University of Konstanz
Department of Information and Computer Science
Master Computer and Information Science

Master Thesis

Navigating Virtuality in Reality

InformationSense: A system facilitating *direct* interactions with digital information spaces *in* the real world

for the degree

Master of Science (M.Sc.)

by

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(01/868948)

Subject of Study:	Computer and Information Science
Specialization:	Human-Computer-Interaction
Topic:	Information Science
First Reviewer:	Prof. Dr. Harald Reiterer
Second Reviewer:	Prof. Dr. Bastian Goldlücke
Thesis Adviser:	M.Sc. Simon Butscher
Submission Date:	September 14, 2016

Selbstständigkeitserklärung

Hiermit erkläre ich das ich die vorliegende Arbeit mit dem Titel

"Navigating virtuality in reality - InformationSense: A system facilitating *direct* interactions with digital information spaces *in* the real world"

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Die gegebene Arbeit basiert zum Teil auf den beiden Dokumentationen:

- M. Dürr. Master Seminar: Navigating virtuality in reality - Approaches to map virtual space to real world space. 2015.
- M. Dürr. Master Project: Navigating virtuality in reality - InformationSense: A system facilitating *direct* interactions with digital information spaces *in* reality. 2016.

Konstanz, September 14, 2016

Maximilian Dürr

Zusammenfassung

Die vorliegende Arbeit beschäftigt sich mit der Entwicklung und Implementierung eines Systems das *direkte* Interaktionen mit digitalen Informationsräumen *in* der Realwelt unterstützt. Die Benutzung eines *verformbaren Stoffs* steht im Vordergrund.

Neben einer kurzen Einführung in Bezug zur *Navigation* von virtuellen Räumen in der physischen Welt, wird das Reality-Based-Interaction Framework sowie ein Modell aus Designräumen betrachtet. Die Vorteile eines Systems welches die Verformung einer Textilie in der Realität ermöglicht werden hervorgehoben. Eine Untersuchung von neun *existierenden Applikationen* im Verhältnis zu *vorher definierten Anforderung*, wird im Kontext der Unterstützung von Navigationsinteraktionen innerhalb elektronischer Räume, vorgenommen. Dies führt zur Identifizierung von *Interaktionstechniken* zur Durchführung unterschiedlicher Aufgaben. Die Techniken werden in Bezug zum Trade-off zwischen Computergestützter Power und Realität betrachtet. Basierend auf den Analyseresultaten wird eine Benutzerschnittstelle, welche eine mit *unsichtbaren Markern* bedruckte, *flexible Stofffläche* verwendet, vorgestellt. Digitale Inhalte werden aufprojiziert. Das System wird zur Unterstützung der detaillierten Erkundung elektronischer Informationsräume durch *feste Linsen* erweitert. Im Rahmen einer Nutzerstudie wurde der entwickelte Stoff mit zwei anderen Systemen, welche eine verformbare Fläche auf einem Multitouch-Tisch simulieren, verglichen. Es wurde eine *Such- und Vergleichsaufgabe* genutzt. Die Resultate deuten auf vorteilhafte Eigenschaften der Touchsysteme in Bezug zu *Pragmatischen Qualitäten* hin. Weiterhin weisen die Ergebnisse darauf hin das Nutzer die echte Textilfläche unter dem Aspekt der *Hedonischen Qualität* bevorzugen. Die Untersuchung von Interaktionen und Kommentaren der Studienteilnehmer gibt Einblicke in Ihre angewandten *Strategien* und zeigt das die Probanden häufig Interaktionen, welche auf bereits *vorhandenem Wissen* aus der *physischen Welt* beruhen, für die Arbeit mit dem realen Stoff verwendet haben. Die Teilnehmer schätzten die *hohen Freiheitsgrade* welche durch das flexible, reale Stoffobjekt unterstützt werden. Im Rahmen einer Zusammenfassung werden, basierend auf den Studienresultaten, *Empfehlungen* für das zukünftige *Design* von verformbaren Displays vorgeschlagen.

Abschließend wird die *Erfüllung* der zuvor aufgestellten *Anforderungen* überprüft. Zusätzlich werden *Vorschläge für die Verbesserung* des erstellten Systems gegeben und *zukünftige Anwendungsfälle* für verformbare Stoffdisplays aufgezeigt und beschrieben.

Abstract

The given work introduces the development and implementation of a system which supports *direct* interactions with digital information spaces *in* reality. The focus resides on the use of *deformable cloth surfaces.*

Besides a brief introduction in regard to the *navigation* of virtual spaces in the physical world, the framework of Reality-Based-Interaction, as well as a model of design spaces is taken into consideration. The benefits of a system which facilitates the deformation of a textile in reality are highlighted. Nine *existing interfaces* are verified, against *predefined requirements*, in context to their support for the navigation of electronic spaces in the real world. *Interaction techniques* for different tasks are extracted. They are surveyed in regard to their tradeoff between computational power and reality. Based on the analysis results, an interface which utilizes a *flexible cloth surface*, imprinted with *invisible markers*, is introduced. Digital content is projected. The system is enhanced with *rigid lenses* to facilitated detailed explorations of electronic information spaces. In course of a user study the developed cloth interface was compared with two other systems which simulate a deformable surface on a multi-touch table. A *search* & *compare* task was used. The results indicate advantageous properties of the touch interfaces in regard to *pragmatic qualities* and suggest that users preferred the real world textile in terms of *hedonic qualities.* The evaluation of participants interactions and comments provides insights into their *strategies* and reveals that they frequently conducted interactions based on their *pre-existing knowledge* of the *physical world* when they worked with the real textile. Participants appreciated the *high degrees of freedom* supplied by the flexible real world cloth object. In conclusion, based on the studies results, *recommendations* for the future *design* of deformable textile displays are proposed.

Finally, the *fulfillment* of previously defined *requirements* is verified. Additionally, *suggestions for the improvement* of the created system are presented and other possible *prospective use cases* for deformable cloth displays are illustrated and described.

Geplannte Einreichung zur Veröffentlichung

Die Veröffentlichung von Teilen dieser Arbeit ist auf der Konferenz

The ACM CHI Conference on Human Factors in Computing Systems

unter folgendem Titel geplannt:

M. Dürr, S. Butscher und H. Reiterer. InformationSense: Exploring Tangible Cloth Displays.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

"Navigation = Wayfinding + Locomotion
'Knowing where to go' + 'Getting there' " [52]

There exists a high manifoldness of possible ways and interactions which are applicable for the navigation through digital information spaces. Much past research addressed the issue. *Frameworks* were introduced [52,97,98] and *usability principles* [77] were defined to improve the navigation of virtual spaces. Multiple works attempted to draw parallels between the navigation of the physical world and the digital counterpart. It was remarked that the problem of *getting lost* when navigating in reality also exists for the electronic world [22]. The utilization of landmarks or other cues, familiar from wayfinding in the physical world, was proposed in order to aid users when navigating virtual spaces [20,21]. To further incorporate advantageous properties from the real world, multiple researchers suggested the use of more physical interfaces. For example, Camarata, Yi-Luen Do, Johnson & Gross [11] introduced a system which facilitates the navigation of information spaces through the manipulation of tangible blocks.

The given work focuses on the utilization of a *deformable cloth surface* for the navigation of digital information spaces *in* the real world. To support more detailed explorations of the virtual space, the system was enhanced with *rigid lenses*. Output is *directly* supplied on the surfaces with which the user interacts. The constructed prototype in line with the insights, which were gained by the conduct of a user study, might facilitate the prospective design of flexible displays and potentially influence the related research in the future.

1.1 Motivation: Navigation is "senseless"

In 2004, O'Sullivan & Igoe [81] stated that classic desktop interfaces are not really fulfilling their role in *supporting their users.* In their eyes, it is more the *users supporting the systems.* They argued that humans have a huge variety of senses and ways to express themselves while only few are used to interact with common technical systems. Let' s compare for example the interactions which are possible with a physical map and the ones feasible with its digital equivalent (e.g. Google Maps[1] on a desktop computer). The paper map facilitates a vast amount of real world interactions like grabing, lifting, lowering, folding, unfolding, rotating or moving the interface within the physical environment. In contrast, the navigation with a virtual map can be seen as nearly "senseless". It solely addresses a very limited spectrum of the human bodies capabilities to perceive its surroundings. Ishii [41] also recognized the issue in 2008. He illustrated the problem by using the metaphor of a seashore at which water meets land, leading life to blossom:

> *"At another seashore between the land of atoms and the sea of bits, we are now facing the challenge of reconciling our dual citizenships in the physical and digital worlds. [...] Windows to the digital world are confined to flat, square screens and pixels, or "painted bits". Unfortunately, one cannot feel and confirm the virtual existence of this digital information through one's hands and body." [41]*

Oakley et al. [79] also saw disadvantages in the shift of interactions from *"the rich multi-sensory environment of the real world"* towards primitive rigid screen based windows into the virtual world. According to them, to conduct this step might result in a deprivation of awareness [23,30,85] and observed attention [42] in relation to collaborative work scenarios.

Unfortunately, most users are still limited in the utilization of their sensory faculties for the navigation of digital data spaces. Traditional desktop interfaces solely support indirect input devices like mouses or keyboards. Especially in the last decade, touch sensitive screens were incorporated in a multitude of consumer products. Although utilizing such displays leads to a more direct feeling of interaction, there is still a large gap towards the richness of movements and manipulations which might be facilitated by a system based on a physical cloth object, deformable in reality.

1.2 Applied Approach: Let's get Real!

In 1998, Harrison et al. [31] predicted *"physical user interface manipulators"* to be *"a natural step towards making the next UI metaphor the real world itself"*. Later O'Sullivan & Igoe [81] proposed to employ a higher amount of human senses by means of creating more physical interfaces. Also advising more realistic interactions, Ishii [41] suggested TUIs[2]. These give users a more direct control over underlying digital structures. Price & Rogers [87] determined that digitally augmented physical spaces

> *"[...] provide greater degrees of freedom than a PC and single monitor to design physical-digital interactions."* [87]

This relates to the framework of *Reality-Based Interaction* which was introduced by Jacob et al. [46] (see Section 2.1). The authors stated that it can be beneficial

[1] https://www.google.com/maps
[2] TUI(s): Tangible User Interface(s)

to place interaction techniques closer to the *real world*[3]. Doing so, might reduce the mental effort needed to navigate through digital data, since users are already aware of the ways in which they interact in reality. This diminution in mental effort can, depending on the given context, have positive effects. Users might *learn quicker* or experience an *increase in performance* in specific situations.

This work aims at bridging the gap between the digital world on the one side and reality on the other. People should have the possibility to exploit a huge amount of their sensing capabilities when navigating through electronic data. Like shown in Figure 1.1, to achieve this, it is necessary to conduct a meaningful mapping between virtuality and reality.

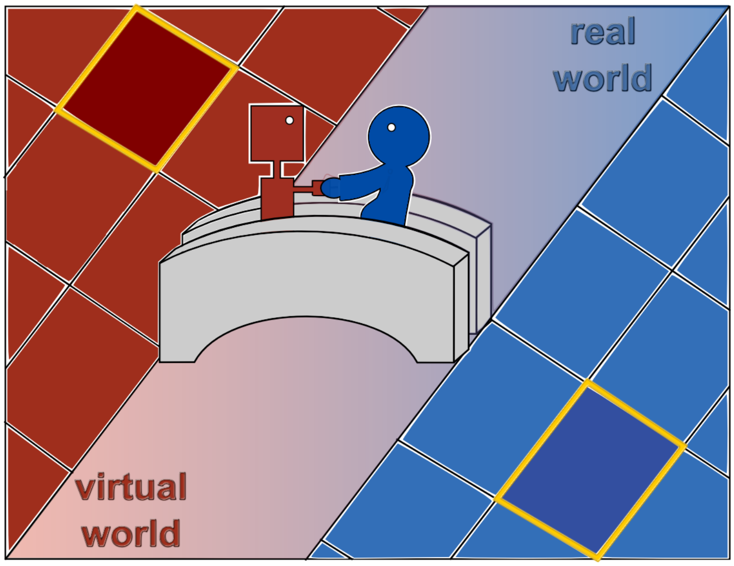


Figure 1.1: Bridging the Gap between Virtuality and Reality. Bringing the virtual world (red) closer to the real world (blue) is like building a bridge. Both worlds need to be mapped together in a meaningful way (e.g. the yellow highlighted pieces of space). [4]

Jacob et al. [46] discern between two types of interactions which leverage users pre-knowledge of the real world. According to them, one might either utilize interactions which take part *in* reality (*Interactions* ***in*** *the real world*) or interactions which solely emulate a process from the physical world (*Interactions* ***like*** *the real world*). For example, the navigation through a map like interface with the gestures pan[5] and zoom[6] on a multi-touch table imitates a procedure from the real world. Both of the gestures are metaphors for the phys-

[3]For the term *real world* the definition of an *"undigital world, including physical, social, and cultural reality outside of any form of computer interaction"* [46] applies for the hole thesis.

[4]In Figure 1.1 the image of a human (blue) was adapted from [19].

[5]i.e. *"translation of the current view port to another location"* [50]

[6]i.e. *"act of changing the level of detail of the current view port"* [50]

ical manipulation of maps. In contrast to simulate this behaviour, one might as well augment a physical map with digital data instead and interact with it *in* reality.

The given work is based on *Interactions **in** the real world*. Interactions of this class make use of more human senses, increase bodily and physical awareness and directly aid real world knowledge. Nevertheless, like elaborated in Section 2.1.2 a gain in realism is often coupled with a loss in terms of computational power.

The physical surface which is utilized in order to navigate virtual data spaces in reality consists of *cloth*[7]. The material was prominently used throughout human history. Different applications like maps[8] were based on it. Swallow & Thompson [105] named certain advantageous properties of soft textile products. According to them, fabrics might be used in order to establish large real world interaction areas. In contrast, they can also be compressed to a reduced size. Further, the materials are in general quite light in respect to the surface they supply in expanded form. When compared with paper, textiles have a better durability. They are not as readily altered with fold marks. Eventually, cloth enables a higher degree of deformability and possibly supports interactions not feasible with paper (e.g. stretching).

1.3 Outline

In the following a brief outline of the thesis is given. Chapter 2 introduces the *Reality-Based Interaction framework* in line with a *model of five spaces*. Both theoretic concepts might be used to analyze applications in the context of navigating virtuality in reality. Additionally, *requirements* for a system which facilitates the navigation of digital data spaces in the real world are listed and described. Chapter 3 presents an *overview of related work* and *examines* the most relevant of the *existing applications* in regard to the previously stated requirements. The analysis leads to the identification of various interaction techniques for four different tasks. The *techniques* are subsequently *surveyed* in relation to the tradeoff between computational power and reality. Based on the analysis results, the *concept* which was proposed for a future system is elaborated. Chapter 4 elucidates the implementation of the developed system. The *physical setting* in line with the *software processing* is explained in detail. Further, *technical limitations* are named and briefly described. Chapter 5 delineates the conducted user study, including the *research question(s) and hypothesis*, the *studies design*, its *results*, a *discussion* of findings, as well as implied *limitations*. Eventually, Chapter 6 provides a *conclusion* in regard to the defined requirements and gives an outlook. *Future work* in line with *prospective use cases* for an interface, based on a deformable cloth, are suggested.

[7]The rigid lenses are based on acrylic glass, covered by a layer of cloth (see Section 4.1.3).
[8]*"The origin of 'map' is the Latin **mappa**, designating a tablecloth"* [45].

Chapter 2

Navigating Virtuality in Reality

Different frameworks and models in relation to the navigation of digital information spaces in the real world were developed. Section 2.1 introduces the framework of Reality-Based-Interaction, including a coordinate plane which might be used to compare interaction techniques or interfaces in regard to their realistic and digital properties. Further, a model of five spaces is presented in Section 2.2. It can be used to describe systems which facilitate the interaction with virtual data spaces. Eventually, the requirements for a future application, which supports the navigation of digital data in reality, are outlined in Section 2.3.

2.1 Reality-Based-Interaction (RBI)

Jacob et al. [46] introduced the notion of RBI in order to describe a new generation of Post-WIMP[1] interaction styles. It succeeds the generations based on command line and direct manipulation interfaces. RBI characterizes a movement from virtual to real world interactions. It incorporates interaction styles like context-aware computing, ubiquitous and pervasive computing, perceptual and affective computing, as well as various others.

This section elaborates the foundation of the framework in form of the four themes of reality. Further, the tradeoff between computational power and reality is described.

2.1.1 The four Themes of Reality

Figure 2.1 shows the four themes of reality which were introduced by Jacob et al. [47]. They differentiate the focus of the RBI framework in relation to the real world. In the following, a short description of each theme, based on the authors definition, is provided. Below each description, an example, in context of the navigation with a real world map, is supplied.

[1]WIMP: windows, icons, menus, pointer

- **Naïve Physics:** Concerns peoples knowledge about the physical world [47].

  If a persons hand is positioned in the center of a paper map and the map is lifted in the air, the outer edges of the map are dragged down by gravity.

- **Body Awareness & Skills:** Concerns peoples awareness of their own physical bodies in line with their abilities and skills to coordinate and control them [47].

  A person using a physical map would be aware of his or her bodies relative position towards the map and which areas of the map he or she could reach with his or her hands without moving it. Also, early developed skills to control body movements would be known (e.g. moving a hand towards the map and dragging it over the table). [47]

- **Environment Awareness & Skills:** Concerns peoples sense of their environment and their skills for negotiating, manipulating and navigating within it [47].

  When interacting with a real world map, people can move around the map, understand its scale and see how different locations are connected. Simultaneously they are aware of ingrained skills to manipulate it (e.g. folding the map or circling locations with a pen). [47]

- **Social Awareness & Skills:** Concerns peoples abilities to perceive others who sorround them in line with their skills for social interaction [47].

  Looking at a group of people, multiple persons could work with colored post-its on a map. They could mark different locations with their own individual color while being aware of things marked by other people at the same time. Also, they could discuss with each other about the steps they take, during the process.

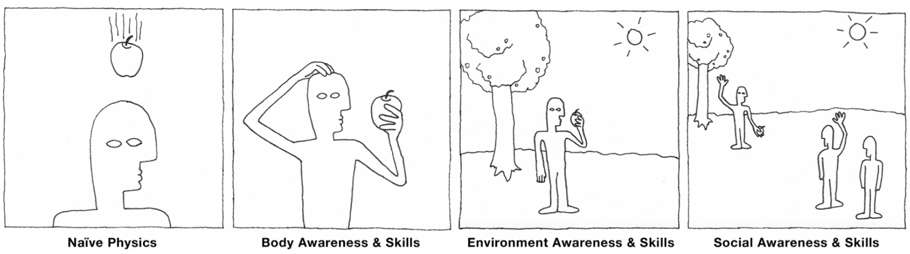


Figure 2.1: The four Themes of Reality. Naïve Physics, Body Awareness & Skills, Environment Awareness & Skills, Social Awareness & Skills. [47]

2.1.2 The Power vs. Reality Tradeoff

An interface for the navigation of virtual information spaces might support the presented themes of reality in order to supply users with more realism and facilitate physical interactions. Nevertheless, Jacob et al. [46] argued, that it is not sufficient to make an interface as realistic as possible. According to them, computational power allows the creation of enhanced interfaces which go beyond a precise imitation of the physical world.

However, the authors stated, that in many cases the adding of more computational power to an application can lead to a loss in terms of realism and vice versa. They argued that there exists a tradeoff between the amount of computational power a system holds and its proximity to the real world. The authors proposed the coordinate plane illustrated in Figure 2.2, in order to aid the design of more physical systems. It can be used to compare different interaction techniques after their tradeoffs. Further, to facilitated the specification of tradeoffs, Jacob et al. [47] formalized six qualities for which designers might accept a decline in realism. These are expressive power, efficiency, versatility, ergonomics, accessibility and practicality.

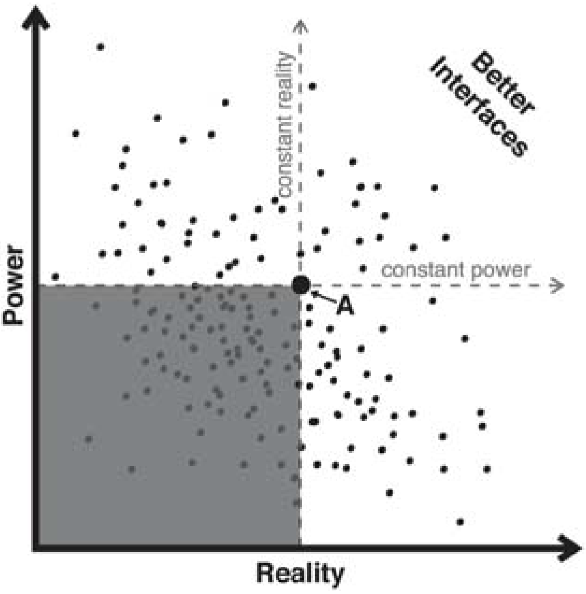


Figure 2.2: The Power vs. Reality Tradeoff. Often, to add more computational power to an application means a loss in reality and vice versa. [46]

A design approach was proposed by the authors. It is based upon the key concept of RBI, to develop new ways of interaction with technical systems which reside closer to the real world. Jacob et al. [46] suggested to create applications and interactions as *close* to the real world as possible and trade reality *only* for computational power when necessary.

2.2 The five Space Model

There are multiple ways to separate space into different categories. This section presents a model of spaces which can be utilized for the description of applications and the interaction concepts they embed.

Eriksson [25] proposed in her analysis of *Spatial Explorations in Interactions* a model depicting four design spaces in the context of SMUI[2]. Spindler et al. [101] also introduced two different spaces to describe their mapping between 3 dimensional virtual information spaces and reality. They did this in relation to their systems for the exploration of digital data spaces [99, 101]. The authors supplied users with lens displays which they could utilize as peepholes to the virtual world. Dependent on a lenses position in the real world, different information from the digital data space was projected on the rectangular object(s). The spaces, defined by Spindler et al. [101] show parallels to the ones provided by Eriksson [25]. Based on the combination of both authors ideas, a model of four different spaces could be extracted. To increase the models preciseness a fifth space, the *Visualization Space*, was defined additionally. In the succeeding all five spaces are described with relation to the illustrations displayed in Figure 2.3. Each of the graphics shows one of the spaces in the context of a lens navigation scenario.

2.2.1 Interaction Space

In relation to their SpaceLens, Spindler et al. [101] define the *Interaction Space* as real-world space in which a lens can be *held* and *moved* in order to explore parts of the virtual space. Eriksson [25] complements this view with her specification of Interaction Space being *"defined as the sensor reading space where movement, fix points and inputs can be sensed"*. Concerning the graphic provided in Figure 2.3a, Interaction Space is the space in which physical objects (e.g. a lens display) in line with a users body parts might be tracked. It is possible to see that only one of the two persons in the image is standing within the Interaction Space. Thus, only this persons lens display is currently tracked and can be used for interactions with the system.

2.2.2 Exploration Space (Digital Space)

Spindler et al. [101] introduce the term *Exploration Space* as the space reflecting the virtual data a user wants to explore. This relates to Erikssons [25] definition of a *Digital Space* which builds upon *"computational things and their output"*. According to her, results can be transfered to users by *"various kinds of feedback"*. Depending on the Exploration Space, different types of data might be given (e.g. 3 dimensional, multi-dimensional or temporal data). In the example displayed in Figure 2.3b, an Exploration Space reflecting 3 dimensional data was mapped directly to an Interaction Space.

