Shape-Changing Interfaces, Future Interactions
Shape-changing interfaces (SCI) are rapidly evolving and creating new interaction paradigms in human-computer interaction (HCI). However, empirical research in SCI is still bound to present technological limitations, and existing prototypes can only show a limited number of potential applications for shape change. In this paper we attempt to broaden the pool of examples of what shape change may be good for by investigating SCI using Science Fiction (Sci-Fi) movies. We look at 340 Sci-Fi movies to identify instances of SCI and analyze their behavioral patterns and the context in which they are used. The result of our analysis presents four emerging behavioral patterns of shape change: (1) Reconfiguration, (2) Transformation, (3) Adaptation, and (4) Physicalization. We report a selection of instances of SCI from Sci-Fi movies, which show how these four behavioral patterns model functionalities of shape change and what they can do. Finally, we conclude by providing a discussion on how our results can inspire the design of SCI.

Deformable User Interfaces

This section presents the contributions to research in deformable user interfaces. This includes the work described in Paper 1 and 2.

Defining Gestures for Elastic, Deformable Displays

Elastic and flexible displays have been widely investigated in the area of deformable user interfaces (DUIs); they allow users to deform the display's surface and give input by stretching, twisting, or folding. Research in this area has seen the production of several prototypes, for instance like Kronos Projector [7], Flexpad [65], or ElaScreen [88]. However, few studies have tried to systematically investigate the use of deformation as input [15,35,78] and a vocabulary of gestures for deformable displays has not been formally established yet. The work presented in Paper 1 (page 35) aims at investigating what gestures users would perform on an elastic, deformable display and for which particular task they would prefer deformation as input. To investigate the aforementioned we have (1) developed a non-interactive prototype of an elastic, deformable display (Figure 2, a) and (2) run a study employing a guessability study methodology [84], where 17 participants performed gestures to solve various tasks, including selection, navigation, and 3D modeling.

We presented the 17 participants with our elastic, deformable display prototype and asked them to suggest fitting gestures for 29 tasks. Each task was presented as two sequential pictures (Figure 2, b) that showed the participant for which particular action they had to suggest a fitting gesture. When the participant felt ready to proceed, he or she could suggest a fitting gesture by performing it directly onto the display's prototype (Figure 2, c). During the study we have collected both quantitative and qualitative data that we have used to describe a user-defined gesture set for elastic, deformable displays, which represent the first step to develop a vocabulary of gestures for such displays. We asked participants to think aloud [89] while performing their gestures, so as to gather information on why they choose to perform a particular gesture and why they thought that gesture was a good fit for a particular task. Also, after having performed a gesture the participants had to rate their choices on two 7-point Likert scales inspired by previous work on surface computing [84].

Overall, the results from our study show that participants used deformable gestures especially for tasks that displayed contents in the three-dimensional space, for instance to move objects back and forth in depth or to deform 3D objects. For other tasks (e.g., map navigation, object selection) participants used either multi-touch or desktop computers inspired gestures, such as drag, swipe, or point and click.

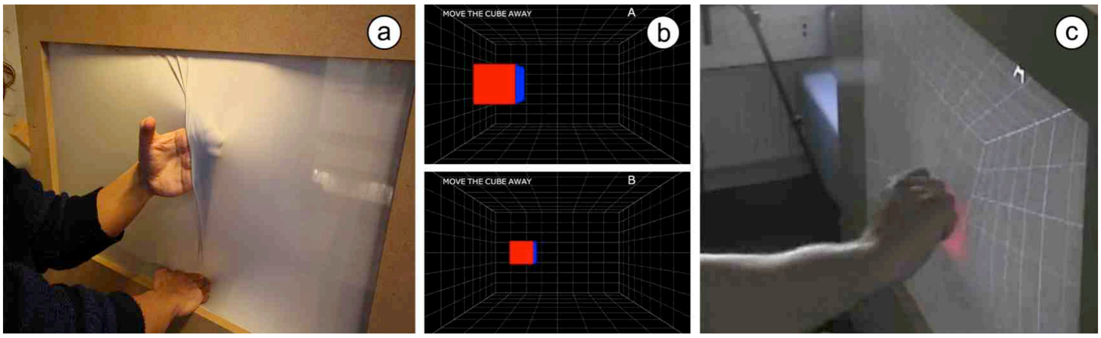

Figure 2: (a) the elastic, deformable display prototype, (b) one example of tasks, (c) a participant performing a gesture on the display.

Deformable Interfaces for Performing Music

Deformable interfaces are interactive computer-interfaces that are made of soft or malleable materials; such interfaces include flexible and bendable smartphones [1,17,34], deformable and elastic displays [33,53,65,77,79,88], and musical interfaces [6,8,25,64]. Although research has proposed various prototypes of deformable interfaces and tested them in various applications (e.g., 3D modeling, mobile technology), it is still unclear how and when deformable interfaces are advantageous compared to rigid interfaces. Also, most of the existing deformable interfaces have been used or evaluated in controlled experiments in the lab. The work presented in Paper 2 (page 44) investigates the use of deformable interfaces for music performances out of the lab. In this way we aimed to gather responses from users that would be less biased by a controlled environment and closer to real-life scenarios. Furthermore, we chose the music domain to investigate deformable interfaces because (1) music is a highly challenging real-time performance that involves much manual control and (2) earlier work have explored deformable interfaces with music [28,68,82,83].

We divided our study in two phases. First, we run three workshops with professional and amateur musicians, in order to receive input on how to use different deformable objects and materials to build musical instruments. Second, based on the input from the workshops we built five deformable interfaces (Figure 3, a) for music performances and gave them to professional musicians to perform live music at their studios (Figure 3, b).

Findings from the workshops showed that different shapes and materials played a key role for participants, especially when they thought about the relationship between deformations and musical parameters. Haptic and tactile qualities of different textures and viscosities influenced the way in which participants generated ideas on how deformable interfaces would be best used to perform music. In synthesis, participants from the workshops argued that deformable interfaces would be best to manipulate rather then generating sounds. Also, according to participants different shapes and materials implicitly suggested what deformation they would be best for. These results were confirmed by the performance study, where we found that (1) the combination of three characteristics (i.e., shape, material, and deformation) determined how and which sounds musicians choose to control with deformable interfaces and (2) musicians used the deformable interfaces exclusively to manipulate sounds even if not instructed to do so.

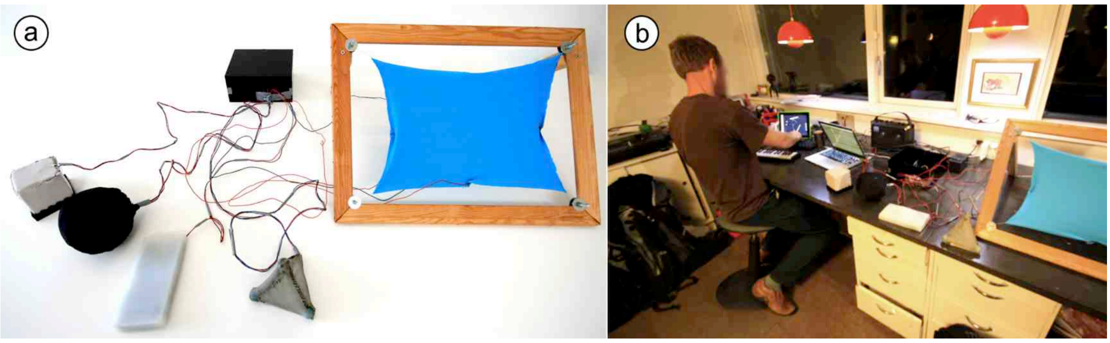

Figure 3: (a) the five deformable interfaces programmed for music interaction, (b) a participant from the performance study setting up the interfaces on his computer

The performance study involved six professional musicians experienced with electronic music and it was conducted at musicians' private studios. We asked each participant to use our deformable interfaces to perform laptop-generated music for a total of five minutes performance. Among the findings from the performance study, participants described the deformable interfaces as embodying the sounds that they manipulate. Therefore, it seemed that the use of deformable interfaces in relation to music generates an embodiment effect, which gives musicians the impression of "having the sound in the hand". These results suggest that deformable interfaces share common qualities with tangible user interfaces (TUIs), such as embodiment facilitation and strong specificness.

Shape-Changing Interfaces

This section presents the contributions to research in shape-changing interfaces. This includes the work described in Paper 3 and 4.

Designing Shape-Changing Interfaces

Shape-changing interfaces are interactive interfaces that can change their shape through the use of smart materials and various forms of actuation (e.g., mechanical, pneumatic). Several work show interactions possibilities with shape change [14,49,67], or the use of different technologies to achieve shape change [19,31,56,85,86]. Furthermore, research in shape change proposes frameworks [57], models [48,59], and designs studies [42,46], that show how the design space of shape-changing interfaces can be systematically explored. However, use of metaphors and dynamic affordances of shape-changing interfaces are still underexplored and it is still unclear what strategies designers use to design such interfaces. The work presented in Paper 3 (page 55) argues that an investigation on the design of shape-changing interfaces from designers' perspectives can help the mature the research about shape change and further understanding its design space. To investigate how designers think about shape change and their design strategies we have asked researchers in the field of shape-changing interfaces to perform two design exercises in form of sketches.

We asked 21 participants to spend about one hour for generating ideas and sketches for either a shape-changing radio or a shape-changing mobile phone. For each case we asked participants to think about two scenarios (1) a *functional* use (e.g., using the radio to adjust the volume) and (2) a *hedonic* use (e.g., using shape change in a mobile phone to convey emotions). We received a total of 42 sketches form participants showing a broad variety of concepts and ideas for the shape-changing radio and mobile phone (Figure 4). The analysis of the sketches was done with three foci: (1) use existing frameworks (especially [57]) to analyze the types of shape changes used by participants in the sketches, (2) analysing explanations and instances of metaphor use, and (3) analysing the use of affordances using the framework by Kaptelinin and Nardi [27]. The analysis on use of shape changes showed a great variation in the frequency of types of shape change, were all types of shape changes (except for *viscosity*) from Rasmussen et al. [57] were represented across the four tasks. Furthermore, we found that designers used shape change in their sketches mainly for iconic or symbolic representation.

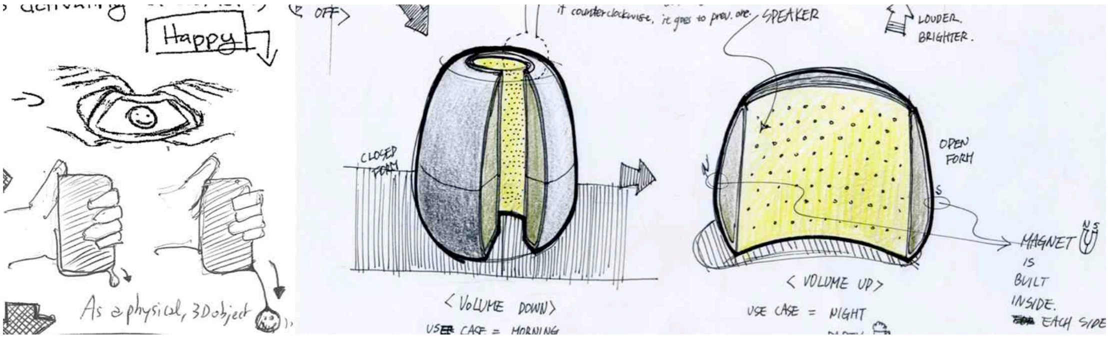

Figure 4: Some of the sketches produced by our participants that show concepts for a shape-changing radio and a shape-changing mobile phone.

The sketches showed that designers make frequent use of metaphors to represent functions and information through shape change. We found that our participants used metaphores especially to represent abstract concepts physically, for instance by using ontological metaphores (e.g., angry-is-pointy) or through the use of particular metaphoric means (e.g., rock-and-roll is twisted). Furthermore, while the majority of sketches for the shape-changing radio showed the use of obvious meatphores, for instance for volume control (i.e., up-is-louder), the rest of the sketches showed less conformity. Regarding the analysis of affordances, the sketches showed a frequent use of either handling or effecter affordances. 24 sketches showed the use of shape change for handling affordances but not for the associated effecter affordances. One such example is a sketch showing a hand folding the corner of a mobile phone (handling affordance), where the effect of this manipulation is not accompanied by a shape change (effector affordance). 33 sketches showed the use of shape change for effecter affordances but not for handling affordances. For instance, one of the sketches shows a shape change that uses both handling (physically "opening" a loudspeaker) and effecter (raising the volume) affordances as part of a single manipulation. In conclusion, results showed in this study serve as material for discussing the design space of shape-changing interfaces, pointing out insufficiencies in current vocabularies and in charting potential benefits for design, using principled approaches to the use of metaphors and affordances.

Shape-Changing Interfaces and Future Interactions

The advent of shape-changing interfaces (SCI) has introduced new interaction paradigms, which take advantage of deformability for input [79] and dynamic shape actuation for output [14]. On the one hand, shape-changing interfaces introduce new gestures for input by using malleable and soft materials, which allow users to stretch [8], bend [1,17], twist [30], or squeeze [74], all of which were impossible with rigid interfaces. On the other hand, shape-changing interfaces can physically and dynamically actuate their surfaces to provide output, for instance through pneumatic actuation [13,31,85], mechanical actuation [14,49,69,71], or by using living organisms [86].

The technical endeavors that research in this field put into prototype development helped refining techniques for better actuation mechanisms and provided potential good applications for shape change. However, despite a significant advance in technological solution for shape change output and sensing methods for input, we still face fundamental questions with shape-changing interfaces: *(1) What are shape-*

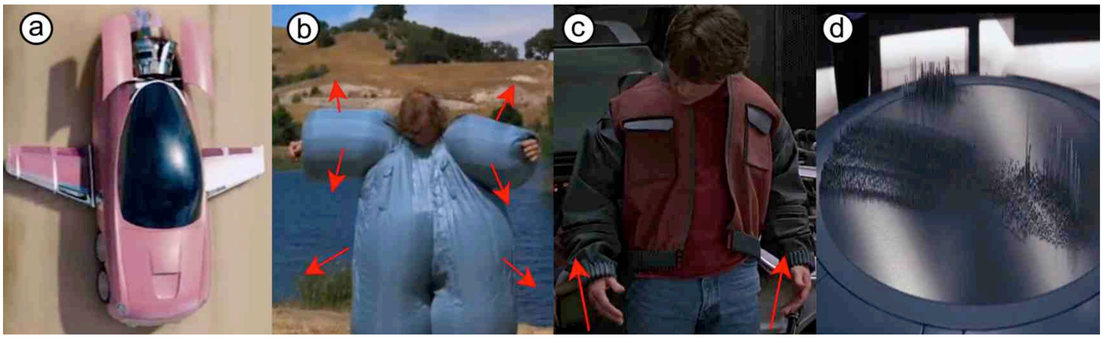

Figure 5: Four SCI behavioral patterns: (a) Reconfiguration, (b) Transformation, (c) Adaptation, and (d) Physicalization.

changing interfaces are good for? (2) In which context the use of shape change can help particular functionalities? The work presented in Paper 4 (page 69) investigates shape-changing interfaces from a perspective that is not strictly technical or pertaining to prototype development. Instead, we use fictional material, and especially Science Fiction (Sci-Fi) movies, to help broaden our view of what shape change *can do* and help us understanding how shape change behaviors can help functionalities of shape-changing interfaces in particular contexts. We argue that Sci-Fi movies are a good source of information for this kind of investigation, in which they often provide concrete scenarios that contextualize the use of forthcoming technology [63].

We investigate behavioral patterns of shape change by doing a large-scale analysis of 340 Sci-Fi movies, through which we identify instances of shape-changing interfaces (defined as SCI). The analysis revealed four emergent behavioral patterns of shape change, namely *Reconfiguration*, *Transformation*, *Adaptation*, and *Physicalization* (Figure 4). Each behavioral pattern was derived from the analysis of various SCI instances from Sci-Fi movies, which show what SCI can do and in which context. For instance, *Reconfiguration* shows example of SCI that automatically *assemble* or *disassemble* for various purposes, such as shape-changing robots that let users access internal components by disassembling, or that re-assemble their original structure from broken parts. Other categories show how shape change can be used with shape-changing dresses to *camouflage,* or how shape-changing robots can *morph* into different shapes (e.g., a car shape-changes into a radio), or how a shape-changing interface can adjust its shape in order to find an *intended* shape and *adapt* to a particular situation.

The results from our analysis complements the ones of previous work that proposed shape change frameworks [57], but focused primarily on the behavioral qualities of SCI and the way in which they support shape-changing interfaces into a particular context or for a particular application. Compared to previous work, our results show how certain types of shape change (e.g., orientation, volume) can be used in the context of *adaptation*, for instance like shape-changing garments (e.g., a jacket, a pair of shoes) that adapt their volume and length in order to fit the body of a user. Furthermore, even though our results describe behavioral patterns of SCI that were inferred by looking at fictional material, we show how our results can be used to also analyze existing prototypes of SCI. For instance, we show how the functionalities of the shape-changing display TRANSFORM [76] are supported by some of the behavioral patterns described in our paper, where the surface is capable of *adaptation* and it is also used to *physicalize* information through shape change and motion.

Methodology

This thesis presented four works that used each a different methodological approach, in order to investigate different aspects of deformable and shape-changing interfaces. This section presents a summary of these methodologies and discusses their benefits and the drawbacks.

In Paper 1 we have used a guessability study methodology to investigate what gestures users would perform on an elastic, deformable display for various tasks. This methodology has been previously employed for studies in different areas of HCI, such as mobile technology [32,60], or augmented reality (AR) [54]. Wobbrock et al. Used the guessability methodology in a study of surface computing [84], and later evaluated the resulting user-defined gesture set against a designer-defined [41]; the study showed that the user-defined set, compared to the designer-defined, was easier for other users to assimilate and master. Furthermore, the guessability methodology is often accompanied by the use of the think-aloud protocol [89], which allows to understand the nature behind users' choices when they are asked to guess how to interact with interfaces that are new.

Therefore, we decided to employ this methodology in the study from Paper 1 where we presented participants with a novel interface (i.e., a deformable display). In that respect, the guessability methodology has shown to be effective in previous work that investigated interfaces that were still not acquired by users [32,54,60]. However, the guessability methodology presents users with content that is non-interactive and that lacks the real-time feedback provided by interactive interfaces. This lack of interactive feedback may bias users' choices and make it difficult to guess fitting gestures where real-time feedback is needed (e.g., 3D manipulation). Therefore, the guessability methodology is good when users are asked to guess gestures for simple interactions (e.g., select, move), but not suitable for more complex or sequential flows of interactions.

Paper 2 investigates the usefulness of deformable interfaces in the context of music performance. This was done in two phases: (1) by organizing three workshops involving professional and amateur musicians, and (2) by carrying out a performance study out-of-the-lab. The structure of the workshops was based on Participatory Design (PD) methods [5], with particular focus on the following activities: experimenting with mock-ups, horizontal prototyping, thinking aloud, and brainstorming. Our workshops were especially inspired by the Future Workshop [75], in which we asked our participants to explore and generate ideas for a new technology that doesn't exist yet. In that respect the Future Workshop has proven to be particularly effective for such cases. The performance study was inspired by previous work that investigated the use of Tangible User Interfaces (TUIs) for music performances [26,51], which showed already how music could be a favorable domain to test novel interactive interfaces.

However, both the workshops and the performance study have limitations. On the one hand, workshops that are based on PD are useful to get insights and ideas from potential end-users, but lack the input of designers and engineers that often help refining interfaces development and bring them beyond the prototyping stage. Therefore, the design and development of deformable interfaces used in the study on Paper 2 are limited in that respect. On the other hand, the performance study is good for testing the use of interfaces out-of-the-lab, but only tests interfaces on short-time uses. Therefore, the performance study does not provide information about long-term use and learning effect, which are often important when users acquire and master the use of novel interfaces.

The investigation carried out in Paper 3 focused on understanding how designers think about and design shape-changing interfaces. To create coherent tasks for our design investigation we looked at previous work of design studies [3,10] and design cognition [9,11], which have a rich tradition of conducting empirical studies on how designers work. However, the designerly investigation presented in Paper 3 differs from the studies listed above, in which those were interested in understanding about the *processes* behind the choices of designers, while our investigation was interested in studying the *properties* of the resulting designs. Inspired by previous work we asked designers to sketch ideas for a radio and a mobile phone that use shape change features for interaction.

The sketching exercise that we used for our study freed our participants from the technicalities of prototyping and allowed them to generate ideas rapidly. Although this method was effective for our case it has intrinsic limitations. For instance, sketching static images on paper makes it difficult to faithfully represent the continuity of motion for particular shape changes. Therefore, the "animation" aspect provided by physical shape-changing prototypes is not present in 2D sketches. Furthermore, sketches as material are by nature ambiguous, and while such ambiguity can be advantageous in the creative stage of design process, it does not help when sketches are used as sources of information for more systematic analyses and categorizations.

Paper 4 investigated shape-changing interfaces and future interactions through the use of fictional material, especially Sci-Fi movies. Our methodology was inspired by the reflective approach to design [4,70,90] and based on studies that investigated HCI using Sci-Fi movies [12,22,61]. Both approaches have shown that fictional and speculative material can be used academically and practically, for instance to inform the design of technology in real-life. The work presented in Paper 4 was inspired by the above-described work and used a similar approach to inform and inspire the design of shape-changing interfaces.

The data extrapolated from Sci-Fi movies were analyzed using affinity diagraming, so as to identify behavioral patterns of shape-changing interfaces. Previous work on proxemics showed that affinity diagraming can be used to help identifying emergent design patterns and meaningful categories when analyzing interactive interfaces [18]. However, affinity diagraming is inherently limited to the source material, and the use of fictional material is to be considered mostly inspirational and needs further scientific validation. As McGrath says in Methodology Matters [40] *"Methods are the tools – the instruments, techniques and procedures – by which a science gathers and analyzes information. Like tools in other domains, different methods can do different things"*. The present thesis presents a varied investigation that looks at deformable and shape-changing interfaces from different perspectives (i.e., user experience, usefulness, and design) and in different contexts (i.e., music, interactive displays, and reflective design). Therefore, the methodologies described in the present thesis are also varied (i.e., guessability, participatory design, out-of-the-lab, and designerly investigation).

McGrath describes three features of research that one should try to maximize when gathering evidence on a particular phenomenon, namely (1) *generalizability*, (2) *precision*, and (3) *realism* [40]. In Paper 1 we have used the guessability methodology [84] along with the think-aloud protocol [89], a self-report questionnaire (i.e., Likert scale), and a semi-structured interview; this allowed to maximize precision in a study where the primary objective was to formalize a set of gestures (i.e., input methods) for elastic, deformable displays. However, the study outlined in Paper 1 evaluates deformable interfaces in a rigorous environment (i.e., lab study), missing the realism provided by the study in Paper 2, where the use of participatory design (PD) techniques and a performance study out-of-the-lab, helped investigating the use of such interactive interfaces in settings that are closer to real-life.

Paper 3 presented a design survey on shape-changing interfaces that used a methodology inspired by empirical studies of designers [3, 9, 10, 11], while Paper 4 used reflective approach [4,70,90] and fictional material (i.e., Sci-Fi movies) to investigate design qualities of shape-changing interfaces. However, Paper 3 systematically analyzes design elements such as metaphors, dynamic affordances, and vocabulary, and tries to formalize their use in the design of shape-changing interfaces, therefore contributing at the theoretical level (e.g., framework). Paper 4 instead, provides an extensive review of Sci-Fi material and draws design considerations out of it; as such, Paper 4 provides inspirational guidelines for the design of shape change and contributes to the field HCI at a methodological level.

Discussion

The work contained in this thesis touches upon various research aspects of deformable and shape-changing interfaces, which all aim at contributing to the following research question: *what are deformable and shape-changing interfaces good for?*

The four papers presented in this thesis attempts to answer the aforementioned research question by investigating (1) how users give input to deformable interfaces, (2) for which particular tasks users find deformability useful, and (3) what particular design elements can support functionalities and feedback with shape-changing interfaces.

In the section, I will discuss the most important findings for deformable interfaces and shape-changing interfaces in turn, in light of previous work, and open up for future research challenges.

Usefulness of Deformable Interfaces and Expressive Control

Paper 1 shows how users can take advantage of deformability for input on an elastic, deformable display. Results form the guessability study showed that users made use of elasticity and deformability of the display to perform various gestures, for instance like *push and pull*, or *grab and twist*; these gestures were used frequently when tasks showed three-dimensional contents to the users. Quantitative results were confirmed by participants' comments in the post-interviews, where they suggested that 3D modeling or 3D interactive gaming (e.g., virtual reality, augmented reality) could be potentially good for deformable displays. These results reinforce the idea that 3D modeling applications can be good for deformable displays as proposed in earlier work [79].

In comparison to previous work with deformable displays where users *pushed* into the display as the only input technique [7,53,79,88], participants in the study of Paper 1 suggested other input possibilities, for instance like *pinch and pull* as an alternative gesture to zoom out on maps, or *grab and pull* to move virtual objects closer in a three-dimensional space. One observation from the study presented in Paper 1 is that users seemed to use deformability of the display especially for tasks that entailed manipulation of contents (e.g., 3D deformation, displacement), whereas multi-touch or desktop computer-inspired gestures where used when tasks required selection or creation of contents. Although Paper 2 investigates deformable interfaces as musical interfaces, findings from the workshops and results from the performance study showed a similar trend with Paper 1.