2.2.3 Social Space

This space incorporates humans joint activities, communications and social conventions, as well as properties like attention, understanding and place [25]. It relates to peoples Social Awareness & Skills, enabling concepts in which users can collaborate in a shared real world space [48]. As can be seen in Figure 2.3c,

[2] SMUI: Spatial Multi-User Interaction

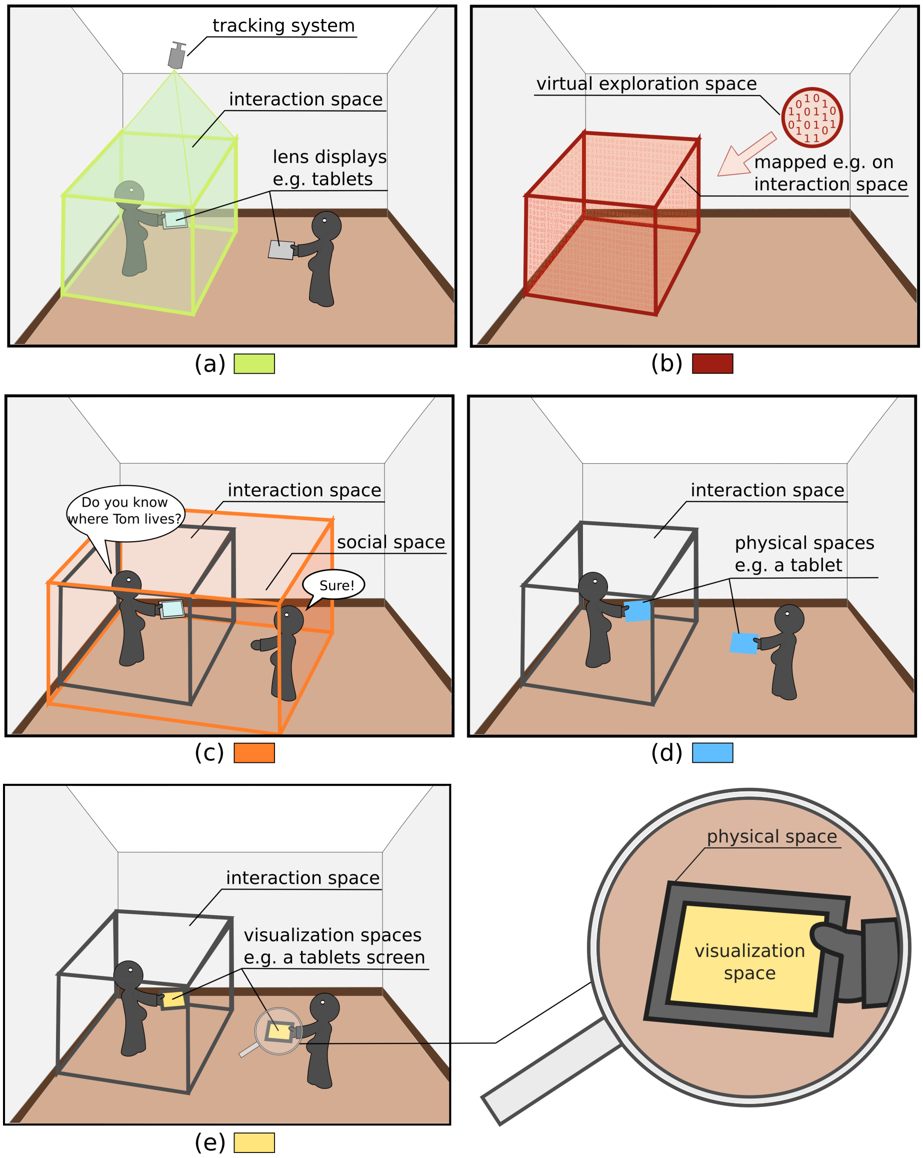


Figure 2.3: The five Space Model. Sketched example scenarios for the five spaces: (a) *Interaction Space.* (b) *Exploration Space.* (c) *Social Space.* (d) *Physical Space.* (e) *Visualization Space.* In each image the described space is highlighted with a certain color. [3]

[3] In Figure 2.3 the image of a human (dark grey) was adapted from [19].

the Social Space can comprise the Interaction Space. Thus navigating in Interaction Space can *include* social interactions which can *develop* to pure interhuman communications. For example, two persons could navigate with their lens displays within the Interaction Space and talk while doing so. Later they might move out of the Interaction Space but keep on discussing within the Social Space. On the other hand, it is as well possible that an interaction of a single person, working with a computer-aided system, *transforms* to a social interaction. A user could hit a problem while navigating within the Interaction Space and ask another person, located in the Social Space but not within the Interaction Space, for help. Depending on the given situation, they could both move in or out of the Interaction Space to solve the problem together. In Figure 2.3c an example, in the context of map navigation, is shown. One person (*user1*), who is located within the Interaction Space, talks to another one (*user2*), asking if he knows where Tom lives. Assuming *user2* knows where Tom lives, he could in respond get his own lens display, move within the Interaction space and navigate to the correct position. Afterwards *user2* could forward the exact position to *user1* or, even simpler, just hand *user1* his lens display.

2.2.4 Physical Space

According to Eriksson [25], *Physical Space* incorporates *"all types of visible things such as humans and computational things"*. It is specified as the space in which the user gets in physical contact with the system. To put Physical Space in a clear relation to the spaces proposed by Spindler et al. [101], it will, in the following, solely be used as a reference to physical objects with which a user can interact. Each of these physical objects will, in the further, be defined as a separate Physical Space. An example is given in Figure 2.3d. It shows two persons with lens displays. Each lens reflects a Physical Space with which users can interact. As long as they are within the Interaction Space while doing so, reactions of the system can be provoked. Letting people interact with natural feeling objects in Physical Space brings applications closer to the real world. It reflects principles of the RBI framework, described in Section 2.1 (e.g. physical objects hold properties of Naïve Physics like being pulled down by gravity when letting lose in the air).

2.2.5 Visualization Space

This space incorporates *only* the part of a Physical Space in which digital data from the Exploration Space can be visualized. Referring to Figure 2.3e, again two persons holding each a lens like display can be observed. Let's assume these displays would be tablet computers. In each case the *hole tablet computer* would reflect the *Physical Space*. Solely the *screen* would conform to the *Visualization Space*. The reason is that only on the screen digital content might be *visualized*.

2.3 Requirements

Six different properties, which a system for the navigation of virtuality in reality should support, were defined. Figure 2.4 supplies an overview of the specified requirements. They are elaborated in the following.

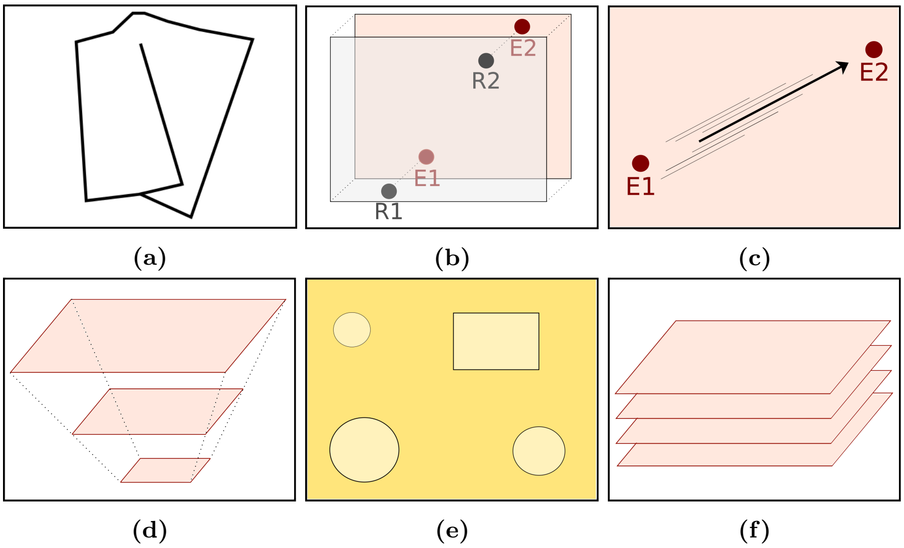


Figure 2.4: System Requirements. (a) Support *deformable* Physical Spaces (cloth). (b) Support a *static* mapping to reality. (c) Support *quick* navigation interactions. (d) Support navigation and orientation in multi-scale. (e) Support multi-focus. (f) Support multiple information layers.

2.3.1 Support *deformable* Physical Spaces (cloth)

When looking at the consistency of physical real world spaces, a general distinction can be made. On the one hand, there exist ***rigid*** *Physical Spaces* like monitors, smartphones, stone or wood. On the other, a designer might utilize ***deformable*** *Physical Spaces* like paper, bendable plastic or cloth. Holman & Vertegaal [37] stated that deformability allows objects and tools to *"adapt their functionality to different contexts"*. Flexibility can simplify real world tasks like e.g. flipping pages when navigating through a book. In contrast, the authors declared that *rigidity* in the design of interfaces sets boundaries to the usability of technical systems regarding the possible actions available to them. Lee et al. [67] and Kildal [56] also both determined that users prefer softer materials or DUIs[4], like paper or cloth, over rigid devices [58]. While the study of Lee et al. [67] involved no interactions, Kildal [56] showed that users have a preference for more flexible interfaces when being engaged in navigation tasks. Further, the employment of deformable materials relates to the RBI framework from Jacob et al. [47] (see Section 2.1). Flexible Physical Spaces facilitate various interactions which build *"on users' pre-existing knowledge of the everyday, non-digital*

[4]DUI(s): Deformable User Interface(s)

world". For example, people are aware of their abilities to crumple, fold or otherwise manipulate a cloth object in reality. To reuse such interactions in a meaningful way, combined with digital data, can result in an intuitively understandable interface. The utilization of flexible materials coincides with the idea of Price & Rogers [87]. They suggested to make interfaces more physical and provide users with *"greater degrees of freedom"*.

Like mentioned in Section 1.2 this work focuses on the use of a deformable surface based on the material *cloth*. Rigid lenses were utilized in order to enhance the created interface with additional functionalities (see Section 3.4.2).

2.3.2 Support a *static* mapping to reality.

There exist different ways to map digital data to real world positions. It is possible to make a distinction between *Mapping virtual data* ***dynamically*** *to the real world* and *Mapping virtual data* ***statically*** *to the real world*.

Figure 2.5a illustrates an example for a *dynamic* mapping. The Exploration Space is reflected in red (e.g. a digital map). Part of the virtual data is visualized on the screen of a touch display. The perceivable digital data points correspond to specific locations on the real world monitor (e.g. E1 corresponds to R). In case a user touches the screen and moves the digital content, for example from left to right, the mapping between virtuality and reality changes dynamically. When the movement is completed, the screen of the touch display reflects different values from the digital data space than before (e.g. E2 corresponds now to the position R in the real world).

On the other hand, it is also possible to reflect digital data *statically* in reality, like shown in Figure 2.5b. In this example, a tablet is utilized as peephole in the virtual world. The device is held upon a table. The real world space is visualized in grey. Which points from the Exploration Space appear on the display, is dependent on the tablets current position in reality. For example, when a user places the device on the left side of the table, certain digital data points are shown on the tablets screen (e.g. E1 which *always* corresponds to R1). Let's consider the tablet is subsequently shifted to the right. After the movement was carried out, different points from the virtual world are visualized on the screen (e.g. E2 which *always* corresponds to R2).

Mou et al. [75] stated that it is possible for humans to encode spatial information in relation to a frame of reference. According to them, this might aid peoples capabilities for spatial memorizing. When comparing the two ways of mapping, solely the static version supports the use of a continuous physical reference frame. In context of the examples, this would be the border of the table in the real world. Users can perceive the distance between each position on the table and the tables edges. While one location in reality always corresponds to only one position in the Exploration Space, a user might be able to transfer the mentioned distance relationship to the digital data points.

The possibility that people might relate virtual points to a continuous physical reference frame was seen as promising. It could facilitate their spatial memorizing capabilities. In contrast to the dynamic mapping, the utilization of a reference frame goes one step further than a sole position detection. Users gain the option to associate digital elements with locations *in reality*. Thus, to use a static mapping complements the utilization of *Interactions **in** the real world* (see Section 1.2).

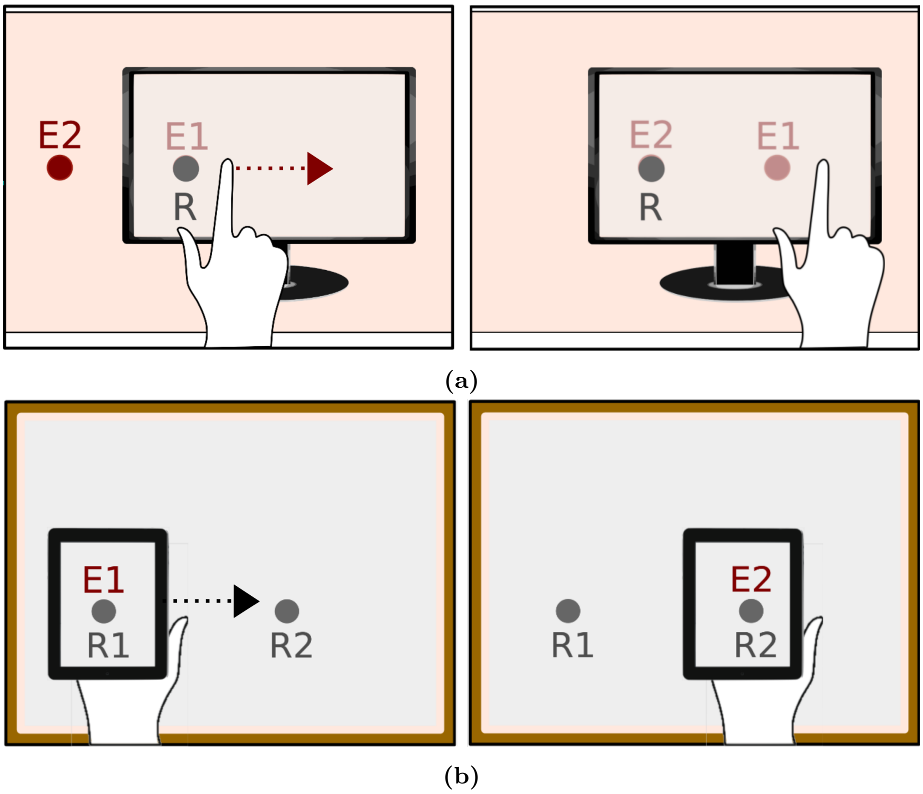


Figure 2.5: Ways to map Digital Data to Reality. (a) Dynamic Mapping: The Exploration Space shown in red (e.g. a digital map) is moved by a user over a screen. Different virtual data points are reflected at the same position in reality. (b) Static Mapping: The Physical Space (e.g. a tablet) is moved by a user above a table. One digital data point corresponds *always* to only one position in the real world.[5]

2.3.3 Support *quick* navigation interactions.

Focusing on the *navigation* of virtuality in reality, it is seen highly relevant to perform interactions related to this process as fast as possible. A minimum of interaction steps should be required to reach a target position. Although there might still be faster solutions, in general the implementation of *zooming* seems beneficial. It can increase navigation speed through allowing *users to view off-screen content in a non-linear fashion* [90]. Contrary to that, one could consider, for example, the navigation in a virtual map interface which supports solely panning interactions on a touch table. In case a target position of an

[5]In Figure 2.5 the images of a hand (white) and an iPad were adapted from [3, 29].

navigational interaction is far from the point of origin, moving there through panning would be a slow process. The navigation would result in *clutching*. Such slow and annoying navigation interactions should be avoided.

2.3.4 Support navigation & orientation in multi-scale.

Cockburn et al. [17] introduced the problem, that for the majority of computational systems its users require to work with more information and interact with a broader range of components, than can be simultaneously visualized on a single display in an appropriate form. They stated that current limitations in terms of technology *"constrain the ability of displays to match the breadth and acuity of human vision"*. Typical mechanisms dealing with this issue (e.g. paging, scrolling or panning) introduce a discontinuity between data visualized at distinct times and places. This causes *"cognitive and mechanical burdens"* for users who have to understand the Exploration Spaces structure in line with ascertaining their own position within it in order to pursue correct navigational actions. As potentially advantageous alternative, the authors suggested the use of interfaces supporting multiple levels of scale. Thus allowing users to *"rapidly and fluidly move between detailed views and broad overviews"*.

However, not only to support the *navigation* in multiple levels of scale is important. It is also necessary to aid the *orientation* of users while interacting with a system. Cockburn et al. [17] proposed the four techniques *zooming*, *overview + detail*, *focus + context* and *off-screen content visualization* for use with multi-scale environments. These techniques supply users with capabilities to gain an overview or relate viewed data to given contextual information.

2.3.5 Support multi-focus.

According to Butscher et al. [9], for many tasks carried out in virtual spaces with multiple scales, it can be a necessity to have the support of multiple foci. Nearly all common user interfaces supply techniques like e.g. pan & zoom to change these foci *over time* (time multiplexing). In contrary, only few interfaces give a user the option to use multiple focus regions together at the *same time* (space multiplexing).

Applying space multiplexing could facilitate tasks related to the *duplication* or *movement* of virtual elements as well as the *comparison* between focus areas. Also it might aid *collaborative work*. Multiple users could have each their own focus region(s) and navigate within these areas independently from others. At the same time they would be able to communicate or even exchange regions of interest.

2.3.6 Support multiple information layers.

For various different kinds of Exploration Spaces the digital information can be divided and represented in form of different layers. This applies, for example, in case of the common task of map navigation (e.g. layers of terrain [99] or layers of positional information about different types of places like gas stations or hotels [54]). Other examples are *"semantic zoom levels of node link diagrams"* [100] or historical data about soil layers. In order to allow the effective navigation within such layered Exploration Spaces, it is required to support interactions connected to them in a meaningful way.

Chapter 3

Analysis

Multiple researchers already addressed the topics *real world interaction* and *interactions with deformable materials*. In this chapter, Section 3.1 provides an overview of *related work*. Some of the systems which were created by researchers in the past were deemed very relevant in regard to the stated requirements. Section 3.2 depicts a detailed review of these *existing applications* against the defined criteria. As result, it was possible to identify different interaction techniques for mainly four tasks. They are *examined* in relation to their *tradeoff between computational power and reality* (see Section 3.3). Based on the outcome, Section 3.4 proposes the *concept* of the implemented system.

3.1 Overview of related Work

This section provides an overview of related research. Especially three general directions of relevant work are surveyed. Like stated in Chapter 1, the created interface supplies users with a flexible cloth surface for the navigation of virtual data in reality. Besides directly related work to surfaces which can be *deformed in the real world*, also systems based on the utilization of *rigid surfaces in reality* and interfaces which *simulate deformability* are reviewed.

3.1.1 Real World rigid Surfaces

Multiple authors proposed interfaces based on rigid surfaces which might be moved through the real world. Spindler, Stellmach & Dachselt [99] showed PaperLens, a system which facilitates the exploration of digital spaces above a table with inflexible lenses. With FoldMe [54], a concept for a double-sided foldable display, in line with a set of suitable interaction techniques, was presented. Additionally, different works in relation to magic lenses and peephole displays were conducted [34, 60, 93, 118].

3.1.2 Simulated deformable Surfaces

Some existing systems emulate the deformation of digital surfaces with interactions which are based on humans real world knowledge. The Information Cloth, which was presented by Mikulecky, Hancock, Brosz and Carpendale [74], might be draped over virtual objects, pulled, stretched or folded. ClothLens [63] facilitates the creation of multiple focus regions in form of lenses on top of a simulated textile surface which displays a map. The cloth surface is stretched or bent, dependent on a users interactions. Butcher, Hornbæk & Reiterer introduced SpaceFold [9], a system inspired by Mélange [24] and past work on multi-touch document folding [15]. It supports the folding of a digital data space with touch gestures. The interactions are based on the real world metaphor to fold a piece of paper.

3.1.3 Real World deformable Surfaces

The works in the area of surfaces which might change their form in reality are split into four subcategories. Deformable surfaces as *input devices*, shape changing screens aided by *actuation*, flexible displays which might be *manually manipulated*, as well as research in relation to *applicable gestures* was reviewed.

Deformable Surfaces as Input Device

There are multiple works which propose flexible rectangular shaped flat objects as novel input devices. They are supposed to provide new ways to control music [14] and television sets [68], as well as to interface with GUI[1] based applications like e.g. photo galleries or Google Earth[2] [26, 35, 91, 111, 113, 119].

Actuation based deformable Surfaces which provide direct Output

Various researchers proposed concepts for surfaces which can change their shape through actuation. Prominent examples are Feelflex [43], as well as the Relief prototype [69]. Both systems utilize an array of motorized pins which is overlayed by a cloth like material. Output is projected on the textiles screen space. Stevenson, Perez & Vertegaal [103] created an inflatable hemisperical multi-touch display. In the context of smartphone applications, MorePhone [27] was introduced. Other authors [107, 110] also showed concepts which use actuation in order to supply deformable or shape changing surfaces.

Manually deformable Surfaces which provide direct Output

A diversity of systems which allow humans to physically deform augmented real world surfaces with their hands, was presented in the past. Some existing prototypes are based on a flexible textile which is spanned over a frame and manipulable through the application of pressure [13, 86, 94, 114]. Other works demonstrate smartphone or tablet like devices which support deformations [8,

[1] GUI: Graphical User Interface
[2] https://earth.google.com

57, 62, 92, 96, 104, 117]. Steimle, Jordt & Maes [102] introduced FlexPad which supplies users with a flexible surface they can move and manipulate in reality. A projection adapts dependent on the provided input. Lepinski & Vertegaal [70] showed an application which supports textiles. The cloth surfaces might be draped over existing physical objects or manipulated in reality by gestures like pinching or stretching. Output is provided via projection on top of the fabrics. The system DeforMe [88] also utilizes a projector. It facilitates the augmentation of various different deformable surfaces like elastic clay, gel sheets or fabrics. PaperWindows [38] shifts common GUI windows to flexible sheets of paper. Further, prototypes of foldable [28, 66] and rollable [55] displays were presented.

Gestures for the Deformation of Surfaces in Reality

Different studies in connection to gestures which might be utilized in order to deform surfaces in the real world were pursued. Lee et al. [67], as well as Troiano, Pedersen & Hornbæk [106] examined ways in which users manipulate flexible displays as input devices. The authors of both papers supplied a set of gestures for the interaction with deformable surfaces. Further, multiple researchers conducted investigations in relation to bend gestures [1, 112, 116].

3.2 Analysis of existing Applications

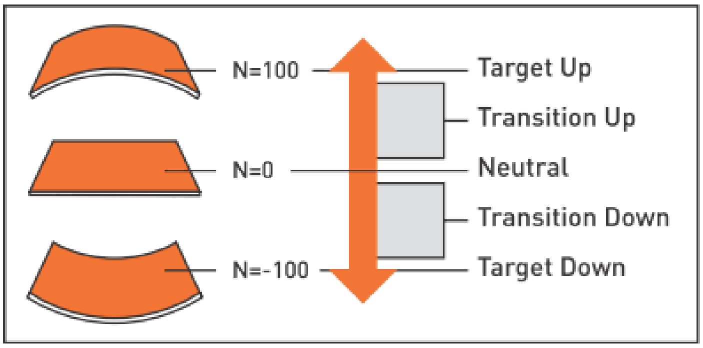
Nine existing applications were examined in more detail. Section 2.3 introduces different criteria which were deemed of interest for a system, facilitating the navigation of virtual data spaces in reality. The aim of the analysis was to determine to which degree and in *which way* the given prototypes fulfill the stated requirements.

In the following each of the surveyed applications is briefly described. In the process its properties which are relevant in relation to the defined criteria are highlighted. Eventually, an overview of the examinations results is provided.

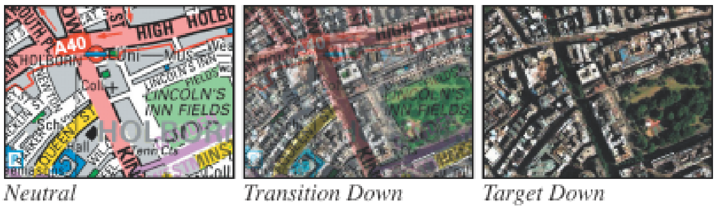
3.2.1 Gummi

Schwesig et al. [96] presented a handheld interface called Gummi. The prototype is based on layers of flexible electronic components. A deformable display is utilized as topmost layer. The system supports bend gestures and has a touch sensitive area for 2D position control on its backside. The touch pad has approximately the size of a credit card. Bending interactions can be used to perform continuous control functionalities, as well as target and transition operations like e.g. selecting screen objects or zooming the interface. In Figure 3.1a, the different bending-states of Gummi are displayed.

It is possible to use the devices 2D position control in order to pan through virtual data. When the given Exploration Space is large, only part of it might be presented on the screen at the same time. While users navigate the digital data space, continually different digital content is visualized on the same position in reality. Thus virtual data is mapped *dynamically* to real world space. According to the authors [96] the interface supports *quick zoom* interactions by *deforming* the device through *bend gestures*. Zoom-through-bending might be combined with panning via the small touch area on the backside. Doing so, possibly enables a way to navigate large Exploration Spaces (e.g. a huge virtual map) with *moderate speed*. However, the benefit over zoom and pan navigation interactions used in common smartphone interfaces is seen rather marginal. The panning area is equally small and zoom through bending the device down employs a weak real world metaphor. Humans usually do not bend objects in reality downwards in order to magnify information reflected on their surface. Further, to place the panning area on the backside is less direct than situating it on the devices front were the user interacts. Figure 3.1b shows a continuous control functionality of Gummi which allows users to navigate through *multiple layers of information* by bending. The device blends different layers of terrain data, dependent on the bending state or event (e.g. neutral or transition down). The illustrated examples for Map-Blending can be related to the bending states and events displayed in Figure 3.1a



(a)



(b)

Figure 3.1: Gummi. (a) Bending states and events of Gummi. (b) *Map Blending* with *multiple information layers.* [96]

3.2.2 PaperWindows.

Holman et al. [38] presented with *PaperWindows* a prototype windowing environment. A rubbing gesture can be used in order to transfer traditional desktop windows to real world paper (see Figure 3.2). The system was designed to *"bridge the divide between the digital and physical world of computing"* [38], according to Weiser's [115] definition of the vision of ubiquitous computing. The authors [38] realized it to track papers, users fingers and pens by enhancing them with IR reflective markers. A Vicon Motion Capturing System[3] was employed for the task. Virtual windows were visualized on the Physical Spaces through utilization of a ceiling mounted projector.

Users can apply gestures like collating, flipping, rubbing or pointing when working with the prototype. However, it is not possible for them to relate digital data directly to real world positions on the paper windows. The Exploration Space is mapped *dynamically* to the *deformable* devices. *Multiple* of the paper screens can be used simultaneously. This enables *focus-and-context* scenarios. To change the scale of the content which is displayed on a paper window, users might utilize a *zoom gesture*. Another way to view a windows data in more detail is to apply a rubbing gesture to transfer the data to another, larger paper screen. Further, different users can *quickly* share virtual data within Social Space. For example, one user can copy a page with the rubbing gesture and hand it to someone else.

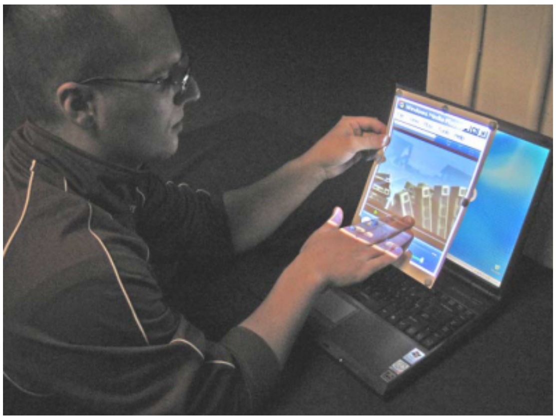


Figure 3.2: PaperWindows. A rubbing gesture is used to transfer a window from a notebooks screen to an augmented paper. [38]

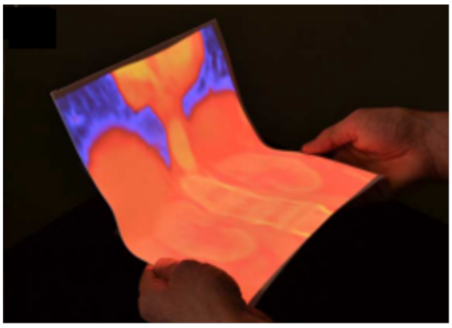
3.2.3 FlexPad.

Flexpad was introduced by Steimle, Jordt & Maes [102]. The system facilitates the transformation of common paper sheets into flexible, spatially aware displays which users can manipulate with their hands. A Kinect camera was mounted on the ceiling to track the paper objects. The authors implemented an algorithm which determines the parameters of a deformation model in a way so that the replication matches the cameras depth input as good as possible. Output is projected on the flexible paper surfaces from above .

The *deformable* interface supports a *static* mapping between digital data and real world space. Each location in the Interaction Space corresponds to exactly one position in the Exploration Space. Like shown in Figure 3.3, users might move a flexible display or manipulate its shape in order to navigate through *multiple layers* of volumetric data or slice through videos in time. Information layers are mapped to different levels of depth along the z-axis. When pursuing

[3] http://www.vicon.com

the navigation interactions, it is possible to deform the display like a wave bend. This allows users to view different layers of information simultaneously (see Figure 3.3b). The physical movements which are utilized in order to navigate the virtual data are expected to be *faster* than the use of e.g. panning on a multi-touch table. However, the speed with which the Interaction Space can be navigated depends on its size. The Interaction Space provided by the authors prototype is restricted due to the Kinect cameras, as well as the projectors range. It is assumed that a real world space of such limited dimensions allows users to reach every of its positions in a fairly *quick* fashion by physical movement. On the other hand, in case the Interaction Space would increase in size, physical ways would grow longer and, thus, navigation performance would be reduced.



(a)

(b)

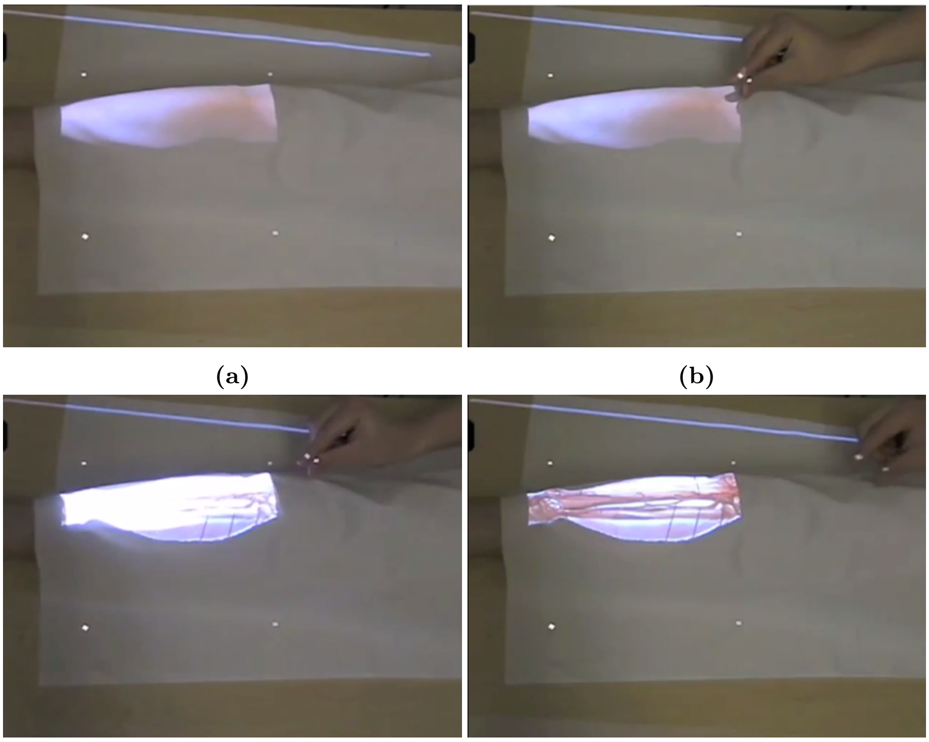
Figure 3.3: FlexPad. (a) Navigation through volumetric images. (b) Moving through time in videos. [102]

3.2.4 Cloth Displays.

Lepinski & Vertegaal [70] devised a cloth based interface. Two eyebox2 cameras[4] are utilized for tracking. A real world cloth, as well as users hands were marked with retro-reflective points to follow their movements. Tracked data points are interpolated by a physics engine. A projector is used to display output on the cloth. Further, remote gestures, which can be performed while hovering over the textile, are interpreted by an implemented gesture engine.

The system supports interactions which build on users pre-existing knowledge (e.g. folding, draping, stretching and touching). Data from the Exploration Space is projected to fixed positions on the cloth object. Thus, the mapping between virtual data and the real world is *static*. The authors introduced different example scenarios for their application. One of them is situated in the domain of medical imaging. They presented a surgical drape which can be placed over a patient and augmented with digital data (e.g. from x-rays). Like shown in Figure 3.4, a pinch & peel gesture might be utilized in order to navigate through *different layers* of the projected information. Further, Lepinski & Vertegaal [70] suggested the use of stretching to *zoom* graphics which are displayed within the Visualization Space.

[4]http://www.xuuk.com/



(c) (d)

Figure 3.4: Cloth Displays. Draping the cloth over a human arm, *layers* of information can be removed with pinch & peel. The illustrations above show the steps which are carried out to remove one layer. These are: (a) *Top most layer shown.* (b) *Pinch top most layer.* (c) *Peel top most layer of.* (d) *Layer below shown.* [70]

3.2.5 Information Cloth.

The Information Cloth system was created by Mikulecky et al. [74]. They combined simulated physics-based cloth interaction on a multi-touch table with the exploration of digital data, aided by lens effects. Their approach leverages people's prior knowledge about interactions between physical artifacts and cloth-like materials (e.g. textiles or paper).

Users are presented with a *simulated* cloth object on a multi-touch table. Not necessarily the hole Exploration Space is visualized on the touch surface at once. Digital data is mapped *dynamically* to the display space. To view different parts of the virtual content, users can move the emulated textile by panning it. However, to utilize this gesture when navigating large digital data spaces might result in an unnerving *clutching* behavior. In order to facilitate different *detail-in-context* approaches like Graphical Fisheye, Document Lens, Constrained Gaussian Lens and Mélange, the authors applied perspective geometry. They based this part of their work on the lens framework supplied by Carpendale & Montagnese [12]. Users are equipped with differently shaped objects which they can place under the virtual textile, in a lens like fashion (see Figure 3.5a). The objects below the cloth are resizeable. The data, reflected on the top of an object, is magnified or shrunk in case an objects dimension is modified along the z-axis. It is possible to create *multiple focal points* by placing various objects under the textile surface. The objects positions might be changed later by moving them. Besides the introduced detail-in-context techniques, the interface also supports interactions like folding, bunching or *zooming* the cloth with a stretch gesture (see Figure 3.5b).

(a) **(b)**

Figure 3.5: Information Cloth. (a) The Information Cloth is presented, covering a rectangular shaped object. The region of the map interface which covers the objects top is elevated. Map data within this area is displayed *magnified.* (b) The sketch illustrates the process of *zooming* data, shown within the Visualization Space, through stretching the cloth interface. [74]

3.2.6 SpaceFold.

(a) (b)

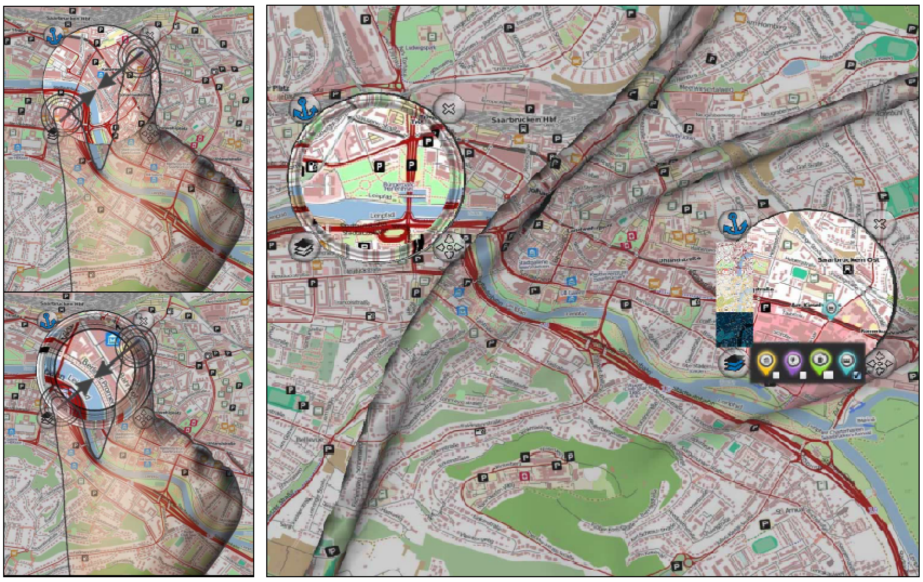
Figure 3.6: SpaceFold. (a) When a user places two fingers on the multi-touch screen for a short time span without significant movement, he or she is supplied with a preview of the fold which might be carried out (highlighted in yellow). (b) The user might move his fingers together in order to fold the presented digital map.

SpaceFold is based upon the *"metaphor of a folded sheet of paper"* [9]. It allows users to interact with a paper like interface on a multi-touch table. The system is inspired by the work of Chiu et al. [15] and Mélange [24].

When navigating virtual data spaces with SpaceFold, users can pan, fold and *zoom* the *paper-like* landscape. An example for the fold gesture is illustrated in Figure 3.6. The combination of the three different interactions enables users to *quickly* view different parts of the Exploration Space. Digital data is *dynamically* reflected on the Visualization Space in reality.

3.2.7 ClothLens.

Lander & Gehring [63] focused with *ClothLens* on the interaction of multiple users on a shared display space in context of a map navigation scenario. They simulated a bend and stretchable textile object on a multi-touch table.



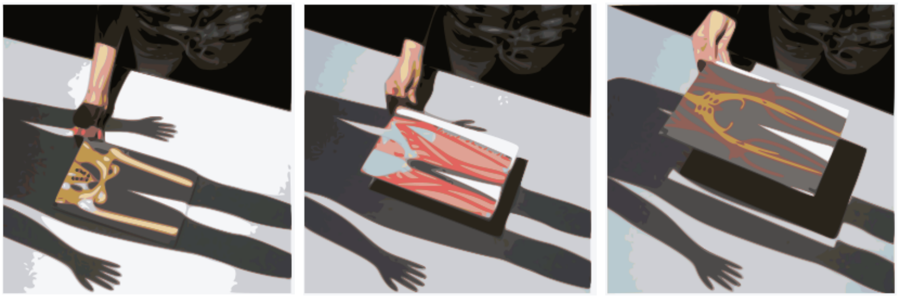
(a) (b)

Figure 3.7: ClothLens. (a) *Zoom* through stretching is shown. (b) Two lenses with associated buttons are visible. In the left bottom corner of each lens, a button which enables a view for switching between different *layers* of terrain can be observed.

In their prototype the authors overlayed their *imitation* of a *deformable* cloth object with the texture of a real world map. They used a *dynamic* mapping between the virtual data and the physical mutli-touch table. The interface facilitates the application of regular pan gestures. Nevertheless, in case the utilized Exploration Space is large, the use of panning might cause *clutching*. The system supports the creation of *focus areas*, in form of transparent virtual lenses, on the map. This feature is based on the concept of magic lenses, introduced by Bier et al. [6]. Inside the *focus regions* it is possible to manipulate content independent from its surrounding *context*. Users can, for example, pursue interactions like *zoom* through stretching (see Figure 3.7a). Another feasible operation is to press one of the buttons associated with each lens (see Figure 3.7b). Doing so, a user might change the *layer of the maps terrain* for the part which resides within the focus area.

3.2.8 PaperLens.

Spindler & Dachselt [99] showed with PaperLens a lightweight handheld display solution. Their application resembles the general concept of a passive lens display approach of Holman et al. [38]. Sheets of paper are tracked through a 3 dimensional Exploration Space with an OptiTrack FLEX V100 IR[5] infrared camera. The virtual data space is mapped to a 3 dimensional Interaction Space which is situated above a reference surface in form of a horizontal tabletop. A ceiling mounted projector is utilized to provide output.



(a) **(b)** **(c)**

Figure 3.8: PaperLens. *Layered navigation*, displaying different features of a model. In the given example, the (a) *skeleton*, (b) *muscle* and (c) *nerve system* layer of the human body can be viewed by moving the lens along the z-axis. The contour of the human body is continuously visible on the tabletop below to give users an *overview* of the Exploration Space. [99]

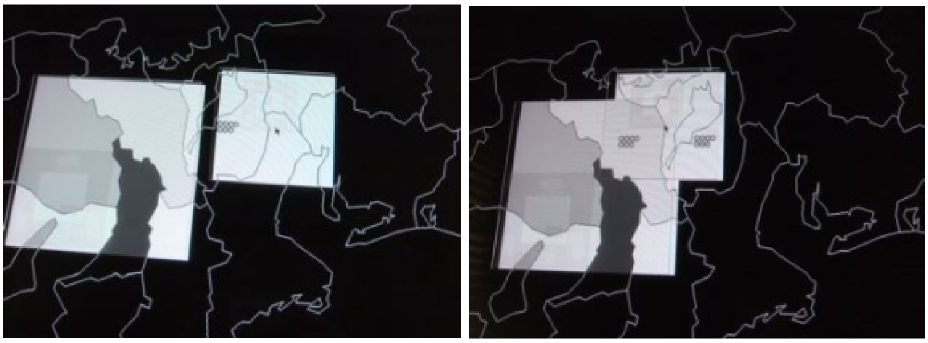
The Systems name suggest deformability. However, the physical PaperLenses were constructed from the *rigid* material press board. The authors introduced multiple different prototypes. All of the prototypes *statically* map the virtual data space to a 3 dimensional Interaction Space in reality. Which part of the Exploration Space a lens reflects depends on its position in the physical world. One of the presented prototypes supports *graphical zooming* by lifting and lowering the lens display along the z-axis. This interaction draws on a real world metaphor. Humans frequently bring objects closer to their eyes for a more thorough examination [99]. On the other hand, to move a physical surface farther away can provide an *overview*. Another of the authors prototypes uses the z-axis in a different way. The up and down movement of lenses is utilized for the navigation through different *layers of information*. While users navigate through various layers, the system continuously provides an abstract visualization of the digital data space on the tabletop. An example is illustrated

[5] http://www.optitrack.com

in Figure 3.8. In contrast to the lenses, which show *detailed* information, the underlying *overview* representation possibly facilitates users orientation within the Interaction Space. Similar to Flexpad (see Section 3.2.3), the system might support relatively *quick* navigation interactions through physical movement. However, again the expected performance depends greatly on the size of the Interaction Space. To navigate a larger real world area will require more physical movement and thus more time. Spindler & Dachselt [99] proposed the use of *multiple lenses* simultaneously in order to support collaborative work scenarios in the future.

3.2.9 Tangible Transparent Magic-Lenses.

Koike et al. [60] introduced the idea to utilize transparent 2D ARToolkit markers [53] for the creation of magic lenses. Their work was inspired by Bier et al. [6] in line with others [7,71]. They mounted a CCD[6] camera above a LCD[7] tabletop. Users might place markers on the LCD and move them around. The markers are tracked by the camera. To realize the transparency effect, the cameras lens was enhanced with a polarization filter[8]. The markers themselves are based on two half-wave plates.



(a) **(b)**

Figure 3.9: Tangible Transparent Magic Lenses. (a) Two transparent markers are used as magic lenses in the context of geographic data. Each reflects a different *layer* of information. The left displays the population of every prefecture in form of a gray-scale. The right shows the number of convenient stores in each prefecture. (b) When overlapping two magic lenses, a *combination* of *both layers information* is visualized in the conjoint areas. [60]

The authors presented different prototypes which utilize the magic lenses. One applies the transparent markers in the context of a geographic Exploration Space. *Context* information in form of a traffic map is displayed on the LCD. Users can put different magic lenses on the tabletop in order to perceive different *layers* of terrain data within *multiple focus regions*. Another prototype

[6]CCD: Charge-Coupled Device
[7]LCD: Liquid Crystal Display
[8]The polarization filter has a perpendicular plane of polarization to that of the light emitted by the LCD.

is displayed in Figure 3.9a. Two magic lenses are placed on the LCD. The left lens depicts the population in the prefectures with a gray-scale while the right reflects the amount of convenient stores. Like shown in Figure 3.9b it is also possible to overlay different information layers in theory[9]. If doing so, a combination of both layers data is visualized in the overlapping areas.

3.2.10 Conclusion.

Table 3.1 provides an overview of the analysis results. Fulfilled requirements are highlighted in blue.

	deform-ability	mapping	quick navi-gation	multi-scale	multi-focus	multiple layers
Gummi [96]	deform-able *in* real world	dynamic	limited: pan & zoom (bend)	zoom (bend)	-	map blending
Paper Windows [38]	deform-able *in* real world	dynamic	-	f+c, zoom (touch gesture)	multiple paper windows	-
FlexPad [102]	deform-able *in* real world	static	physical move-ment	-	-	lift & lower (depth differ-ence)
Cloth Dis-plays [70]	deform-able *in* real world	static	-	f+c (fisheye lens), zoom (stretch)	-	pinch & peel
Information Cloth [74]	deform-able *like* real world	dynamic	slow: pan only (clutch-ing)	f+c, zoom (stretch, objects below cloth)	objects below cloth	-
SpaceFold [9]	deform-able *like* real world	dynamic	pan & zoom (touch gestures)	zoom (touch gesture)	-	-
ClothLens [63]	deform-able *like* real world	dynamic	slow: pan only (clutch-ing)	f+c, zoom (stretch)	digital lenses	buttons on lens

Table 3.1: Results - Analysis of Existing Applications. (-) No information. (f+c) Focus+context. (o+d) Overview+detail. (m-s) Multi-scale.

[9] Due to technical limitations the authors did not fully support the feature in their prototype.

	deform-ability	mapping	quick navi-gation	multi-scale	multi-focus	multiple layers
PaperLens [99]	rigid	static	physical move-ment, zoom (lift & lower)	o+d, zoom (lift & lower)	(future: multiple lenses)	lift & lower
Transparent Lenses [60]	rigid	-	-	no m-s, but: f+c	multiple lenses	each lens is a layer

Table 3.1: Results - Analysis of Existing Applications. (-) No information. (f+c) Focus+context. (o+d) Overview+detail. (m-s) Multi-scale.

As can be seen in the table, none of the examined applications fulfilled all of the defined criteria (see Section 2.3). However, all of the surveyed systems show interesting approaches and concepts. Various different interaction techniques were utilized in the prototypes. Most of these techniques can be associated with one of the four tasks *navigation*, *zooming*, *multi-focus* and *layered navigation*. Additionally, each of the four tasks can be related to one or more of the specified requirements (see Figure 3.10).

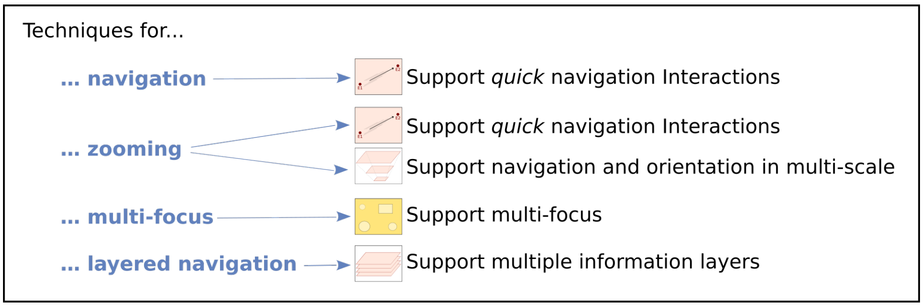


Figure 3.10: Extracted Techniques related to Requirements. Different techniques for the four tasks *navigation*, *zooming*, *multi-focus* and *layered navigation* could be identified. Each technique is related to one or more of the in Section 2.3 specified requirements.