The main research question in Paper 2 was: *how and when do users think deformable interfaces are useful, and for what operations*. In response to the aforementioned research question, participants suggested that deformable interfaces for music performances should be used to either control sound effects or manipulate filters applied to pre-existing sounds (i.e., contents); to generate sounds participants would prefer to use simpler input (e.g., touch, push) with rigid interfaces like MIDI keyboards. This communality between the results of Paper 1 and 2 suggest that deformable interfaces might better fit input techniques and interaction tasks that require more than simple touch, and therefore becoming useful when higher expressivity in control is needed. It is not accidental that participants from performance study in Paper 2 described the deformable interfaces as “expressive” tools because of their haptic qualities; this ultimately generated a strong embodiment effect where participants had the impression of “having the sound in the hand”.

To support the idea that deformable interfaces could be used for expressive controls, sensor reading from the performance study revealed that different deformable interfaces led to different intensities in control. For example, musicians seemed to use deformable interfaces that could be *squeezed* with two hands more “aggressively” compared to the ones that could be *pressed* with only one hand. Furthermore, participants to the study in Paper 2 often stressed out how deformable interfaces are favorable for eyes-free control when a particular shape is linked to a precise deformation (e.g., a *sphere* that can be *squeezed*), and how different deformations made it easy to remember sound-to-deformation mappings because of the material-deformation-to-sound relation.

In summary, results from Paper 1 and 2 suggest that deformable interfaces afford interaction techniques that are more complex and elaborated compared to rigid interfaces, and that tasks that involve more complexity (or expressivity) in control might benefit from deformable input. However, while both Paper 1 and 2 introduce the idea that multiple deformations can be used for simultaneous inputs in particular tasks (e.g., *grab* to select an object and *pull* to displace it), neither of the two papers investigates the use of multiple and simultaneous inputs with deformable interfaces. This opens up to research challenges for future work with deformable interfaces, where implications of multiple-dimension of control should be investigated. Such investigation would be essential to push control possibilities beyond one-dimensional control (e.g., only *bend* as input), and understand how and if multi-dimensional input can further exploit the interactive possibilities offered by deformable interfaces.

Use of Metaphors with and Behavioral Patterns of Shape Change

Paper 3 and 4 investigated design elements of shape-changing interfaces and drew various considerations out of their investigations. Paper 3 focused on extrapolating use of metaphors, dynamic affordances, and vocabulary of shape change from 42 sketches proposing ideas for a shape-changing radio or a shape-changing mobile, while Paper 4 identified emergent behavioral patterns of shape change from an extensive analysis of fictional material.

The sketching exercise from Paper 3 asked 21 participants to generate ideas for both input and output interactions with shape-changing interfaces; the resulting 42 sketches suggested various gestures for input (e.g., *twisting*, *pinching*, *squeezing*, *bending*, *stretching*, or *crumpling*) and uses of shape change for output (e.g., a radio inflates as the volume of sound increases). Regarding the use of shape change for input, compared to Paper 1 and 2 the investigation from Paper 3 shows how input techniques can be coupled to the use of metaphors to make certain interactions intuitive. For instance, one sketch proposes *stretch* as input to “break” the display of a mobile phone when airplane mode is selected; the physical metaphor of breaking is used to represent wireless connection as a material that can be pulled apart to be disconnected. Regarding the use of shape change for output, the sketches analyzed in Paper 3 showed how orientational metaphors were often used to express particular meaning through shape change, where a shape-changing mobile bends upwards to express happiness (happy-is-up), or a shape-changing radio “inflates” as the volume of the music raises (louder-is-larger). Designers used structural metaphors to show how iconic and symbolic conventions could represent different modes or status of shape-changing interfaces. For instance, a mobile phone takes the shape of an airplane when in flight mode (flight-mode-is-an-airplane), or a shape-changing radio closes or opens its surface (very much like an Armadillidiidae insect) to inform the user about different statuses (e.g., usable, non usable).

Part of the analysis in Paper 3 used established frameworks [57] to analyze the use types of shape change in the 42 sketches. The results show that, although designers consistently used at least seven out of the eight types of shape change proposed by Rasmussen’s et al. [57], their sketches also indicated areas where the vocabulary is insufficient for such analysis and needs to be further developed. For instance, while simple changes in shape (e.g., volume, orientation, form) can be easily described using Rasmussen’s vocabulary, more complex shape changes (e.g., iconic, symbolic) are difficult to describe using the vocabulary in its present version.

Paper 4 focused on extrapolating behavioral patterns of shape change from a large-scale analysis of 340 Sci-Fi movies. The design considerations outlined in Paper 4 show how behavioral patterns of shape change can model or help support specific functionalities of shape-changing interfaces. As in Paper 3, the analysis of the data in Paper 4 also considers types of shape change from existing frameworks [57]. However, differently from Paper 3 were the analysis uses Rasmussen’s et al. framework to identify the types of shape changes used in the sketches, in Paper 4 the analysis focused on how different types of shape change could be used to better support functionalities of shape change. For instance, some instances of shape-changing interfaces from Sci-Fi presented in Paper 4 show how types of shape change like *orientation* and *volume* [57] can support *adaptation*, where a shape-changing bed from the movie *2001 A space Odyssey* adapts its orientation to find a good position for the head of the user, or how a shape-changing garments from the movie *Back to the Future II* adapt their volume and length in order to fit the body of different users.

In comparison with previous work, the analysis of shape-changing interfaces from Sci-Fi movies from Paper 4 provides examples of how shape change behaviors can serve functional purposes that go beyond design inspiration. For instance, we show how in Sci-Fi movies shape-changing interfaces use transformational behaviors such as *morphing* to embed multiple functionalities into a single interface; an example is a wallet that can morph into a gun from the movie *Judge Dredd* or a robot that can shape shift into a radio in the movie *Transformers*. Another example provided by our analysis shows how the same *spatial* reconfiguration behavior presented by Rasmussen et al. [57] is used in Sci-Fi movie for a clear functional purpose; the example in question appears in the movie *The Adventures of Pluto Nash*, where nine spheres automatically assemble in a triangular shape on a pool table and let users restart a new game without having to replace each sphere manually.

Although the results presented in Paper 4 describe behaviors of shape change that were extrapolated from fictional material they can be used to analyze existing prototypes of shape-changing interfaces. By looking at shape-changing displays like TRANSFORM [76], we can see how some of its functionalities can be explained through the behavioral patterns described in the paper. For instance, TRANSFORM is capable of *adaptation*, in which its surface can adapt to the shape of objects that users place onto it. The very same surface can act as a display that *physicalize* information to display digital content in a physical form, for instance by generating dynamic wave-like patterns to represent sounds such as sine waves or drum beats. Results from Paper 4 can be considered inspiring and helpful to reflect on how certain shape change behaviors can help functionalities. However, at this stage it is still unsure whether the results from Paper 4 are applicable to design practices and how they can concretely help to advance the design of shape-changing interfaces.

In conclusion, Paper 3 and 4 point to directions for future work that should focus on further investigating (1) the use of metaphors for input and output with shape-changing interfaces, systematically exploring them as physically dynamic constructs, (2) further developing present vocabulary of shape change that include more complex types of shape change, and (3) further investigate the practical applicability of design inspirations for shape change that are derived from the analysis of fictional material.

Future Work

The investigation of deformable and shape-changing interfaces presents research challenges that should be accounted for by future works. In the following, I present my research vision for future work and explain how I plan to tackle the research challenges of deformable and shape-changing interfaces.

The work contained in the present thesis shows potential uses for deformable interfaces and tries to identify meaningful design elements of shape-changing interfaces. The empirical research outlined in my work serves the broader scope of showing the next trend of interactive interfaces, which features non-rigid, deformable, and shape-changing elements as part of the human-computer interaction experience. This trend is different from today's experience with interactive interfaces, where computers are becoming always more powerful and portable (i.e., smartphones, tablet), but the interaction with them it's mostly based on rigid one-dimensional (e.g., touch) or two-dimensional (e.g., touch and pressure) input, which strongly limits human hands expressivity. Furthermore, most of the feedback provided by today's interactive interfaces to the users is based almost exclusively on visual information that appears on flat displays. However, throughout my thesis I have showed that the use of deformable and shape-changing interfaces allow for new input (e.g., bend, stretch) and output (i.e., dynamic actuation) possibilities. My research vision is to use the interactive possibilities offered by shape-changing and deformable interfaces to help re-defining the way in which users interact with computers – which comes after rigid interfaces. In concrete, my plan for future work is to investigate two particular aspects of using deformability and shape change for interaction: (1) deformable input, especially multi-dimensional and simultaneous inputs with deformable interfaces, (2) a systematic understanding on the use of metaphors for output with shape-changing interfaces.

My previous research focused on investigating: (1) what gestures user perform on an elastic, deformable displays, (2) how deformable interfaces that allow for one-dimensional input are used for music performances, and (3) how designers sketch shape-changing interfaces. This provided preliminary results on deformable gestures, usefulness of deformable interfaces, and use of metaphors and dynamic affordances with shape change. However, implications of multi-dimensional input with deformable interfaces and conventional use of metaphors with shape-changing interfaces are still underexplored. For this reason, future work should broaden up the interaction space for deformable and shape-changing interfaces and: (1) investigate in depth multi-dimensional input control with deformable interfaces, including on-body interfaces, (2) develop applications for multi-dimensional deformable input, and (3) further investigate the use of metaphors for shape change output.

Work In Progress: Multi-Dimensional Input with Deformable Interfaces (MUDE)

Related work in the area of deformable interfaces has investigated multiple inputs and proposed interactive applications for two-dimensional input. An example is BendID [44], where a bendable interface is used for controlling a car videogame; the car can be driven through bend interaction while acceleration can be controlled through pressing. Future work should further investigate techniques for deformable interfaces

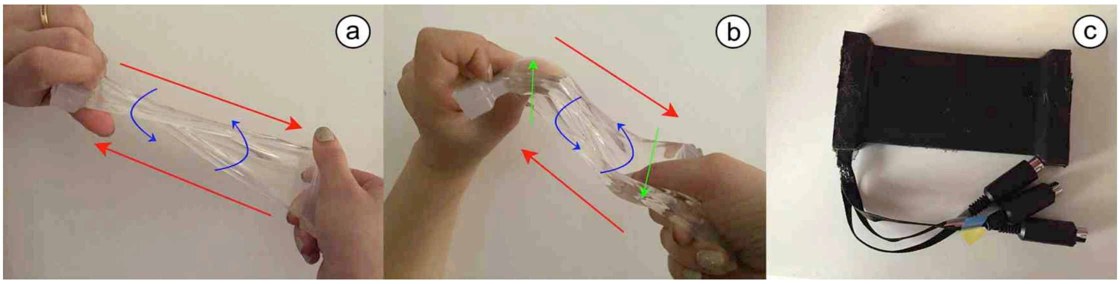

Figure 6: Some of the interaction techniques that I envision with MUDE (a) a combination of stretch and twist, (b) a combination of twist, stretch, and press. One prototype that senses twist and bend is already available (c). However, I do not limit interaction possibilities to the above examples. For instance, I plan to investigate more input techniques with the same sensing technology (e.g., shear, pinch, poke, squeeze), as well as using the interface onto the body and with different form factors.

that afford multiple and simultaneous input and related applications. In that respect, an understanding of how users perceive and manipulate multiple deformations to control interactive applications is a fundamental first step. Multi-dimensional input interaction has been investigated in previous studies with rigid interfaces, which showed how multiple dimensions of control can improve interaction when tasks are integral and require continuous input [24]. However, a study that investigates multiple inputs with deformable interfaces that afford more than two inputs simultaneously has not been carried out yet. A study on multi-dimensional inputs with deformable interfaces will show how users can benefit from multiple deformations, use those for simultaneous input operations, and open up to new interaction possibilities that can further exploit human hands expressiveness.

At present, not many prototypes of deformable interfaces can sense more than two deformations, and very little is known about the users' ability to control multiple deformations. One prototype that can sense three deformations simultaneously was developed as part of my Ph.D. in collaboration with LEAP technology, a Copenhagen based company that fabricates electro active polymers (EAPs). The prototype is called MUDE (MUlti-DEformation, Figure 6), and it is made of soft PDMS silicone, embedded with three layers of EAP electrically connected to computer through PS2 connectors. The available prototype produces three different electrical signals if stretched, twisted, or bent. My approach for future work with shape change input will be to further develop MUDE and other deformable interfaces that afford multiple inputs to investigate the following: (1) how users handle simultaneous deformations for the control of interactive applications and (2) what types of application are good for multi-dimensional deformable input.

The present version of MUDE features a soft silicone casing that is roughly the form factor of an iPhone 6 (i.e., 1cm x 8cm x 12cm). The silicone casing is embedded with three electro-active polymer (EAP) sensors placed at different heights inside its surface. The sensors are capable of sensing three distinct types of deformation when input is given, namely *bend*, *press*, and *stretch*. However, several are the issue with the actual version of MUDE:

1. The actual prototype uses silicone material that is different from the one we initially planned to use. We wanted to use Ecoflex®[1] silicone because is very soft and highly stretchable, and because it has been successfully used in

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[1] https://www.smooth-on.com/product-line/ecoflex/

previous work [85]. However, the first attempt at building the MUDE prototype with Ecoflex® failed in which the silicone was releasing poisoned gases due to oil softeners contained in the material, which compromised the correct functioning of the EAP sensors. For this reason, a harder silicone provided by LEAP had to be used until a solution could be found with softer silicones that don't make use of oil softeners.

2. The signal from the sensors can be read only through a multi-meter or through a dedicated electronic analog-to-digital converter, which can be interfaced with a computer only through proprietary software provided by LEAP technology. At the actual stage we have no custom or open-source software that we can use to interface the sensors with a computer. Therefore, the raw data output from the sensors cannot be fully accessed for programming.

3. Preliminary tests show that the sensor can be used to discriminate between *stretch* and *bend* (Figure 7, 8), also between *upward* and *downward* bend. However, *press* (Figure 9) produces the same signal as *stretch* only within a smaller range, making it difficult to distinguish between the two deformations.

4. The actual silicone encasing is compatible with the electro-active sensors but it is not very soft, which makes repetition of certain deformations like stretching very tiring and stressful over time. With the help of LEAP technology we found a solution with softer silicones that do not use oils, and therefore do not poison the EAP during the molding process. However, we did not have the time to develop a new interactive prototype with the new silicone material.

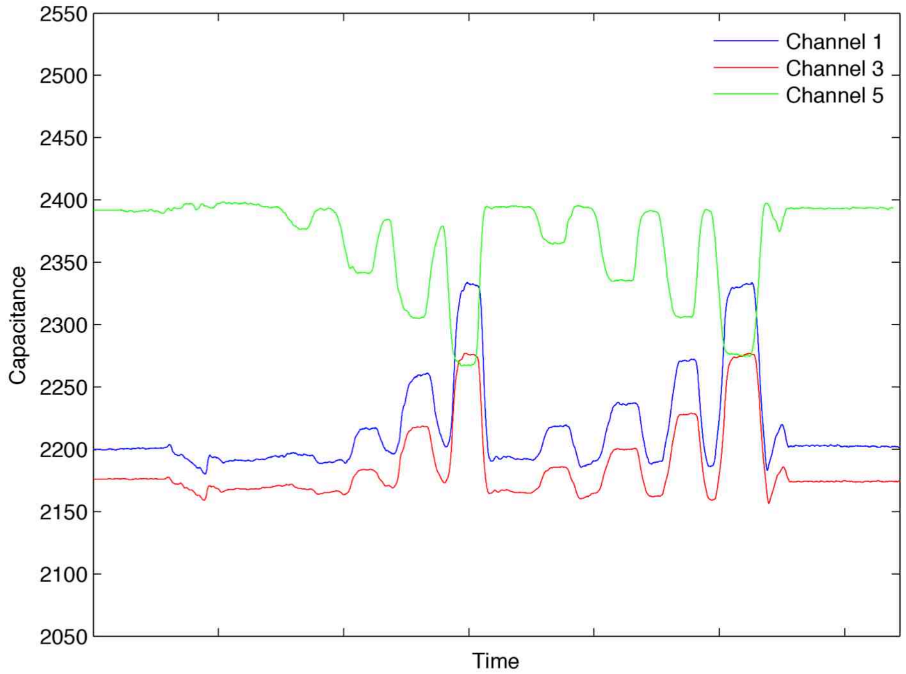

Figure 7: The capacitance value in pF output by the three EAP when MUDE is bent downwards with one hand.

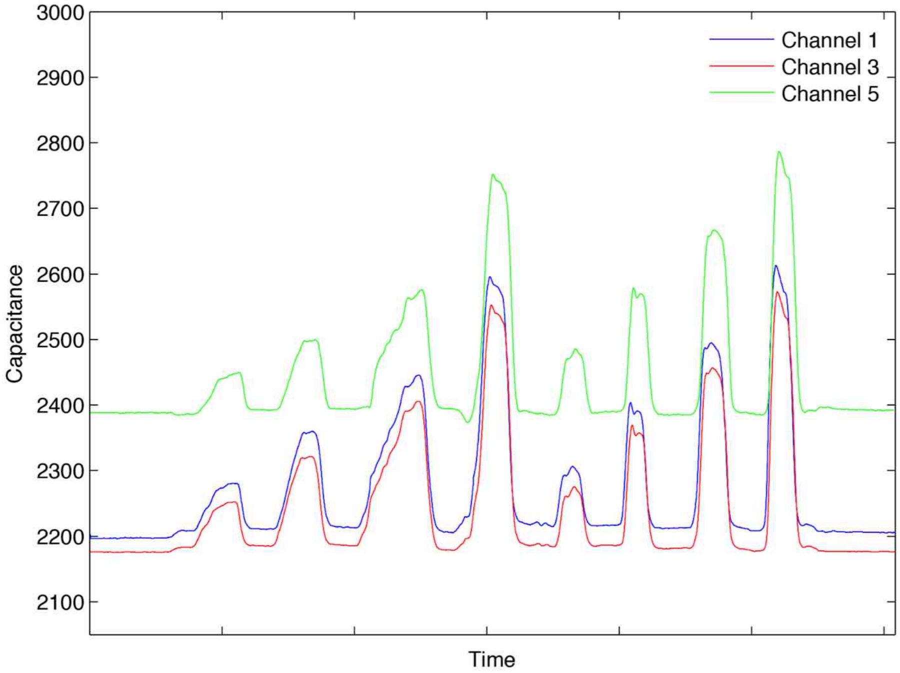

Figure 9: The capacitance value in pF output by the three EAP when MUDE is stretched with two hands.

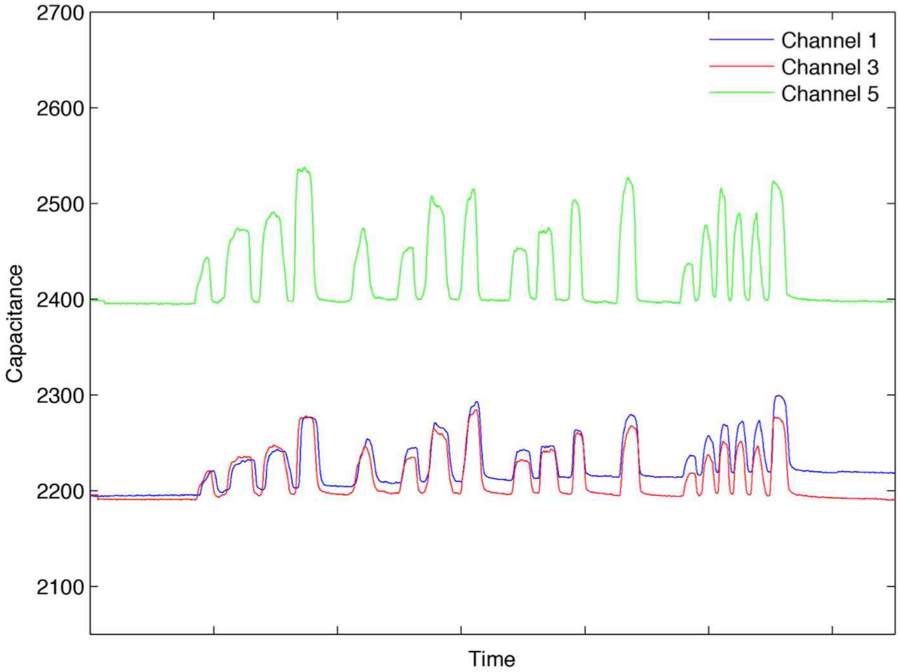

Figure 8: The capacitance value in pF output by the three EAP when MUDE is pressed on the surface.

The next step of the MUDE prioritizes the building of a new prototype that is capable of sensing at least three deformations simultaneously. Also, the new prototype will feature a softer silicone that allow for effortless stretch, therefore allowing for a less tiring experience while using MUDE for a prolonged period of time. The actual configuration has three layers of EAP sensor placed parallel to each other at different heights inside the silicone casing. This configuration produces different outputs when MUDE is *bent* or *stretched*, however *press* and *twist* cannot be distinguished from *bend* and *stretch* at the actual stage. The building of a new prototype should use a new configuration for sensors placement inside the silicone casing to resolve this problem.

The current MUDE prototype uses cable connection with an analog to digital converter to communicate with a computer. The next prototype should feature a wireless connection, so as to allow for freer actions when using MUDE for interaction. Finally, future prototype developments might consider embedding a flexible display into MUDE, so that users can manipulate contents directly on the interfaces as if they were using a deformable display (i.e., a smartphone).

To classify the different deformations I will use machine-learning techniques, for instance like support vector machines (SVM). I plan to use MUDE for two user studies: (1) a study that borrows methods from psychophysics [16], in order to test users' perception of various magnitudes of deformations, and (2) a study that tests users' ability to control multiple inputs (i.e., deformations) simultaneously. This investigation will contribute the following to the filed of shape change: (1) empirical results on users' perception of multi-dimensional input with deformable interfaces and (2) a series of interaction techniques and applications for multi-dimensional deformable input. These contributions will be oriented towards technology development, researchers, and designers, so as to provide a better understanding of the benefits and drawbacks of multiple inputs with deformable interfaces.

In future work I will use MUDE to answer the following research questions:

1. *How do users handle simultaneous deformations for control?*

Making use deformable interfaces that sense multiple deformations will contribute to create novel forms of interaction. However, it is not yet understood how users will react to this interaction techniques and how they will manage multiple deformations simultaneously. For example, it will be fundamental to investigate how accurately users can control each individual deformation when single dimensions of control cross each other. Future work with MUDE will evaluate these implications and the results will be used to inform the design of new interaction techniques, which make use of multi-dimensional input with deformable interfaces for interaction.

2. *What applications are good for multi-dimensional deformable input?*

Aside from the aforementioned technicalities of multiple dimensions and deformations, I envision that the resulting interaction techniques could be used to enhance expressive control for various applications. For instance, artistic applications and performances might greatly benefit from deformable interfaces and the expressive control that they can afford (see [72]). Future work with MUDE will also investigate the use of multi-dimensional input with deformable interface for the control of interactive applications. This will imply that various interactive applications should be developed and used to evaluate the usability of MUDE and user experience (UX).

To investigate the aforementioned questions, an experimental design for a user study will be developed in which users will be tested on multi-dimensional control for input using methods from psychophysics. A first study will test users' perception of deformations when manipulating a multi-dimensional deformable interface through tasks like *ratio* and *magnitude production* (see [50]). The study will follow up with a test where users are asked to control various parameters simultaneously while using the MUDE interface. Finally, a third study should test MUDE for the control of interactive applications (e.g., photo manipulation, videogame, multi-scale navigation, music). Next, an initial plan for the three studies will be described.

Study 1: Ratio and Magnitude production
This user study will be carried out to answer the following questions: (1) How do users perceive the magnitude of individual deformations when they are performed simultaneously? (2) Does the perception of magnitude of one particular deformation produces more perceptual discrepancy compared to other ones? The study will be carried out in lab settings and it will use approximately 20 participants, which will be asked to perform the following tasks:

1. *Ratio Production Task*
   This task will ask participants to produce ratio between different magnitudes of a single deformations using the MUDE interface. The participant will be asked to exert two forces successively that should be in a relation 2:1. For instance, the participants will be instructed to initially stretch the interface moderately, then to repeat the same deformation at half of the strength, and finally at double the strength. The *ratio production* task will ask participants to perform the same deformation five times for each force (i.e, light, moderate, and heavy), for a total of 15 trials per deformation. The order at which stimuli will be presented will be reversed and counterbalanced among participants. No visual feedback will be provided for this task.

2. *Magnitude Production Task*
   This task will test the discrepancy between the *perceived* and the *actual* magnitude of multiple deformations performed simultaneously by users with MUDE. The participant will be initially explained that a "moderate" deformation corresponds to the number 10. Successively, the participant will be asked to perform various deformations at various magnitudes, where the values of reference will be 3, 6, 10 (moderate), 20, and 30. Each participant will perform different combinations of deformation (e.g., bend + stretch, bend + stretch + twist) for each magnitude value (i.e., from 3 to 30). The *magnitude production* will ask participants to perform multiple deformations, with at least two deformations simultaneously. A display will be used to show the type of combinations that the users need to perform (e.g., bend + twist) and the magnitude for each of the deformations (bend 20, twist 3). No visual feedback will be provided for this task.

Study 2: Controlling Multiple Inputs
This user study will be carried out to answer the following questions: (1) How many deformations for input users can control at the same time effectively? (2) What are the users' preferred combinations of deformations? The study will be carried out in lab settings and it will use approximately 10 participants, which will be asked to perform the following tasks:

Tasks
This task will test the ability of users to control multiple deformations with MUDE. The participants will be asked to control multiple deformations simultaneously, in

order to match specific values, where the values will be displayed in form of visual feedback on a screen and will have different shapes according to the type of deformation that the user is required to perform. For instance, visual feedback for *twist* deformation might be displayed as a circle, while for *press* the visual feedback might be displayed as a vertical bar.