To determine which of the found techniques might be preferred for implementation in a future system, it was deemed necessary to analyze them further. They were surveyed in regard to their tradeoffs between computational power and reality (see Section 2.1.2). The examination is elaborated in Section 3.3.

3.3 Analysis of Interaction Techniques

In the previous section an analysis of various existing applications is outlined. Among the examination results, different interaction techniques for the tasks of *navigation*, *zooming*, *multi-focus* and *layered navigation* could be extracted. To determine which of the found techniques might be applied in order to aid each of the tasks best, they were analyzed in more detail. The interaction techniques for each task were assessed in relation to their tradeoff between computational power and reality. The examination regarded the fact that the future system was supposed to facilitate interactions with a deformable cloth object in reality.

This section introduces the different interaction techniques and compares them against each other. In conclusion, favored technique(s) to fulfill the related requirements are suggested.

3.3.1 Interaction Techniques for Navigation

Three different techniques for the *navigation* of virtual spaces in reality could be identified (see Figure 3.11). They are analyzed in the following.

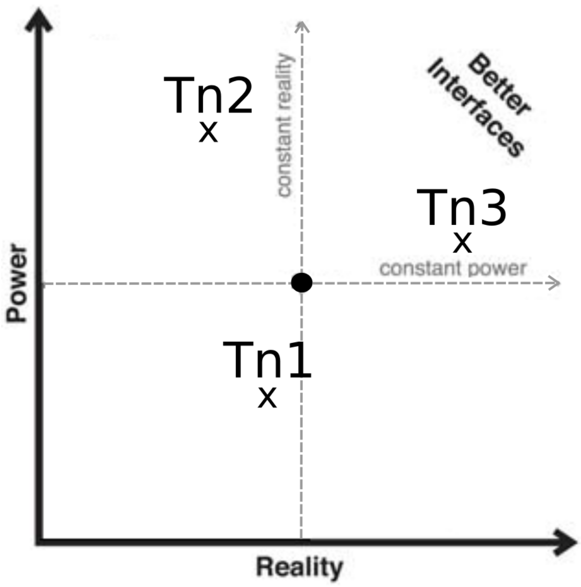


Figure 3.11: Power vs. Reality Tradeoff - Techniques for Navigation. Shows the placement of the three different techniques *navigation through pan only touch gestures (Tn1)*, *navigation through pan & zoom touch gestures (Tn2)* and *navigation through physical movement (Tn3)* in the coordinate plane defined by Jacob et al. [46].

Tn1: Navigation through Pan only Touch Gestures [63, 74]

The panning gesture which is commonly employed on touch displays is closely related to the real world behaviour of moving a flat object over a surface (e.g. a piece of paper or cloth over a table). However, the interaction lacks the physicality of actually grabbing and moving something in reality. Further, to solely utilize panning for the navigation in digital data spaces might result in *clutching*. Especially in case only a small part of the Exploration Space is reflected in the Visualization Space at the same time, users might have to pan repeatedly to reach their goal.

Tn2: Navigation through Pan & Zoom Touch Gestures [9]

To enhance the before mentioned panning with zooming via a two-finger gesture can increase speed when navigating to off-screen content [90]. It provides users with a possibility to conduct very precise navigation interactions[10]. However, even if the combination of pan & zoom is quite powerful, the utilized zoom gesture is a concept remote from real world interactions which are used for the magnification of viewed information (e.g. lifting a newspaper closer to ones eyes).

Tn3: Navigation through Physical Movement [99, 102]

Another way to navigate through digital data is to move a physical object through a real world Interaction Space. Interactions like pan & zoom might be conducted in reality, instead of merely emulating a real world behavior. On the other hand, in exchange for more realism, computational power is reduced. For example, when one zooms by lifting & lowering an object in the physical world, the scale for zoom operations is limited. Users cannot go farther down than the ground or higher up than their arms are long. Further, the accuracy with which navigations can be conducted is lower than with a system which utilizes pan & zoom touch gestures[11].

Summary

The aim of this work was to use a deformable cloth surface for the navigation through virtual data spaces. Thus, although it incorporates less computational power than pan & zoom touch gestures (Tn2), the utilization of navigations through physical movement (Tn3) seems advantageous. The technique places navigational interactions *in* the domain of the real world, making use of peoples Body Awareness & Skills and characteristics of Naïve Physics (see Section 2.1.1). To increase computational power, one could think about ways to facilitate zoom interactions with a higher scale range and precision. To bring these properties closer to the capabilities supplied by the touch based zoom gesture (Tn2), might create an interaction technique which is settled in the coordinate planes top right corner.

3.3.2 Interaction Techniques for Zooming

To adapt the zoom concept for a system allows users to work at different levels of detail. It might support persons while navigating through virtual environments

[10] For example, when zooming very far in, e.g. on a map interface, a pan gesture still moves the same amount of visible pixel but a smaller amount of the digital data than before the zoom. Thus, a very detailed movement through the Exploration Space is possible.

[11] In Tn3 the absolute position in the Exploration Space is not dependent on the zoom level. Due to this, even when zooming far in, it is still hard to navigate precisely.

and possibly aids their orientation within large Exploration Spaces. Four interaction techniques which could be applied for the task of *zooming* were extracted when analyzing existing applications (see Figure 3.12). They are subsequently surveyed in more detail.

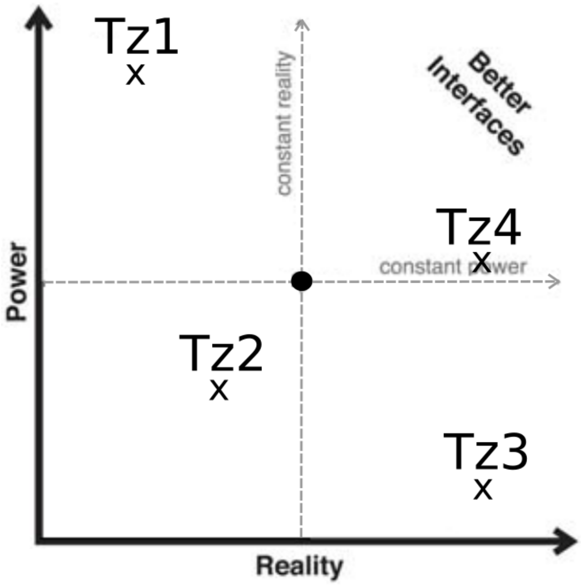


Figure 3.12: Power vs. Reality Tradeoff - Techniques for Zooming. Shows the placement of the four different techniques *zoom through touch gestures (Tz1)*, *zoom through cloth stretching (Tz2)*, *zoom through putting real objects below cloth (Tz3)* and *zoom through lifting* & *lowering (Tz4)* in the coordinate plane defined by Jacob et al. [46].

Tz1: Zooming through Touch Gestures [9, 38]

It is very efficient to implement zooming with touch gestures. The technique supports quick switches between different zoom levels and facilitates a large range of scale. While users solely need two of their fingers for the interaction, it is accessible for a broad range of persons, including many groups of disabled people. On the other hand, the technique utilizes only a very limited amount of the human bodies sensory capabilities. Further, it lacks a relation to how humans proceed when they view content more detailed in reality.

Tz2: Zooming through Cloth Stretching [63, 70, 74]

The technique of zooming through stretching part of a textile interface is limited. Cloth can, depending on the exact type, only be stretched in a specific scale range[12]. Also, resiliency might be unfavorable when being exploited through

[12]The scale range depends on the strain range of the cloth. Very tight and thick cloth, may not be stretchable at all.

the given technique. The problem is, that removing the fingers from the cloth display after stretching it, causes an elastic fabric to immediately snap back to its initial condition. Thus, fixing a certain zoom level is not possible without keeping ones hands continuously placed upon the textile or by the utilization of an additional user interface component (e.g. a button which can be pressed to fix a degree of magnification). On the other hand, while users manipulate a real cloth object, zoom through stretching is closer to the real world than the before mentioned touch gesture. Even so, still the interaction of stretching itself is mapped to the wrong digital pendant. When stretching cloth in reality, content displayed on the fabric would not be magnified, but skewed.

Tz3: Zooming through putting Real Objects below Cloth [74]

This technique adapts the concept of putting digital objects beyond a simulated cloth to emphasize certain areas [74]. Instead of virtual objects, real, physical ones can be moved underneath a piece of fabric in order to create magnified regions. This makes use of humans real world experiences. People know that they can put an object, e.g. a cardboard box, below a piece of cloth in order to bring it constantly closer to their eyes. However, the technique is also very limited. One physical object is always associated to only one level of zoom. To change the degree of magnification, it is required to exchange the object under the cloth with another, differently sized one. Thus, the process of switching between different zoom levels is tedious and slow. Further, the scale range is limited. That is, one can not zoom farther out than removing all objects below the cloth or farther in than placing the highest of the given objects underneath the cloth.

Tz4: Zooming through Lifting & Lowering [99]

Viewing content shown on a real world object in greater detail is usually accomplished with moving the Physical Space closer to ones eyes. The technique of putting objects below a textile (Tz3) already made use of this metaphor. To lift & lower the Physical Spaces for zooming as well adopts the concept. The difference between the two techniques is that lifting & lowering supports continuous zooming and thus a quick changing between different degrees of magnification. However, like Tz3, to move objects up and downwards solely supports a limited, finite amount of zoom levels.

Summary

Overall, to lift & lower Physical Spaces (Tz4) holds a lot of potential. Zooming interactions are performed *in* the real world and more power is incorporated than by stretching a textile (Tz2) or putting objects below it (Tz3). However, the amount of given computational power could still be higher. To adopt the support of a larger scale range, like given by zooming through touch gestures (Tz1), would enable users to perceive higher degrees of detail. Tz3 also holds an interesting property. Placing physical objects below a cloth allows to fix a certain level of magnification within a specified area. A powerful interaction technique could result from enhancing Tz4 with the concepts supplied by Tz1 and Tz3. At the same time, the resulting technique would rest upon a real world metaphor.

3.3.3 Interaction Techniques for Multi-focus

Three different techniques for the realization of *multi-focus* were extracted (see Figure 3.13). They are in the succeeding surveyed in more detail.

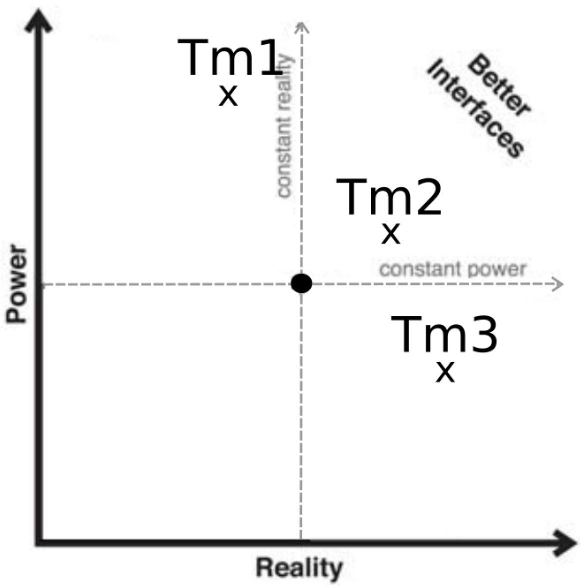


Figure 3.13: Power vs. Reality Tradeoff - Techniques for Multi-focus. Shows the placement of the three different techniques *multi-focus through virtual lenses (Tm1)*, *multi-focus through real lenses (Tm2)* and *multi-focus through putting real objects below cloth (Tm3)* in the coordinate plane defined by Jacob et al. [46].

Tm1: Multi-focus through Virtual Lenses [63]

Virtual lens regions could be created on the clothes surface through e.g. a finger gesture like forming a square or a circle. The concept of lenses is also used in reality to focus on parts of an object. However, when looking through a real world lens, viewed content is usually perceived magnified[13]. A drawback of virtual lenses is that they cannot be physically grabbed and placed at different positions. Instead users are solely able to move them via a less realistic pan gesture. On the other hand, virtual lenses also hold some advantageous properties. It is, for example, possible to resize them. Further, they support the display of additional control elements on lens frames (e.g. buttons) and to dynamically

[13]Of course it is possible to apply automatic zooming of content inside a virtual lens as well. Nevertheless, this behavior might not be desired in most scenarios when exploring virtual data with aid of multiple focus areas.

change the color of the frames dependent on the users currently "owning" the lenses.

Tm2: Multi-focus through Real Lenses [38, 60, 99]

Instead of using virtual frames (Tm1), real world lens objects could be placed on the cloth display (e.g. a plastic or wood frame, or a transparent marker [60]). Using this technique is more realistic while lenses can actually be grabbed and placed at other positions. However, expressive power is lost. For example, no resizing of lenses or placing of additional virtual control elements on their frames is possible. Additionally, the physical frames can slide over the cloth when being lifted. Despite this behavior being realistic, it might not be beneficial in every case.

Tm3: Multi-focus through putting Real Objects below Cloth. [74]

Another technique, which could be applied in order to create multiple focus areas, is the placement of various real world objects under the cloth display. This approach has a strong relation to reality while elevated areas draw humans attention and can be used to separate currently focused content from the surrounding context. Opposing this, the interface is not very efficient and expressive. Using physical objects underneath the fabric implies restrictions. The objects are hard to move without lifting the cloth. Also, they lack some properties given by virtual lenses (Tm1). For example, no quick resizing of lenses is possible.

Summary

Considering the three proposed techniques, using real lenses (Tm2) or objects (Tm3) together with the cloth display is far closer to the real world than the application of virtual lenses (Tm1). Tm2 obtains the best balance between reality and computational power. However, it still leaves room for improvement. Power might be increased by adapting some of the concepts given by Tm1. For example, it could be thought about creating a resizable physical frame.

3.3.4 Interaction Techniques for Layered Navigation

Considering the analyzed prototypes, four different techniques for the navigation of layered Exploration Spaces were discerned (see Figure 3.14). They are subsequently discussed further.

Tl1: Layered Navigation through (Touch) Buttons [63]

It is very efficient and powerful to use buttons for the navigation of layered structures. The technique facilitates it to quickly switch through a large amounts of different information layers. In contrast, the interaction is not based on users pre-existing knowledge of the real world.

Tl2: Layered Navigation through Pinch & Peel [70]

Lepinski & Vertegaal [70] proposed the use of a pinch & peel gesture in order to remove layers of information from their prototype of a textile display. Users had to pinch their fingers together while hovering above the cloth. Subsequently they could peel a layer of by moving their hand. The technique remotely draws on the real world metaphor to lift a layer of textile from a larger stack. However, it lacks a real physical contact with the cloth and the layer. The authors also miss to mention where users might access removed layers and how they can return them to the "stack". Further, layers can solely be removed in sequence. This causes, in a scenario which incorporates numerous layers of data, a slow navigation between the highest and lowest layer in the "stack".

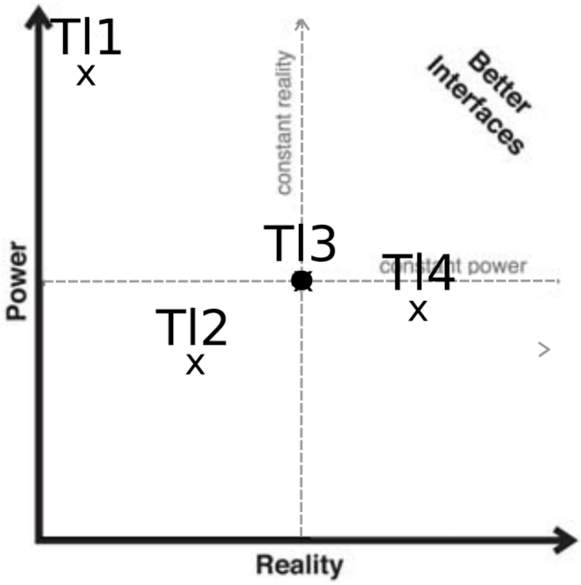


Figure 3.14: Power vs. Reality Tradeoff - Techniques for Layered Navigation. Shows the placement of the four different techniques *layered navigation through (touch) buttons (Tl1)*, *layered navigation through pinch & peel (Tl2)*, *layered navigation through lifting & lowering (Tl3)* and *layered navigation through physical lens layers (Tl4)* in the coordinate plane defined by Jacob et al. [46].

Tl3: Layered Navigation through Lifting & Lowering [99]

To lift & lower a Physical Space in reality, exploits more of its physical qualities than to use buttons (Tl1) or to apply a pinch & peel gesture (Tl2) in order to navigate through multiple layers of information. Users actually have to grab the object with their hands. However, the degree of realism the technique implicates, when being used for layered navigation, depends on the given Exploration Space and the applications use case. One may consider, for example, a system designed to show different layers of soil. Soil layers are stacked above each other in reality. Thus, it is highly realistic to navigate through these by up and down movements. On the other hand, let's imagine a map navigation scenario which utilizes physical lifting & lowering to view different layers of terrain information. In such a case the real world metaphor of "stacked layers" does not apply. The layers are not stacked above each other in reality. Further, to navigate through physical movement might be slightly faster than if using a pinch & peel gesture (Tl2). Nevertheless, both interaction techniques hold the disadvantage that one can only switch between different layers sequentially.

Tl4: Layered Navigation through Physical Lens Layers [60]

Putting physical lenses on top of a cloth interface, in order to visualize different layers of information within these lenses areas, is like using overlays in reality. For example, in the real world an overhead projector in combination with multiple sheets of plastic, each containing a different layer of information, might be utilized. Placing one of the sheets above another either shows the information of the overlayed sheet (non-transparent layer on top) or a combination of the data given in both layers (partially transparent layer on top). An advantage in contrast to pinch & peel (Tl2) and lifting & lowering (Tl3) is that layers can be placed upon the cloth in any order instead of forcing a sequential navigation through them. On the other hand, the handling of multiple such layers might become irritating or cumbersome to users. To place to many on the top of a textile could create visual clutter. Further the process of switching between lens layers is slower and might be less convenient than just pushing a button (Tl1).

Summary

In case an Exploration Space which reflects *naturally stacked layers* of information (e.g. layers of soil) is given, it could be beneficial to lift & lower a Physical Space in order to navigate the different layers. To increase the realism further, one could enhance Tl3 with additional contextual information. For example, considering the scenario of navigating soil layers, a vertical background visualization, e.g. a screen or a projection, could show all layers which can possibly be explored. This might help users to differentiate in which layer they are at a certain moment of time and where they could move.

If the supplied layers of information are *not stacked in reality* it could make sense to trade realism for more digital power. Buttons might be applied to navigate layers (Tl1). The pinch & peel gesture (Tl2) lacks direct contact with Physical Spaces and a logic way to put layers back was not provided. To use multiple real world layers which can be placed on top of a Physical Space might get inconvenient for users. It is expected that they deem it cumbersome to exchange the layers manually when they just want to switch them for short durations while e.g. searching for information in different layers. Thus, it was decided to accept a decrease in realism when users navigate *not naturally stacked layers* and supply them with buttons which allow quick switching interactions.

3.3.5 Conclusion.

In course of the analysis, various interaction techniques for four different tasks were compared. In conclusion, it was possible to identify one or multiple favorites for each task. Figure 3.15 provides an overview of the proposed techniques in regard to the corresponding tasks and the related requirements.

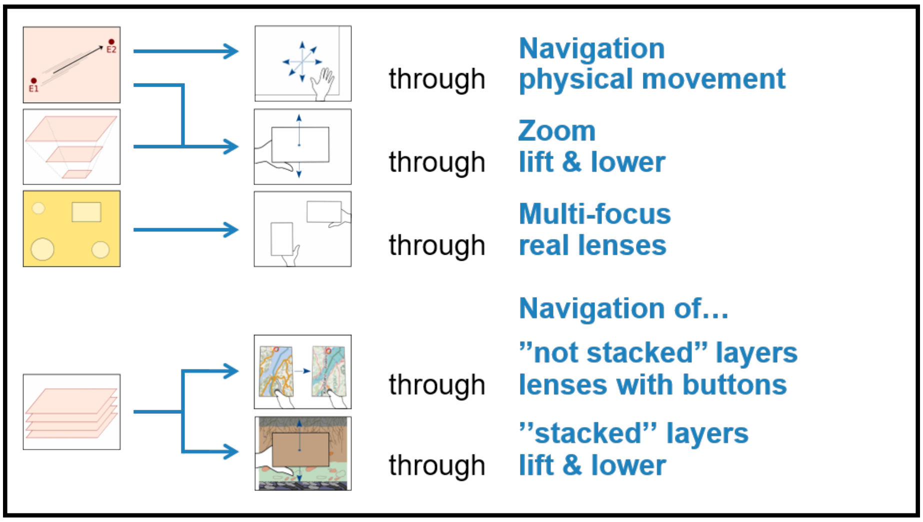


Figure 3.15: Proposed Interaction Techniques. The interaction techniques which were favored are displayed in connection to the requirements they relate to.[14]

3.4 Proposed System Concept: InformationSense

In the last two sections, existing applications were analyzed and favored interaction techniques extracted. Based on the examinations results, a concept for a future system was established. The proposed interface is elaborated in the following. It consists of a deformable cloth surface and utilizes rigid lenses as extension for detailed explorations of digital data spaces, respectively to aid multi user scenarios.

3.4.1 A deformable Cloth Surface

At the time when the system concept was defined it was not possible to purchase an existing flexible display which fulfilled the requirements in terms of deformability and material consistency. There were multiple prototypes for deformable screens shown (e.g. e-ink displays like the E INK MOBIUS[15] and different

[14] In Figure 3.15 the map data was taken from [80].
[15] http://www.eink.com/display_products_mobius.html

flexible OLEDs[16] [59, 108] like the Samsung YOUM[17]) or in development (e.g. displays from New Vision[18] and Vision Multimedia Technology[19]). However, none of the systems was advanced sufficiently in order to supply users with a screen which can be deformed while feeling and behaving like a real piece of cloth. Therefore the decision was made to utilize *projection*.

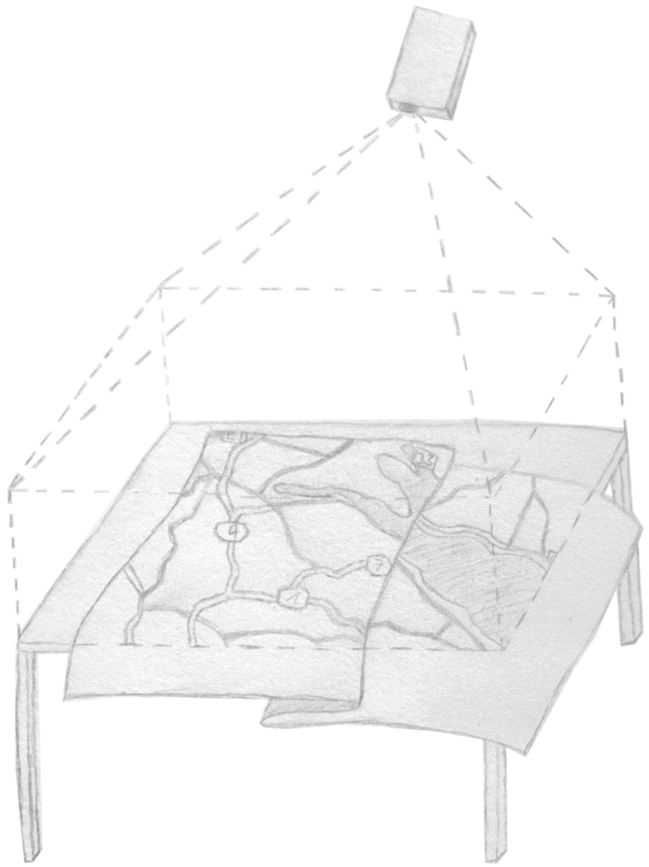


Figure 3.16: Proposed System Concept - A deformable Projection Surface. The projector generates output which is displayed on top of the cloth object placed on the table. The table borders mark the boundaries of the Interaction Space along the x and y-axis. The projectors field of view in line with the area supported by the utilized tracking system limit the space along the z-axis. In the sketch, the dashed lines given an example for a 3 dimensional, rectangular Interaction Space above a table.