Study 3: Interactive Applications for MUDE

The third user study with MUDE will use a series of applications that use multiple deformations for controlling various events. For instance, such applications might be 3D modeling, gaming, or graphical manipulation. With those applications, multiple deformations of control could be used by users to manage integral tasks, for instance to simultaneously manipulating color, brightness, and size of a picture, or to control multiple actions in a video-game as in BendID. MUDE could also be used for interaction with applications where real-time video and audio contents can be manipulated, such as VJ or electronic music software.

On-Body Deformable Interfaces

Another direction for future work with shape change should be using deformable interfaces for input on the human body. With the advent of 3D printers personal fabrication has become always more accessible to users, and with the use of soft printable materials is now possible to create custom deformable objects of various sizes and stiffness. This represent a possibility for deformable interfaces to be easily customized and used as ubiquitous interfaces for giving input in different forms than just rigid touch or multi-touch. An example of such possibility is shown in previous work like iSkin [80], which uses how on-body deformable interfaces for mobile computing.

However, the interaction techniques proposed in iSkin are still mostly based on touch input and the application scenarios are related to mobile applications (e.g., SMS writing, answering calls, listening to music). Inspired by the work iSkin and previous work on skin input [81], my goal is to develop on body deformable interfaces that can afford multiple deformations for control and that incorporate touch input along with other deformable gestures (e.g., shear, pinch, stretch). Furthermore, I plan to extend the interaction space of on-body deformable interfaces to applications other than mobile computing, for instance like desktop or laptop computer interaction, musical interaction, and artistic performances (e.g., dance, painting, VJing). Finally, the on-body deformable interfaces that I envision should be also able to actuate their surfaces so as to provide users with feedback through shape change. In this respect, a deeper understanding on the use of metaphors for shape change output will be essential to establish conventions that help designing shape change feedback that can be understandable and intuitive for users.

Use of Metaphors for Shape Change Output

For shape change output, there has been a lot of focus on the use of metaphors and affordances with GUIs and TUIs, but only recently such investigation analysis has been done with shape-changing interfaces [58] – so far the term metaphor or dynamic affordance has been used simply as a mean to describe features of shape change.

In Paper 3 I showed how designers of shape change frequently use metaphors and dynamic affordances to design particular behaviors for shape change output, which help communicate various information to users. For instance, orientational metaphors were used to express particular meaning through shape change, like a mobile phone that bends upwards to express happiness (happy-is-up), or a shape-changing radio that inflates as the volume of the music raises (louder-is-larger). Future work that investigates shape change output should focus on the use of metaphors and affordances, so as to better understand the relationship between metaphor-feedback-functionality of shape change, establish conventions for the design of shape change output, and build shape-changing interfaces that give feedback based on those conventions.

As Donald Norman says, *"metaphors are slow to be adopted and, once adopted, slow to go away"* [47]. Therefore, it is fundamentally important at this stage to understand which metaphors can work best in combination with physical shape change, so as to create conventions that can be easily acquired by users. Based on my previous work [58], I intend to build prototypes of shape-changing interfaces that perform the shape changes suggested by designers, and use them for user studies that investigate the relationship between metaphors and shape change feedback. One approach would be to employ a guessability study methodology (e.g., [87]), in order to let users identify and suggest the best fit between metaphors and shape changes.

Contribution

In conclusion, I propose research for future work that will contribute the following to deformable input and shape change output: (1) an understanding of how users perceive and control multiple deformations simultaneously, (2) new input methods for deformable interfaces that use multiple and simultaneous deformations, (3) a number of interactive applications that can take advantage of multi-dimensional input with deformable interfaces, and (4) a systematic understanding of the relationship between metaphors and shape change output, and what do they mean to users. I believe that the research objectives that I propose for future work will offer significant contributions to the field of shape change: it will afford the design of new interactive techniques based on multiple deformations and will allow a broader range of applications with deformable and shape-changing interfaces.

Conclusion

This thesis presented empirical research and results on deformable user interfaces and shape-changing interfaces.

In the area of deformable interfaces, the thesis presented a guessability study conducted on a prototype of elastic, deformable display, and a study of deformable interfaces for performing music where six professional musicians used a set of five deformable interfaces to perform electronic music. The elastic, deformable display was used with 17 participants that suggested fitting gestures over 29 tasks; the results showed that deformability was used more frequently when three-dimensional contents were displayed. To investigate the usefulness of deformable interfaces we developed a set of interactive deformable interfaces for the control of music. The five interfaces were developed based on input received during three workshops, and were later used for real-time laptop generated electronic music performances. The performance study showed that deformable interfaces are used mostly for sound manipulation and filtering, rather than for sound generation.

In the area of shape-changing interfaces, we presented an investigation into what strategies designers use to design a shape-changing radio and mobile phone, for both hedonic and functional purposes. We asked 21 participants to generate ideas on how to design the shape-changing radio and mobile phone using sketches accompanied by textual explanations. The results showed that designers sketched the use of shape change especially for iconic and symbolic representation, making frequent use of metaphors and illustrating how dynamic affordances can be used to design users' interaction. Furthermore, the thesis presented an investigation of shape-changing interfaces and future interactions from Sci-Fi movies. The resulting 101 instances have served as material to discuss and develop meaningful categories of shape change, as well as outlining key design attributes for shape-changing interfaces and users' interaction.

Overall, the results presented in the thesis showed that (1) deformable interfaces can change input strategies and the perception of control due to their physical characteristics, especially in particular contexts like music, and that (2) shape-changing interfaces introduce design challenges that relate to dynamic affordances, use of metaphors, and specific categorization, which need further investigation and systematization.

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Paper 1: User Defined Gestures for Elastic, Deformable Displays

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User-Defined Gestures for Elastic, Deformable Displays

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ABSTRACT

Elastic, deformable displays allow users to give input by pinching, pushing, folding, and twisting the display. However, little is known about what gestures users prefer or how they will use elasticity and deformability as input. We report a guessability study where 17 participants performed gestures to solve 29 tasks, including selection, navigation, and 3D modeling. Based on the resulting 493 gestures, we describe a user-defined gesture set for elastic, deformable displays. We show how participants used depth and elasticity of the display to simulate deformation, rotation, and displacement of objects. In addition, we show how the use of desktop computers as well as multi-touch interaction affected users' choice of gestures. Finally, we discuss some unique uses of elasticity and deformability in gestures.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Human Factors; Experiment; Design; Measurement

Author Keywords

Elastic; deformable display; guessability; gestures; think-aloud; user interfaces

1. INTRODUCTION

Interactive displays that can deform and change their shape are emerging in the field of Human-Computer Interaction (HCI). Due to their elasticity and flexibility, these interfaces allow users to deform the surface dramatically – for instance by stretching, twisting, or folding. Whereas hard interactive tabletops and other flat displays allow only for two dimensional multi-touch input methods, deformable displays can afford interaction that physically extends in depth or in relief [15]. Previous work with deformable hand-held devices [3,5,8,19,22,26] and cloth displays [11] have shown possible applications for displays that deform. Other studies have shown how the size and stiffness of materials can affect users' interaction [5,9].

As suggested by Gründer et al. [4], deformable displays may be divided into two types: (1) *Flexible,* deformable displays, namely displays that are highly flexible and may allow for permanent deformation; (2) *Elastic,* deformable displays, namely displays that are elastic and allow only for temporary deformation. Our work relates to the body of research that investigates the latter. Elastic, deformable displays do not retain shape, and include interfaces like the Khronos Projector [2], where users can push an elastic membrane to interact. The present paper focuses on investigating elastic, deformable displays with the size of multi-touch tabletops (see [2,15,28]), placed at a vertical orientation. Related work shows applications for elastic, deformable display in virtual 3D modeling [23], map navigation [20], and gaming [28,29]. However, user studies that evaluate interaction with these displays are limited [28] and little is known about how users would make use of deformability for input. Furthermore, while hard multi-touch displays have a well-defined set of gestures (e.g., pinch to zoom), no such set exists for elastic, deformable displays.

To address these shortcomings, we conduct a study of elastic, deformable displays employing a guessability study methodology [25]. The aim is to investigate what gestures users would perform on displays that afford deformation, as well as how and when they would take advantage of deformability and elasticity for input. Using a think-aloud protocol and semi-structured interview, we gather qualitative information and insights on why users choose to perform particular kind of gestures. This work contributes (1) a user-defined set of gestures for elastic, deformable displays and (2) insights into why users choose specific gestures as input.

2. RELATED WORK

We base our work on research in elastic, deformable displays and on previous guessability studies. In this section we review related work in both of these areas.

2.1 Elastic, Deformable Displays

Table 1 shows a summary of related work on elastic, deformable displays, focusing on five points: (1) material, (2) projection, (3) tracking, (4) applications and (5) gestures. We believe that these are the key points that describe previous work from both the interactive and the technical point of view. Next we discuss each point in the table. Because gestures are performed in the context of interactive applications, points 4 and 5 will be discussed together.

The type of *materials* used in elastic, deformable displays have had a key role in shaping the interactions. It has been described how the action of sliding a finger on the display can become easy or hard, depending on the amount of friction produced by the surface's material [1]. With the hemispherical inflatable multi-touch display [20], the shortcoming of latex (high friction) was addressed by inflation and deflation of the surface, which dynamically changed the stiffness of the material. A PVC inflatable balloon was used to create the surface of Inflated Roly-Poly [7], where users could only punch on the display as input. This approach made it easy and fun to interact with the PVC surface, but resulted in limited gestures. eTable [28], the Kreek Prototype [29], ActiveCurtain [30], CloudPink [31], Firewall [32], and Elascreen [27] all featured the use of fabric, allowing for comfortable pushing, stroking, and sliding. However, because their fabric is slippery, pinching, pulling, and stretching were not used to interact. The Deformable Workspace [23] and DepthTouch

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[15] used a mixture of lycra and spandex. These materials have higher elasticity compared to other fabrics, allowing for easier grabbing and pulling. However, finding a material that may easily allow heterogeneous gestures remains a challenge.

In order to create interactive applications, *projection* of graphical contents on the surface is used in many elastic, deformable displays. Only two of the prototypes shown in Table 1 do not use projection [21,32]. Rear-projection is common [2,15,23,28], and it has the advantage of preventing users from covering the projection with their hand's shadow. However, this approach is not always applicable. For instance, Impress [33] used projection from above onto a display made of a thick layer of foam covered with a white cloth; the light of the projector could not have passed through it if placed behind. Furthermore, images projected onto a deformable surface should take into account possible dynamic deformation, and algorithms for the compensation of image deformation should be used if aiming for a realistic effect (see [23]).

Detecting and *tracking* gestures, as well as surface deformation on a deformable display, are hard. The Khronos Projector [2] used an infrared source and a camera with an infrared filter to acquire a grey-scale image. The gray-scale image was used to compute the size of the area deformed by the user, and then mapped onto depth coordinates. The same authors later used a sensing mechanism based on projecting an array of 1,100 spots on the back of the display, and then computing the coordinates of a 3D point for each spotlight in the pattern [23]. With the use of this technique, multi-touch detection was possible. Multi-touch could also be detected by Stevenson et al. [20] with the use of an infrared camera and a strip of infrared emitting lights. A similar technique was used with Inflated Roly-Poly [7], whereas Metamorphic Light [12] and Impress [33] used a camera-based approach to detect deformation. Thanks to the commercialization of the Kinect, recent prototypes take advantage of the depth sensor to rapidly detect multi-touch input in three dimensions. However, many challenges remain open (e.g., how to effectively detect complex deformations and multi-touch on the display at the same time).

Table 1: Five Characteristics of Related Work

Papers	Material	Projection	Tracking	Applications	Gestures
Khronos Projector [2]	Lycra	Back	IR dots array	Video exploration, image navigation	Push
The Deformable Workspace [23]	Lycra	Back	IR dots array	3D modeling, image navigation, 3D rotation, 3D displacement	Push, Grab, Squeeze, Stroke
DepthTouch [15]	Lycra, Spandex	Back	Kinect	Physics simulation, entertainment	Pinch, Pull, Push
Impress [33]	Foam, Fabric	Above	Camera	Music, RSS feed navigation, 3D modeling	Push
Elascreen [27]	Fabric	None	Kinect	Multi-dimensional data navigation	Push
Metamorphic Light [12]	Paper	Above	Camera	Image manipulation, animation	Push, Grab, Tap, Stroke
An Inflatable Hemispherical Multi-Touch Display [20]	Rubber, Latex	Back	IR camera, FTIR	Map navigation, fMRI navigation	Push
Inflated Roly-Poly [7]	PVC	Back	IR camera, IR LEDs	Gaming, entertainment	Punch
A Malleable Surface Touch Interface [21]	Latex	None	Camera	3D modeling	Push
eTable [28]	Fabric	Back	Kinect	Gaming, fMRI navigation	Push, Grab Expand
Firewall [32]	Fabric	Back	Kinect	Entertainment	Push
Kreek Prototype [29]	Fabric	Back	Kinect	Entertainment	Push, Expand
Active Curtain [30]	Fabric	Back	Kinect	Rehabilitation	Push
Cloud Pink [31]	Fabric	Back	Kinect	Entertainment	Push

Early prototypes of elastic, deformable displays showed potential *applications* and *gestures* for such displays. Khronos Projector [2] allowed for simple push interaction to explore the spatio-temporal volume of videos. A 3D modeling application, where a virtual spring mass could be deformed by pushing on a malleable medium, was proposed by Vogt et al. [21]. The idea of manipulating virtual objects through a physical deformable display seemed to enhance virtual 3D modeling. A similar concept was proposed with Impress [33], where users could model virtual 3D objects by simply pushing onto the display. The Deformable Workspace [23] featured a virtual 3D modeling application, where users could push and squeeze the display to deform objects.

Pushing was used for multi-dimensional data navigation [27], to explore multi-dimensional fMRI images [28], and generally in most of the prototypes [29,32,30,31]. DepthTouch [15] adds pulling gesture to pushing, where both can be used to influence the physical behavior of virtual spherical objects. Inflated Roly-Poly [7] introduced the punch gesture, whereas Metamorphic Light [12] allowed users to poke the display to animate the picture of a human face, press or stroke it to play videos, or grab and squeeze it to create real-time animations. However, a well-defined set of gestures for elastic, deformable displays has not been developed yet, and no systematic investigation has been made of which gestures are preferred by users.

2.2 Guessability Studies

The guessability study methodology has been used in previous work to elicit users' gestures for various types of devices and interactive contexts. It has been used for generating user-defined gestures in mobile interaction [18], for interaction across devices [6], and also to understand deformation-based gestures on hand-held devices with various level of flexibility [10]. It consists of eliciting an unbiased input from users by prompting them with specific stimuli, and gathering qualitative information by making users think aloud.

Wobbrock et al. used it in a study for symbolic input guessability [24] and to elicit user-defined gestures for surface computing [25]. The same authors later evaluated the user-defined gesture set against a gesture set created by designers [13], showing that the user-defined set, compared to the designer-defined, was easier for other users to assimilate and master.

Previous work on guessability also shows how users would focus on familiar gestures even if explicitly asked to create new ones [14]. Recently, this method has been used to develop a user-defined gesture set for augmented reality (AR) applications [16,17]. We believe that this methodology can help us investigate gestures for elastic, deformable displays by letting participants suggest fitting gestures for specific tasks, as well as understanding the nature of their choices by the use of a think-aloud protocol.

3. STUDY

This section describes a guessability study performed on an elastic, deformable display. We base our method on the guessability studies mentioned above, in particular the work of Piumsomboon et al. [17], and Wobbrock et al. [25]. The goal is to investigate what gestures users produce on an elastic display that affords deformation, as well as how users take advantage of deformability and depth for input.

3.1 Participants

Participants were recruited among students and professionals at our university. A total of 17 people participated in the study, 13 participants were male and 4 were female. 14 participants had previous experience with multi-touch devices. The average age was 24.7 years (*SD* = 4.8) and all participants were right-handed. At the end of the session, participants received a gift as a compensation for their time.

3.2 Apparatus

We developed a prototype of elastic, deformable display for the study. To choose the material for the surface of the prototype, a pre-study was run with 10 participants to test five different materials. The materials were (1) a rubber sheet made of latex, (2) a mixture of cotton and elastane (95% cotton, 5% elastane), (3) a mixture of cotton and spandex (90% cotton, 10% spandex), (4) a mixture of polyester and spandex (92% polyester, 8% spandex) and (5) a mixture of lycra and elastane (90% lycra, 10% elastane).

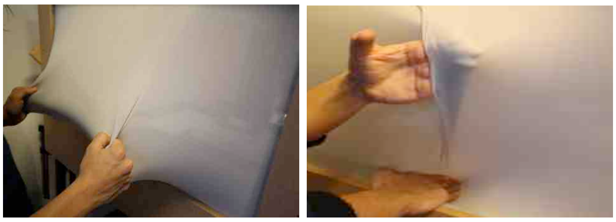

Figure 1: Two pictures that show the elasticity of the material.

Participants chose the mixture of lycra and elastane (90% lycra, 10% elastane) as the best material due to high resistance, stretchability, and smoothness. Figure 1 shows the material. The final prototype to be used in the study was made with a rectangular piece of lycra and elastane attached to a wooden frame. The surface was measuring 76×47 cm, with visual contents rear-projected at 1280×768 pixels.

The software Preview was used by the experimenter to easily switch between tasks using a remote clicker.

Four cameras placed at four different angles were used to record each session. The cameras were placed (a) to the right of the display, (b) to the left of the display, (c) behind the display, and (d) on the side of the display. Figure 2 shows both the prototype and the video recorded by the cameras.

Figure 2: The prototype of an elastic, deformable display used in the study (left). The video recorded by the four cameras (right).

3.3 Tasks

Participants were presented with 29 tasks. For each task two pictures were shown, indicating the *start-state* and the *end-state* of a certain action. After being shown the pictures, participants were asked to perform a fitting gesture. To make each task clear, a text at the top left of the display showed information indicating the purpose of the task. For instance, if the task entailed taking a cube and moving it closer, the text on the display would show the sentence "Bring the Cube Closer". Figure 3 shows an example of a task.

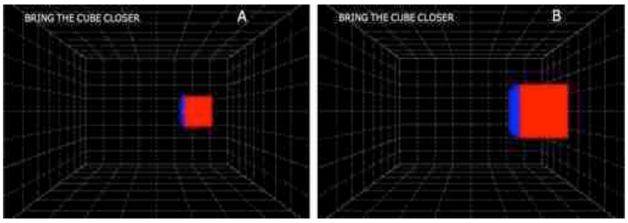

Figure 3: An example of a task. Picture A (left) shows the *start-state*; picture B (right) shows the *end-state.*

To create the set of tasks for the present study, we have used 2D tasks, 3D tasks, and tasks based on previous work on elastic, deformable display. 2D tasks entailed navigating maps, scrolling text, and editing objects (e.g., select, copy, cut and paste). 3D tasks were inspired by 3D modeling applications, as well as applications used in previous work with elastic, deformable display. They included displacing and rotating geometrical shapes in 3D space [23,33], spreading and gathering small objects [15,29] and creating magnifying lens effect [2].

Table 2 shows the 29 tasks used for this study. The objects that the participants manipulated during the tasks were all generic geometrical shapes (e.g., squares, cubes, circles, spheres).

3.4 Qualitative Data Collection

During the task, participants were asked to explain their choices by thinking aloud. After the completion of each task, participants rated their gesture on two 7-point Likert scales: (1) The gesture was a good match for its intended use (2) The gesture was easy to perform. The scales were taken from Wobbrock et al. [25].

Table 2: The 29 tasks presented to the participants. Transform, Selection, 3D modeling, and simulation tasks are inspired by [15,23,33]

Category		Tasks		Inspired by
Transform	**Move**	1.	Bring Object Closer	Watanabe et al. [23]
		2.	Move Object Horizontally	
		3.	Move Object Back	
	Rotate	4.	Rotate X (Roll)	Watanabe et al. [23]
		5.	Rotate Y (Pitch)	
		6.	Rotate Z (Yaw)	
	Scale	7.	Resize Bigger	Watanabe et al. [23]
		8.	Resize Smaller	
	Mixed	9.	Rotate and Transform	N.A.
Selection		10.	Select All	Wobbrock et al. [25]
		11.	Select Multiple	
		12.	Select Single	
Navigation		13.	Pan	Wobbrock et al. [25]
		14.	Pan and Zoom In	
		15.	Pan and Zoom Out	
		16.	Zoom In	
		17.	Zoom Out	
3D Modeling		18.	Deformation (1)	Watanabe et al. [23], [33]
		19.	Deformation (2)	
		20.	Deformation (3)	
Editing		21.	Create	Wobbrock et al. [25]
		22.	Delete	
		23.	Cut and Paste	
		24.	Copy and Paste	
Simulation		25.	Gather	Peschke et al. [15], [29]
		26.	Spread	
		27.	Inflate	
		28.	Magnifying Lens	
Browsing		29.	Scroll	N.A.

3.5 Procedure

Participants were welcomed and introduced to the purpose of the study, the structure of the session and the apparatus. Before proceeding to the session, participants read and agreed to a consent form. A brief warm-up phase introduced them to the material. During the warm-up, participants were asked to pinch, pull, push, and grab the display, as well as performing a trial task (i.e., moving a drawing of a car from the right to the left of the display). The warm-up phase was intended to make participants familiar with the material and let them get a sense of gestural possibilities. When ready to proceed, participants were asked to complete the 29 tasks.

The tasks were presented in random order. Each picture was displaying a letter on the top right, indicating picture A as the *start-state* and picture B as the *end-state* (see Figure 3). When the transition returned to the *start-state*, participants were asked to suggest a fitting gesture by performing it on the display. The transition could be repeated as many times as the participant asked for and no restrictions were applied on performing gestures with one or two hands.

While performing the gestures, the participant also explained his/her choice by thinking aloud. After the gesture was performed, the participant rated the suggested gesture on the two 7-point Likert scales. The two elements were presented on the display after the completion of the task. The participant was asked to do rating by pointing with the finger at the score on the scale and explaining the rating.

4. ANALYSIS

The software Observer XT 11.5 was used to analyze the videos recorded during the study. We also transcribed think-aloud explanations and subjective ratings using the same software. The coding of gestures was done using Excel. The video for each participant was divided into short sub-videos of individual tasks and then re-organized in correspondent folders (e.g., all the sub-videos of the task “Bring the Cube Closer” stored in a folder with the same name).

4.1 Coding the Gestures

A coding manual was created through an iterative process. Each task was analyzed, and a new definition of gesture was generated and added to manual whenever needed. The basis for coding was understanding gestures as being composed of *actions*. A single action would be *grabbing* or *pushing*. The table below shows the complete list of actions sorted by frequency of repetition.

Table 3: The type of actions performed by participants during the study (total number of tokens 906)

Action	Freq(%)	Action	Freq(%)
Push	18	Stretch	1
Drag	12	Gather	1
Expand	9	Release	1
Grab	9	Lasso	0,9
Pinch	8	Punch	0,7
Pull	6	Tilt	0,6
Hold	5	Follow the contour	0,4
Rotate	3	Slice	0,3
Shrink	3	Throw	0,3
Draw a shape	3	Draw a line	0,2
Swipe	3	Slingshot	0,2
Tap	3	Round a shape	0,1
Twist	2	Rub	0,1
Squeeze	2	Spread	0,1
Slide	1		

Along with actions, the number of fingers used in the performed action was coded. If more than three fingers were involved in the action, number of fingers would have been coded as *whole hand*. After the coding manual was finalized, one author coded all the tasks, while a second author independently coded a sub-set of tasks (10% of the whole set). An inter-rater reliability analysis was performed using Cohen’s Kappa statistic to determine consistency among raters. The inter-rater reliability for the raters on *Actions* was found to be Kappa = 0.84 ($p < 0.01$), 95% *CI* (0.7490, 0.9406), while *Fingers* was found to be Kappa = 0.76 ($p < 0.01$), 95% *CI* (0.6084, 0.9124).

4.2 Agreement Score

In order to calculate consensus among the suggested gestures, an agreement score A was calculated with the following equation:

$$A = \sum_{P_s} \left(\frac{|P_s|}{|P_t|} \right)^2$$

where P_t is the total number of gestures performed within the task, t, and P_s is a subset of similar gesture from P_t, and the range of A is [0, 1]. The equation is taken from Piumsomboon et al. [17]. Our definition of similarity is based on previous work [17], where the metrics used to define similar gestures are minor variations of *hand poses* and *path*. Let us consider as an example the agreement for the task *Select Single*. For this task we compute:

$$A_{Select\ Single} = \left(\frac{12}{17}\right)^2 + \left(\frac{4}{17}\right)^2 + \left(\frac{1}{17}\right)^2 = 0.55$$

The agreement score for all tasks is plotted in Figure 4. The maximum score was reached in *Scroll* task (A = 0.58), whereas *Deformation (3)* reached the minimum agreement score (A = 0.05). For certain tasks, participants reached a better agreement in two-handed gestures than they did for one-handed ones. These tasks were specifically: *Gather, Spread, Zoom In, Zoom Out* and *Pan and Zoom Out*.

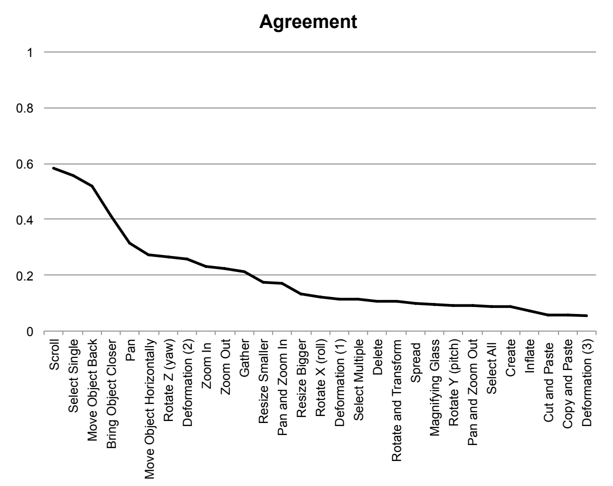

Figure 4: Plot of the agreement score.

5. RESULTS

A total of 493 gestures were generated from 17 participants performing 29 tasks. For each participant, data collection included video and audio recorded from the four cameras placed around them. A user-defined set of gestures is outlined as a result of the study. Also, subjective rating, transcription of think-aloud and qualitative data from semi-structured interviews are reported.

5.1 User-defined Gesture Set

We construct the user-defined gesture set from the group of similar gestures that obtained the largest agreement score for a particular task. We define the gesture identified from the group with the largest agreement as the *consensus gesture*. Therefore, this section describes a user-defined set made of 27 consensus gestures. The 27 gestures are assigned to 25 tasks. The tasks *Cut and Paste, Copy and Paste, Rotate Y (pitch)*, and *Deform (3)* were not assigned any gesture, because participants could not reach an agreement in those tasks.

To make the user-defined gesture set conflict free, consensus gestures that were identical or similar could be assigned to different tasks only if they did not fall into the same category (see Table 2). For the tasks *Delete* and *Pan*, participants reached the same agreement score for more than one gesture. Therefore, these tasks were assigned two consensus gestures.

Of the 27 consensus gestures, 20 were unimanual, 5 bimanual and 2 were a combination of unimanual and bimanual, indicating that overall participants preferred one-handed interaction over two-handed.

By observing the gestures performed by participants, and by reading the comments they provided through think-aloud, we distinguish three main factors that affected the gestures produced during the study: (1) the influence of elasticity and deformation of the display, (2) the influence of previous use of multi-touch technology, (3) the influence of previous use of desktop computers. Next we discuss each of these factors in turn.

5.2 Influence of Elasticity and Deformation

In this section we discuss the consensus gestures that have been influenced by the elasticity and deformability of the display. Seven consensus gestures (26% of the user-defined set) were identified in which participants made use of depth and deformation to solve tasks such as 3D modeling or deformations. They are illustrated in Figure 5 and 6. When having to rotate, displace and deform objects, participants seem to treat the virtual objects as if they were physical, or used a metaphorical approach when lacking a physical reference.

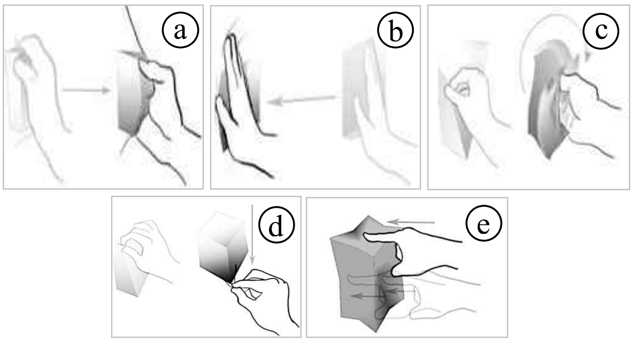

Figure 5: The gestures generated by participants using deformation and depth, where objects were treated physically: (a) *grab and pull*, (b) *push with flat hand*, (c) *grab and twist*, (d) *pinch and drag*, (e) *push with index finger*.

Grabbing, pulling, and pushing on the display (Figure 5a, 5b) were suggested by participants as fitting gestures to displace a cube back and forth in a three dimensional space. 35% of participants found these gestures physically intuitive and easy to perform: *"I can grab the object and pull it because it's an intuitive motion and the material can afford it"* – P3. Twisting the shape by physically twisting the display (Figure 5c) was also described as easy to perform on the elastic display. Furthermore, 41% of the participants said that the cube must be grabbed in the middle to obtain the deformation. A similar concern was expressed when rotating the cube on the x-axis (pitch), where the top corner was used as the point of rotation (Figure 5d). This shows how the geometrical properties of the objects influenced some of the gestures performed.

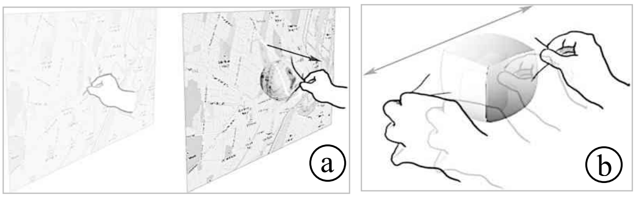

Figure 6: The gestures generated by participants using deformation and depth, where objects were treated metaphorically: (a) *pinch and pull*, (b) *grab and stretch.*

Five participants (29%) pushed with the index finger into the display to deform the sides of the cube in the *Deformation (1)* task (Figure 5e). Among them, two participants (12%) also wanted to deform the top and bottom sides of the cube: *"...I then grab and pull the bottom corner and push underneath, cause I imagine the bottom deforms too…"* – P6. This shows that when modeling 3D objects, these participants extended their perception of the object to the third dimension. Due to its deformability, the display could complement this perception also in a physical way.

A metaphorical approach was used to solve the task *Inflate*, where participants pinched and stretched the display (Figure 6b), hoping that the system would understand the motion and instantly inflate the cube. The deformability of the display was used also to create a magnifying lens on a map, where 18% of participants pinched and pulled the display (Figure 6a), hoping that the system would understand and magnify the deformed area of the display.

5.3 Influence of Multi-touch

In this section we discuss the consensus gestures that seem influenced by the use of multi-touch. We show that, although the prototype used for the study could be deformed, operations like navigation and browsing were solved with multi-touch inspired gestures. The multi-touch inspired gestures account for 62% of the consensus gestures in the user-defined set.

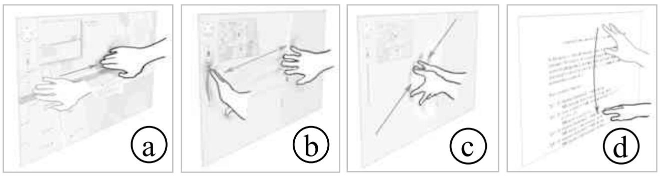

Figure 7: The gestures inspired by multi-touch in navigation and browsing tasks: (a) *drag with whole hand*, (b) *expand with two hands*, (c) *shrink with two hands*, (d) *swipe*.

For navigation tasks participants were mainly inspired by multi-touch interaction (Figure 7 and 8). In order to pan on a map, 52% of the participants suggested drag or swipe as fitting gestures (Figure 7a and 7d), and 30% explained that the use of iPad and Google Maps influenced their choices.

This also had an impact on other navigation tasks, namely *Zoom in*, *Zoom out*, and *Pan and Zoom* (Figure 7b, 7c, 8a, 8b): *"just like as you would zoom on tablet but with a bigger motion"* – P10; *"this is like how you do with maps on touch computers and big touch screens"* – P7. This shows how the massive use of multi-touch devices is shaping user's navigation techniques. However, it can be seen from Figure 7b and 7c how participants, while performing zoom operations, still applied force on the surface and slightly deformed it. In this case we had the impression that, while zooming on the display, participants also wanted to dig into the display. However, the use of depth was not totally intentional according to the participant's feedback, and therefore we did not include these gestures among the ones where the participants explicitly make use of depth.

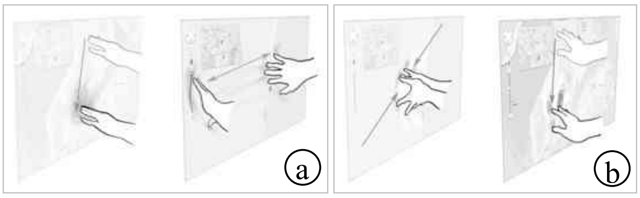

Figure 8: The gestures inspired by multi-touch that combined unimanual and bimanual actions: (a) *drag and expand*, (b) *shrink and drag*.

A swipe motion was suggested as a fitting gesture to scroll a text (Figure 7d), where 30% of the participants explained that they would scroll like in OS X or iOS systems (i.e. scrolling up to go down and vice versa), and 12% imagined a scrolling bar would appear on the side of the display when moving the text.

Gestures performed to resize and rotate objects were also influenced by multi-touch. In order to resize a cube and make it bigger, 35% of the participants chose to do it by placing the index and the thumb from the same hand on the corners of the cube, and expand it by moving two hands apart from each other (Figure 9b). However, only one participant explained that this gesture is similar to how one scales things on a multi-touch tablet.

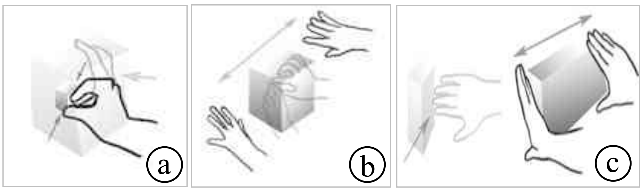

Figure 9. Gestures inspired by multi-touch to resize objects: (a) *shrink*, (b) *expand with two hands*, (c) *drag and expand.*

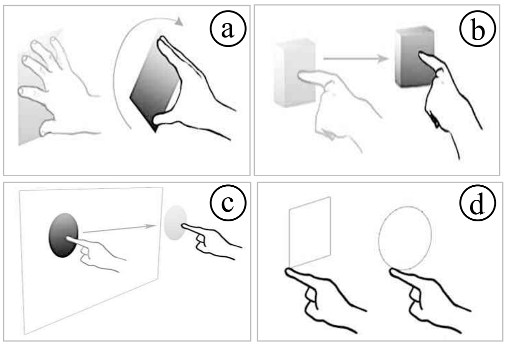

Figure 10: Gestures inspired by multi-touch rotate, move create and delete objects: (a) *rotate*, (b-d) *drag with index finger*, (c) *draw a shape.*

To resize a cube and make it smaller the one handed approach was slightly preferred, where all the five fingers from the hand were placed on the object and shrunk so as to make the object smaller (Figure 9a). To rotate (pitch) and stretch the sides of a cube in the task *Rotate and Transform*, 24% of the participants used a combination of *drag* to rotate and *expand with two hands* to stretch the sides (Figure 9c). The open hand pose was also used to rotate a cube on the z-axis (Figure 10a), where 47% of participants used the wrist as the center of rotation and rotated the hand around it in order to rotate a cube.

Delete, *Create*, and *Move Horizontally* were solved with one-point contact gestures inspired by touchscreen. To move an object horizontally, participants used the index finger in order to drag it (Figure 10b). They did likewise to delete an object (Figure 10c), but eventually dragging it outside the boundaries of the display. For these gestures 40% of the participants talked about touchscreen computers and smartphones, and 12% imagined a bin in the corner of the display.

To create an object, 35% of the participants drew the outline of what they wanted to create on the display the outline of what they wanted to create (Figure 10d). 33% of the participants optionally pulled or pushed the display after drawing the shape so as to extrude the form of the object, showing how the deformability of the display could be used to add third dimension to bidimensional contents. However, 30% wished a contextual menu to appear on the display, which could allow them to either create the object or to choose among options like color, size, and so forth.

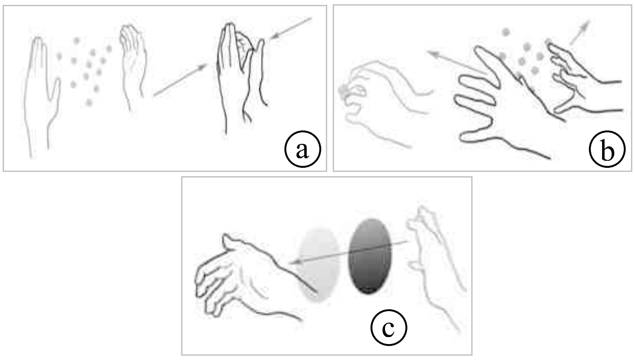

Figure 11: Multi-touch gestures that resembled real physical actions: (a) *gather*, (b) *grab and expand*, (c) *swipe.*

When gathering or spreading objects (Figure 11a, 11b), 47% of the participants referred to real physical actions, like making snowballs, squeezing beads in a plastic bag, or spreading small objects on a table, and two participants also talked about multi-touch gestures. When swiping to delete (Figure 11c), 18% of participants thought they were physically throwing an object out of the screen. This kind of physical approach is probably inspired by actions that participants would perform in the real world.

5.4 Influence of Desktop Computers

In this section we discuss the consensus gestures that have been influenced by previous use of desktop computers. We identified 3 consensus gestures of this kind (12% of the user-defined set). These gestures are illustrated in Figure 12.

In order to select a single object, 70% of the participants pushed onto them directly with their index finger (Figure 12a). This approach was explained by 35% of the participants with reference to point and click from desktop computers or tap selection from touchscreen: *"it is like pointing and clicking, I do the same with my computer, or like when I touch to select an icon on my tablet"* – P17. When selecting multiple objects, participants simply repeated the same gesture as many times as the number of objects to be selected (Figure 12b), while *Select All* was solved by 18% of participants with a lasso selection (Figure 12c). They all explained this gesture as similar to what they would do in a drawing program in order to select an area.

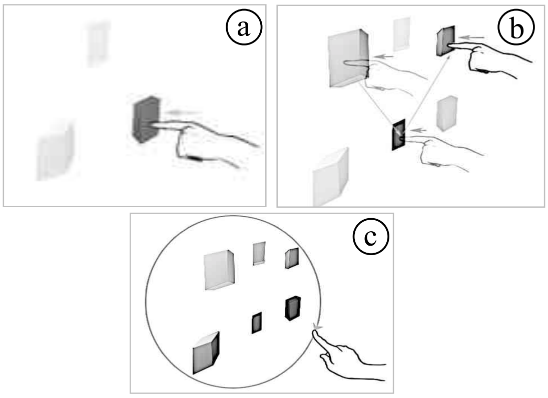

Figure 12: The inspired by desktop computers: (a-b) *push with index finger*, (c) *lasso.*

5.5 Subjective Rating

Subjective rating results show a correlation between ratings of goodness and of ease. The Pearson's correlation coefficient shows a very strong, positive correlation, $r(27) = 0.805$, $N = 29$, $p < 0.01$. This indicates that when a gesture was regarded as easy to perform, it was also perceived as a good match for the task, with goodness rated generally lower than easiness.

5.6 Semi-structured Interview

Comments from semi-structured interviews revealed that most participants (70%) enjoyed interacting with the surface of the prototype, and said that multi-touch gestures were easier to perform on it than on a glass display. Furthermore, 65% of participants explained that they pushed a bit the display also when performing multi-touch gestures because the surface naturally afforded it.

For 53% of participants grabbing or pinching the surface was hard, 23% said they would stick to known gestures from multi-touch and desktop computers, and 30% said elasticity and deformability would greatly enhance gaming. 18% of participants said they would like such a display to be real and commercialized, and two participants noticed that pushing and grabbing became harder if moving towards the corners of the display. Finally, one participant suggested that the deformable display could have the shape of a cube, so that one could interact by fully pushing the hands inside of it.

6. DISCUSSION

Earlier work on elastic, deformable displays have used gestures such as push, grab, pinch, and pull. Our results show gestures that produced more extreme deformation of the display, such as twist and stretch. Watanabe et al. [23] showed how moving virtual objects far from the self in a three dimensional space could be mapped to push gesture. We show that the reverse action can be mapped to grab and pull gesture. Also, we show how participants, when manipulating 3D objects in a 3D context are likely to use deformation and depth for input. This result confirms that interacting with 3D modeling applications, as proposed in earlier work [20,23,27], can be enhanced on elastic, deformable displays.

Similarly to Wobbrock et al. [25], our agreement scores show that tasks involving simple actions (e.g., moving objects, selecting, scrolling) reached higher agreement than tasks involving complex actions. However, our results also show that actions happening in the three dimensional space, such as moving an object back and forth, reached higher agreement. This means that experience with multi-touch has just partially influenced the level of agreement among participants. This becomes clearer when observing tasks that, despite being solved with multi-touch alike gestures, were rated lower because of their conceptual complexity (i.e., create, select all).

Besides gestures from the user-defined set, like twisting and stretching, participants performed other types of interesting gestures, but these were not included in the final results because participants did not agree on them. For instance, some participants used the elasticity of the display to simulate a slingshot, others reached behind the display and pulled it to move objects closer. These gestures were not reported in previous work and they would be difficult if not impossible to perform on flexible displays like Flexpad [19] or Impress [33].

A substantial number of gestures from the user-defined set were inspired by multi-touch. This shows that the influence from already known interfaces had a strong impact on certain tasks. However, most participants accidentally used depth also for those multi-touch alike gestures. This may present issues when implementing a gesture recognition system. Preventing depth interaction from being accidentally triggered when unwanted, could be mitigated by using a threshold for depth or dynamic filtering techniques.

Implementing the recognition of gestures from this user-defined set can present other challenges besides the accidental depth issue. While bidimensional multi-touch gestures and depth detection can be achieved using existing approaches (e.g., blob tracking, depth sensor), detection of stretching, twisting, or folding the hand into the surface of the display would be harder. Developing a gesture recognition system that is able to recognize various deformations efficiently will require more elaborate techniques. The implementation of such system will be paramount to verify the validity of our results, and extend them beyond the present study.

Finally, we must consider sources of error and limitations in our approach. We have used a guessability study methodology, which has the advantage of not biasing users' choices. However, for certain tasks, like 3D modeling or simulation, participants explained that the lack of real time feedback made it really hard to find a suitable gesture. Furthermore, tasks that resembled multi-touch operations may have led participants to perform already known gestures. This suggests that for future studies a set of tasks specifically designed for elastic, deformable displays may be used.

7. CONCLUSION AND FUTURE WORK

We have presented a study of elastic, deformable display that outlines a user-defined set of gestures based on participants' agreement over 493 gestures. Using the agreement among the elicited gestures, 27 consensus gestures were selected to compose the user-defined set. We have also shown how previous use of multi-touch and desktop computers influenced choices in certain tasks, such as navigation, selection and scale. We will also conduct further studies to validate the user-defined gesture set and investigate those gestures that did not reach enough agreement. A new group of participants will try these gestures with interactive applications to confirm the validity of the consensus set, and hopefully better explain the gestures discarded in the present study.

8. ACKNOWLEDGMENTS

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Paper 2: Deformable Interfaces for Performing Music

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Deformable Interfaces for Performing Music

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ABSTRACT

Deformable interfaces offer new possibilities for gestures, some of which have been shown effective in controlled laboratory studies. Little work, however, has attempted to match deformable interfaces to a demanding domain and evaluate them out of the lab. We investigate how musicians use deformable interfaces to perform electronic music. We invited musicians to three workshops, where they explored 10 deformable objects and generated ideas on how to use these objects to perform music. Based on the results from the workshops, we implemented sensors in the five preferred objects and programmed them for controlling sounds. Next, we ran a performance study where six musicians performed music with these objects at their studios. Our results show that (1) musicians systematically map deformations to certain musical parameters, (2) musicians use deformable interfaces especially to filter and modulate sounds, and (3) musicians think that deformable interfaces embody the parameters that they control. We discuss what these results mean to research in deformable interfaces.

Author Keywords

Deformable interfaces; user interfaces; music; controller; usefulness; user study.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces.

INTRODUCTION

Deformable interfaces are emerging in the field of HCI, for instance as elastic displays [19], bendable smartphones [5], or soft controllers [11]. Because they are made of flexible materials, deformable interfaces allow for unique gestures such as crumpling [30], squeezing [9], and stretching [29], all of which would be impossible with rigid interfaces. Yet, it is unclear how and when deformable interfaces might be advantageous compared to rigid interfaces.

Existing prototypes of deformable interfaces have been used and evaluated mainly in the lab during controlled experiments [16]. While lab studies have helped to test prototypes in a systematic way, they provided little data on users' reactions in the wild or on the usefulness of deformations in a particular domain.

The present paper argues that a study of deformable interfaces conducted out of the lab would show more realistic use and responses from users, indicating when these interfaces can be useful and how they are used. We report such a study in the context of electronic music. We chose the music domain because much earlier work have explored deformable interfaces for music [4,7,10,26,35], and because performing music is a highly challenging and expressive real-time activity. Such a study will help understand how users take advantage of different materials, shapes, and deformations to control sounds.

To investigate the use of deformable interfaces for performing music, we run three workshops borrowing techniques from participatory design [3] to receive input from musicians on how to use deformable interfaces in music. Next, we give a set of interactive deformable interfaces to professional musicians, and ask them to use those to perform music at their studios. Also, to understand how musicians would incorporate deformable interfaces with their existing equipment, we allowed them to integrate the use of non-deformable interfaces (e.g., MIDI controllers) in their performances.

The present paper makes two contributions to research on deformable interfaces. First, we contribute design implications for deformable interfaces by reporting findings from three workshops on how different materials and shapes relate to musical features. Second, we contribute findings on the use of deformable interfaces out of the lab by reporting results from a performance study where musicians used deformable interfaces to play music and commented on their experiences. Since our primary goal is not develop new musical interfaces, we discuss how the results of the workshop and the performance study extend beyond the music domain and what they mean to research on deformable interfaces.

RELATED WORK

Deformable interfaces have been proposed as elastic displays [6,18,21,34], flexible and elastic hand-held devices [7,9,20,24,31,32], bendable smartphones [1,5,12,13], sponge and foam controllers [21,23], and music controllers [4,7,10,26,35]. Studies have shown how deformations can be used as input techniques for various applications in HCI,

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including depth navigation on mobile devices [5], animation [28], and 3D modeling [25]. Several studies have evaluated deformable interfaces, for instance by exploring the effect of interfaces size and materials stiffness on users' interaction [14,16], users' preferred gestures [15,17,29,32], and the use of multi-touch input on deformable surfaces [2]. However, deformable interfaces have not yet proven to suit a specific domain and possibilities for experimentation are still open. Since we evaluate deformable interfaces in music performances in the present paper, we focus the rest of this section on reviewing related work that introduces deformable interfaces to music.

Deformable Interfaces in Music

Table 1 shows a summary of the key related work on deformable interfaces used in music. We choose these papers in particular because they appeared either at NIME or CHI conferences, providing results for research on both musical interfaces and deformable interfaces. We discuss these deformable interfaces focusing on: (1) materials and deformations, (2) sensing technology, and (3) their use in relation to music.

Materials and Deformations

Deformable interfaces need to resist extreme deformations while being able to be controlled effortlessly. Therefore, materials used to build them need to be both robust and flexible. Foam is soft, robust, and affords well deformations like squeeze, push, and twist. Foam has been used to build cubic [11] and spherical [9,10] deformable music interfaces, which sometimes were also covered with fabric [35] or woolen yarn [9], so as to deliver organic feel in touch. However, foam is not very stretchable and stretch deformation, if too extreme, might feel uncomfortable or even break the material. Fabric can be more flexible than foam; for instance, materials like lycra or elastane can be allow for extreme stretching because they are very elastic. However, fabric can wear or tear with prolonged use [7]. Rubber and silicone can endure more than fabric with repeated use and have been used to build shape-retaining deformable interfaces [26,37]. They allow for easy bending or twisting, but they can be hard to stretch. Sculpton [4] used flexible metal springs and wooden spheres covered in latex to create a soft music controller in the shape of tetrahedron, allowing for squeezing, stretching, and pressing. Clay has also been used for musical interaction [33]; it is shape-retaining and can be broken and rejoined. However, the above listed materials have been presented to users only individually and no previous studies attempted to investigate how users understand or react to different shapes and materials that deform.

Paper	Materials and Deformations	Technology	Use
Sonic Banana [21]	Rubber, (bend, twist, stretch)	Bend sensor	MIDI Controller
The Embroidered Music Ball [29]	Fabric, conductive thread, (squeeze, stretch)	Pressure sensor	MIDI Controller
A Malleable Interface [11]	Conductive foam, (poke, twist, press, squeeze)	Conductive foam, copper wire	Sound Controller
A Malleable Device [18]	Paper board, rubber, wood, (press, push)	Camera sensor	Data Sonification
Clay Tone [27]	Clay, (stretch, twist, squeeze, press)	Camera sensor	Sound Controller
Zstretch [7]	Fabric, wood, (stretch, squeeze, twist)	Resistive strain gauges	Sound Controller
MARSUI [30]	Silicone, metallic wire mesh, (bend)	Bend sensor	Auditory Feedback
The Music Ball Project [10]	Sponge, (squeeze)	Microphone	Sound Controller
NoiseBear [9]	Conductive foam, woolen yarn, (stretch, squeeze, twist)	EEG electrodes, conductive thread	Sound Controller
Sculpton [4]	Wooden spheres, metal springs, latex, (squeeze, stretch, press)	Slide potentiometer, light dependent resistor (LDR)	Sound Controller

Table 1: Key related work and their main four characteristics

Sensing Technology

Sensing deformations presents various challenges. To sense deformations, a camera-based approach may be used, or materials need to be either conductive or embedded with sensors. Bend sensors were embedded in Sonic Banana [26] to sense bend and twist. However, bend sensors are fragile at their terminal part and can break with frequent use. To overcome this problem, MARSUI [37] used electrical semi-conductive tape as custom-made bend sensor. Kiefer used conductive foam to sense various degrees of pressure and squeeze [11]. NoiseBear [9] improved the robustness of Kiefer's design by adding conductive threads and cushion stuffing, so as to lower the latency of the conductive foam. Zstretch [7] used resistive strain gauges sewn at the edge of a lycra cloth in order to detect stretch. However, this approach presented problems over time, such as lowered sensitivity and the need for frequent repairs. Sculpton [4] embedded a slide potentiometer in its first version and light dependent resistor (LDR) in its second version, so as to detect when the springs are stretched. The configuration with LDR was functional but required several connections. Finally, two deformable interfaces have used a camera-based approach in order to sense deformations [19,33]. Camera-based approaches are good for prolonged use and can be effective, but deformations are sensed only when the interface is in the visual field of the camera.