Figure 3.16 gives an overview of the final system concept. A projector was mounted above a table in order to supply visual output. The tables borders limit the Interaction Space along the x and y-axis. The z-axis is restricted by the projectors field of view and the region covered by the utilized tracking system

[16]OLED: Organic Light-Emitting Diode
[17]http://www.oled-info.com/samsung-youm
[18]http://www.newvisiondisplay.com/
[19]http://vmt.co.jp/display/index.html

(see Section 4.1.2). Users are able to *move* and *manipulate* a real cloth object *physically* within the 3 dimensional Interaction Space. The projection on top of the textile adapts depending on its current position within room space. Virtual data is solely visualized on the parts of the cloth which are situated inside the Interaction Space. It is possible to map different Exploration Spaces to the Interaction Space in order to apply the flexible display in context of various use cases.

The systems concept reflects ideas shown in the FlexPad [102] and SpaceFold [9] prototypes. Like FlexPad, the proposed approach is based on a flexible surface which displays output by projection. However, the InformationSense system was supposed to facilitate an even higher degree of deformability. In contrast to the SpaceFold interface, which supports only horizontal, respectively vertical folds, users should be able to fold the cloth without restrictions. Like in reality, the possibility to place e.g. diagonal folds, rotate or crumple the cloth in order to facilitate quick visual comparison operations should be given. The goal was to create an interface which enables users to apply their pre-existing knowledge of the real world and utilize their capabilities for physical perception.

3.4.2 Extension: Detailed Explorations with Lenses

The concept, proposed in Section 3.4.1, supplies users with a textile object in order to navigate virtual data spaces in reality. Nevertheless, to solely provide the deformable cloth surface might limit users set of feasible interactions. For example, the shown concept does not facilitate the creation of focus regions which could allow detailed explorations or collaborative work scenarios. To support further navigation interactions, it was suggested to utilize additional Physical Spaces in form of rigid real world lenses (see Section 3.3.3). These rectangular objects might be held by users above the textile surface in order to create focus areas. The part of the virtual data space which corresponds to the current lens position is projected on top of the Physical Spaces surface.

In contrast to the PaperLens system shown by Spindler & Dachselt [99] it was suggested to enhance the lenses with additional control elements and thus make them more powerful. Like described in Section 4.2.1, in course of the implementation flic buttons[20] were utilized. The buttons support the interactions *Single Click*, *Double Click* and *Press, respectively Release Button.* They were incorporated in the concept as follows:

- **Single Click:** As elaborated in Section 3.3.4, to map the movement through different layers of information to the process of lifting & lowering a Physical Space might feel natural to users. However, as was determined, this is probably only the case if the data reflected by the layers belongs to parts of the physical world which are stacked in reality as well. Further, it was also suggested to utilize up & down movements of a Physical Space to support zooming. It was considered problematic to map two different interactions to the same physical process. Thus, the decision was made to utilize *layered navigation with buttons* instead. This technique was suggested in Section 3.3.4 for *not naturally stacked layers.* The idea was to

[20] https://live.flic.io

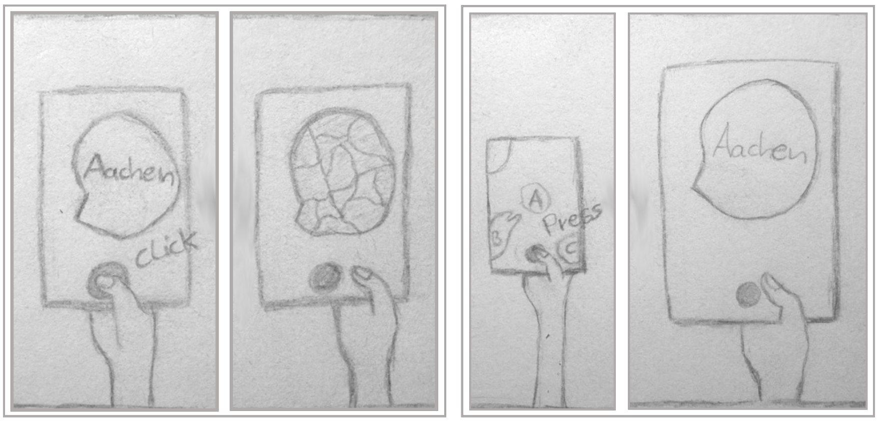


Figure 3.17: Extension - Explorations with Lenses. (a) Switching between different information layers by pressing the lens button (e.g. switch from the *city-layer* to the *district-layer*). (b) Zooming through lift & lower. Users might press the attached button to "dive" deeper into the virtual data space, or move farther out.

map the single click event of the flic buttons to the navigation through lens layers. Figure 3.17a illustrates an example. A user might view part of a map on one of the lenses. With a single click on the button, attached to the lens, he or she can switch from the *city-layer* to the *district-layer*, in case e.g. the number of districts from a city is of interest.

- **Double Click:** It was proposed to utilize the double click, supported by the flic buttons, in order to *lock* the lenses content temporary. Spindler & Dachselt [99] suggested the implementation of such a *"freeze-mode"* to avoid fatigue. Users might lock the data currently shown on the Physical Space and subsequently survey it in a more comfortable position. They could also put the lens aside and review the temporary "stored" information later. Another double click might be used to *unlock* the lens.

- **Press, respectively Release Button:** It was suggested to use the technique of lifting & lowering a Physical Space to facilitate zoom interactions (see Section 3.3.4). The lenses already allow the application of *natural zooming* by default. Users might move a lens closer to their eyes to perceive a part of the digital information space in more detail. Like shown in Figure 3.17b, the zoom effect can be enhanced through pressing a lens button while navigating along the z-axis. When a user releases the button, the lens is automatically put in the *locked-mode.* Thus, the zoomed content is displayed on the lens. This enables zoom operations in a theoretically indefinite scale range. For example, users could lift & lower the lens in multiple occasions. Each time they might release the attached button when they move it downwards and keep pressing it while lifting the Physical Space. Doing so allows them to "dive" continuously deeper into the digital data space by using a gesture known from the real world. They might apply a double click in order to *unlock* the lens.

Besides supplying users with a way to navigate the Exploration Space in a more detailed fashion, the lenses could also facilitate multi users scenarios. Like described in Section 2.2.3, each person might has his own lens device. Different people could interact within Social Space by talking while some, or all of them, interact with the system at the same time.

Chapter 4

System Implementation

The creation of the InformationSense system took several months. In this chapter its actual implementation is elaborated in detail. Section 4.1 introduces the systems *physical setting* while Section 4.2 provides an elucidation of the *software sided processing*. Eventually, the implementations *technical limitations* are listed and briefly elaborated.

4.1 Physical Setting

This section provides an overview of the physical setting which was established in order to track a cloth object and rigid lenses while they are moved in the real world. First an overview of the in-room setting is depicted. Subsequently the concept which was applied to track a deformable surface is described. Finally, the utilized lenses with buttons are introduced.

4.1.1 Overview

Like illustrated in the sketch shown in Figure 4.1, a metal frame was created. It holds the Kinect v2 camera, used for tracking, as well as the projector which supplies the systems output, in place. A table is situated below the frame. When users work with the system they might move the trackable cloth on or above the table. It is possible to exchange the table against a differently sized one which fits under the frame. However, the current implementation solely supports rectangularly shaped tables.

4.1.2 A trackable Cloth

To follow *rigid* surfaces, like the PaperLens from Spindler & Dachselt [99], through room space has been widely applied and studied. However, the tracking of highly *flexible* materials is still a rather complex task. Figure 4.2 illustrates the problem. To locate a static material continuously within room space, few tracking points are sufficient. Like shown in Figure 4.2a, Spindler & Dachselt [99] used *3 to 5 points* in order to track their rigid lenses. The static objects can

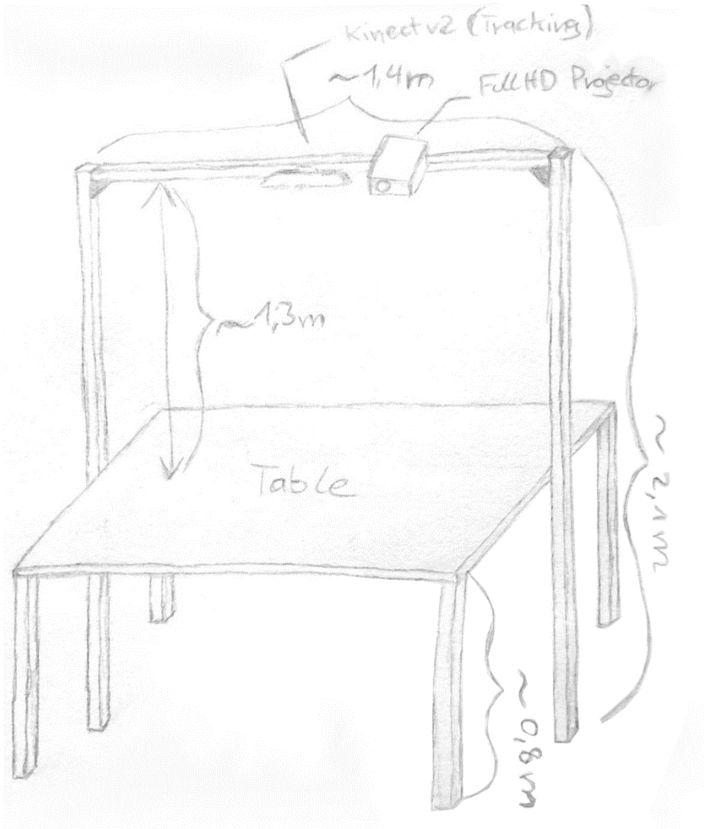
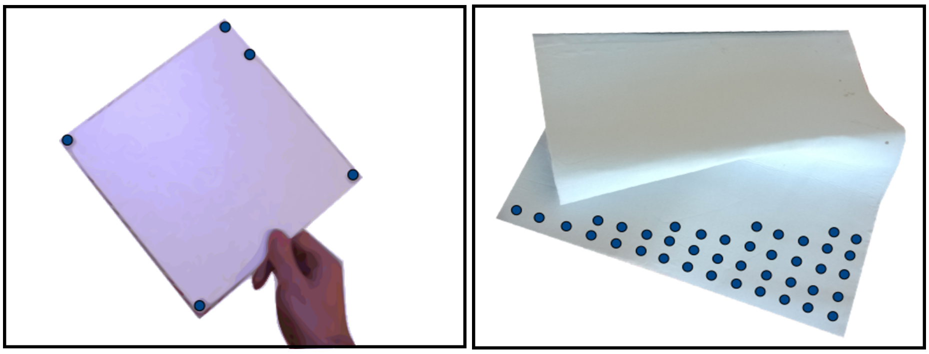


Figure 4.1: Physical Setting. A camera and a projector are mounted on a metal frame. A table is placed between the two side pillars of the frame. The camera is used for tracking while the projector supplies output.



(a) (b)

Figure 4.2: Tracking of Rigid vs. Flexible Surfaces. (a) Example of a *rigid* surface (PaperLens [99]). *3 to 5* Tracking Points are sufficient while the inflexible material *cannot overlap* itself. (b) Example of a *flexible* cloth surface. *Multiple* tracking points are necessary while it is possible that the deformable textile *overlays* part(s) of itself.

under *no* circumstance *overlap* themselves. On the other hand, when looking at deformable cloth surfaces, it is necessary to obtain *far more tracking points* (see Figure 4.2b). Otherwise it might not be possible to reconstruct the correct position of the textile in room space. Also, one has to consider that *selfoverlaps* can occur while users manipulate the cloth in reality.

To find an adequate technique for the tracking of a deformable surface, the concept which Buxton [10] proposed for *design* was adapted. Different techniques, applicable for tracking, were examined against established requirements. The goal was to select the *right* approach for the proposed system. In succession iterative prototyping was utilized to get the chosen technique *right*.

In the following, the defined requirements are introduced and the final concept is presented.

Tracking Requirements

Six different properties, which should be supplied in order to track a cloth through reality and project digital content on its surface, were established (see Figure 4.3). They are subsequently described briefly.

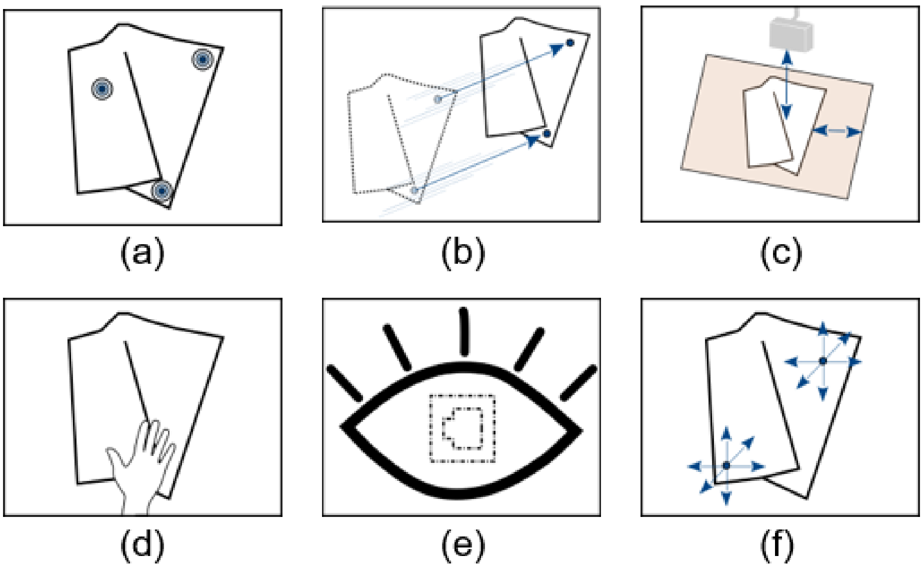


Figure 4.3: Requirements for Tracking Cloth. Six different properties which the tracking system should support could be identified: (a) Support high tracking precision. (b) Support high tracking performance. (c) Support global position determination. (d) Support preserving of "cloth-feel". (e) Support undistracted visual output. (f) Support 3d tracking.

- **Support high tracking precision:** To guarantee an accurate placement of the projected output on top of the cloth surface, the tracking precision should be as high as possible.

- **Support high tracking performance:** While the processing of the tracked data will also take a considerable amount of time, it is essential that the tracking system supports real time processing.
- **Support global position determination:** A projector, mounted above a table, is used to display output. To adapt the projection correctly while the textile is moved, it is necessary to determine the global position of the cloth object within room space.
- **Support preserving of "cloth-feel":** The alteration of the cloth objects natural properties should be kept at a minimum. Users should have the feeling to interact with a normal textile object like they know it from their daily lives.
- **Support undistracted visual output:** Visible patterns on the cloth distract the visual output and might confuse users working with the system. They should be avoided if possible.
- **Support 3d tracking:** To allow movement of the cloth object along the x, y and z-axis, tracking in 3 dimensions should be facilitated.

Final Tracking Concept

After comparing different technical approaches against the stated requirements, the use of *invisible markers* was proposed. Five different prototypes were created in an iterative process. The final tracking concept utilizes a grid of AR-Toolkit[1] markers which are invisible. They can solely be perceived through an infrared camera.

Before creating the first prototype, past research in regard to the tracking of invisible markers with infrared cameras was reviewed. Different research projects applied or discussed a specific, strongly infrared reflecting ink [49, 51, 82, 83]. Unfortunately, it was not feasible to use it. The ink is not UV light resistant. When coming into contact with UV light, it loses its property to show up in the view of an infrared camera within one week. Other materials like infrared powder [49], LEDs [4, 72] or tape [76] also posed different problems. The reviewed powder would have required a visible light source for stimulation, the infrared LEDs were visible in reality and impacted the cloth surfaces physical properties. The tape was also slightly visible in reality and reflected the infrared light so strong that no clear marker edges could be detected.

On this grounds a different approach was developed. A black piece of cloth was utilized as basis. Subsequently a marker pattern was printed on top of the textile in black. The black ink has the property that it absorbs more infrared light than the underlying surface. Thus, a contrast gets visible when the cloth is viewed in the infrared frame of the Kinect v2 camera. However, it is not possible to project data on a black surface and there was no way determined to establish the contrast with two different white materials. The solution was to overlay the black textile with multiple layers of very thin white ironing cloth. This resulted in a continuous light grey surface in reality and a marker pattern which is trackable with an infrared camera. Figure 4.4a illustrates the applied

[1]AR-Toolkit: Augmented Reality Toolkit, https://artoolkit.org

layers, while Figure 4.4b depicts the difference between viewing the cloth in reality and through an infrared camera.

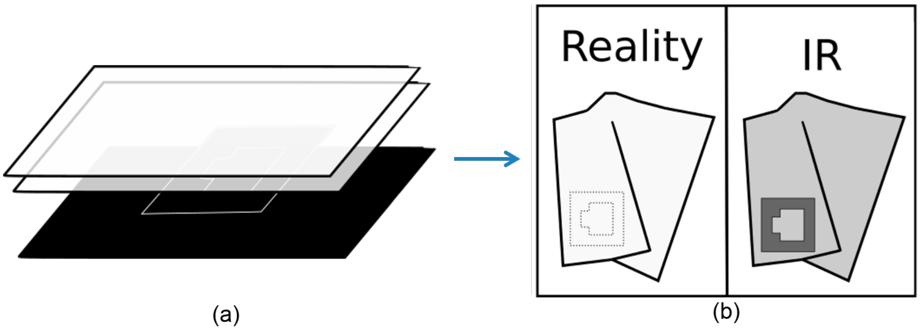


Figure 4.4: Tracking with Invisible Markers. (a) Markers were printed with black ink on a black cloth surface. The ink absorbs infrared light stronger than the underlying textile. Multiple layers of thin, transparent white cloth were ironed on top. (b) The markers are invisible in reality. Viewed through the IR (infrared) frame of the Kinect v2 camera the markers show up in a dark grey.

For the final prototype a pattern consisting of *209 (19x11) AR-Markers* was created. To reduce the risk of missdetection, BCH[2] (13, 9, 3) coded markers where used. Each of the markers is sized to *6x6cm*. The pattern was printed on top of the textile. After the paint was dried, two layers of thin, transparent white cloth were attached on top. This resulted in the light grey projection surface which is displayed in Figure 4.5a. The underlying black cloth is a neoprene

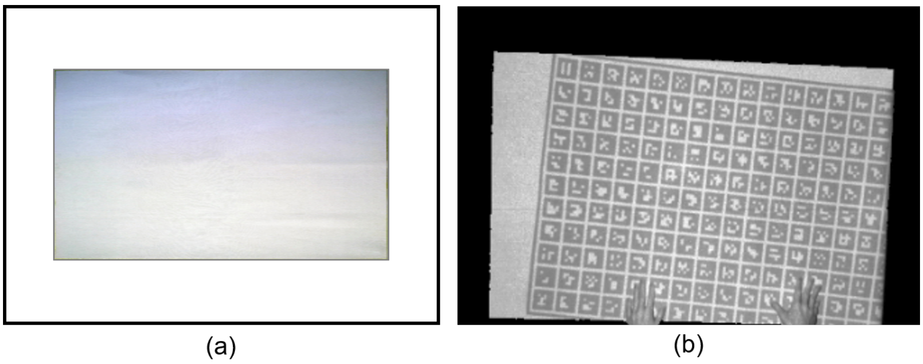


Figure 4.5: A trackable Cloth. (a) The final textile object. (b) A pattern of *209 AR-Markers* gets visible when the cloth is viewed through an infrared camera.

[2]BCH: Bose-Chaudhuri-Hocquenghem

imitation[3] with a thickness of *2mm*. The final prototypes has an approximate size of *135x85cm*. This leads to an aspect ratio close to *16:10*. Figure 4.5b shows how the final prototype looks when viewed through an infrared camera.

4.1.3 Lenses with Buttons

The rigid lens objects utilize the same tracking concept as the deformable cloth. Acrylic glass plates with a thickness of *2mm* were utilized as base. They have a size of *28x18cm* and an approximate aspect ratio of *16:10*. A black cloth object of the same size, with six printed AR-markers, was affixed on the acrylic surface. Again the markers have the dimensions *6x6cm*. Two layers of thin, transparent white cloth were ironed on top of the lenses. Eventually, a flic button[4] was attached to each of the rigid rectangular objects. Figure 4.6a displays a final lens, while Figure 4.6b shows how it looks in the view of the infrared camera when it is held above the textile.

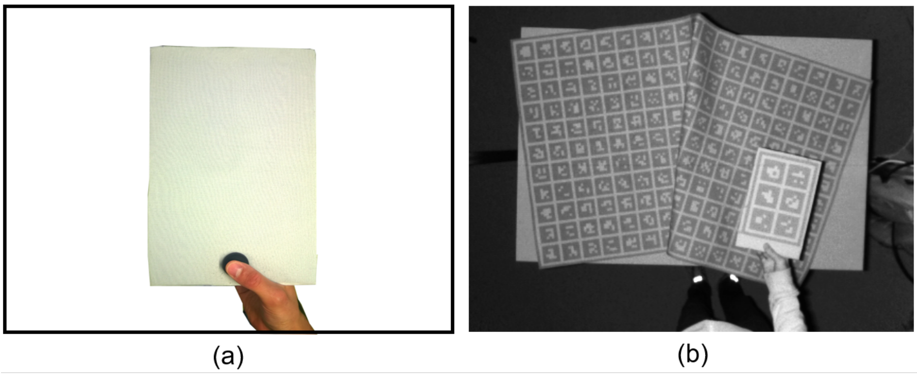


Figure 4.6: Lenses with Buttons. (a) The final version of a lens. (b) A pattern of *six AR-Markers* gets visible when the lens is viewed through an infrared camera.

4.2 Software Processing

This section provides an overview of the software implementation and the related processing pipeline. Subsequently the different steps in the pipeline are described. They range from the systems calibration to the final visualization of output on the cloth and the lens objects.

[3]The decision to use a neoprene imitation was made to simplify the segmentation process. When the neoprene is folded, the depth difference at the fold lines is in most cases higher than when doing the same with a softer textile. This makes it easier to detect the fold lines as edges when analyzing the depth image.

[4]https://live.flic.io

4.2.1 Overview

The created software was written in the language C++. Various different existing libraries and development kits were used in course of the implementation. The *Kinect SDK 2.0*[5] was utilized to access the cameras streams. *OpenCV*[6] was used for tasks like filtering, edge detection or the computation of image transformations. Error logging was implemented with *Boost*[7]. The *ARToolkit*[8] was integrated to track the AR-Markers on the cloth and *OpenGL*[9] facilitated the rendering of output.

An Android Phone was utilized in order to support the communication between lens buttons and the created desktop application. At the time when the system was implemented, the developers of the flic buttons solely supplied an API for android or apple devices. Thus, an android app which connects to a

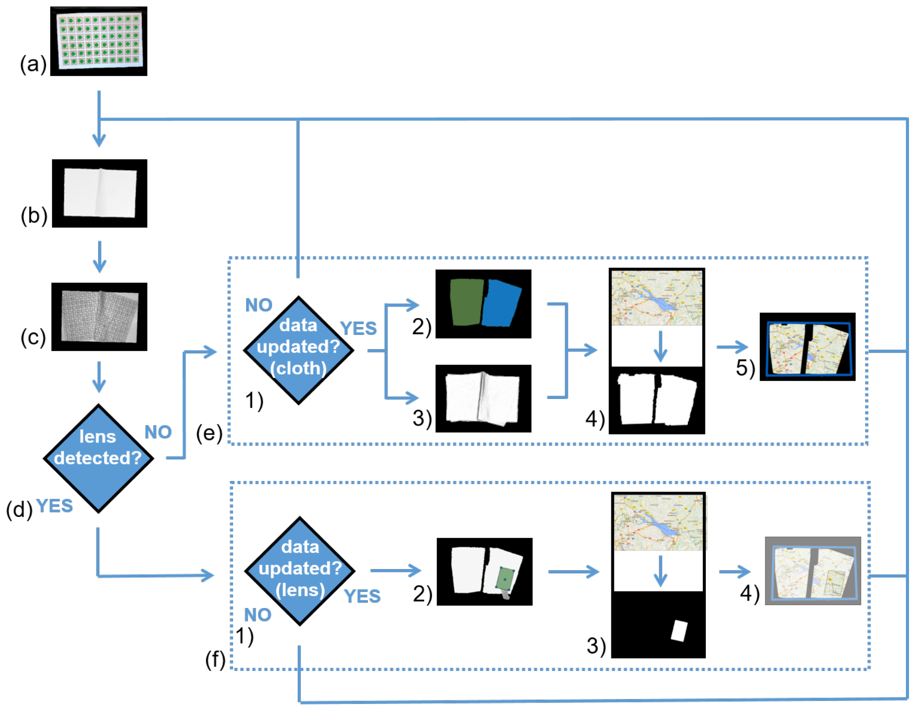


Figure 4.7: Processing Pipeline. (a) Calibration. (b) Fetch & preprocess streams. (c) Marker tracking. (d) Verify if a lens was detected. (e) Processing of detected cloth: 1) Verify if the marker data was significantly updated. 2) Segmentation. 3) Mesh generation. 4) Compute the texture mapping. 5) Draw the visualization. (f) Processing of detected lens(es): 1) Verify if the marker data was significantly updated. 2) Determine lens position above the underlying mesh. 3) Compute the texture mapping. 4) Draw the visualization.