Use and Evaluation

Earlier deformable interfaces for music, like Sonic Banana [22], were mostly used as MIDI controllers to manipulate sound parameters such as speed, pitch, and note duration. One quality that deformable interfaces showed in relation to music was their intuitiveness and ease of control. For instance, NoiseBear [35] supported simple squeeze interaction to control various sounds and it could be easily used by novices as well as experienced musicians. Other interfaces like Zstretch [7] showed how a stretchable controller could be used to manipulate volume, pitch, and speed in an alternative way. Sculpton [4] was used to control and generate sounds by stretching and squeezing the body of a soft tetrahedron and it was used by its creator for several live performances [39]. Kiefer used conductive foam to build a small cube-shaped interface [11] and evaluated it with eight musicians, who described Kiefer's interface as more expressive compared to regular knobs or faders. However, his study evaluated the interface only based on qualitative information, where participants were constrained to modify only specific sound parameters (i.e., phase modulation).

The deformable interfaces described above were mainly evaluated and used in the lab. Only few studies exist that are not lab-based (see [10,33]). Furthermore, users were never presented with different interfaces together, or asked how different materials and shapes affect musical interaction. Therefore, the empirical understanding of the use of deformable interfaces in music is rather one-sided in terms of methodology. To address these shortcomings, we organized three workshops to gather insights from professional and amateur musicians and a study out of the lab to investigate the use of deformable interfaces. In the next section we describe the workshops.

WORKSHOP

We conducted three workshops with nine musicians (three musicians for each workshop) on how to use deformable objects for music performances. The aim of the workshops was to inform us on how deformations could map to musical parameters and how different shapes and materials invite to musical interaction.

The structure of the workshops was based on principles of participatory design, focusing especially on activities such as experimenting with mock-ups, horizontal prototyping, thinking aloud, and brainstorming [3]. We decided to use the workshop method because it has proven to be effective when wanting users to explore and generate ideas on new technology [31]. Findings from the workshops were used for designing the deformable interfaces to be used later in the performance study.

Participants

Participants were recruited among professional and amateur musicians experienced with electronic music. We recruited a total of nine participants. Four participants were DJs, while five were performing live electronic music; all of them were experienced with music production. Furthermore, four participants were experienced with building MIDI controllers and modifying electronic music devices through circuit bending. Eight participants were male and the average age was 29.7 (*SD* = 4.5). We ran three workshops with three musicians per workshop. At the end of each workshop, participants received a small gift as a compensation for their time.

Materials

Based on related work we developed a set of 10 non-interactive mock-ups (see Figure 1). Participants used the 10 mock-ups as the main inspirational tool throughout the workshop. Table 2 indicates the similarities and differences between the mock-ups and related work.

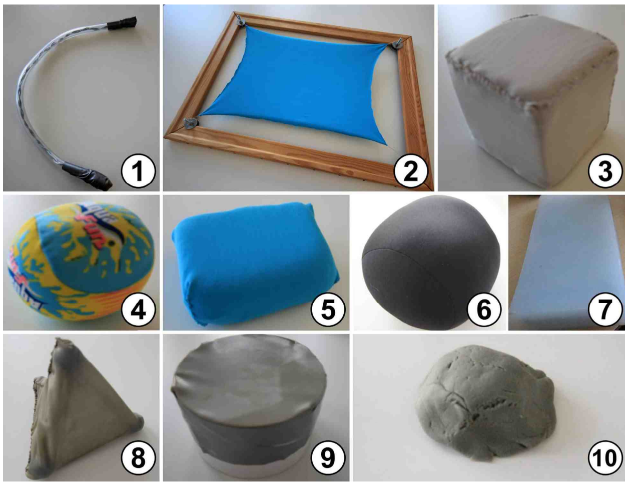

Figure 1: The object used during the workshop inspired by related work.

Workshop Set-Up

Each workshop was divided into three phases: (1) a *familiarization* phase, (2) a *simulation* phase, and (3) a *brainstorm* phase.

The *familiarization* phase was designed to introduce participants to the deformable objects. The goal of this phase was to let participants explore different materials and the deformations that they afforded. We encouraged the participants to start thinking about deformable objects as music interfaces already in this phase.

The *simulation* phase was designed to simulate possible real uses of the deformable objects for controlling sound. The goal of this phase was to receive suggestions from

No.	Paper	Original	Our Objects
1	Sonic Banana [21]	Orange rubber, 60 cm length	Transparent rubber, 60 cm length
2	Zstretch [7]	Green lycra fabric, wooden frame (36 cm length)	Blue lycra fabric, wooden frame (60 cm length)
3	A Malleable Interface [11]	Conductive foam, cube shaped, hand-sized	Foam, cube shaped, fabric covered, hand-sized
4	The Embroidered Music Ball [29]	Cushion stuffing, conductive foam, woolen yarn covered, hand-sized	Cushion stuffing, foam, fabric covered, hand-sized
5	The Music Ball Project [10]	Ball shaped sponge, rectangle shaped sponge, hand-sized	Ball shaped sponge, rectangle shaped sponge, hand-sized
6	NoiseBear [9]	Conductive Foam, Woolen Yarn	Stretch, Squeeze, Twist
7	MARSUI [30]	Blue silicone + metallic wire mesh, size N.A.	White silicone + metallic wire mesh, 18 cm
8	Sculpton [4]	Wooden spheres, metal springs, red latex, hand-sized	3D print spheres, metal springs, grey latex, hand-sized
9	A Malleable Device [18]	Paper board cylinder (16 cm radius, 7 cm height), transparent rubber, wood	Plastic cylinder (16 cm radius, 7 cm height), grey latex
10	Clay Tone [27]	Clay	Clay

Table 2: Differences and similarities between related work and our objects.

participants on how deformations could map to different musical parameters. During this phase a selection of sounds was played, which participants were asked to map to deformations. Each time a sound or an effect was played the participants picked a deformable object and suggested a potential deformation for that specific sound. Participants explained their choices by thinking aloud. The sounds played during this phase were: (1) generative sounds (keyboard, drums), (2) samples and loops, (3) sound modulations (volume, pitch, tempo, frequency), (4) filters (low pass, band pass, high pass), and (5) sound effects (delay, reverb, chorus, flanger, distortion, bit-crush). We used sounds from the default set of most electronic music software (e.g., Ableton Live®, Logic Pro®).

Finally, the *brainstorm* phase was included to let the participants generate ideas on how to use deformable objects for performing music. The goal of this phase was also to understand which of the 10 deformable objects the participants would use for real music performances. To help participants generate ideas, we used various support tools such as big paper sheets and colored post-its. We instructed participants to only generate ideas based on the 10 deformable objects used in the workshop.

Procedure

The participants were welcomed and introduced to the set-up, the workshop's purpose, and its structure. The workshop started with the *familiarization* phase, where participants could explore the deformable objects for 15 minutes. Then after a five minute break, participants went through the *simulation* phase for 50 minutes. After this, participants took another five minute break before going to the *brainstorm* phase. The *brainstorm* phase lasted 40 minutes.

Analysis

We used Microsoft Excel to code the videos recorded during the workshops. We coded each instance of deformation suggested by participants that related to musical parameters. For instance, if a participant suggested a twist deformation to apply more effect to a sound we would code this as "Twist to Increase Effect". All the instances of deformation were coded by one author and grouped into clusters, where each cluster contained identical instances of deformation-to-musical parameters.

We transcribed participants' think-aloud comments on how physical features of materials and deformations related to music (e.g., stretching the surface of a cloth would change the speed of the tempo). From those transcriptions, we identified trends and report the most interesting comments. We discuss these findings in the next section.

FINDINGS FROM THE WORKSHOPS

In this section we discuss: (1) how the participants mapped deformations to musical parameters, (2) how the participants described physical properties of deformable objects in relation to music, and (3) what deformable objects from the set the participants would use for real music performances.

Deformations to Musical Parameters

During the *familiarization* and the *simulation* phases the participants provided many suggestions on what actions to perform when playing music with deformable objects. We have identified two major trends among their suggestions, namely using simple surface contact (e.g., tap, poke, push) to generate sounds, and using object deformation (e.g., twist, stretch, bend) to modulate or applying effects to sounds..

Sound Generation

When suggesting how to play keyboard notes or drum sounds, the participants mostly tapped or poked the surface of deformable objects. Participants explained that in order to generate sounds one does not need to use complex deformations. Instead, a simple contact with the object would be enough to play a sound. Participants said that any of the objects could be used for that purpose. These results are obvious with respect to the participants' previous experience with rigid musical interfaces, in which they mostly use tapping, poking, or plucking strings to generate sounds.

Sound Manipulation

While sound generation involved mostly tapping and pushing, the participants deformed the body of the objects in many different ways when simulating sound effects and modulations. Participants generally explained that applying effects or modulating sounds has a strong analogy with sculpting or modeling physical objects.

Six participants twisted an object to increase or decrease the amount of a sound effect. According to a participant, this deformation was inspired by previous experience with knobs embedded in synthesizers and MIDI controllers. Six participants suggested stretching to modify the pitch of a sound. One participants said that pitch can be stretched to become higher or squeezed to become lower: *"I think that a stretched surface 'feels' and 'looks' like a high pitched sound, because the sound also sounds stretched"*. Two participants also showed how stretching could be used to apply reverb effect to sounds, where stretching would increase the room size or the amount of reverb.

Three participants suggested *pressing* down the body of an object to increase tempo and three participants suggested the same deformation to filter sound frequencies with high pass (HP) or low pass (LP) filters. In the case of tempo, they all explained how compressing an object should also compress the duration of a sound, thereby increasing its speed. In the case of filters, participants explained that by pressing down the body of the object they would either cutoff sound frequencies or emphasize them.

Six participants showed how *squeezing* an object in one or two hands could be used to crush or distort a sound. One participant explained the relation between squeezing and sound destruction like this: *"I can imagine that if I squeeze* *the object completely I will have a distorted or crushed sound. I think it's because it physically resembles the sound that I hear, because it feels like I'm destroying the sound in my hands".*

One participant showed how pushing a latex membrane upwards would emphasize certain frequencies, while pushing it downwards would cut frequencies (see Figure 2). The participant explained: "*When I push up, the latex has the shape of a peak, so I imagine this would emphasize the frequencies, whereas pushing it down should do the opposite and cut the frequencies".*

Figure 2: A participant pushing upwards and downwards on a latex membrane to manipulate sound frequencies.

We can conclude that the participants saw the deformable objects and their deformations mostly as tools for sound filtering and modulation. This suggests that a deformable interface may be useful in music performances to model and dynamically change the sonic characteristics of pre-generated sounds.

Physical Properties of Objects Related to Music

Participants were presented with both objects that retained shape and objects that did not. Participants used this property in order to simulate different musical interactions.

Non Shape-Retaining Objects

Some materials would return to their default state (shape) after being deformed. Participants explained how this property could be used to generate dynamic or automated sound events. For instance, two participants showed how non shape-retaining objects could be used to generate dynamic changes of volume. They did so by pressing on the surface of an object and explained: *"While I press down the volume is loud and we can hear the note. Then I release the surface and the faster the material goes back to its default state, the faster the volume decreases".*

Figure 3: A participant modeling the silicone object to generate different waveforms.

Surface vibration was suggested to control dynamic sound modulations, for instance like vibrato or low frequency oscillations (LFO). One participant commented: *"I can shake the cloth and control sound oscillations in this way. But it also vibrates for a while after I touched, and somehow it feels like the surface is alive".*

Shape-Retaining Objects

Participants explained how shape-retaining objects could be used to "lock" sound parameters or to generate sound automations. For instance, one participant showed how the silicone object could be bent and locked in place to generate loops or modeling waveforms (see Figure 3).

Because clay can be torn into pieces, participants showed how this material could be used to break a sound into smaller parts (i.e., smaller sound samples). For instance, one participant showed how this feature could be used to perform what in electronic music is known as "granular synthesis".

We conclude that participants would make a distinct use between objects that retain and do not retain shape, were the former would be used to lock sound parameters, and particular types of synthesis or automated looping events, while the latter would be used for expressive control and dynamic events. However, we have noticed that participants slightly preferred non shape-retaining objects, which were mostly inspiring participant's ideas in the *brainstorm* phase.

Preferred Deformable Objects

During the *brainstorm* phase participants showed a particular interest for 5 of the 10 deformable objects, especially objects number 2, 3, 6, 7, and 8 from Figure 1. Most of the ideas produced during the brainstorm focused on these objects. Also, participants suggested what deformations would be best to use with those objects. Object 2 was preferred for stretching, while 8 was preferred for twisting. Objects 3 and 6 were preferred for pressing and squeezing, respectively. Finally, object 7 was preferred for bending. Therefore, we embedded sensors into the five objects that were preferred by the participants and made them interactive for the performance study.

PERFORMANCE STUDY

The performance study aimed to investigate how deformable interfaces are used for music performances out of the lab. Our approach to the performance study was inspired by studies of interactive interfaces in the wild [22]. We were particularly interested in how musicians perform music with deformable interfaces in a realistic environment and how they describe their experiences about using them. We asked six musicians to use five deformable interfaces in order to perform some music piece at their studios. With this study we wanted to investigate the following questions: (1) How are deformable interfaces used out of the lab to perform music? (2) What are they used for? (3) Do they change the feeling of control? (4) Are deformations systematically mapped to specific parameters? (5) Do musicians find deformable interfaces useful to play music?

Participants

Six professional musicians, all male, with an average age of 35 (*SD* = 8.8) participated in the study. Participants had between 5-25 years of experience with live performance or studio production of electronic music. None of the participants took part in the workshops or had previous experience with deformable interfaces. At the end of the session, participants received a gift to compensate for their time.

Apparatus

The set-up included interactive versions of the five preferred deformable objects (see Figure 4) as well as the musicians' own equipment (e.g., MIDI controllers, studio recording devices, laptops).

We embedded force resistive sensors (FRS) into objects 1 and 2, in order to sense when participants pressed or squeezed them. Two conductive rubber chords were sawn on the back of object 3 to sense stretch in both vertical and horizontal orientations. A single flex sensor was embedded into object 4 to sense bend deformation. Finally, we placed a rotary potentiometer inside object 5 to sense twist deformation. All the sensors were soldered to cables, plugged into a breadboard and connected to an Arduino Mega 2560, in order to send sensors' signal to the laptop. We enclosed the Arduino Mega and the breadboard in a laser cut casing.

We processed the signal coming from the Arduino Mega with the software Pure Data, using the Firmata library and Pduino, before sending the signal to the computer. In order to broadcast input from the objects as MIDI data we scaled sensors' input to values between 0 and 127 (the standard MIDI value range). In order to reduce signal noise we averaged the sensors' values over 20ms. Since we deliberately did not investigate multi-dimensional input control in the performance study, we programmed each object to sense only one type of deformation.

Procedure

The study had two primary activities: (1) mapping musical parameters to the deformations afforded by the deformable interfaces, and (2) using the mappings to perform a music piece of maximum five minutes.

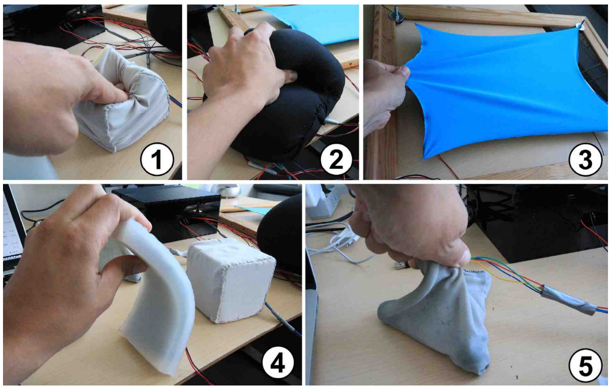

Figure 4: The deformable interfaces used during the performance study.

Before the study, participants were asked to prepare musical material for their five minutes performance and make sufficient space in their studios to use the deformable interfaces. However, we did not ask the participants to organize their performance set-up in any particular way, but rather let them choose their own space configuration. Furthermore, we instructed all the participants to download and install the software required in order to receive input from the deformable interfaces (i.e., Pure Data, Arduino and Processing).

Once at their studios, we explained to the participants the purpose of the study and introduced them to the deformable interfaces. We started by showing the participants what deformations the interfaces could support and how to control MIDI events. We guided participants through the mapping of deformations to sounds until they could handle this process autonomously. We did not impose any constraints on which musical parameters participants could choose to map. Moreover, we allowed them to use their existing studio equipment together with the deformable interfaces.

All the participants choose to control MIDI events and sounds parameters with the music software Ableton Live®. When participants were satisfied with their configuration they could start performing music. As previously said, the performance could last for a maximum time of five minutes. We imposed this time constraint to emulate the pressure of a real performance and to force the participants to perform a coherent music piece rather than randomly exploring the objects.

Once participants finished their performance, we concluded by interviewing them on their experience about using the deformable interfaces.

Data collection

We collected data for further analysis by video recording the participants' performances, as well as by storing the sensors' values in log files. Log files included timestamps (milliseconds) and streamed values from sensors sampled at a rate of 100 samples per second. Finally, we collected qualitative information from participants by video recording their interviews.

Analysis

One author coded the videos and transcribed the interviews using Microsoft Excel. From the videos we coded instances of mapping between deformations and musical parameters. Moreover, we analyzed the videos of participants' performances, focusing on how deformable interfaces were used to perform music and how they were integrated with existing instruments. Finally, we analyzed the data from the log files using MatLab, in order to investigate how long each deformable interface was used for and the how their values were controlled.

RESULTS FROM PERFORMANCE STUDY

In this section we report on (1) how participants performed music using deformable interfaces, (2) which deformations map to which parameters, (3) the time spent using each interface, and (4) how the interfaces were controlled.

Use of Deformable Interface

All participants took advantage of the haptic and tactile feedback of the deformable interfaces to quickly retrieve the sounds that they wanted to control. These observations were confirmed by the participants' comments. For instance, one participant said: *"I was looking for the low pass filter while I wanted to modify something in the program. I remembered that the filter was mapped to the squeezing ball, so I just touched the objects until I found the round shape and started to squeeze it to control the filter*" – P2.

We observed some cases where participants would use the flexibility of interfaces in a particular way. For instance, one participant mapped the pitch to bend deformation with the silicone object (Figure 4, object 4) and in order to generate a vibrato effect, he started to deform the interface with a wavelike movement. This particular use of the deformable interface supports the observation of some participants that these interfaces differ from knobs and faders present on most music controllers: *"This objects are different from faders and knobs. They make you feel like you are holding the sound in your hands and you can actually shape it"* – P3.

Because one deformable interface had springs inside and it would spring back fast if released (see Figure 4, object 5), one participant used this feature to generate quick changes in pitch; he commented like this: *"It is nice that this one springs back so fast to the center, it's dynamic and I can modulate the pitch fast. It generates an interesting conversation between the performer, the interface, and the sound"* – P1.

When we questioned participants about precision of control, they all said that it was not a concern for them during the performance, and that they rather focused on the expressive possibilities of the interfaces. We observed, however, that participants would initially monitor the sensors' values on the display. As they progressed through their performances they focused more on using the deformable interfaces and stopped looking at the display.

We observed that sometimes participants would use two or more interfaces simultaneously to modify different sounds at the same time. Five participants often used the pressing and squeezing interfaces simultaneously (Figure 4, object 1 and 2) in order to control two parameters of the same modulation or filter (e.g., the rate and the amount of a LFO). Twist and bend were also controlled together by four participants, where bend was used to modulate a sound (e.g., pitch, filter) and twist to apply effects (e.g., delay, distortion). Eventually, two participants managed to use three interfaces simultaneously, involving the use of one hand and the forearm to press and squeeze two interfaces at the same time while bending another one in the other hand.

Finally, it was interesting to notice that, even though participants were never instructed to use deformable interfaces only to control filters, effects, or modulations, they used them exclusively for those purposes. Therefore, the way participants incorporated deformable interfaces in the instrumental set-up was mainly as tools to filter or manipulate sounds, whereas the MIDI controllers and keyboards were used only when the participants wanted to trigger notes or samples.

Further Comments

All participants described the deformable interfaces as objects that embody the sounds, stressing out how the elements of a sound would be directly transposed to the interface and become physical: *"It feels like the object itself is somehow embodying the sound"* – P3.

All the participants found the deformable interfaces useful for playing music and also more inspiring and expressive than rigid interfaces. Four participants said that they would use deformable interfaces as a performative tool during live performances, while two participants would use them as creativity tools in the studio to be inspired during composition. All participants described deformable interfaces as very intuitive, easy to learn, and fun to play with. Finally, all participants described the deformable interfaces as having a more organic feel compared to rigid interfaces.

Mappings

Table 3 shows mappings between deformations and musical parameters defined by the participants. Participants mostly used the deformations to control filters and modulations.

Filters were used the most with high pass filter (HP) and low pass filter (LP), mapped overall eight times. These filters were mapped mostly to press, squeeze, and bend deformations. Participants modulated the volume and the frequency of sounds with low frequency oscillation (LFO); this modulation was mapped five times to either press or

P	Press	Squeeze	Stretch	Bend	Twist
P1	Volume (Increase)	Bit Crush (Amount)	Reverb (Amount)	Pitch (Transpose)	Pitch (Transpose)
P2	LFO (Amount)	LFO (Rate)	LP Filter (Cutoff)	LP Filter (Cutoff)	Delay (Feedback)
P3	HP Filter (Cutoff)	FM(Rate)	Beat Repeat (Note Interval)	LP Filter (Cutoff)	Delay (Feedback)
P4	LP Filter (Cutoff)	LP Filter (Cutoff)	Delay (Feedback)	Pitch (Transpose)	Distortion (Amount)
P5	LFO (Amount)	LFO (Rate)	Reverb (Amount)	Pitch (Transpose)	Panning
P6	LP Filter (Volume)	LP Filter (Cutoff)	LFO (Rate)	LP Filter (Cutoff)	Beat Repeat (Note Interval)

Table 3: Mappings between deformations and musical parameters.

squeeze deformations. The predominance of filters and modulations among the mappings confirms the idea emerging during the workshops that deformable interfaces are best for sound manipulation.

Bend was the most frequently used deformation to control pitch, while twist was used the most to control effects, such as delays, distortions, and beat-repeat. These uses also relate to findings from the workshop, where participants associated bend with pitch modulation and highlighted twist as a good deformation to control the amount of effects. Finally, stretch deformation was mostly used for effects such as reverb and delay.

Usage Time

Figure 5 shows how much each interface was used on average. This results shows that participants tend to use all the interfaces during their performance, with a slightly higher preference for pressing interaction (22.2% of the time) and less preference for stretching (15.9% of the time).

Control of Values

To understand how participants controlled the interfaces during their performances, we looked at the values registered by the embedded sensors, expressed as a percentage from not actuated (0%) to fully actuated (100%). Results showed clear trends for press, squeeze, and stretch, where most time was spent on the highest value (i.e., 100%), with respectively 9% of the time for press, 24% of the time for squeeze, and 26% of the time for stretch. These results suggest that press deformation was used less aggressively compared to squeeze and stretch.

DISCUSSION

We have collected reactions from nine musicians to 10 non-interactive objects and investigated how six musicians would use deformable interfaces to perform music. Overall, our results confirmed the usefulness of deformable interfaces in the musical context. Next, we discuss our results in detail, point to limitations of the present paper and outline future work.

Feeling of Control

One goal of our study was to investigate how deformable interfaces change the perception of control. However, few musicians commented on the precision and level of control of the deformable interfaces. Instead, musicians highlighted their ability to inspire and how they allow for serendipitous discoveries and epistemic actions [24]. The musicians also valued the haptic and tactile feedback provided by the deformable interfaces. The analysis of the log files showed that the deformable interfaces led to different interaction behaviors. For example, squeezing caused more extreme interactions than pressing. However, more studies are needed to investigate whether these implied behaviors are specific to the musical domain or to deformable interfaces in general.

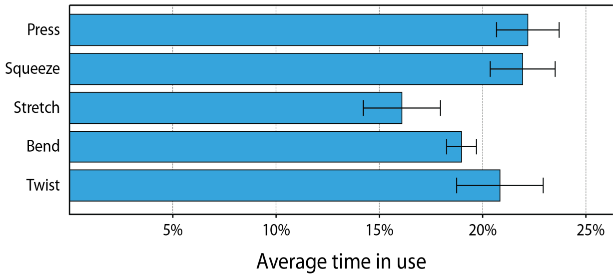

Figure 5: The average time spent by participants using each deformable interface.

Embodiment and Strong Specificness

Another important finding from the performance study is that the musicians see a stronger relation between action and effect when using the deformable interfaces than when using a regular controller. The deformable interfaces left the impression of *"having the sound in the hand"* and some musicians reported that the deformable interfaces made it easier to remember mappings than regular controls. These comments are supported by our observation of clear trends in how deformations and filters were mapped – both across individual musicians and between the workshop and the performance study. This suggests that deformable interfaces share qualities described in studies of tangible user interfaces as embodiment facilitation [24] and strong specificness [36].

Shapes, Materials, and Deformations

We found that shapes and materials played a key role for participants in both the workshop and the performance study. The haptic qualities of different materials influenced the way in which participants generated ideas on deformable interfaces and how they used them to perform music. Also, different shapes and materials implicitly suggested what deformation they would be best for. We found that these three characteristics (i.e., shapes, materials, deformations) determined how participants choose to use deformable interfaces to perform music. These results suggest that the combination of shapes, materials, and deformations are key for the design of deformable interfaces.