[5] https://www.microsoft.com/en-us/download/details.aspx?id=44561
[6] http://opencv.org
[7] http://www.boost.org
[8] https://artoolkit.org
[9] https://www.opengl.org

server on the desktop computer was implemented. The app forwards the buttons signals which are received by an android smartphone. Due to this, it is possible to adjust the content reflected on the lenses dependent on users button presses.

Figure 4.7 illustrates the systems processing loop. As can be observed, it is, in the current implementation, not supported to change the position of cloth and lens objects simultaneously. This capability might be added in the future.

In the following sections the different steps of the applications processing are elaborated in detail.

4.2.2 Calibration

The calibration is only run at the start-up of the application. It was attempted to make the procedure easily understandable. Users get visual feedback throughout the hole calibration process and solely need to push the <*enter*> key to proceed between steps. Figure 4.8a shows the window which is displayed at the applications start-up. The user is asked to press <*enter*> in order to begin the calibration. The calibration procedure can be divided in two parts which are processed sequentially:

- *Camera Calibration.* In order to calibrate the camera, at first the underlying table is detected. The Kinects depth frame is used to find a rectangular shaped region which has a contour length above a defined threshold t. If such a region is determined, its outline is transformed to color space. A green overlay in form of the detected outline is drawn on top of the color image which is received from the Kinect v2 (see Figure 4.8b). The resulting graphic is displayed to the user. The user is asked to hit the <*enter*> key in case he or she is satisfied with the outcome of the table detection. If no table could be detected the system also acknowledges the user visually, like shown in Figure 4.8c. After the table was detected correctly and the user hit the <*enter*> button, the camera calibration is conducted in the background. The coordinates of the detected tables corners are used in order to compute a transformation matrix. The matrix transforms an input point in a way that the camera is placed straight above the center of the table (90 degree angle) and rotated so that the table sides lie parallel to the borders of the camera image. To accomplish this, the cameras offset to the table center as well as its rotation in respect to the table (pitch, yaw, roll) is calculated. Later, every pixel in the depth image is converted to a 3d coordinate and transformed with the computed matrix. This makes it easily possible to determine if a pixel lies on or above the table or not.
- *Projector Calibration.* The projector is calibrated through the projection of a black AR-Marker pattern on the table. To make the pattern distinguishable from the tables surface, it is necessary that the tabletop has a light color. At the beginning of the projector calibration the user is requested to make sure that the tables surface is light (see Figure 4.9a). If the table has a dark surface the user is asked to temporarily place a white sheet on the table (only until the calibration is completed). When it is assured that the table surface is light the user may press the <*enter*>

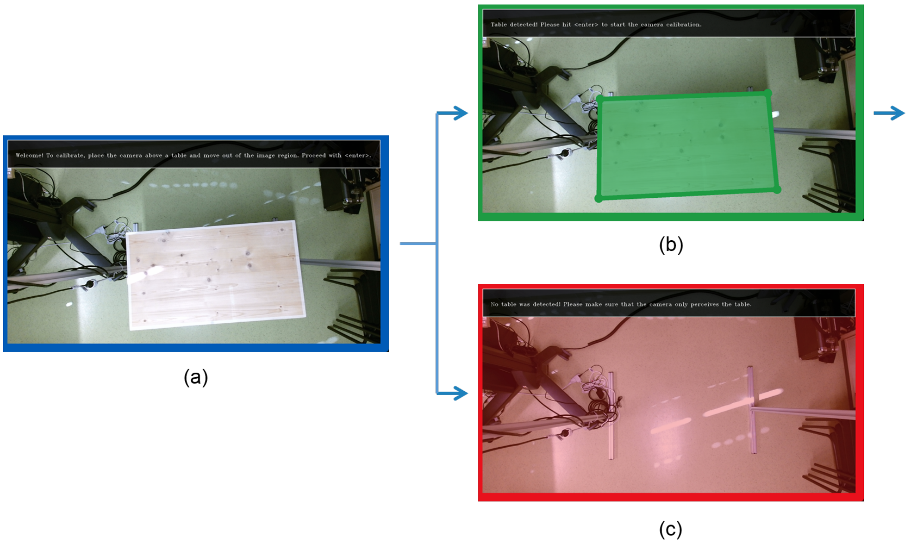


Figure 4.8: Calibration - Camera. (a) Start-up visualization of the application. (b) Table successfully detected. (c) No table detected.

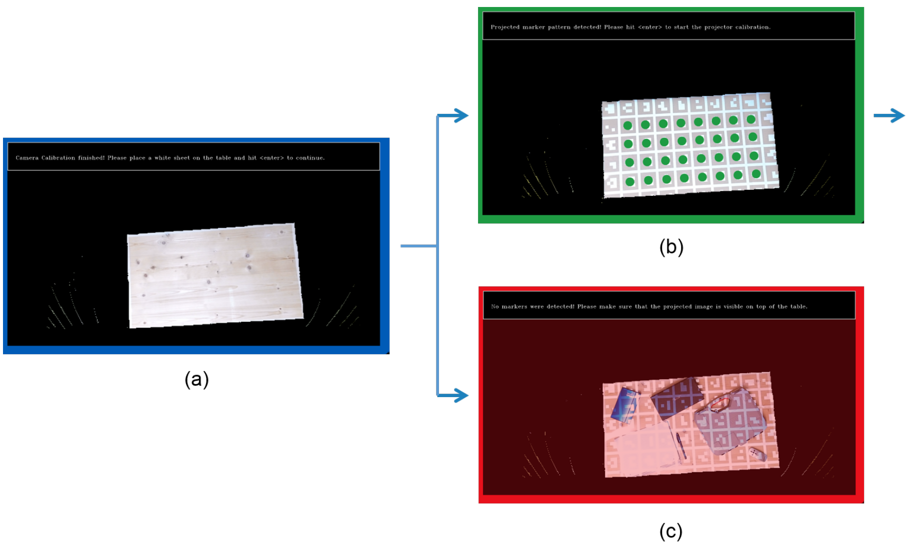


Figure 4.9: Calibration - Projector. (a) Start of the projector calibration. The user is asked to make sure that the table surface is light and cleared in order to make the later projected marker pattern detectable. (b) A sufficient amount of markers was detected. (c) Not enough markers could be detected (e.g. objects lie on the table).

key. After doing so, the mentioned AR-Marker pattern is projected. The projected markers are detected by evaluation of the Kinects color stream. The user again receives a visual feedback. He or she sees which of the projected markers were detected and if the amount of identified markers is sufficient to conduct the projector calibration. Like during the camera calibration, overlays in green (success, see Figure 4.9b) or red (no success, see Figure 4.9c) color in line with short text messages are drawn on top of the Kinects color frame. In case enough markers were detected and the user is satisfied with the visual feedback, he or she might push the <*enter*> key once more to proceed. Succeedingly, the projector calibration is carried out in the background. While the transformation between camera and table is already given, it is possible to calculate the perspective correction from the detected AR-Markers.

4.2.3 Fetch & Pre-process Streams

After completion of the calibration, the system enters the *processing loop*. The first step of the loop is to fetch the infrared and depth stream through the Kinect SDK and preprocess the data[10]. The streams are filtered. All pixel which lie not within the Interaction Space (on or above the table) are set to 0. The remaining pixels of both frames are normalized in the range of 0-254. During the normalization of the infrared frame the inverse square law[11] is applied in order to reduce the divergence of brightness values across the detected image. Figure 4.10a shows the depth stream before the preprocessing, while Figure 4.10b illustrates how it looks afterwards. In Figure 4.10c the Interaction Space above the table is highlighted in green. Only pixels detected within this Space will be "kept" during the processing. All other pixels are set to 0.

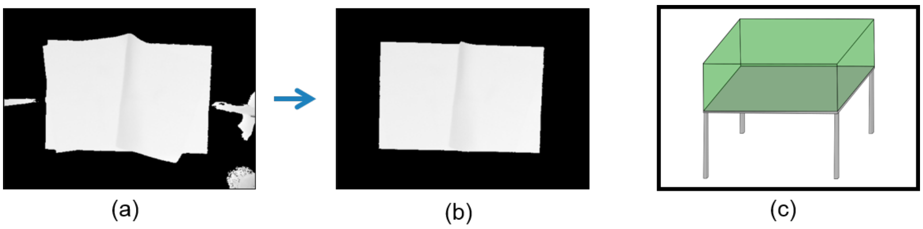


Figure 4.10: Fetch & Preprocess Streams. (a) Depth frame before preprocessing. (b) Preprocessed depth image. (c) Interaction Space above a table, highlighted in green.

[10] The color stream is only utilized during the calibration phase.

[11] Choe et al. [16] verified that the inverse square law holds for the Kinect v1. No detailed examination was conducted to ensure that the property also holds for the Kinect v2. However, when testing the formula with samples at different distances, the inverse square law seemed to be applicable for the Kinect v2. Based on this, it was incorporated in the current version of the prototype. To ensure the validity of the law for the Kinect v2, one would need to conduct a more detailed examination.

4.2.4 Marker Tracking

In the next step, the infrared frame is used to detect the AR-Markers on the cloth. Based on the determined marker information, lines, which reflect the textiles borders, are approximated. These lines are later used to aid the segmentation. To conduct the marker detection with the ARToolkit, first, the greyscale infrared frame must be converted to a binary image. Although the inverse square law is applied before, it is not possible to filter the markers by a simple fixed thresholding. The problem is, that the cloth might be placed under the camera in different angles. Depending on the angle, more or less infrared light is reflected to the camera lens. Figure 4.11a shows a sample infrared image after the preprocessing which illustrates the mentioned problem. Where the cloth is not lying flat on the table, less infrared light is reflected back to the camera and the makers appear darker in the infrared image. Thus, instead of a fixed threshold, adaptive thresholding is applied. Utilizing this on the sample frame results in the binary image which is displayed in Figure 4.11b. The parameters of the adaptive thresholding were optimized by testing.

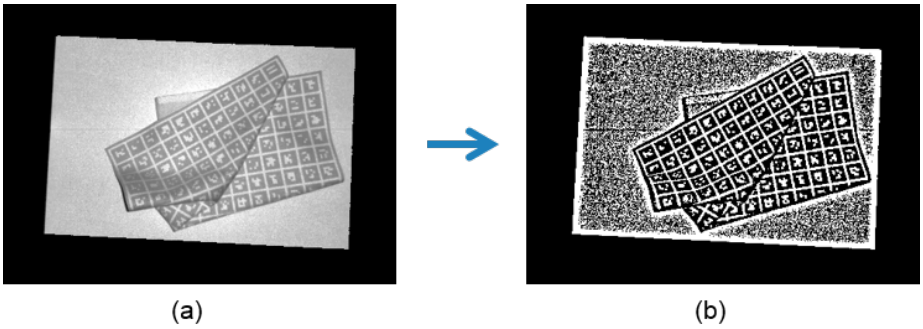


Figure 4.11: Marker Tracking - Adaptive Thresholding. (a) Sample infrared image. Where the cloth does not lie flat on the table, less infrared light is reflected. The markers show up darker. (b) The outcome of applying adaptive thresholding to the infrared frame.

Next, the binary image, created through the adaptive thresholding, is forwarded to an ARToolkit function. An array of detected markers is returned. The toolkit supplies a confidence value for each of the identified markers. This value states how high the probability is, that the marker was detected correctly. Only markers which have a probaility of $\geq 85\%$ are kept. Others are instantly discarded. Succeeding, the markers are categorized in either markers positioned on one of the four borders of the cloth (left, top, right, bottom border) or on its inner area (see Figure 4.12a). The detected border markers are sorted in the order, in which they originally appear on the cloth, from left to right, respectively from top to bottom. Further, for each of the detected border markers, the original and the current distance[12] which the marker has to the next detected one is computed. The border markers as well as the values related to them are then used to extract multiple border line fragments, like displayed in Figure 4.12b. While the center of the detected markers is used to determine the border lines, it is necessary to shift the lines to the real cloth border (see Figure 4.12c). After this was done, the extracted border lines are extended to the images borders, like shown in Figure 4.12d. Both, the shifted version of the short as well as the extended border lines, are utilized later to aid the identification of cloth segments.

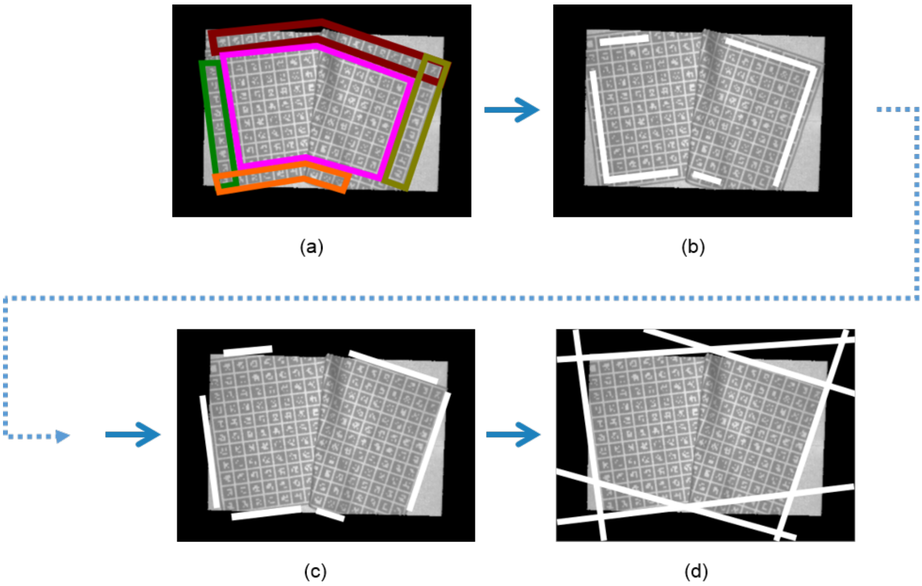


Figure 4.12: Marker Tracking - Border Extraction. (a) Markers are grouped in border markers (left, top, right, bottom) and markers which lie in the textiles center. (b) Extracted short border lines. (c) Short border lines, shifted to the real cloth border. (d) Extended border lines.

4.2.5 Verify if a Lens was detected

Before the processing is continued, the system checks if a lens was detected. The necessary information is provided by the Marker Tracking utility. To determine if a lens was held in view of the camera, the number of markers whichs ids belong

[12]The term *original distance* refers to the distance which lies between two markers on the cloth in reality (when the cloth is not folded). On the other hand, the *current distance* is the distance between two marker positions which were currently detected by the ARToolkits algorithm. These distances may differ strongly. For example, the cloth can be folded and the current position of two markers might be much closer than their original distance. It is also possible that a marker was detected with a wrong id and thus its real location differs from the detected position. In most cases it is possible to ascertain fold lines and missdetected markers by comparing the original and the current distance between marker pairs. This process is utilized to extract valid borders. Only markers which have an original distance which (almost) equals their current distance are considered as potential candidates for the start and end position of a border line.

to the same lens are counted. If the amount is higher than a predefined threshold t, the lens is accepted as detected. When no lens was detected, the system continues by attempting to process cloth related information (see Section 4.2.6). Otherwise the data in regard to detected lens(es) is reviewed in more detail (see Section 4.2.7).

4.2.6 Processing of detected Cloth

This section describes the steps which are carried out in case no lens was detected. Data in regard to the cloth surfaces is processed.

1) Verify if the Marker Data was significantly updated

The Marker Tracking utility supplies the information if the *cloth was moved* as well as, if *a significant number of previously undetected markers was detected*. Based on this data the application decides if the remaining steps in the pipeline are executed or not. In case the marker data was significantly changed (either the cloth was moved, or new markers were detected) the processing continues. Otherwise the program goes back to the first step in the pipeline and fetches new stream data.

This step was conducted in order to avoid a continuous rendering. In an earlier version of the application, each input frame was utilized to update the displayed visualization. However, this lead to a *jittering* output image. A custom ARToolkit marker history was implemented within the Marker Tracking Utility. Different thresholds are utilized to determine the described information, if the cloth was moved or a significant number of previously undetected markers was detected.

2/3) Segmentation & Mesh Generation

In case the processing is continued, two steps are conducted in parallel. Cloth segments are extracted and a mesh model is generated via the Kinect Fusion API [44].

Let's focus on the segmentation first. While it is possible that the cloth is folded, there might be different parts of it which need to be textured separately. The fold lines provide edges which can be used to pursue a segmentation. In order to identify different segments, a concept, introduced by Hulik et al. [40], was applied. The authors compared multiple approaches for plane segmentation based on depth images in their paper. While performance was an important factor, in the current version of the application, the fastest method they introduced was implemented[13]. Depth accumulation in combination with the watershed algorithm was utilized. However, the chosen method was not directly "copied" from the paper. In order to improve the segmentations outcome, the

[13]However, one could easily replace the segmentation method later (e.g. if more processing power would be available).

concept was slightly enhanced[14]. Each of the procedures steps is described in the succeeding.

To extract edges, at first depth accumulation was applied according to the following formula [40]:

$$f_D(\mathbf{x}) = \sum_{\mathbf{r} \in W(\mathbf{x})} \begin{cases} 1 & \text{if } |d(\mathbf{x}) - d(\mathbf{r})| > t \\ 0 & \text{otherwise} \end{cases}$$

The value $d(\mathbf{x})$ is the depth information at pixel $\mathbf{x}$. The neighbours in the window W around each pixel $\mathbf{x}$ are visited and the difference between their depth values is computed. A threshold t is specified. The number of neighbouring pixels which have a higher depth difference than the threshold is counted. The larger the amount of neighbours with a depth difference above t, the more likely is an edge at the given position. Unfortunately, the result of the edge detection shows very much noise. There are especially a lot of very small edges detected. To reduce the amount of undesired lines, all edges which are based on only one neighbour are discarded during the detection. However, this improves the outcome only slightly. To clear the image further from noise, smoothing in form of a median filter is applied. Afterwards the canny edge detector as well as a fast contour line detection are processed. This results in a contour image which shows the fold edges, but leaves out most of the noise.

However, the borders of the cloth are not considered by this approach, yet. The segmentation is based on depth only and requires a height difference above a certain threshold to work. If the cloth is lying flat on the table and one of the textiles borders is visible, the elevation of the cloth in contrast to the table is not high enough to detect an edge. To incorporate this information, the border lines which were computed by the marker tracking utility are taken into account. The short lines, shown in Figure 4.13a, as well as the extended lines, displayed in Figure 4.13b, are used to determine intersection points between the borders. As a result, more accurate cloth border lines can be extracted (see Figure 4.13c). The border lines are eventually drawn on the contour image which resulted from

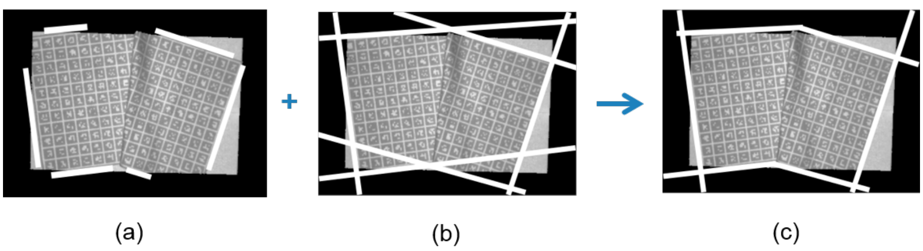


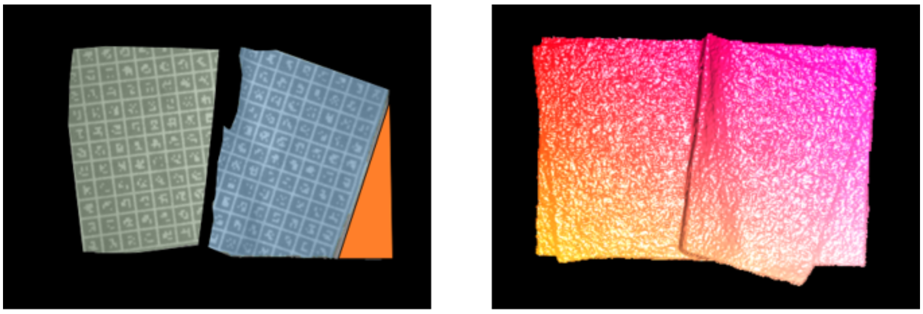
Figure 4.13: Segmentation - Borders with Intersection Points. (a) Short, detected cloth borders. (b) Extended, detected cloth borders. (c) More accurate cloth borders which result after computing the border lines intersection points.

[14]It was not verified if another of the papers [40] methods would outperform the implemented, modified version of *depth accumulation* & *watershed* in terms of accuracy and performance. This could be investigated in the future, to identify potential for improvement.

the edge detection. Thus, depth based edges are combined with the identified cloth borders.

Next, the watershed algorithm[15] is applied. After its processing and the evaluation of the output, each of the depth images pixels has received a segment id. Pixels with an equal id belong to the same segment. In some cases it can happen that large parts of the table are also detected as segments. In order to remove these, segments which have no AR-Markers on them are discarded. An example for this is illustrated in Figure 4.14a. Three segments are given as result of the watershed algorithm. The one highlighted in orange is part of the table. Since no markers can be detected within this segment, it is discarded.

Like mentioned before, this step of the pipeline does not only process the segmentation. A mesh model is generated in parallel. The models degree of detail might be changed through the adjustment of some parameters given by the Kinect Fusion API [44]. However, there exists a tradeoff. The higher the meshs level of quality is set, the longer it takes to generate it and process the structures data.



(a) (b)

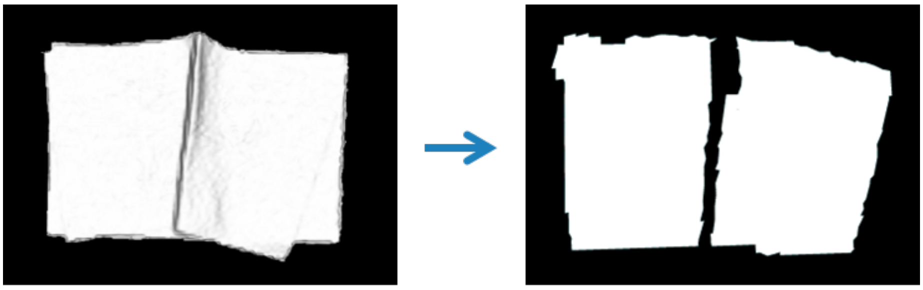
Figure 4.14: Segmentation & Mesh Generation. (a) Example result of the watershed algorithm, visually enhanced with marker information. The orange table segment has no AR-Markers on it and can thus be identified as being not part of the cloth. It is therefore discarded. (b) Example for a mesh generated with the Kinect Fusion API [44].

4) Compute the Texture Mapping

In order to project output on the cloth, the application loads a high resolution texture at start-up. This texture reflects the data which is later shown on the textile (e.g. a map). In order to display the image on the cloth, the generated mesh model is split according to the previously identified segments. Figure 4.15a shows an example mesh before its division and Figure 4.15b illustrates the outcome.

[15]OpenCVs watershed implementation was used: http://docs.opencv.org/3.1.0/d7/d1b/group__imgproc__misc.html

To pursue this process, each of the meshs triangles is categorized first. The considered categories are for example *all vertices in same segment*, *one vertex in one segment and two vertices in no segment*, *one vertex in one segment and two vertices in another segment* and so forth. Each triangle which does not fully belong to one segment, but has at least one vertex which is part of a segment, is cut in order to better fit the segments outline(s).



(a) (b)

Figure 4.15: Texture Mapping - "Cutting" the Mesh. (a) Generated mesh model before splitting. (b) The mesh, cut into different segments.

After the mesh model is divided, it is necessary to determine which part of the texture should be mapped to each of the segments. To do this, the detected markers are used. For each marker its original position on the cloth, and with that its uv coordinates[16] on the texture, are known. Further, the markers 3d coordinates as well as the 3d coordinates of the other points on the mesh are given. To find the uv coordinates of the points on the mesh, for each mesh segment, the 3d coordinates of the markers detected in it are projected to 2d space. Afterwards a homography matrix between the projected coordinates and the known uv coordinates is computed. Eventually it is possible to project all 3d coordinates of the mesh segment to 2d space and use the calculated matrix to compute their corresponding uv texture coordinates.

5) Draw the Visualization

The last step in the processing-pipeline is to draw the visualization and project it on the cloth. The textured mesh is visualized with OpenGL like shown in Figure 4.16a. There are two overlays applied when painting the mesh structure. To increase performance, the currently used mesh quality is quite low. As can be seen in Figure 4.16a this results in "unclean" borders surrounding the segments. In order to create better looking borders, the in Figure 4.16b displayed overlay is applied. To make the boundaries of the Interaction Space more obvious to users, further, a table border overlay is drawn on top of the visualization (see Figure 4.16c). The mesh with the two overlays results in an output image like shown in Figure 4.16d.

[16]The term *uv coordinates* is common in literature. It describes the x and y coordinate pair of a 2d texture which is mapped to a mesh. The reason for using u and v instead of x and y is that the coordinates of the meshs vertices are already denoted with the letters x, y and z.

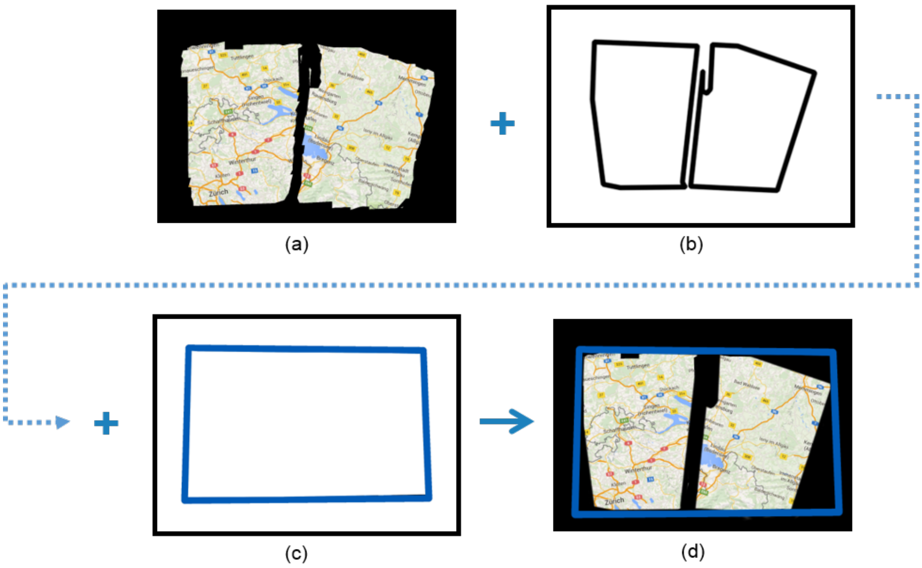


Figure 4.16: Draw the Visualization. (a) Textured mesh without overlays. (b) Segment border overlay. (c) Table border overlay. To highlight the Interaction Space. (d) Textured mesh with overlays.

Figure 4.16 illustrates how the final system looks at runtime when a map of the city Konstanz and its surrounding area is used as background texture.

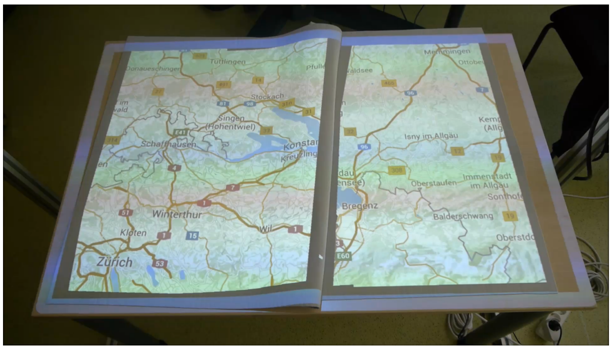


Figure 4.17: Final Visualization - Cloth. The final system at runtime. A map of the city Konstanz and its surroundings is projected on top of the cloth. (Map data ©2016 GeoBasis-DE/BKG (©2009), Google)

4.2.7 Processing of detected Lens(es)

In case one or multiple lenses were detected, the system continues by processing lens related data.

1) Verify if the Marker Data was significantly updated

In order to avoid *jittering* output, the step, described in Section 4.2.6, is also applied in context of the lenses. The system checks if *a significant amount of markers was updated*. Solely if this is the case, the processing of the lens data is continued. Otherwise the application moves back to the start of the processing loop and fetches new stream data.

2) Determine Lens Position above underlying Cloth

In case the marker data was updated, the current lens position in regard to the underlying cloth is determined. The relative coordinates of the markers on a lens are known. For each lens, a homography matrix between the detected markers depth space coordinates and their relative positions on the rectangular object is computed. The relative coordinates of a lenses corners are also given. They are shifted for a predefined offset to the relative lens center and transformed to depth space with the computed matrix[17]. Figure 4.18a illustrates an example of the steps result. Subsequently, the camera space coordinates which correspond to the computed depth space points are fetched from a precomputed array. The array reflects the camera space point which belongs to each position in the depth frame. Eventually, the center of the 3d coordinates is calculated and the corner coordinates are shifted back for the beforehand applied offsets. As result, the lenses 3d center and corner coordinates are given (see Figure 4.18b).

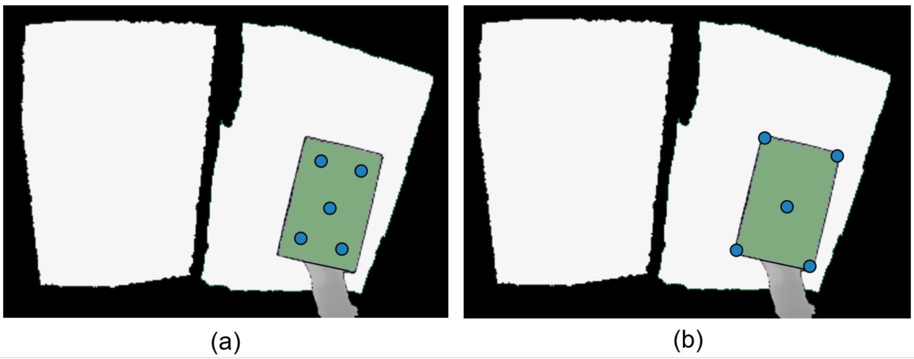


Figure 4.18: Determine Coordinates of Lens Corners & Center. (a) The relative corner coordinates are shifted closer to the lens center in order to determine valid camera space points on the rectangular object. (b) The computed camera space points are shifted back for the applied offset. As result, the 3d corner points of the lenses are given.

The shifting of the coordinates was applied while it is not possible to directly transform the relative lens corners to depth space and fetch the corresponding camera space coordinates without problems. The issue is that, in many cases, the marker detection is not sufficiently accurate to guarantee that the estimated lens corners correspond to valid camera space coordinates. If one transforms

[17]Of course, the shifting of the relative coordinates is only applied once at the startup of the application. From than the system directly uses the precomputed values.

the lens corners directly to depth space, it can occur that the related camera space coordinates reside slightly next to the lenses border. To use these values would result in mapping errors.

3) Compute the Texture Mapping

Before output is rendered on the lenses, it is necessary to determine the correct texture coordinates corresponding to the lenses corners. By default, the data which is displayed on the part of the cloth, situated below a lens, is supposed to be shown on the rectangular surfaces. This is only feasible if a lens is held above a part of the textile which was mapped with texture data when the last frame without a detected lens was processed. The lenses do not show anything, if not at least the lenses center and two of its corner points is situated above a beforehand detected segment of the cloth. An algorithm is applied to determine which of the points (corner and center) lies above which of the previously calculated meshs segments.

If a sufficient part of the lens covers a valid segment of the textile, the uv coordinates are computed. Like described in step 4 of Section 4.2.6, when processing cloth related data, a transformation matrix is calculated for each segment of the mesh. The matrix which was determined for the part of the textile which is situated below the lens, is utilized to transform the lenses corner points to the correct uv coordinates. First the 3d points are projected to 2d space and subsequently the matrix is applied.

In case a lens button was pushed, the texture mapping might differ slightly. For example, if a lens was *locked*, the just described steps are not carried out. Instead, the uv coordinates which were computed for the lens before locking it are reapplied in order to map the same texture data as before.

4) Draw the Visualization

(a) (b)

Figure 4.19: Final Visualization - With Lens. (a) The final system at runtime. A user holds a lens above the textile. (b) After a person presses the button on a lens, the displayed layer of information changes. (Map data ©2016 GeoBasis-DE/BKG (©2009), Google)

The last processing step is to draw the correct visualization and project it on the lenses. First, the data related to the underlying cloth is drawn as elaborated in step 5 of Section 4.2.6. The information in regard to the lenses is painted on top. An example, for the final visualization is depicted in Figure 4.19a. Figure 4.19b illustrates how it looks if a lenses layer of information was changed by pressing the attached button.

4.3 Limitations

Like every technical system, the implementation is not free of limitations. In the following the most prominent ones are listed and briefly described:

- **Performance & Perceivable Delays:** Although the processing speed was improved[18], it is still possible to perceive a slight lag when moving the textile very quickly. However, especially the implemented lenses show a clearly perceivable delay. This has two different reasons. The first is, that the lenses, like the cloth, utilize the developed custom marker history to avoid *jittering* output. The history functionality uses thresholds to determine if a lens or the textile was moved or marker data was updated. This leads to a tradeoff situation. It is possible to set the thresholds in a way that users can hold the rectangular lenses in the air and view output which does not *jitter*. However, people usually do not keep their hands completely still when they hold something up. They pursue very slight movements. To filter these out, the threshold must be large enough. On the other hand, to set the threshold higher leads to the effect that the movement of the lenses is registered with a delay by the system. For example, the lens might be moved for a few millimeters, but the system does not render new while the threshold was not exceeded, yet. The effect is not so strongly perceived when the cloth is used. Much more markers are given on the textile to detect changes and users mostly do not hold it in the air continuously. Nevertheless, the issue can also occur with the cloth. Another problem in regard to the lenses is that, in some cases, the signal forwarding from the flic buttons to the desktop system is influenced by slight delays.

- **Segment Size & Segmentation of the Cloth limited:** In the current implementation, the size of segments as well as the quality of the segmentation is limited. The smaller the size of the segments grows, the more likely it is that the amount of detected marker coordinates is not sufficient to calculate the required transformation matrix. In such cases, the segment is not textured. However, the segmentation was already improved in contrast to an earlier version of the system. Besides markers center points, the ARToolkit also provides information about corner coordinates. In case the amount of detected center points is to low for the computation of the texture mapping (see step 5 of Section 4.2.6), corner coordinates are utilized additionally. In order to support even smaller

[18]Parts of the code was parallelized with OpenMP (http://openmp.org) and a performance analysis was conducted with JustTrace (http://www.telerik.com/products/memory-performance-profiler.aspx). As result of the performance analysis especially time consuming functions were identified and subsequently optimized.

segments in the future, one may attempt to reduce the markers size[19]. Nevertheless, this would require the print of a new cloth. A related issue is the segmentations quality. As mentioned in step 2 of Section 4.2.6, speed was favored over accuracy when implementing the related part of the system. This might result in the problem that a fold in the cloth is not detected if a user presses it down with his or her hand(s). In such a case, the distance in terms of height along the fold line can get to low to be identified as an edge. A way to optimize this behavior would be to further incorporate the marker data into the segmentation process. The distances between detected markers might be compared with their original distances on the cloth, like done in order to extract valid border lines (see Section 4.2.4). This could aid the identification of fold lines which were not, or only partially, determined by the edge detection.

- **Boundary Detection / Approximation Errors:** Another issue are errors which are related to the detection and approximation of boundary lines. Although these failures occur not very frequently, they have the potential to irritate users in case they do. There are mainly three different reasons for this type of issue. First, it can happen that the approximation of the segments boundaries, which is computed to draw the boundary overlay on top of the mesh structure (see step 5 of Section 4.2.6), is inaccurate. Second, it might transpires that a marker is detected with a wrong id and interpreted as part of a border, although it is not. Third, a failure can happen when the intersection lines between the cloth objects borders are computed. In some seldom cases it might occur that one border, which would be necessary to compute the correct end of another border line, is not detected (e.g. a users places his or her hand over a required marker). This can result in the extension of the identified border into another segment and thus distort the output.

- **No Signifiers on Lenses:** According to Norman [78]:

  > *"People need some way of understanding the product or service they wish to use, some sign of what it is for, what is happening, and what the alternative actions are."*

  He proposes to use *signifiers* if possible interactions are not self explaining. The lenses currently lack this kind of information. Although users might push the attached buttons in three different ways to interact with the system, they will not instantly understand the meaning of the click events. At present it is necessary to provide people with an explanation. Further, also the recent version of the application does not show any feedback to users if, e.g. a lens is *locked*. It is suggested to add more information in the future.

[19] One has to be careful when changing the markers size. There is an obvious tradeoff given. The smaller the markers are made, the lower gets the maximum distance between camera and cloth.

Chapter 5

User Study

As described in Section 1.2, it is expected to be beneficial to use interactions *in* the real world in contrast to solely facilitate interactions *like* they are pursued in reality. A comparative study was conducted in order to determine what kind of advantages or shortcomings might arise by supporting the *deformation of cloth in reality.* The differences between the created system and two other user interfaces was researched. The InformationSense system provides high degrees of freedom for interactions. In contrary, the other two interfaces impose clear restrictions and are less physical. However, they also offer more computational power to their users. The information which was gathered in course of the study might be used to guide the future design of flexible displays. The procedure focused on *navigation* and *deformation* interactions. All reviewed interfaces support *movement* and *folding* of the digital data landscape. Additionally to measure participants *performance*, an attempt was made to identify *strategies* which people pursue in order to complete *search* & *comparison tasks* with each of the surveyed interfaces. Participants were asked about their *preferences*, as well as their *subjectively perceived workload.* Further, in regard to determine recommendations for the future design of flexible displays, it was considered interesting to extract *different ways in which the deformable cloth surface is moved and manipulated* by users.

Hornbæk [39] stated that it is not always ideal to survey all features of an application when conducting a study. To limit the considered factors might allow the use of a simpler task, as well as to focus the research on the *"essential features"*. As mentioned, the main interest was to determine how people interact with the flexible cloth surface in contrast to interfaces which solely simulate the deformation of a physical object. On this grounds, it was decided to exclude the developed lenses with buttons from the study. Solely the flexible cloth was taken into account. The other two user interfaces which were utilized are different variations of the SpaceFold system [9] (see Section 3.2.6). One *with* and the other *without* the support of zooming. Both versions supply users with the possibility to conduct fold interactions on a large multi-touch table. As already mentioned, the interfaces facilitate less physical interactions than the InformationSense system, but also incorporate more digital power. For example, searched objects are represented in an abstract form in case they are positioned within fold lines (see Section 5.2.2). The version of the SpaceFold system which supports zooming is the most powerful of the three interfaces. The zoom interaction provides users with an option to get an overview and thus might speed up their workflow. On the other hand, the interface of the InformationSense system supports real world interactions like crumpling, diagonal folding or the rotation of the cloth object. Figure 5.1 shows the placement of the three user interfaces in relation to the power vs. reality tradeoff, described in Section 2.1.2.

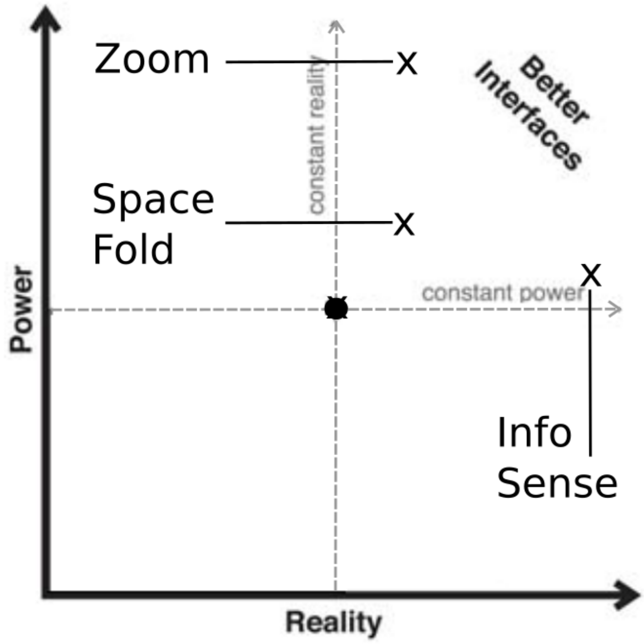


Figure 5.1: Power vs. Reality Tradeoff - Compared User Interfaces. Shows the placement of the three compared user interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)* in the coordinate plane defined by Jacob et al. [46].

In this chapter, Section 5.1 elucidates the studies aim and expectations, in form of *research question(s)* and *hypothesis*. In Section 5.2 the *study design* is introduced. This includes a description of the studies task, the reviewed user interfaces, the different steps of the procedure in view of a participant and the methods which were applied for the collection and evaluation of interface and participant related data. In Section 5.3 the studies *results* are elaborated. The findings are *discussed* in Section 5.4. Eventually, Section 5.5 addresses *limitations* which are implied by the utilized setting, the conducted evaluation and the interpretation of results.

5.1 Research Question(s) & Hypothesis

As mentioned in the introduction of this chapter, the main focus of the study was to find differences between the deformation of a cloth surface *in* the real world and interactions which solely emulate this behavior.

When people navigate through virtual data spaces they frequently *search* & *compare* multiple objects in the digital landscape. For example, a person might desire to determine the location of two cities on a digital map in order to find out which has the larger radius. Another possible scenario would be, the search of an information visualization with the aim to compare the percentage of votes various political parties received in different states of a country. The conduct of such tasks should be facilitated by systems which allow the navigation through virtual data. Throughout the study, participants were asked to search & compare digital objects. In respect to the studies design, to utilize a search & compare task had the advantage that participants had to navigate (search) and were animated to carry out fold, respectively deformation interactions (compare) when working with the reviewed user interfaces.

Different research questions were established in regard to the study. Based on these, related hypothesis were specified. The research questions, as well as the hypothesis, are elaborated within this section in more detail.

5.1.1 Research Question(s)

To make the goal of the user study more clear, the defined research question (RQ) and sub research questions (SQ) are outlined in the following.

- **RQ:** What are differences, when people work with interfaces based on *Interactions* ***in*** *the real world* in contrast to interfaces based on *Interactions* ***like*** *the real world*?
    - **SQ1:** How well is *performance* for each condition?
    - **SQ2:** How do *strategies* to pursue *search* & *comparison tasks* differ for interfaces which support interactions from either of the two introduced classes?
    - **SQ3:** Do users apply interactions which are solely facilitated by an interface that supports *high degrees of freedom* in reality, or will they interact with such a system in the same way as with a *restricted, less physical* interface?
    - **SQ4:** How does working with interfaces which facilitate interactions in the real world affect users *workload*, in contrast to interfaces which only emulate a process from reality.
    - **SQ5:** Is an interface based on interactions *in* or *like* the real world *preferred* by users to conduct *search* & *comparison tasks* and what do they perceive as *benefits* respectively *shortcomings*?

5.1.2 Hypothesis

The stated research questions led to different hypothesis (H). These are listed and briefly described in the succeeding. In connection to each hypothesis, its related research sub question is mentioned. However, none of the hypothesis concerns SQ2 or SQ3. In regard to these questions, data was collected and evaluated exploratively.

- **H1 (related to SQ1):** Users perform *faster* when working with *SpaceFold (with and without zoom)* than with the InformationSense prototype.

  Both versions of the SpaceFold system are more powerful than the third interface. Users might locate objects quicker while they can perceive them in an abstract form within folds or apply zooming to get an overview (see Section 5.2.2). Further, it is expected that participants physical effort is lower, than if working with the InformationSense system. This might also impact their performance.

- **H2 (related to SQ4):** Users perceive the *subjective workload* for all three interfaces *equally high.*

  In general, people are expected to feel a lower workload when they interact with a system which facilitates their real world knowledge and supports interactions in reality. However, the SpaceFold based interfaces supply more power. This might ease up users workflow. Thus, it is assumed that there will be no significant difference in terms of subjective workload between the three conditions.

- **H3 (related to SQ5):** Users prefer *SpaceFold with zoom* in terms of *pragmatic quality.*

  The zoomable version of the SpaceFold interface facilitates a quick overview of the hole digital data space. It is presumed that participants will perceive the system more *goal-directed*, for the conduct of search & comparison tasks, than the other user interfaces. The powerful zoom functional might make them feel in control and probably increases their efficiency.

- **H4 (related to SQ5):** Users prefer *InformationSense* in terms of *hedonic quality.*

  It is assumed that, although the participants probably consider the InformationSense interface *new* and *modern*, they will also *feel familiar* with the medium cloth and its properties from their daily lives. They are expected to find pleasure in the *haptic qualities* of the textile based interface. It supplies them with the possibility to grab the fabric *in* reality and *directly* manipulate it like desired.

- **H5 (related to SQ5):** Users will *not* want to *restrict* the process of *folding* for the *InformationSense* system.

  When interacting in reality users can directly base interactions on their pre-existing knowledge from the real world. Restrictions, like e.g. a grid of plates weaved into the textile, might irritate them and reduce their possibilities for interactions. It is presumed that users will *appreciate* it to have *high degrees of freedom*, when they deform a real world cloth object by folding and that they do *not* desire to give them up.

- **H6 (related to SQ5):** Users will *not* miss the possibility to place folds *freely* when they work with the *touch based interfaces*.

  The SpaceFold systems facilitate solely restricted fold interactions. Users can only fold horizontally, vertically or both at once. Nevertheless, it is expected that the *structure*, which is provided by the touch based interfaces due to the fold restrictions, might aid their work. To supply free folding on a 2 dimensional touch table possibly leads to confusion by users. For example, they cannot perceive complex overlappings of the folded surface in the same way as in reality. Instead, they might think it simpler to be *guided* and prefer more *computational power* over an increase of realism when they work with touch interfaces.

5.2 Study Design

The study utilized a *within-subjects factorial design* with three independent variables. These are:

- **Levels of Task Complexity:** low (two compare objects), medium (three compare objects), high (four compare objects)
- **Task Distances:** short (no folding mandatory to view all compare objects at once), far (folding or zooming is necessary to see all compare objects at the same time)
- **User Interfaces:** InformationSense, SpaceFold, SpaceFold with zoom

As dependent variables the task completion time was measured and user interactions were extracted from log files and video data. Participants were queried about their preferences, as well as search & comparison strategies they applied while conducting the tasks, in form of a semi-structured interview. Further, two different questionnaires were utilized in order to measure the subjective task load (NASA TLX), as well as the hedonic and pragmatic quality in line with the attractiveness (User Experience Questionnaire) for each of the user interfaces. A third, custom questionnaire was used to inquire about some task specific issues. The applied methods are elaborated in more detail in Section 5.2.4.