Limitations and Future Work

The present paper has a number of limitations, for which we aim future work to compensate. The aim of our paper was to understand differences between atomic deformations. As a consequence, the deformable interfaces were deliberately designed to support only one type of deformation. However, the capability to support many degrees of freedom is often highlighted as the prominent feature of deformable interfaces [28]. A natural next step would therefore be to merge the functionality of our five interfaces into a single deformable interface and investigate if and how this changes our findings. Second, while the performance study sought to emulate some of the pressure relating to performing music, it was still conducted in the relatively safe studio environment of the musicians. An interesting next step would be to perform a concert evaluation as Pedersen and Hornbæk [20], to investigate also how the secondary user group (i.e., the audience) experience the interfaces. Our study imposed a short time constraint (five minute) for musicians to perform with the deformable interfaces. With this approach we wanted to engage musicians in a realistic use of the interfaces rather than a random exploration. However, musical interfaces, especially if novel, may need a longer use to be assimilated by musicians. A logical next step would be to do a study where musicians train with the deformable interfaces for a longer period of time and finally go to perform live on stage with them.

CONCLUSION

Deformable interfaces afford new ways of interacting and open new possibilities for control. We have presented results from three workshops on deformable interfaces in music, and described how participants explain musical properties of shapes, materials, and deformations, and how they would use them to perform music.

With the performance study we investigated the usefulness of deformable interfaces for music performances out of the lab. We evaluated deformable interfaces with musicians performing music with a set of five deformable interfaces. The performance study showed that deformable interfaces are used mostly for sound manipulation and filtering, rather than for sound generation. They are also perceived as expressive and as embodying the sounds that they control. Finally, musicians used particular deformable interfaces for particular filters and effects.

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Paper 3: Sketching Shape-Changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances

Majken K. Rasmussen, Giovanni Maria Troiano, Marianne G. Petersen, Jakob G. Simonsen, and Kasper Hornbaek. Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances. *In Proc. CHI'16,* ACM Conference on Human Factors in Computing Systems, ACM, New York, NY, USA.

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Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphor Use, and Affordances

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ABSTRACT

Shape-changing interfaces allow designers to create user interfaces that physically change shape. However, presently, we lack studies of how such interfaces are designed, as well as what high-level strategies, such as metaphors and affordances, designers use. This paper presents an analysis of sketches made by 21 participants designing either a shape-changing radio or a shape-changing mobile phone. The results exhibit a range of interesting design elements, and the analysis points to a need to further develop or revise existing vocabularies for sketching and analyzing movement. The sketches show a prevalent use of metaphors, say, for communicating volume though big-is-on and small-is-off, as well as a lack of conventions. Furthermore, the affordances used were curiously asymmetrical compared to those offered by non-shape-changing interfaces. We conclude by offering implications on how our results can influence future research on shape-changing interfaces.

Author Keywords

Shape-changing Interfaces; Actuated interfaces; Organic interfaces; Design.

ACM Classification Keywords

H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces.

INTRODUCTION

Research on shape-changing interfaces is maturing, providing a wide range of examples that illustrate different interactions possibilities (e.g., [27,28]), uses of material (e.g., [13,33,37]), as well as studies of user experiences with shape-changing interfaces (e.g., [11,17,27,40]). Furthermore, work looking beyond single research prototypes is emerging in the form of frameworks [34,41], models [38,42], and studies across several designs [24,33], which illustrate how frameworks can drive systematic exploration of a design space. Yet, much of the design space of shape-changing interfaces remains underexplored. For example, we have only seen a few accounts of design processes of shape-changing interfaces, such as [23,46], both illustrating sketches from the design process and concepts beyond technical implementation. Furthermore, concepts such as *metaphor* and *affordance* have been widely used for understanding the design of and interaction with other types of interfaces. While the literature on shape-changing interfaces has frequently mentioned these concepts, there has been little *systematic* use of them to inform the design of shape-changing interfaces.

We suggest that further understanding of the *design of* shape-changing interfaces may help mature the research field of shape-changing interfaces. Concretely, we posit three approaches to do this: (i) using existing frameworks to analyze shape-changing interfaces can help identify weaknesses in and directions for frameworks that inform design; (ii) investigating the use of metaphors can assist in the design of shape-changing interfaces; and (iii) performing a principled investigation of affordances in shape-changing interfaces may inform future designs for user experience. The approaches are based on the belief that investigating designers' work with shape-changing interfaces is key to supporting richer and more ambitious designs by developing practice-based recommendations and to discussing and qualifying current recommendations on the design of shape-changing interfaces.

The design of shape-changing interfaces might be studied by cataloguing and analyzing existing designs. However, clearly such designs are shaped by technical feasibility and practical difficulties in construction, which likely overshadow the potential of shape change and the imaginations of designers. Consequently, to explore what shape-changing interfaces might become, rather than what they are, as well as to investigate approaches i-iii above, we have asked researchers in the field of shape-changing interfaces to perform two design exercises in the form of sketches. Twenty-one participants each spent about one hour generating ideas for either a shape-changing radio or a shape-changing mobile phone. For each case, we posed two scenarios, one for functional use (e.g., adjusting volume) and one for hedonic use (e.g., conveying emotions).

We present an analysis of the sketches made by the participants along three lines: the sketches were analyzed for types of shape change using (a) an established vocabulary framework [41], (b) analysis and reflection on

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metaphors using the categories of Barr et al. [1], and (c) analysis and reflection using the notion of instrumental affordance from Kaptelinin and Nardi [24].

The present study makes three contributions. First, we picture a design space through sketches of a mobile phone and a radio, mapped out by 42 answers to the design exercises. Second, we analyze the design elements used in terms of three principled approaches: vocabulary, metaphor use, and affordances. We provide a critical discussion on how designers may employ these elements for the design of shape-changing interfaces and how these elements may both inform the design process and expose concrete challenges to designs using shape change. Third, we use these insights to reveal future directions for the research and design of shape-changing interfaces.

RELATED WORK

In the following, we position this paper in relation to (1) frameworks for shape-changing interfaces; (2) metaphor use in shape-changing interfaces; and (3) affordances of shape-changing interfaces. Finally, given that our study uses graphical sketches as materials, we briefly outline previous work on empirical studies of designers.

Frameworks and Vocabularies for Shape Change

Research on shape-changing interfaces has sought to provide an understanding of the design space through frameworks [34,41] and models [38,42], contributing vocabularies to support designers and researchers in designing and reasoning about shape change. In 2012, Rasmussen et al. [41] reviewed 44 papers to describe eight types of shape change, according to purpose (e.g., functional and hedonic) and characteristics of movement, transformations, and types of interaction. Coelho and Zigelbaum identified three main design elements: topology, texture, and permeability [6]. Parkers and Ishii [38] provided a model of shape change, offering a design vocabulary for motion prototyping. Morphees [42] described ten features of shape change, such as area, granularity, and porosity.

In spite of existing work, the design space of shape-changing interfaces has yet to be fully investigated, and to our knowledge, no previous study has provided insights by asking researchers to sketch shape-changing interfaces.

Metaphors in Shape-changing Interfaces

Metaphors are widely mentioned within research on shape-changing interfaces, but the work does not consider established *categories* of metaphors, such as the taxonomy provided by Barr et al. [1]. Despite the absence of a theoretical foundation for the use of metaphors, previous work has employed a varied use of the notion of metaphors, describing how it applies to shape, moment, and interaction.

Ninja Track [25] used shape change to evoke different metaphors; for instance, a bent shape denotes "saxophone" and a stick shape denotes "drumstick." The design exploration of Jung et al. [23] used metaphors from living creatures, such as hedgehogs and potato bugs, as design inspiration for a computer mouse. Interaction metaphors are evident in Bendi [39], where a shape-changing mobile phone doubles as a joystick. SpeakCup [48] used the notion of physical substance as a metaphor for sound. Hemmert et al. [20] explored users' experience with a shape-changing mobile phone, indicating how users described the shape changes of an abstract form using "animal metaphors," for instance describing an approaching movement as "a cat that wants to be stroked."

While ample work has shown that shape-changing interfaces can evoke different metaphors because of their physical and dynamic characteristics, it remains unclear how to interpret those metaphors and how they can be used to improve the design of shape-changing interfaces.

Affordance and Shape-changing Interfaces

Many papers have argued that shape-changing interfaces create new possibilities for addressing the notion of *affordance* in designing technology (e.g., [6,13,14,47]). However, the uses of the term "affordance" are diverse: Coelho [5] mentioned *interaction* affordances, Dawson et al. [10] *device* affordances, and Yao et al. [47] *dynamic physical* affordances and *haptic* affordances. A range of papers have argued that a key property of shape-changing interfaces is their ability to provide *dynamic* affordances (e.g., [14,21,30]). Yet, what particular authors see as dynamic affordances has differed. For instance, Rasmussen et al. [41] defined dynamic affordances as *"perceived action possibilities that change with changes in shape,"* while Ishii et al. [21] described dynamic affordances as the way in which an object communicates its transformational capabilities. Therefore, understanding the role of using shape change to create affordances within interaction design largely remains an open question.

Empirical Studies of Designers

Design studies [2,8] and design cognition [4,9] have a rich tradition of conducting empirical studies of how designers work. The key interest is to understand how designers think, as well as to generate skills and knowledge over time. In design studies, there are many examples of insights established from interviews with designers (e.g., [2,8]).

In HCI, such studies are much less prevalent, but are beginning to emerge. Zimmerman et al. [49] and Sas [43] conducted interviews with design researchers to investigate the sources and results of research through design [49] and how they deal with the transition from empirical studies to design implications [43]. More specific themes have been investigated through interviewing design practitioners, such as how practitioners use specific tools (e.g., moodboards [31]) and personas [32]. Investigations of specific design cases have included exploring how intended design qualities were evident in later designs [44] and documenting details of material explorations in a design process [22].

The difference between our work and the above is that, while design cognition and its associated work in HCI are interested in understanding the *processes* of the designer, we are interested in studying the *properties* of the resulting designs. However, we are inspired by the method of design cognition in developing empirical materials through asking designers to perform an artificial design task.

METHOD

We invited a group of researchers in the shape-changing interface field to complete two short design tasks, spending approximately one hour sketching ideas. Sketching was chosen because it is fast paced and frees participants from technical limitations of prototyping while being exploratory and suggestive.

Participants

To recruit participants, we invited researchers who have published papers at CHI or TEI within the last five years (2011-2015) on shape-changing interfaces, organic user interfaces, or actuated tangible user interfaces. We chose participants with these characteristics because they had previous experience with shape change. We compiled a list of 264 people, who were sent an email invitation; all positive responses were added to the pool of participants. This resulted in 21 participants from 16 countries, with an average age of 32 years (SD = 4.9).

Three-quarters of the participants have developed shape-changing interfaces, including shape-changing mobile phones, deformable interfaces, and flexible displays. Beyond shape-changing interfaces, participants had experience with the design of tangible user interfaces, actuated interfaces, and robots. Eighteen participants are active researchers on HCI, and 13 have published scientific papers specifically on shape-changing interfaces, either introducing technological advances and prototypes or presenting results of user studies with shape-changing interfaces. In addition, some of our participants had design experience in fields other than HCI, including digital arts, music, and embodied interaction. The participants were compensated with an Amazon gift card with a value equivalent to $25.

Design Tasks

We randomly assigned participants to generate sketches for either (1) a shape-changing radio or (2) a shape-changing mobile phone. The two artifacts were chosen to obtain information about how shape change could be applied to a simple and common artifact that has not been explored in research on shape-changing interfaces, the radio, and to obtain information on how sketching, rather than building, might extend the design space of a well-explored artifact within research on shape-changing interfaces, the mobile phone (e.g., [16,20,26,39,40]).

For each of the two artifacts, two tasks were developed, focusing on *pragmatic* use (A) and *hedonic* use (B), respectively. The tasks were chosen to be exploratory and are based on earlier work [41] that has shown how these foci can lead to very different shape-change designs. The tasks also aimed to strike a balance between a broad and a focused task, as a very broad task might not stimulate participants' creativity by introducing restrictions, whereas a highly focused task might lead to responses that are too homogenous. The instructions for the tasks were as follows.

1A Radio Volume (pragmatic)
Please sketch one or more examples of how physical changes in shape can be used to indicate the volume level on a radio. Your answer should explain how the user could see and change the volume level.

1B Radio Genre (hedonic)
Please sketch one or more examples of how physical changes in shape can be used to indicate the genre of the music playing on a radio. Your answer should explain how the user sees and changes the mood of music playing.

2A Mobile Mode (pragmatic)
Please sketch one or more examples of how physical changes in shape can be used to indicate a mobile phone's mode (e.g., flight mode, silent, or normal). Your answer should also illustrate how the user changes the mode.

2B Mobile Emotion (hedonic)
Please sketch one or more examples of how physical changes in shape can be used to convey emotion in text messages on a mobile phone. Your answer should illustrate both how messages are created and received on a mobile phone.

The participants were asked to produce sketches (e.g., drawings, pictures, or videos) and supporting descriptions; they were free to choose any technique or material to complete the tasks. However, we asked the participants to use at least two or more images to illustrate the transitions from one shape to another and to illustrate users' interaction with the artifacts. In addition, we asked them to include clear written explanations of the design strategies and design elements used. Finally, we asked participants to emphasize creative solutions over technical feasibility.

Procedure

We communicated with each participant individually by email. After they agreed to participate in the study, they were sent a PDF file containing detailed instructions on how to complete to the tasks, a link to a questionnaire with questions on age and experience, and a link to an online folder for uploading sketches.

Material

We received answers from 21 participants, each submitting answers to two tasks, for a total of 42 answers. The full set of sketches is available in high resolution as supplementary material. A majority of the answers (39) used hand-drawn sketches to describe their ideas, augmented with handwritten descriptions, while one participant used a simple 3D model to illustrate a concept. Three participants used pictures of physical mock-ups, where different materials, such as paper, napkins, and clay had been used to communicate the concepts. Two responses used a collection of images, either close-ups of material textures or product

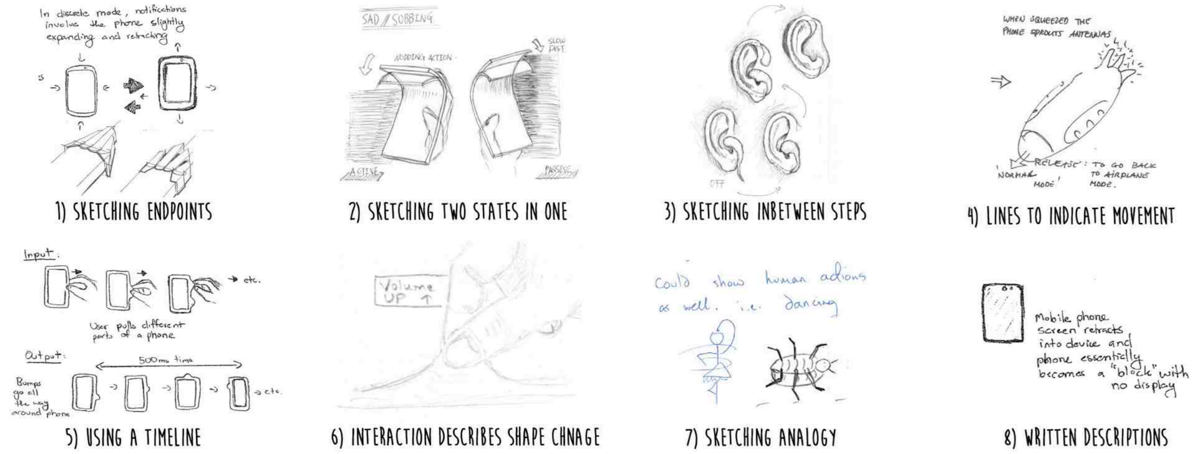

Figure 1: Eight strategies for communicating shape change

images, to illustrate different changes in texture and color. Sketching shape-changing interfaces is a challenge, as the dynamic qualities of the design must be conveyed in a static medium. Figure 1 illustrates eight different sketching strategies used by the participants. Participants generally used more than one strategy in their sketches (16 participants used two to four strategies), whereas five participants used a single strategy (sketching endpoints) to illustrate the transformations in shape.

Analysis

We analyze participants' sketches using thematic analysis [1] with three foci: (1) *vocabulary*, (2) *metaphors*, and (3) *affordances*. The following presents the theoretical framing of the analyses.

Vocabulary analysis

To understand the use of different types of shape change and transformations in the design tasks, we analyze the sketches using the vocabulary framework proposed by Rasmussen et al. [41]. The vocabulary consists of three parts:

(a) Types of shape change, which comprise changes that preserve the original topology of the artifact (*topologically equivalent*), *orientation, form, volume, texture, viscosity,* and *spatiality*, and those that do not (*topologically non-equivalent*), comprising changes in *permeability* and changes that *add or subtract* from the form.

(b) Types of transformation, classified according to *kinetic parameters* (*velocity, path, direction,* or *space*) or *expressive parameters*, either *adjectives* such as "soft" or *associations* such as a faucet resembling an elephant's trunk.

(c) Types of *interaction*, which include *no interaction, indirect interaction*, where implicit input is used together with shape-changing output, or *direct interaction,* comprised of both shape-changing input and output, which can occur locally or remotely.

Metaphors analysis

In traditional user-interface design, metaphor has played a considerable though controversial role [3]. To understand how metaphors could be used in shape-changing interfaces, we analyze the sketches and explanations for instances of metaphor use. We use the taxonomy of Barr et al. [1]. This taxonomy builds on work by Lakoff and Johnson [29], who describe the use of metaphors as "understanding and experiencing one kind of thing in terms of another" (p. 5 [29]). The taxonomy identifies three primary categories of metaphors: orientational, ontological, and structural metaphors. In brief, *orientational* metaphors use concepts of spatial orientation, such as up, down, left, and right, to leverage our everyday understanding of spatiality to convey useful information. *Ontological* metaphors use a basic category of existence in the physical world, such as "substance," "object container," or "entity," to explain concepts. Finally, *structural* metaphors use a detailed real-world concept or object to describe an abstract concept, similar to how the trashcan icon in modern operating systems illustrates file deletion.

In addition, we consider *metaphoric means* [19] and *metaphoric entailment* [1]. Metaphoric means are the ways in which the source cues are transferred to the target, such as form, sound, movement, material/texture, smell/taste, name, or graphics. *Metaphoric entailment* is a description of what the signifier implies about the signified [1]. For example, a trashcan icon used for file deletion may, though not intended by the designer, might imply that the lid can be removed or must be emptied by a garbage collector.

Affordances analysis

According to Gibson's notion of *affordance* [15], as popularized in HCI by Norman [35,36], affordances are "the fundamental, actual properties of an object that define how it can be physically interacted with." To understand the ways in which shape change can be used for supporting or augmenting affordances in interfaces, we employ the framework by Kaptelinin and Nardi [24], which suggests that *instrumental* affordances more adequately describe

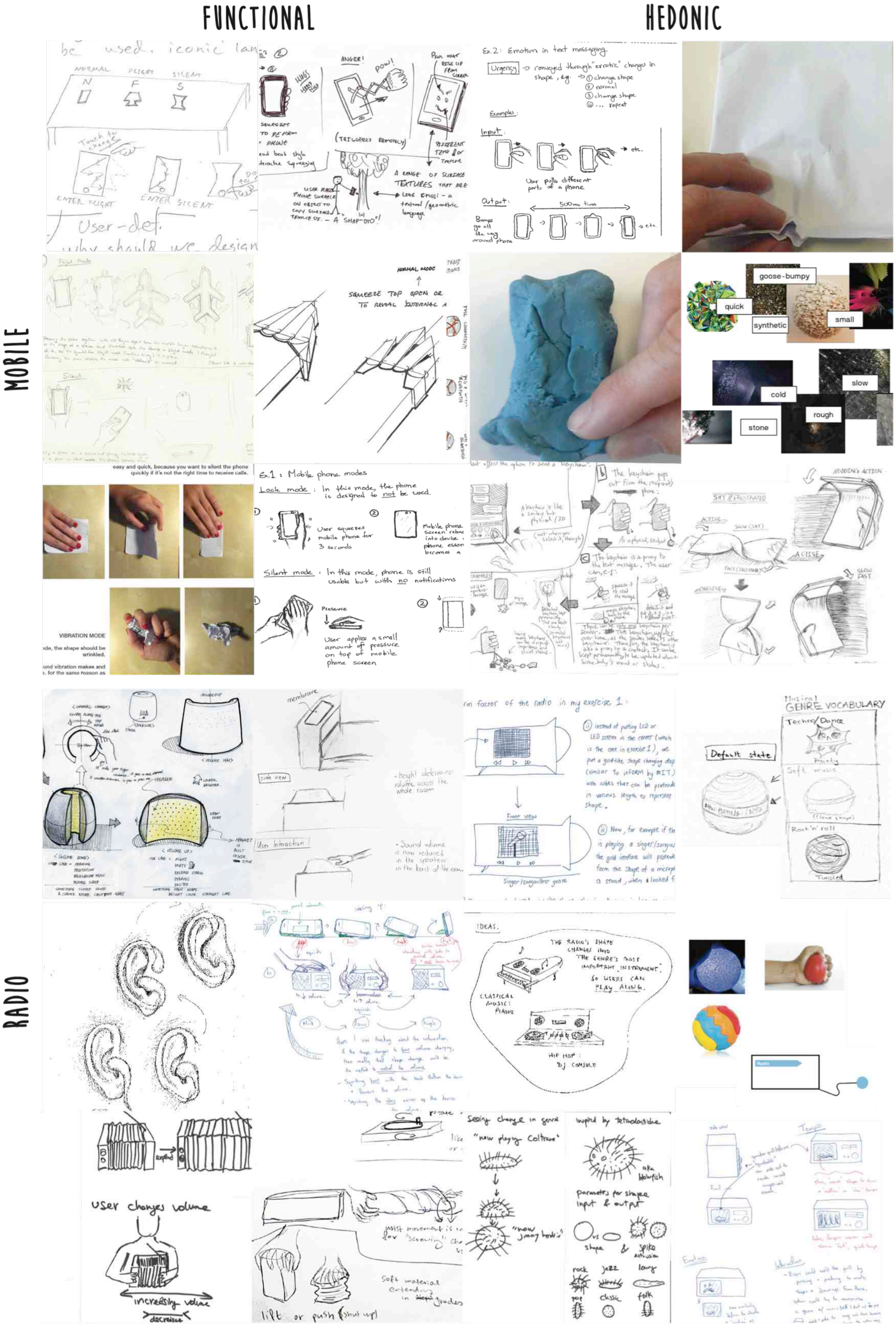

Figure 2: Excerpts from sketches. The sketches are available as supplementary material.

different facets of the human use of tools. An instrumental affordance comprises (a) a *handling* affordance, a possibility for interacting with a tool and (b) an *effector* affordance – a possibility for using the tool to cause an effect on an object. As an example, consider a single button situated at an elevator door. A user perceives the *handling* affordance of pressing the button and the *effecter* affordance of calling the elevator. As indicated in [18], the instrumental affordance may have associated *signifiers* or visual cues (e.g., the button being raised from the surrounding surface or text saying "press here to call elevator"). The instrumental affordance may have *feedback*, cues that alert the user to whether the action was successful (e.g., a sign illuminating or an audible ping when it arrives). In this view, Norman's notion of affordance corresponds to handling affordances with its associated signifiers. In an instrumental affordance, the handling and effecter affordances may be *tightly coupled* (i.e., the relationship between the handling and effecter affordance is clear to the user) or *loosely coupled.* Loosely coupled handling and effecter affordances may result in poor usability. For example, if the button is situated too far from the elevator doors, without clear visual cues to associate it, it is an example of poorly integrated handling and effecter affordance.

RESULTS

The following presents the results from the analysis of the sketches through three lenses: *vocabulary*, *metaphor use,* and *affordances*.

Vocabulary

Types of shape change

Among the 42 answers received, participants used all types of shape change described by Rasmussen et al., except *viscosity*. *Topologically equivalent* shape changes were highly predominant, while *topologically non-equivalent* changes were used in only two answers.

The sketches showed a varied use of the different types of shape changes, illustrating both input shape change (e.g., folding the phone in half to engage silent mode) and output shape change (e.g., a mobile phone bending downwards to express sadness). Changes in *orientation* were used in 17 answers, such as a mobile phone that twists to express frustration or stress (two answers) or a mobile phone that changes its angular position to express volume loudness (one answer). Participants illustrated how changes in *form* (21 answers) could be used to convey specific information to the user, such as when the shape of a radio conveys information about the music, generating a spiky shape when techno music is playing or a cloud shape for classical music. Changes in *form* were also used for iconic representation (e.g., a mobile phone that shifts to an airplane shape when set in flight mode). Twenty answers used changes in *texture,* such as expressing emotion using a coarse texture to indicate anger on a mobile phone or using changes in texture to inform the user about the tempo of the music and allowing the user to mold the texture to retrieve particular musical genres. Physical changes in *volume* were used in 12 answers, using, for example, size to indicate the sound volume on a radio or the urgency of an incoming message on a mobile phone. *Spatiality* was used in one answer, where the user could raise or lower floating spheres containing different musical genres.

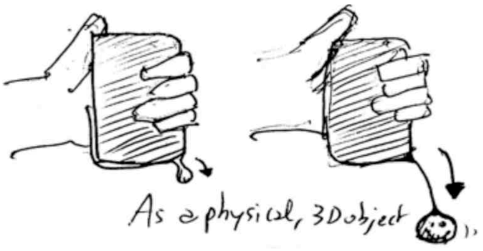

Figure 3: An example of adding/subtracting shape change

Two answers used topologically *non*-equivalent shape change. One used *permeability*, where the number of pinholes in a mobile phone's speaker would increase/decrease according to the volume level, and one example of *adding/subtracting* in the case of a mobile phone that pops out a message as a physical keychain (see Figure 3).

Types of transformation

The sketches used both *kinetic* parameters (e.g., velocity) and *expressive* parameters (e.g., adjectives or association) to explain the movements of the shape change. The participants used expressive parameters slightly more frequently (used in 38 answers) than kinetic parameters (used in 35 answers) to describe the shape changes.

For *expressive* parameters, participants often used different *adjectives* to describe the movement of the shape change, such as text describing the qualities of the movement (e.g., quick, mellow, or smooth). The personality traits of the shape and movement were also described in that they displayed, for instance, anger, sadness, and happiness. Furthermore, the *association* between shape and movement was also described through zoomorphic traits, such as a phone curling up like a bug, or through anthropomorphic traits, such as expressing sadness through a human-like sobbing pose or describing the movement as dancing. No written associations were made to nature or mechanical characteristics. Given the prevalent use of abstract forms, however, the transformations portray more *mechanical* transformations (26 answers) than *organic* transformations (12 answers).

The *kinetic* parameters of the sketches were less clear from the descriptions; however, some participants did seek to describe the velocity of the movement (seven answers) through describing the speed or with a diagram sketching the movement over time (see Figure 1).

Figure 4: A sketch of a shape-changing mobile phone that can be shaped like a "mouth" to send a kiss via message

Types of interaction

Among the 42 answers, *direct interaction* was used the most (34 answers), encompassing a range of different types of interactions, such as *squeezing* (e.g., squeezing a mobile phone at a certain rate to change the emotional content of messages), *pressing* and *squeezing* in combination (e.g., to turn the volume on a shape-changing radio up or down).

Pinching, pressing, and *pulling* were used as transitional interactions to show how users can *mold* shape-changing mobile phones into smiling, sad, or kissing phones (see Figure 4), giving them an anthropomorphic look. Classical multi-touch input was used to show how users could slide or touch either to provide textual input with a mobile phone or to control the volume on a radio. Finally, one participant sketched an extreme case of shape change, where stretching a mobile phone would be used to "break" the display and have two separate screens to interact with simultaneously. Among these examples, 29 answers used both *shape-changing input and output* in the same shape, while only a few answers used *shape-changing input and remote output* (five answers). Finally, four answers did not show any interactions.

Summary and analysis

While great variation in the frequency of types of shape change was seen, all types except viscosity were represented across the four tasks. However, some particular types of shape change were used only in the radio exercise (i.e., spatiality) or in the mobile phone exercise (i.e., adding/subtracting and permeability). Furthermore, the sketches show that changes in form were used almost solely for iconic or symbolic representation; we also see a prevalence of sketches using mechanical features over organic features, especially in shape transformations. This suggests that researchers still rely more on mechanical and technical transformations to represent shape change, even though shape-changing interfaces have been regarded as a chance for HCI to make interactive interfaces more organic or lifelike [40].

Metaphors

Among the 42 answers received, a majority used orientation metaphors (18 answers) and structural metaphors (17 answers); ontological metaphors were more rarely used (seven answers). A selection of answers grouped into the three types of metaphors can be seen in Figure 5.

Orientational metaphors

Orientational metaphors were primarily used in the **radio pragmatic** task for showing volume (used in nine out of ten answers). The prevalent use of metaphor for volume shows how existing metaphors, such as sliders, have influenced the sketches. It also illustrates how simple orientational metaphors, particularly loud-is-up, helped participants in this task. While "up" was often used as a way to portray volume, less familiar orientational metaphors, such as open-is-more, were also used (e.g., the speaker aperture opening to show increased volume).

Orientational metaphors were also used in five answers to give shape to emotion in the **mobile emotion** answer, such as linking a direction to an emotion, such as happy-is-up. Metaphors were also used to communicate the state of the mobile phone, for instance, by opening or closing the shape to reveal an antenna-like structure that indicates whether the phone is in regular or flight mode (see Figure 5). The size of a message was also used to indicate its importance, as shown in Figure 5 (left).

Structural metaphors

Structural metaphors use real-world objects as metaphors, such as smile-is-happy, shape-is-function, or radio-is-accordion. Structural metaphors were divided relatively equally between the four tasks (three to five uses each) and employed a varied range of real-world objects.

Six answers based their structural metaphors on animals or

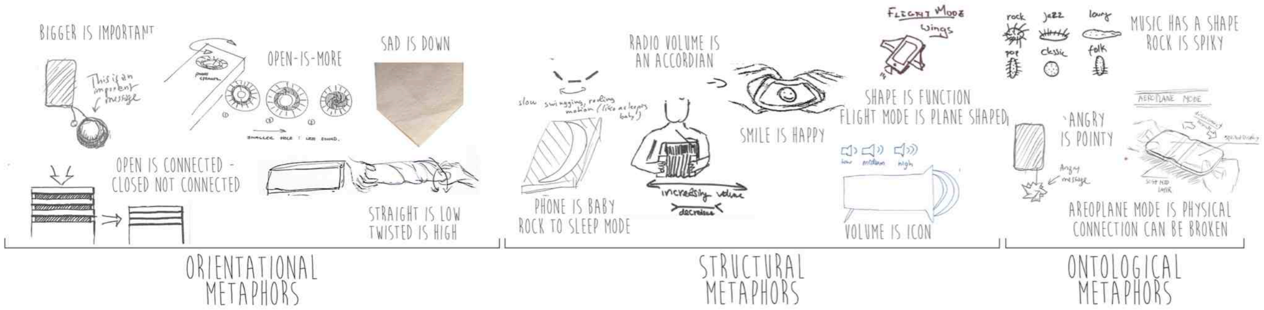

Figure 5: Three categories of metaphors

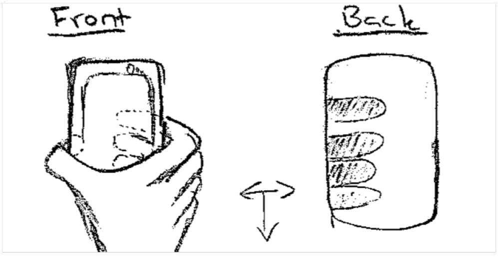

Figure 6: Imprinting directly, rather than by metaphors

humans, such as mapping emotion to a sobbing pose or happiness to the form of a smile or likening the radio to a body and using body language to express the volume level.

The use of structural metaphors varied from very literal use, such as using a plane shape to indicate flight mode (see Figure 5), or creating a radio shape that imitates the shape of the speaker icon used on computers. Others pursued a more symbolic use, such as using a moon shape to indicate "do not disturb" mode. Whether symbolic or literal, these metaphors help map from user interface features to physical form. However, some participants, particularly for the **mobile emotion** task, decided against any such mapping and instead used the direct imprinting of shape manipulations from a sender's phone to a receiver's phone, as shown in Figure 6.

Ontological metaphors

Ontological metaphors give abstract concepts a substance, such as angry-is-pointy, or seeing a wireless connection as a material that can be pulled apart to be disconnected. Ontological metaphors were not used in any of the **radio volume** answers, but occurred in two to three answers for each of the other three tasks.

Ontological metaphors use form to express a concept rather than drawing on parallels to a source domain. For example, when communicating music and emotion, four answers mapped music to abstract shape representations (e.g., techno-is-spiky, classical-is-round-and-soft). Another ontological metaphor viewed the wireless functionalities on the phone as a physical material that can be broken to switch from normal to flight mode (see Figure 5).

Metaphoric means

Mostly, metaphors are shown in the form of an object, such as a giving music a shape (rock-and-roll-is-twisted; classical-music-is-a-piano) or emotion a shape (happy-is-a-smile). However, in two answers, the metaphor is linked not to the shape of the interface, but instead to movement. Consequently, the metaphor would only become apparent through movement, such as using a nodding movement to express sadness. *Hiding and revealing* parts of the object were a particularly interesting strategy (see Figure 7).

Two answers used interaction to support or even create the metaphor. One sketch showed the use of a rocking gesture to put a phone to sleep, as if it were a baby, or seeing sending messages as throwing a ball. The message-as-a-ball metaphor uses the characteristics of balls, namely that they can be thrown to somebody, roll around, be thrown with different force, and used for playful interaction with others.

Metaphoric entailment

Metaphoric entailment is particularly relevant for structural metaphors, where not all parts of the source metaphor are transferred to the target. Take the example of an accordion shape being used to set the volume of a radio (see Figure 5, middle). By turning the frequently used loud-is-up metaphor on its side, it resolves an interaction challenge of the metaphor, namely that pulling is more difficult than pushing. However, the metaphoric entailment of the shape (the accordion) suggests that the user has to pump in and out for the music to play or could even play along – none of which seems intended with the sketch. Another sketch similarly altered the shape of the radio to familiar musical instrument shapes, a piano shape when playing classical music and a DJ console when playing hip-hop music. However, here, the metaphoric entailment is resolved by allowing the user to play along with the music, consequently, altering the functionality of the radio and making it more than just a device for listening.

Summary and analysis

The answers show a very prevalent use of metaphors, as 37 answers used one or more metaphors. Because all three types of metaphor seek to make abstract concepts physical, either through spatial or artifact relations or by giving them a physical substance, metaphors are an obvious approach for designing shape-changing interfaces. What is clear from the sketches is that, while a majority of answers for the **radio volume** task uses an up-is-louder metaphor similar to the one found in tangible controls or UI design, the rest of the answers show less conformity. Consequently, a challenge for shape-changing interfaces is a lack of conventions, and the question is how much shape-changing interfaces should follow existing metaphor conventions used in other types of interfaces or whether new conventions should be developed.

Affordances

In the analysis of affordances, it was clear that a majority of

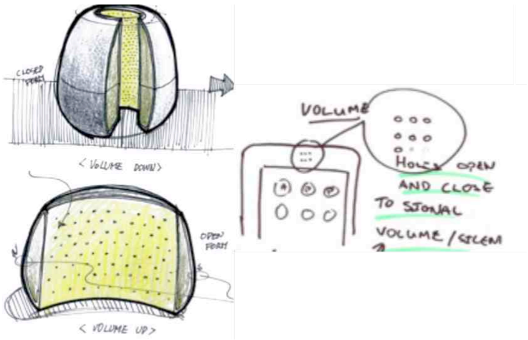

Figure 7: Hiding and revealing as a design metaphor for the entire shape (left) and for holes in a shape (right).

the sketches contained either handler or effector affordances. Only a minority managed to make these well integrated into the design.

Handling affordances

Twenty-four answers use shape change for handling affordances but not for the associated effecter affordances, such as using *corner* or *edge* folding where the effect of manipulation is not accompanied by a shape change. For example, in the two hand-drawn sketches in Figure 8, it is clear that the corners can be bent. However, in the first example, the lower corner must be bent to enter silent mode, and in the second, it is the top-right. The corresponding effecter affordance (entering silent mode) in the two cases is not accompanied by a shape change; indeed, no feedback is indicated at all. In the third sketch, the phone is folded in the middle to achieve silent mode, but again, no association between the handling affordance (folding the phone) and effecter affordance (entering silent mode) is evident to the user. These examples illustrate a common theme among most of the sketches, namely that the mapping between manipulation (handling affordance) and effect relies on UI mechanisms that are not yet common or agreed upon.

Effecter affordances

Thirty-three answers use shape change for effecter affordances but not for handling affordances. For 10 answers to the **radio volume** task, the effect of an adjusted sound volume is immediately clear from the adjusted volume level itself, and there is no need to deliberately design for it in the same way as handling affordances. For two answers, shape change is integrated as part of the feedback of effecter affordances for volume level, in addition to sound level. One of these shape changes is used both for handling (physically "closing" or "opening" a loudspeaker) and effecter (closing/opening lowers/raises volume) affordance as part of a single manipulation.

Coupling of handling and effecter affordances

Eight answers show tightly coupled handling and effecter affordances. One example is shown in Figure 9, where the control of the volume of the phone and the radio is tightly connected to the effect of manipulating the object. To adjust the volume, a ring around the speaker can be turned, hiding or revealing the speaker. The remaining 34 sketches show a loose coupling between handling and effecter affordances and in general contain very little information or sketching on signifiers (that could make users aware of a handling affordance if it is not obvious) or feedback. However, this may be due to the nature of some of the tasks – in the **radio volume** task, there is immediate auditory feedback – or the fact that the participants were asked to sketch with a focus on shape change, which may have led to a lack of details concerning traditional cues such as those given effectively on displays.

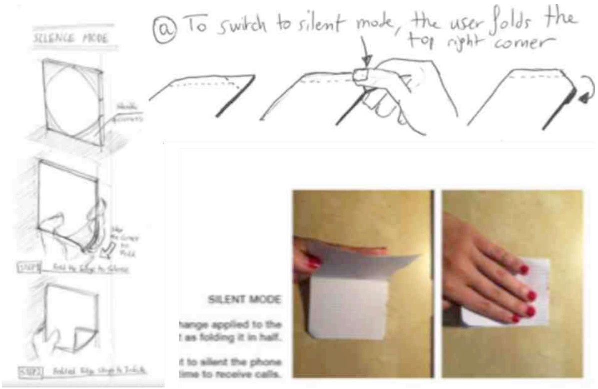

Figure 8: three examples of handling affordances using folding to enter "silent mode" on a mobile phone

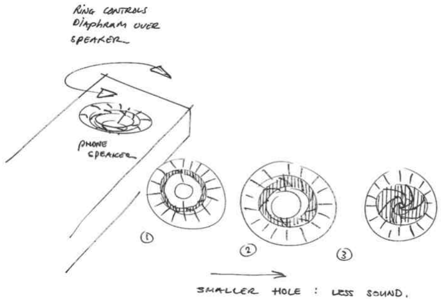

Figure 9: Tightly coupled handling and effecter affordance

Summary and analysis

The answers show a dominant focus on *either* handling *or* effecter affordances. Furthermore, shape-changing interfaces are not a panacea for good design, and designing for well-integrated handler and effecter affordances should be encouraged. Complementing shape-change design with traditional modes of interaction (e.g., displays or other visual or auditory means) should be considered. This observation is particularly pertinent, as the mappings between a user's manipulation of a shape-changing device, the designer's intended consequence of this manipulation, and the output or feedback in the design sketches are often tenuous. Shape-changing interfaces are also challenged in that designs cannot in general rely on learned habits or supposedly commonly accepted metaphors that do not yet exist among researchers in the shape-changing device field, let alone among users.

DISCUSSION

In the following, we discuss our results and analysis and describe their implications for design and research on shape-changing interfaces.

Vocabulary, Metaphor Use, and Affordance

While several frameworks and vocabularies exist for shape-changing interfaces, it is notable that applying one of the richest, the vocabulary by Rasmussen et al. [41], indicated areas where the vocabulary is insufficient and needs to be further developed. First, while simple changes in shapes are easily described using the shape vocabulary, more complex changes in shape, such as changes in shape from a piano into a DJ console, are difficult to describe using the vocabulary. However, according to the vocabulary used, this change in shape is categorized together with much less rich changes, such as changing from a square to a round shape. Consequently, while the vocabulary might serve to describe the simple shape transformations in existing shape-change research, for more complex shape changes, the vocabulary either needs further conceptual development or must be accompanied by explanations of (i) the dynamic physical properties of its changes in shape, (ii) what the new shape entails for the user, and (iii) how the actual interaction with the interface occurs (as also suggested in [34]). The sketches provided by the participants showed many varied forms of interaction, such as twisting, pinching, squeezing, bending, stretching, or crumpling, which are not well accounted for by [41] or by other frameworks.

As a concrete example of the inadequacy of existing frameworks, the four answers in our study that use a *hide/reveal* approach (as in Figure 7) employ a strategy that has neither been covered in research on shape change nor is clearly present in the vocabulary of [41]. However, as evidenced by the design sketches, the strategy can be employed to great effect using shape change and presents new opportunities for design.

While there are many discussions of *metaphor use* for GUIs and TUIs (e.g., [3,7,12]), we are unaware of any specific analysis for shape-changing interfaces. With respect to shape-changing interfaces, the term has primarily been used simply as a means to describe features of an interface. Nonetheless, our results point to several areas of interest for considering metaphors. First, orientational metaphors are physically instantiated and can be physically dynamic (happy-is-up; louder-is-larger). Second, structural metaphors all draw on real-world objects as metaphors, but the metaphors may be implemented at very different levels, ranging from hyper-literal (flight-mode-is-an-airplane) to very abstract (disconnected-is-divided).

A different argument for using principled analyses is seen in our analysis of affordances. While the notion of affordance has been widely mentioned with respect to shape-changing interfaces (e.g., [13,14,47]), there exists no analysis of how affordances can be designed using shape change. Our use of *instrumental affordances* revealed a lack of examples of *tightly coupled* affordances in the sketches, suggesting that these might need to be supported by design mechanisms other than shape change. It is conceivable that similar principled approaches may be useful for revealing design challenges in concrete designs of artifacts that employ shape change.

The sketches show an extensive use of metaphors in the design of shape-changing interfaces, as 37 answers out of 42 used metaphors; this was not required by the tasks. Consequently, the sketches illustrate a potential for employing metaphors in the design of shape-changing interfaces. However, as the sketches also revealed, there is presently a lack of well-established *conventions,* which results in the same means of manipulation (e.g., corner folding) being mapped to many kinds of behaviors. While the sketches showed familiar metaphors, such as up-is-more, they also showed alternatives, such as the degree of openness as signaling more or less. Consequently, research needs to be carried out on the use of metaphors in shape-changing interfaces, systematically exploring metaphors as physically dynamic constructs, as well as deal with how to adopt conventions from 2D or static interfaces and how to ensure that conventions are not formed haphazardly once the first mass-produced shape-changing interfaces are developed. As Norman put it, "*they are slow to be adopted and, once adopted, slow to go away"* (p. [36]).

Strengths and Limitations of the Use of Sketches

The sketches used in the study were completed in a very limited time and consequently do not represent fully elaborated and coherent ideas and might not survive scrutiny in a further design process. Furthermore, using sketches as materials for the study is challenged by the fact that sketches are, by nature, ambiguous [45]. While such ambiguity may be a positive quality in the *design process*, it is far from positive when using sketches as *sources of information* to be analyzed and categorized. A further challenge is that shape-changing interfaces are dynamic, whereas sketching on paper is static. Thus, movement and interaction are difficult to describe precisely.

However, the sketches illustrate a diverse range of strategies for communicating dynamicity. The question remains whether appropriate tools can or should be developed to support such communication. A further advantage of the rapid nature of sketching is that it may be used to elicit information about existing or emerging design conventions: the sketches have a prevalence of design choices that could tacitly and perhaps detrimentally become conventions (up-is-more; corner bending). Sketches from more designers could serve to uncover such trends and make them explicit, forcing the community to reassess emerging conventions before they become standard.

CONCLUSION

The 42 answers to the design tasks have served as a valuable material in discussing the design of shape-changing interfaces, pointing out insufficiencies in current vocabularies and in charting potential benefits for design, using principled approaches to the use of metaphors and affordances. Thus, we have illustrated the strength of bridging exploration of shape-changing interfaces using design with a principled analysis in the spirit of research through design and we invite others to further the advances sketched out in this paper.

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Paper 4: SCI-FI: Shape-Changing Interfaces, Future Interactions

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SCI-FI: Shape-Changing Interfaces, Future Interactions

An Analysis of Shape Change Behaviours and Functionalities from Sci-Fi Movies

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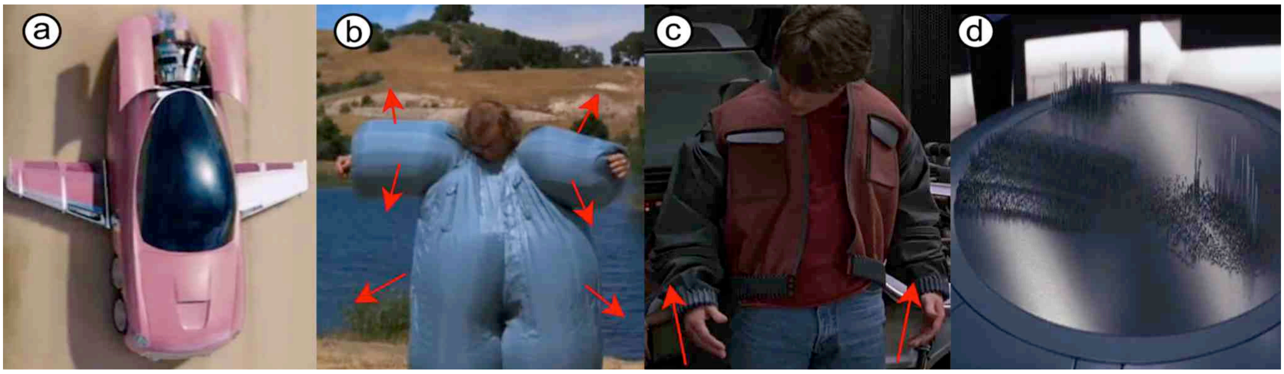

Figure 1: Four SCI behavioral patterns: (a) Reconfiguration, (b) Transformation, (c) Adaptation, and (d) Physicalization.

ABSTRACT

Shape-changing interfaces (SCI) are rapidly evolving and creating new interaction paradigms in human-computer interaction (HCI). However, empirical research in SCI is still bound to present technological limitations, and existing prototypes can only show a limited number of potential applications for shape change. In this paper we attempt to broaden the pool of examples of what shape change may be good for by investigating SCI using Science Fiction (Sci-Fi) movies. We look at 340 Sci-Fi movies to identify instances of SCI and analyze their behavioral patterns and the context in which they are used. The result of our analysis presents four emerging behavioral patterns of shape change: (1) *Reconfiguration*, (2) *Transformation*, (3) *Adaptation*, and (4) *Physicalization*. We report a selection of instances of SCI from Sci-Fi movies, which show how these four behavioral patterns model functionalities of shape change and what they can do. Finally, we conclude by providing a discussion on how our results can inspire the design of SCI.

Author Keywords

Shape-changing interfaces; user interfaces; interaction techniques; science fiction.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces.

INTRODUCTION

Shape-changing interfaces (SCI) are introducing new interaction paradigms through dynamic affordances, shape actuation, and deformability, which are redefining the way we interact with computers. For instance, SCI can afford new gestures through the use of malleable and soft materials (often referred to also as Deformable Interfaces or DUI), which allow users to input through stretch, bend, twist, or squeeze (e.g., see [38,40]). Several prototypes of SCI propose the use of actuation and shape change for various purposes (e.g., [6,7,24,25,42,45]); these work show how the dynamic affordances [11,15] provided by SCI can change the relationship between users and interactive interfaces. In light of the new interactive possibilities offered by SCI various studies have systematically investigated new input modalities that use shape change [1,27,39,43], while others measured the emotional response of users to SCI [28]. Also, models of shape change and frameworks that can help the design of SCI are emerging [30,31]. However, in spite of the increasing number of studies and technical endeavors, our understandings of what SCI are good for is still limited, and the relationship between shape change behaviors and functional purposes is still unclear. We want to look at SCI from a perspective that is not necessarily bound to technical limitations of prototyping, so as to broaden our view on what shape change can do. We argue that Sci-Fi, and specifically Sci-Fi movies, may represent a valid source of information in that respect, due to their creative and inspirational approach towards the vision of future technology. Also, Sci-Fi movies often provide concrete scenarios that contextualize the use of forthcoming technology [34]. Furthermore, it has been shown how a reflective approach to design [2,36,47] and studies of HCI inspired by Sci-Fi movies [5,14,33] can be used to inform concretely the design of technology for future scenarios. We present an analysis of 340 Sci-Fi movies through which we identify instances of SCI and analyze them using affinity diagraming similarly to previous work on proxemics interactions [10]. Our work contributes the following to the field of shape change: (1) an analysis of SCI instances from Sci-Fi movies that describes four behavioral patterns of shape change and what they can do, and (2) a discussion of how our results can help better understanding the relationship between certain shape change behavior and functional purposes. Our contributions are mainly directed towards designers to inspire them in the design of future SCI.

RELATED WORK

We position our work in relation to (1) shape-changing interfaces and (2) interactive interfaces investigated through science fiction, especially Sci-Fi movies. Next, we review related work in both areas.

Shape-Changing Interfaces

Previous work with SCI showed how interactive interfaces that use dynamic motions and physical actuations could be used for various purposes. For instance, SCI have been used as shape-changing mobile phones that express particular emotions through motion, such as avoidance or approach [12]. Other work show how a shape-changing faucet can be used to make users aware of water consumption [37], or how a shape-changing display could physically augment graphical contents through shape actuation [7]; such displays could be used to physically explore data [35], or for navigating on shape-changing maps [23]. Among the various applications proposed by existing prototypes are also pneumatically actuated lamps [44], shape-retaining interfaces [6], shape-changing robots [4,21,22], actuated garments [29], and broad range of shape-changing mobiles [8,9,17,18,20,26,27,46]. However, existing prototypes of SCI provide examples of shape change that are limited to the present technological advance. As a consequence, many applications and contexts for the use of shape change are still unexplored or remain conceptual (e.g., Ishii's *Radical Atoms* [15]). Because Sci-Fi movies are free from such technical limitations, we argue that they might show us new and unseen examples of shape change. Furthermore, no previous work on SCI has tried to analyze the relationship between shape change behavior of SCI and their functionalities, or gathered insight from Sci-Fi movies and tried to use them to help and inspire visions of future design for SCI.

Sci-Fi Movies and HCI

Sci-Fi movies have been used in previous work in HCI as source of inspiration and information. These studies often highlighted how Sci-Fi movies can represent a valid source to investigate future technologies, in which they creatively inspire the vision of future technology and often display their use into context. Previous work investigated the link between real world and Sci-Fi technologies, showing how the fictional and the scientific fields can mutually influence each other. Schmitz et al. [33] carried out a survey on how the design of technology in HCI can be influenced by Sci-Fi movies. Their work shows how Sci-Fi movies often anticipate future technologies and influence audiences' expectances towards them. For instance, they point out how the Tricoder appearing in *Star Trek: Next Generation* anticipated technology like PDA already in 1987.

Kurosu investigated user interfaces (UI) that appeared in Sci-Fi movies and analyzed their feasibility in real-life [19]. His analysis produced two main points of reflection: (1) it seems that technological advance in HCI influences the way directors design technologies that appear in Sci-Fi movies, and (2) Sci-Fi movies can provide a clear context to help designers and researchers in HCI imagining the role of future technology. Sherdoff et al. presented results from a five year's investigation on Sci-Fi movies [34] from which they outline insights for designers of interactive technologies. The authors define four ways in which Sci-Fi influences designers: (1) *Inspiration*, (2) *Expectations*, (3) *Social Context*, and (4) *New Paradigms*. In synthesis, the authors explain that Sci-Fi has directly *inspired* the technological development of certain interactive interfaces (e.g., Xenotran Mark II), providing *expectations* for future interactions (e.g., the Star Trek communicator anticipating the Motorola Star-TAC), depicting the *social contexts* in which the interfaces are used, and proposing *new paradigms* of interaction (e.g., Minority Report and its mid-air input).

Finally, Figueirado et al. analyzed 24 Sci-Fi movies [5], from which they collected and categorized a compilation of hand gestures and interactions. Their work is an example of how Sci-Fi movies can be used as research materials to concretely inspire designers on new input methods for interactive interfaces. The work that we present in this paper is inspired by the above-described work, which used Sci-Fi movies to investigate and inspire the design of interactive interfaces. We apply the same principles to the investigation of SCI, hoping that the creative output of Sci-Fi movies will help us understand design implications that can be academically and practically applicable.

METHOD

We perform a large-scale analysis of 340 Sci-Fi movies selected among those released between 1920 and 2015. We choose to look at Sci-Fi movies in which they visually represent their speculations on future technologies, and exclude other mediums (e.g., Sci-fi literature), so as to be able to identify instances of SCI with less ambiguity [23]. Next, we (1) provide the rationale for our movies' list, (2) explain the method that we used to identify instances of SCI, and (3) describe the method we used for analyzing the data.

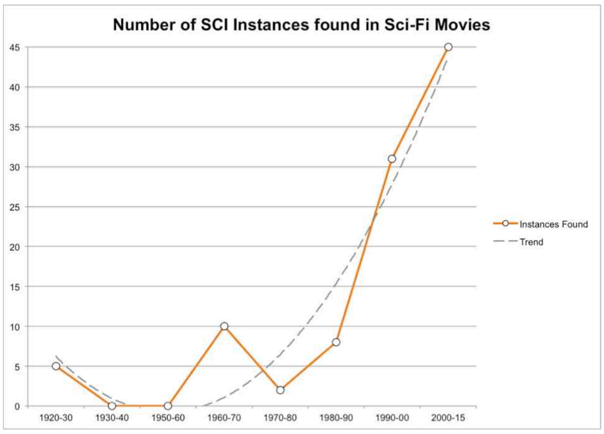

Figure 2: A graph showing the trend of SCI instances from 1920 to 2015, divided per decades (except for years 2000-15).

Movies Selection and Sources

We initially identified 375 Sci-Fi movies for our list, which we compiled from two main sources (1) Wikipedia and (2) IMDB. Our list includes movies that were released between the earliest years of Sci-Fi cinematography (1920) and the present days (2015), which portray the future of humankind and their technology. We did not include TV-series into our list for the present work, in which we decided to focus on feature films only. After an extended online and offline search we managed to collect and watch 340 Sci-Fi movies; 35 movies could not be accessed because they were either not available online or they could not be found on physical supports (e.g., DVD). All 340 movies were accessed either through YouTube or through personal archives. The movies from our personal archives were acquired through years of collections and the ones that were not present in our personal archives were legally acquired online.

Defining SCI for Our Analysis

Our analysis aimed at identifying instances of SCI from Sci-Fi movies. By looking at previous work that propose framework for SCI [30], we have noticed that shape change is often described as a change in the appearance or in the structure of an interface. Therefore, in our analysis we defined a SCI an interface that changes either (1) its **appearance,** as the effect of physical and esthetical distortion, or (2) its **structure** as the effect of structural reconfiguration or collapse, or changes the both**.** We distinguish between change in *appearance* and *structure* because it seems that they affect the shape of a SCI in different ways. For instance, a change in *appearance* can radically change the shape of an interface where the shape loses its original character (e.g., a cube that turns into a sphere, e.g., [13]). Instead, a change in *structure* can preserve the recognizability of the interface's shape while changing its configuration.

Movie Analysis

We watched each movie of the 340 present in our list and identified instances of SCI and coded all the identified instances of SCI in an excel sheet. We watched all movies at a faster speed (i.e., 8x) as suggested by previous work [5]. To visualize the movies at a faster speed we used: (1) a Chrome plug-in called *Video Speed Controller*, and (2) *PotPlayer.* Among the 340 movies analyzed, 61 movies contained instances of SCI. Furthermore, we also analyzed the trend of SCI instances in Sci-Fi movies according to movies' years of production. The trend revealed that the number of instances present in Sci-Fi movies increases almost exponentially between the years 1990 and 2015 (Figure 2). This trend seems to be in line with Kurosu's observation on how the technological advance in real-life influences the one that appears in Sci-Fi movies [19].

Figure 3: Two examples of *Reconfiguration*. (a) Total Recall (1:00:06) a shape-changing mask that disassembles automatically, (b) Terminator 2 (2:10:49) a robot that re-assembles its foot displaying a fluid-like behavior.

SCI Analysis

We identified a total of 101 instances of SCI from 340 Sci-Fi movies. We coded those instances of SCI, identifying the type of shape change (e.g., apparent or structural), and the context in which it was used. The coded instances of SCI were analyzed using affinity diagraming and clustered into specific groups. We used the online software Mural.ly for our affinity diagramming. At the first session, we went through all the instances, starting to group them individually, and move the instances from one group to another. At this stage we did not discuss validity of groups, but rather let them emerge naturally. After several iterations, we identified four groups that describe behavioral patterns of SCI. Furthermore, we divided each group into sub-groups, and identified 10 different functionalities and context of use for shape change that are supported by the behavioral patterns. The analysis took approximately two weeks to be completed.

SCI BEHAVIOURAL PATTERNS

The Sci-Fi movie analysis revealed 101 instances of SCI from which we identified four main behavioral patterns: (1) *Reconfiguration*, (2) *Transformation*, (3) *Adaptation*, and (4) *Physicalization*. Each behavioral pattern presents various examples that show what SCI can do and in which context. Next, we describe each behavioral pattern in turn.

Reconfiguration

Reconfiguration expresses the capacity of a SCI to change in formation or to reconfigure its structure. We report example of such SCI from Sci-Fi movies, that show how reconfiguration helps various functionalities of shape change, such as assembling or disassembling, restructuring

Figure 4: From the movie AI (0:03:38) a robot disassemble its face and reveals hidden components.

the configuration of physical environments, or extending interactive functionalities (see Figure 3).

Assembling / Disassembling

SCI that assemble were depicted in Sci-Fi movies as interfaces made of modular elements that can change their configuration or re-assemble, for instance to match particular shapes or to reveal internal parts. We found an example of such SCI in the movie *The Adventures of Pluto Nash* (2002) where nine balls automatically gather into a triangle shape at the center of a pool table every time users need to restart a new match. The movie *Terminator 2* (1991, Figure 3, b) shows an instance of a shape-changing robot that can automatically re-assemble individual parts, such as arms, hands, the head, and other bodily parts when these are into close proximity. This particular example shows a SCI that has the capacity of changing its physical state from solid to fluid; that can allow the shape-changing robot to sneak through narrow door gaps or to re-assemble its body in a fast and organic-like way.

A particular instance of assembling SCI appears in the movie *The Time Travellers* (1964), where cables made of smart material automatically combine together when users place them close to each other. Finally, the movie *Man of Steel* (2013) shows a shape-changing helmet that automatically assembles from a thin frame when the user wears it around the neck. SCI that disassemble show the same shape change behavior as the ones that assemble but achieve the opposite. In the movie *AI: Artificial Intelligence* (2001), a robot opens up and splits its face into two different parts to let the user access internal components (Figure 4). Another instance of SCI that disassembles appears in the movie *Total Recall* (1990), where a three-dimensional mask collapses its shape automatically to let a user reveal his identity (Figure 3, a).

Figure 5: From the movie Cloud Atlas (1:02:18) a shape changing room (a) before reconfiguration, (b) and after.

Figure 6: From the movie Judge Dredd (0:07:48) a microphone pops out from the frame of the helmet to amplify the voice of the user.

Reshaping Environments

Some of the Sci-Fi movies from our list presented instances of SCI as shape-changing environments, which could reconfigure some of their elements or their entire structure for protecting privacy, redecorating rooms, or saving space. In the movie *Babylon AD* (2008) a SCI acts as a shape-changing wall that automatically expands (with an accordion-like motion), to separate rooms when users need privacy. The movie *Cloud Atlas* (2012) shows a shape-changing room made of several SCI (e.g., chairs, walls, and the floor), which change their shapes, textures, and colors to change the configuration of the entire room (Figure 5). Finally, the movie *Things to Come* (1936) shows how shape change features are used to reveal new architectural elements in a house, such as bed, sink, and mirrors that extend from the walls automatically when users are into close proximity with them.

Revealing Interactive Parts

These particular instances showed SCI that posseses interactive elements embedded into the original interface and that reveal themselves to the user when needed; this behavior can make a SCI a multi-purpose interface. Such SCI instances appear in the movie *Judge Dredd* (1995) where a helmet automatically pops out a microphone for the user when he or she needs to amplify their voice (Figure 6). Another example SCI that reveal interactive parts appears in the movie *Futureworld* (1976), where a regular table transforms into an interactive TV station through a movable section placed in the middle (Figure 7).

Transformation

Transformation expresses the capacity of a SCI to change in form and in appearance. We report examples from Sci-Fi movies that show how by mean of transformation a SCI can

Figure 7: From the movie Futureworld (0:06:10) a shape-changing table that rises interactive monitors in the middle.

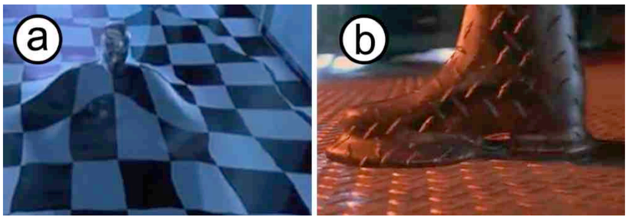

Figure 8: Form the movie Terminator 2 (0:53:15) a robot changes from a floor into a human-like shape (a), (2:12:55) the same robot changes texture to camouflage with the floor (b).

camouflage with the surrounding environment or morph to embody multiple functionalities into one location.

Camouflage

SCI that camouflage are changing their appearance in order to hide or integrate with the surrounding environment. We have found two examples of this kind of SCI. In the movie *After Earth* (2013) a user is wearing a whole-body suit that changes its shape, texture, and color when entering a forest; the suit changes from red to green and grows a moss-like kind of texture to imitate the surrounding nature. Another example of camouflage SCI is shown in *Terminator 2* (1991), where a shape-changing robot melts its body or pops out a relief texture to camouflage with a floor (Figure 8).

Morphing

Morphing can change both the structure and the appearance of a SCI. This type of transformation can also radically change the functionality of the SCI, for instance by morphing the hand of a robot into a pin, a cutting tool, or a weapon (Figure 9, a). The movie *Transformers* (2007) presents instances of SCI as anthropomorphic robots that can morph into many different interfaces, for instance to be used as a car or as a radio depending on user's necessity (Figure 9, b). Another example of morphing SCI is shown in the movie *Judge Dredd* (1995), where a user is pulling the ends of a metallic wallet to transform it into a small gun (Figure 10). The movie *Interstellar* (2014) shows a morphing robot that can extends its structure to have prehensile arms and being able to lift objects (Figure 11, a). The same robot morphs from a rectangular shape into a star-like shape to be able to move faster when having to rescue a human from drowning (Figure 11, b).

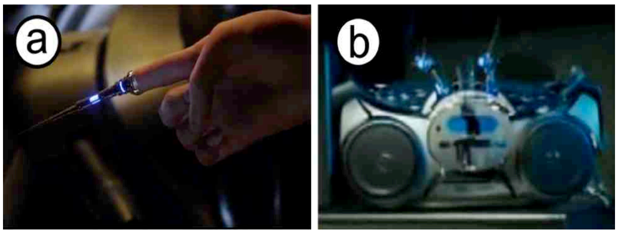

Figure 9: From the movie Terminator 3 (0:28:52) a robot morphs its hand into an electronic pin for computer hacking (a). From the movie Transformers (0:32:18) an anthropomorphic robot morphs into a radio (b).

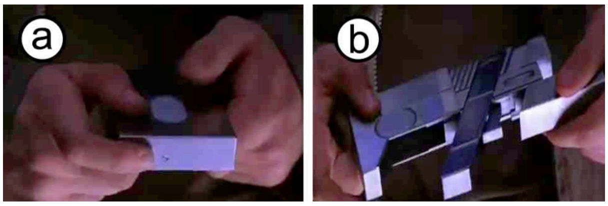

Figure 10: From the movie *Judge Dredd* (0:18:44) a user is transforming a wallet (a) into a small gun (b).

Adaptation

Adaptation expresses the capacity of SCI to adjust their shape, so as to fulfill users' needs or adapt to specific situations. For instance, SCI as self-adjusting garments can dynamically fit the body of various users with different body-builds. We report examples of such SCI from Sci-Fi movies that show for instance how expansion or reversing types of shape change can be used in the context of adaptation.

Finding the Intended Shape

SCI can use their dynamic features in order to find an "intended" shape. Sci-Fi movies showed examples of such SCI as shape-changing garments that automatically find the appropriate shape to fit the body of a user. We saw two examples of such SCI from the movie *Back to the Future II* (1989, Figure 12), where a user wears a jacket that automatically fits the sleeves to the length of his arms, and a pair of shoes that automatically tightens to his feet as he wears them. Other examples of SCI that adapt shape to the user's need were shown in Sci-Fi movies as shape-changing beds. A bed or a resting surface that possesses shape change feature can find an appropriate shape to best accommodate the user's body. We saw two distinct examples of this kind, one in the movie *2001 A Space Odyssey* (1968), a user talking through an intercom needs to move his head up to be able to look at the screen; the headrest of the bed automatically elevates to lift his head (Figure 13). A similar SCI is shown in the movie *The Wolverine* (2013), where a paralyzed user is lying on a shape-changing bed that moves his body through several rods that actuate and move simultaneously.

Expanding

Two Sci-Fi movies showed SCI that dynamically expand and increase their size to fit particular user needs. The movie *Spacehunter* (1983) shows a self-unfolding sleeping

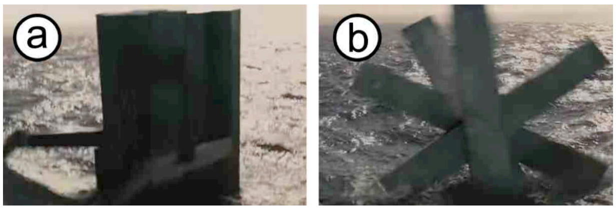

Figure 11: From the movie Interstellar (1:11:07) a robot extends part of his body to have arms (a) (1:11:21) the same robot shifts into a star-like shape to move faster (b).

Figure 12: From the movie Back to the Future II (0:13:38) a shape-changing jacket adapt its length to the arms of the user (a), (0:08:34) self-tightening shoes adapts to the foot's size of the user (b).

bag that automatically expands for the user when he or she needs it. Another example is shown in *Back to the Future II* (1989) where a user has a telescopic baseball bat that can be automatically enlarged by tightening the grip (Figure 14). Because they can shrink or enlarge, the two instances presented above can also be described as space-saving SCI.

Reversing Shape

Two movies from the *Terminator* saga show SCI as shape-changing robots that can reverse their shape in order to adapt to different situations. The movie *Terminator 2* (1990) shows a humanoid shape-changing robot that reverses its entire body after a violent collision with a wall (Figure 15, b). In *Terminator 3* (2003) a shape-changing robot reverses the position of its waste to be able to trap a person behind using the legs (Figure 15, a).

Physicalization

Physicalization expresses the capacity of a SCI of extruding shapes from its surface to physicalize digital information or to ultimately generate physical matter. We report examples from Sci-Fi movies of such SCI that show how physicalization can help shape-changing displays representing urban configurations to users, or how to physically materialize data from the surface of the display.

Representation

By mean of physicalization a SCI can become a display that uses shape change and motion to generate physical visualizations. The movie *X-Men* (2000) shows an instance of such display, which extrudes the map of a city for users that need to study its urban conformation; this shape-changing display is similar to existing prototypes [7]. Another shape-changing display that is capable of physicalization appears in the movie *Man of Steel* (2013). However, this shape-changing display is not constrained to a tabletop surface, but it can grow around users and surround them at 360 degrees while generating physical contents (Figure 17).

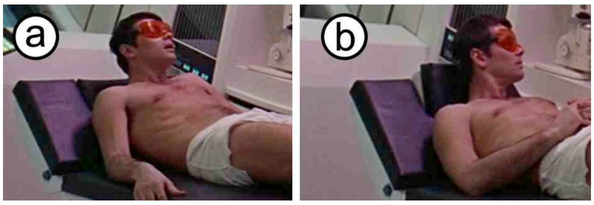

Figure 13: From the movie 2001 A Space Odissey (1:04:52) a shape-changing bed lifting up the user's head.

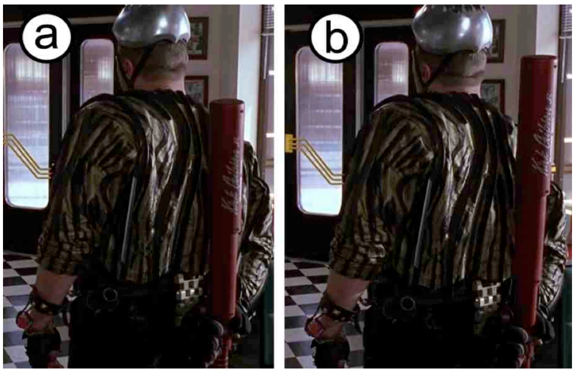

Figure 14: From the movie Back to The Future II (0:17:41) a telescopic bat that automatically shrinks or enlarges when the user tightens the grip.

Materialization

In the movie *Man of Steel* (2013) one instance of SCI brings shape change to the extreme end of content materialization. The movie shows a shape-changing display that can physically generate matter from its surface (Figure 18). This particular shape-changing display acts like a very fast 3D printer, which generate physical data that the user can dethatch from the display and use as stand-alone object.

DISCUSSION

We have analyzed instances of SCI from Sci-Fi movies in order to broaden up our vision of what shape change can do and in which context. The SCI were analyzed with respect to the behavior that they displayed and how they helped particular functionalities of shape change. Next, we discuss our work in relation to previous ones in the field of shape change and elaborate on how they can help the design of SCI. Finally, we discuss how the behavioral patterns listed in our results can apply to existing prototypes.

Shape Change Behaviors and Functionalities

Theoretical and reflective research on SCI has produced various frameworks [30] and models [31] of shape change, in order to systematically describe SCI design features. In particular, Rasmussen et al. [30] identified eight types of shape change and various shape change parameters, and reported a number of examples from previous research that contextualize their use. Our work complements these

Figure 15: From the movie Terminator 3 (1:20:30) a humanoid robot reverses its legs to catch a person behind (a). From the movie Terminator 2 (2:14:11) a humanoid robot reverses its body shape after hitting a wall (b).

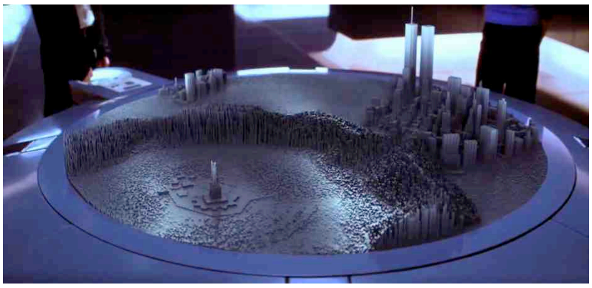

Figure 16: From the movie X-Men (1:08:40) a shape-changing display is used to physically visualize the urban conformation of a city.

reflections, but focusing on the behavioral qualities of SCI and the way in which they can fit to a particular context or application. For instance, we know that SCI can change in *orientation* or *volume* [30]. Our results show how these two types of shape change were used in Sci-Fi movies in the context of *adaptation*, where a shape-changing bed adapts its orientation to find a good position for the head of the user, or how a shape-changing garments (e.g., a jacket, a pair of shoes) could adapt their volume and length in order to fit the body of a user. Previous work questioned how certain behaviors of shape change could serve functional purposes that go beyond design inspiration [30], and sought to see more exploration into the effect of shape transformation and how it could be used. In response to these reflections, our results include examples that show functional uses of shape transformation and its effect on a SCI. For instance, we show how in Sci-Fi movies a form of *transformation*, and specifically *morphing*, was used in a SCI to embed multiple functionalities into a single interface, and transform a wallet into a gun or a robot into a radio. Rasmussen et al. [30] report an example of a SCI using spatial *reconfiguration*, where an array of 740 spheres is used for a kinetic sculpture to form the shape of a BMW car [48]. In our results we report an example from Sci-Fi movie that shows how this behavior can be used for a clear functional purpose; the example shows a number of spheres that automatically *assemble* in a triangular shape on a pool table, and let users restart a new game without having to replace each sphere manually. Shape-changing display that can physicalize data already exist [7,35], and research has proposed data physicalization as a potential application for SCI [16]. However, existing prototypes can only achieve 2.5 dimension of extrusion and most current applications are limited to that configuration. The examples that we reported from Sci-Fi movies show technology that can generate physical visualizations extending beyond 2.5D, which can surround users at 360 degrees or even generate physical matter from the very surface of the display. Even though these examples show shape change technology that might not be available any time soon, they still provide inspiration for potential future applications.

Figure 17: From the movie Man of Steel (0:45:33) a shape-changing display that dynamically generates 3D content and surrounds the users.

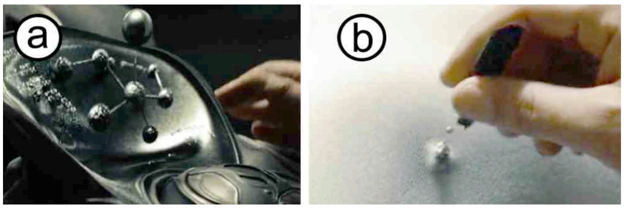

Figure 18: From the movie Man of Steel (0:10:13) a shape-changing display that generates physical matter (a), which can also be dethatched from the surface (b).

Applicability of Our Results to Existing SCI

Our results describe behavioral patterns of SCI that were inferred by looking at and analyzing fictional material. However, the four behavioral patterns listed in our results can also be used to analyze existing prototypes of SCI. Let us take as a first example the work TRANSFORM by the Tangible Media group at MIT [41]. If we analyze the functionalities of this particular SCI, we can see how some of the behavioral patterns described in the present paper apply to those functionalities. TRANSFORM is capable of *adaptation,* in which the surface of this SCI can conform its shape to the one of the objects that users place onto it. For instance, if a user places an orange on the surface of TRANSFORM, the interface will adapt its shape and generate a concave area that acts as a container for the orange. The surface of TRANSFORM is also used to *physicalize* information through shape change and motion. For instance, the surface would generate dynamic wave-like patterns to physically represent particular sounds, such as sine waves or drum beats. Another example of how our results apply to existing SCI are earlier work in the field of robotics that have proposed self-reconfiguring robots [3,32]. These work show how shape *reconfiguration* and *assembling* behavior are key with robots that need to be adaptable to various tasks and different environments. The same authors introduce modular robots called Crystalline [32] and show how their robotic system can *transform* a dog-shaped interface into a couch-shaped interface. This example displays the same behavioral quality as the *morphing* instances of SCI that we presented earlier in our results section.

Limitations and Future Work

The present paper has a number of limitations that we aim to overcome in future work. Our work presented a large-scale analysis of 340 Sci-Fi movies that aimed to identify instances of SCI, in order to reflect on their behaviors and functionalities. While this material allowed us to identify four behavioral patterns of SCI and a number of examples show what they can do, our investigation deliberately focusesed on Sci-Fi feature films only. Therefore, our results are limited to the source material and it does not include many other sources that might be relevant for SCI. For instance, we did not consider existing prototypes in our analysis. Including existing prototypes of SCI in future investigation might unfold behavioral patterns and their relationship to functionalities that are not present in our results. Future work should include these sources to unfold more behaviors of SCI. The present work provides reflective material that is based on speculations of future technology from Sci-Fi movies. Our results can be considered inspiring and helpful to reflect on how certain shape change behaviors can help functionalities. However, at this stage we cannot claim the practical applicability of our results in design practices. A logical next step for future work would be conducting design-based workshops on shape change, where designers use our results to design SCI. In this way we might be able to validate our results and show how they could be practically used in the design process of new SCI.

CONCLUSION

We have presented a large-scale analysis of 340 Sci-Fi movies that identifies instances of SCI and describes their behaviors and how they affect shape change. Furthermore, the SCI instances have served as material to reflect on the qualities of four behavioral patterns of SCI and the ways in which they support certain functionalities. Finally, we concluded by discussing our results in relation to previous work with shape change and showed how they can be used to explain behavioral patterns of existing prototypes of SCI. We hope that our results will help and inspire researchers and designers when thinking about the design of future SCI.

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