5.2.1 Task

In the utilized task, participants had to compare colored objects. The search & compare task was based on the work of Butscher, Hornbæk & Reiterer [9]. Their general idea was adopted, but the task itself was altered due to differences in the study setups. The original version offers shortcomings when being used with partially rotatable user interfaces[1]. While the InformationSense system supports full and partial rotation of the cloth, this might have caused trouble. Further, the authors designed the task solely for the comparison of two objects. However, it was deemed of interest to see how participants perform when they should solve more complex tasks (three or four compare objects).

In the modified task, participants had to search & compare circle objects, like the one shown in Figure 5.2a, with each of the three user interfaces. The circle objects are randomly rotated and placed on a white background. The in Figure 5.2b displayed eight different colors were utilized for the objects creation.

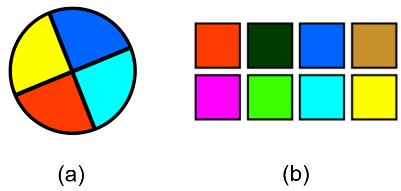


Figure 5.2: Structure of Compare Objects. (a) Randomly rotated circles with four colors were utilized as compare objects. (b) The eight different colors which were used to create the circles.

Participants had to find out if *ONE color was given in ALL of the circle objects* which were lying within the virtual data space *or NOT*. To do so they could manipulate the digital data space through the interactions which are feasible with the different interfaces (see Section 5.2.2). When a participant determined the answer to a task, he or she could hit one of two labeled buttons on a modified keyboard, illustrated in Figure 5.3, in order to tell the system. Participants had the options to reply with:

- *Equal:* Yes, all circles have one color in common.

  or

- *Unequal:* No, not all circles have one color in common.

It was possible that almost all circles had a color in common but one lacked it. On the other hand, the case that there is more than one color given in all of the compare objects was not existing. To begin a task, a participant had to push the *start* button in the middle of the keyboard. Participants could decide by themselves if and at what time they would like to fully or partially *reset* the cloth by opening all or some of the created folds. They could also reuse

[1]The authors [9] proposed the use of compare objects based on five colored rectangles. They let participants determine if all rectangles of two such objects matched in terms of color and position or not. The InformationSense system facilitates the rotation of the cloth in line with other real world manipulations which might cause one or more of the compare objects to get rotated. This could make the comparison of the objects difficult. Participants might check the wrong rectangles against each other, in case one or multiple objects are rotated.

beforehand established folds for the succeeding task(s) if they wanted[2].

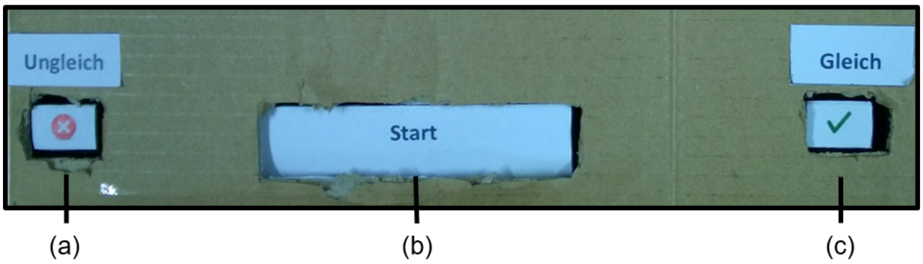


Figure 5.3: Study Keyboard. Participants had three different buttons they could press: (a) Unequal. (b) Start. (c) Equal.

As already mentioned, it was seen relevant to facilitate tasks with different levels of complexity. There might be interesting differences in terms of performance, fold interactions and search & comparison strategies given. Therefore, the independent variable *levels of task complexity* was defined. Participants were asked to compare *two (low complexity)*, *three (medium complexity)* and *four (high complexity)* circle objects (see Figure 5.4).

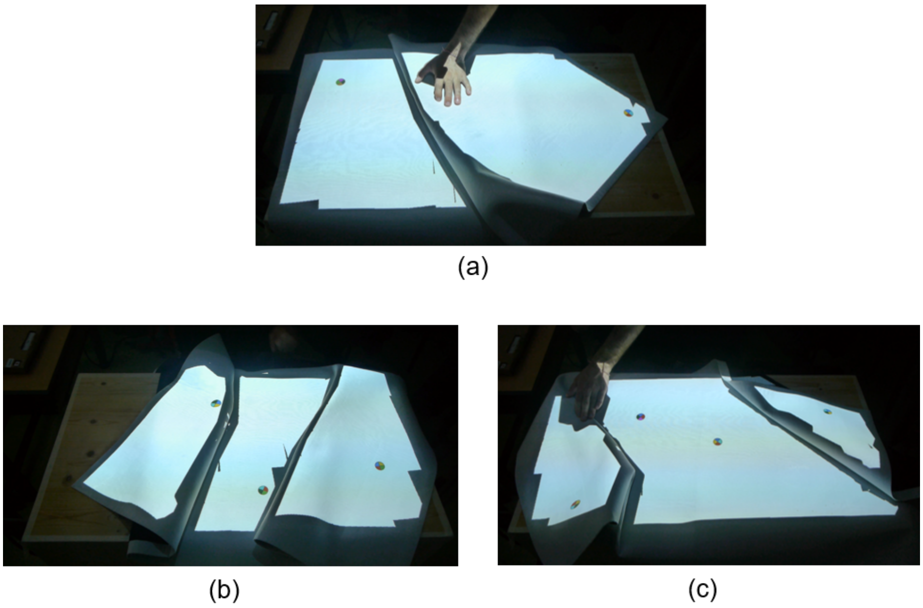


Figure 5.4: Levels of Task Complexity. (a) Two circles (low complexity). (b) Three circles (medium complexity). (c) Four circles (high complexity).

[2]This increases the external validity. In reality, people are usually also not forced to reset their interfaces between multiple search & comparison tasks. However, to allow participants to keep folds from the previous task(s) also impacts the measuring of the task completion time. While the main focus of the study was not to compare performance, more realism was traded for less accurate task durations.

Additionally two different task distances were supported. It was distinguished between tasks in which participants may see all of the circle objects at once without folding and zooming (*short distance tasks*) and tasks in which this was not feasible (*far distance tasks*). Figure 5.5 gives an example of the two conditions. The outer rectangles depict the hole digital data space at a zoom level of 100%. In case of the InformationSense system, this space is mapped statically to the cloth. Thus, for the textile based user interface, the outer rectangle corresponds to the cloth. The dark grey colored inner rectangles reflect the size of the Interaction Space[3]. Again using the example of the InformationSense system, this would be the dimensions of the tables surface. In short distance tasks participants might move the virtual data space (InformationSense: move the cloth) in a way that they can perceive all circles at once without folding (see Figure 5.5a). On the other hand, this is not possible in far distance tasks, like the one displayed in Figure 5.5b.

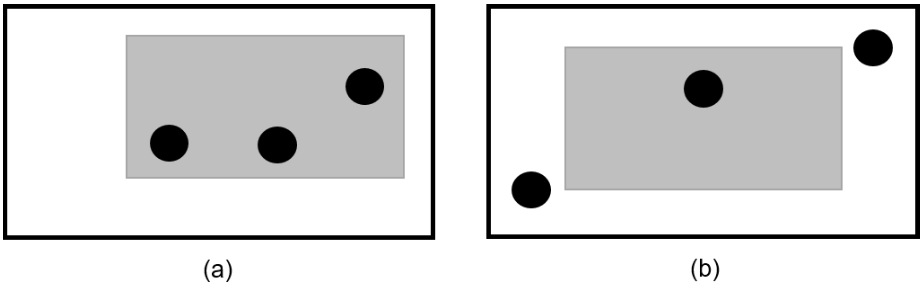


Figure 5.5: Task Distances. (a) Short distance: Participants might move the virtual data space so that all circles are visible within the Interaction Space without folding. (b) Far distance: Participants need to fold or zoom the digital landscape in order to view all of the circle objects at once.

In order to create a well distributed placement of the circle objects for the different tasks, a generator was written. Input parameters are for each task its level of complexity along with the desired distance. The tasks orientation is computed randomly. It can either be vertical or horizontal. There are different intervals for the placement of circles defined. Lets assume a short distance task is desired. Circles are placed within a region which has the size of the Interaction Space, like shown in Figure 5.6a. In the given case, the computed orientation is horizontal and the task complexity low. The two circles are placed randomly within the two blue areas on the border of the grey region[4]. Afterwards the points within the grey area are shifted along the x and y-axis, according to a

[3]In the InformationSense system the cloth is larger than the table surface which marks the borders of the Interaction Space along the x and y-axis. Thus, a participant can never look at the hole digital data space at once. This condition is equally true for the other interfaces. On the multi-touch table, the virtual data space is also far larger than the screen space which is supplied for interactions with the system. Only in the version which facilitates zooming, a participant might shrink the size of the digital data space temporarily in order to get an overview. For more details, see Section 5.2.2.

[4]The generator makes sure, that at least two circles lie (almost) as far apart along the randomly computed orientation, as is valid for the defined task distance.

randomly computed offset[5]. If the task complexity is medium, the third circle is positioned within a region which lies between the two outer areas, like illustrated in Figure 5.6b. For high complexity tasks, two middle regions are utilized for the placement of the two circles which do not lie close to the grey regions border (see Figure 5.6c). The creation of far distance tasks follows the same general pattern. The difference is that circles are not placed within a region of the Interaction Spaces size and shifted according to an offset later. Instead, they are instantly distributed across the hole digital data space. Figure 5.6d-f gives examples for vertically oriented far distance tasks with low, medium and high complexity.

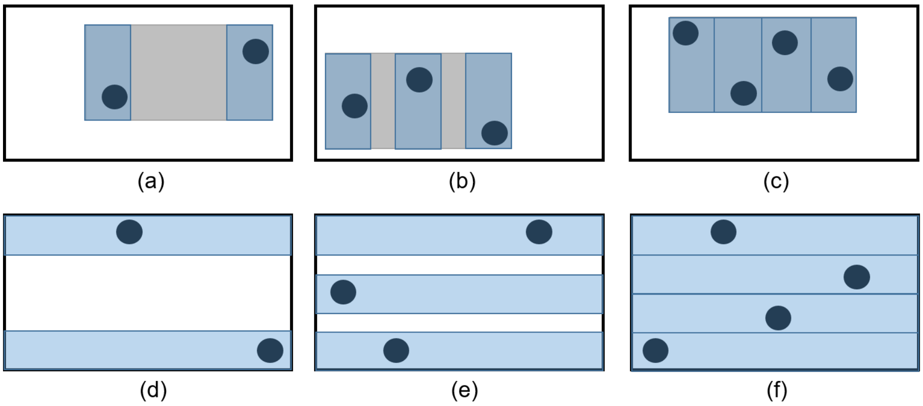


Figure 5.6: Task Placement. (a) Short distance, horizontal, *low complexity.* (b) Short distance, horizontal, *medium complexity.* (c) Short distance, horizontal, *high complexity.* (d) Far distance, vertical, *low complexity.* (e) Far distance, vertical, *medium complexity.* (f) Far distance, vertical, *high complexity*

5.2.2 User Interfaces

As already mentioned, three different user interfaces were utilized in the study. All of the systems were run on a Core i7-4770K with 3.50GHz and 16GB ram. When participants interacted with one of the user interfaces, it was assured that, in each case, the room lights were off and the blinds drawn. The goal was to avoid reflections on the multi-touch table, used by SpaceFold (both versions), and increase the perceptibility of the InformationSense systems projection. In the following, the setup of the systems in line with the interactions feasible with each of the interfaces, are described.

InformationSense

The implementation of this system was already introduced in Chapter 4. For the study, a table with a height of *90cm* was used. Its surface is sized to *93x52.3cm*. The table top is smaller than the utilized cloth which has the

[5] All points are shifted with the same offset. This step is taken to randomly distribute the, in grey illustrated, short distance regions.

dimensions *135.6x79.6cm*. Like described in Section 3.4.1, the borders of the tables surface limit the systems Interaction Space along the x and y-axis. Thus, it was not possible for participants to view the hole digital data space, which was projected on the cloth, at the same time. The utilized projector has a resolution of *1920x1080*.

Participants were able to manipulate the cloth on top or above the table in any way they desired. For example, they could *move*, *fold*, *rotate* or *crumple* it. Output was only visualized on the parts of the textile which were positioned within the Interaction Space (see Figure 3.16).

SpaceFold (without zoom)

The SpaceFold system, which was already briefly described in Section 3.2.6, was run on a multi-touch table[6] with a resolution of *1920x1080*. The tables screen has the dimensions *121x68.2cm*. To limit the Interaction Space to the same size as the one supplied by the InformationSense system, the SpaceFold based interfaces displayed a black border (see Figure 5.7). It was assured that the

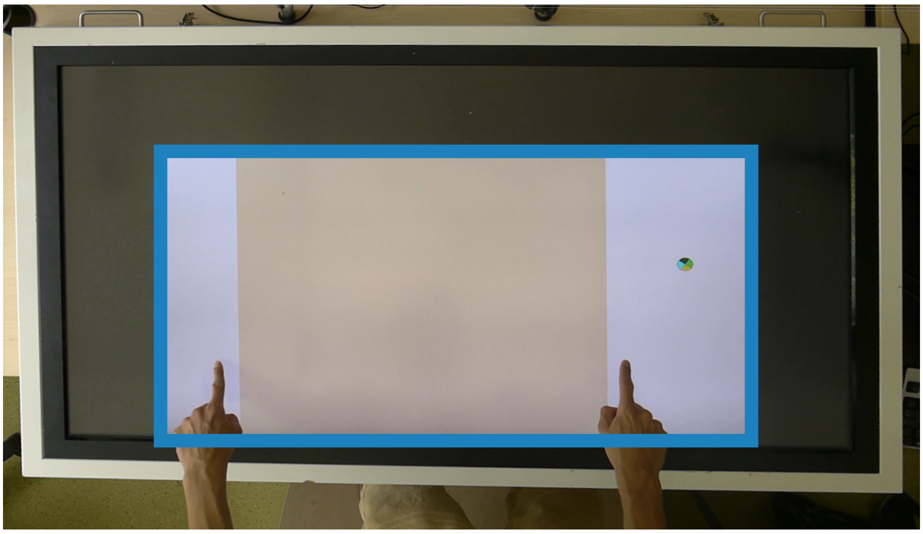


Figure 5.7: SpaceFold - InteractionSpace. The Interaction Space of the SpaceFold interface, highlighted by the blue rectangle, was limited to the dimensions of the InformationSense systems table surface along the x and y-axis.

multi-touch tables elevation above floor level matched with the one of the table which was utilized by the InformationSense system. Both had a height of *90cm*. The same kind of virtual data space, which was projected on the cloth when using the InformationSense interface, was rendered on the multi-touch table when working with SpaceFold. The real world size of the visualized digital landscape corresponded to the dimensions of the InformationSense systems textile.

[6]Citron DreamTouch 55"

Participants had various ways to interact with the user interface. Like described in Section 3.2.6, they were able to create vertical or horizontal folds by placing their fingers on the multi-touch table, wait shortly and subsequently move the fingers closer together. In case the fingers were placed diagonally on the screens surface, the interface facilitated the creation of a horizontal and vertical fold at the same time (cross fold). It was also possible for them to modify existing folds. Sometimes it could happen that a circle object lay within a previously created fold line like shown in Figure 5.8a. Circles which lay in folds were presented in an abstract form, as solid black dots. A participant could press a finger on either side of the fold and adjust it by moving one of his or her fingers orthogonal to the fold line. Figure 5.8b illustrates the state after a fold, which contained a circle, was modified.

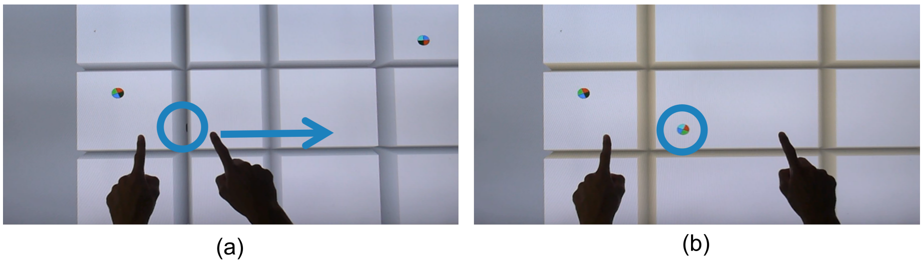


Figure 5.8: SpaceFold - Modify Folds. (a) Abstract representation of a compare object which lies within a fold, highlighted by a blue circle. The user places a finger on either side of the fold and moves the rightmost finger to the right. (b) The circle object, again highlighted in blue, was "dragged" out of the fold.

Another possible interaction was the merging of two or more folds with the same orientation. As can be observed in Figure 5.9a, a participant could place two fingers on either side of multiple parallel fold lines in order to merge them. The participant could simply move one of his or her fingers towards the other, or both towards each other, and therefore "melt" the folds in between together.

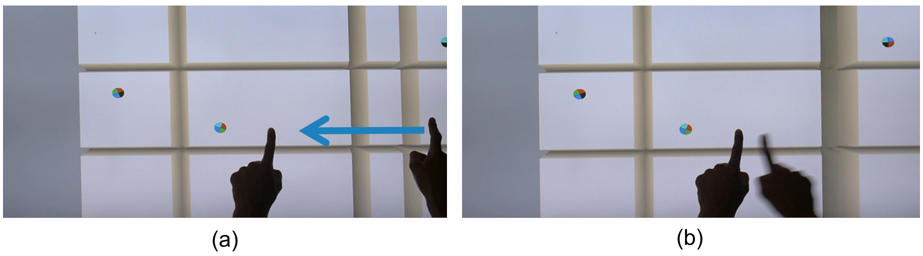
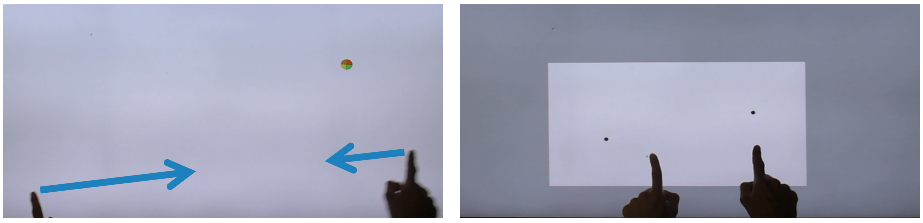


Figure 5.9: SpaceFold - Merge Folds. (a) A participant puts two fingers on the sides of two parallel fold lines. In order to merge them he or she moves one finger towards the other. (b) The two vertical fold lines were merged together.

SpaceFold with zoom

The setting of SpaceFold with zoom completely corresponds with the one of SpaceFold without zoom, with exception of the zoom functionality. In order to zoom, participants could apply the common gesture of placing two fingers on the multi-touch table and either moving them closer together or farther apart. Figure 5.10a provides an example of a user who zooms the interface out. After applying the zoom gesture, the circles are shown filled with solid black color. It was obvious that participants would have just zoomed out and compared the circles, if their colors would have been visible independent of the zoom level. However, the zoom functionality was only supposed to provide more power in form of an overview. Participants should still fold the virtual data space in order to compare the circle objects. Therefore the circles colors were hidden as soon as the zoom level was unequal to 100%.



(a) (b)

Figure 5.10: SpaceFold - Zoom. (a) A participant could place two fingers on the multi-touch screen and move them towards each other in order to zoom out. (b) When the zoom level is unequal to 100%, the circles are displayed in an abstract form.

5.2.3 Procedure

The studies procedure is illustrated in Figure 5.11 from the view of a participant. The study was conducted in a controlled environment. A lab room of the universities Human-Computer-Interaction Group[7] was utilized. The approximate time for the hole procedure was 90min. Participants received a welcome letter after their arrival and were subsequently asked to sign a declaration which stated their agreement to be recorded while doing the tasks[8]. As last step of the procedures introductory phase a demographic questionnaire was handed out to the participants.

After they had filled the questionnaire, the participants were introduced to the task. While a within-subject design was used, each of them had to work with all three interfaces. To avoid learning effects, the order of the interfaces was fully balanced between participants. The steps were the same for each user interface. The investigator showed and described the interaction techniques which are possible with the interface to the participant. Afterwards the camera

[7] http://hci.uni-konstanz.de

[8] The welcome letter as well as the declaration of consent (recording) were based on the samples given by Krug [61]

was switched on and the participant was asked to try out all of the feasible interactions. When the participant was done he or she was told to press the start button and begin with the first task. The participants had to complete three blocks of eight tasks (24 tasks) with each interface. They had to stand while working with the systems. The tasks in each block had a different level of task complexity. For example the first block had only low, the second only medium and the third only high complexity tasks. The task blocks were balanced, with a latin square, between participants. 50% of the tasks in each task block were short distance and 50% far distance tasks. The tasks were generated only once for all participants and their order within one block was randomize for each participant and every interface. After a participant finished the last task for an interface he or she was asked to fill three questionnaires. First the NASA TLX, then the User Experience Questionnaire and eventually a short custom questionnaire with five likert scale questions.

Subsequently to the completion of all user interfaces and the related questionnaires, the investigator conducted a semi-structured interview with each participant. Eventually, participants received their payment in form of 12€, had to confirm it, and were seen off. All of the documents which were handed out to the participants are listed in Appendix A.

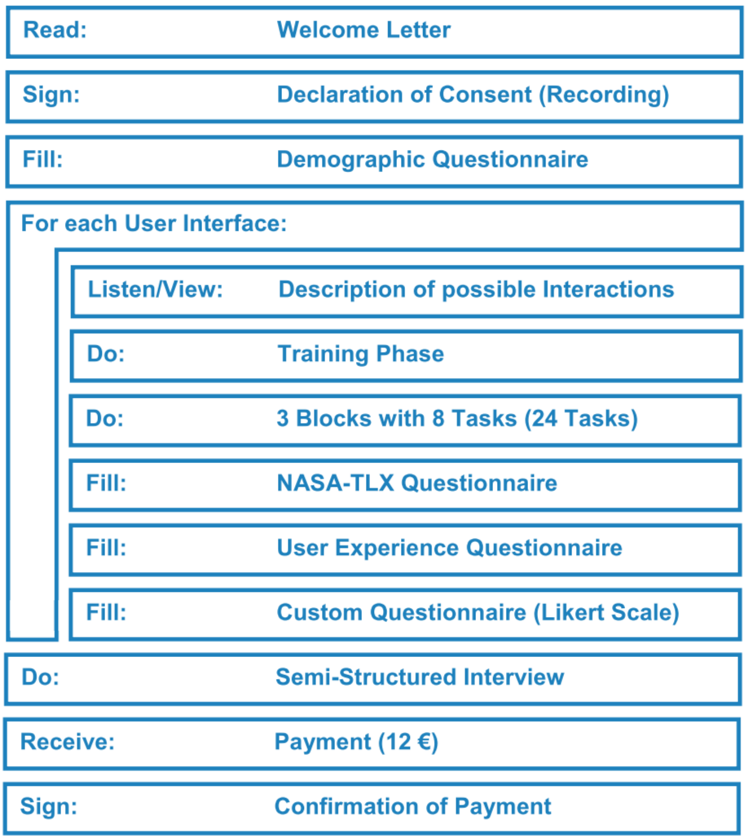


Figure 5.11: Study Procedure. The different steps of the studies procedure, described from the view of a participant.

5.2.4 Methods for Data Collection & Evaluation

Mainly four different methods were utilized in order to collect data during the conduct of the study. These are *multiple questionnaires*, *automatic logging*, *video recordings* and *semi-structured interviews*. The gathered data was evaluated in respect to the studies goals. This section elaborates the different methods for data collection in line with the practices which were pursued in order to assess the gathered information.

Questionnaires

Every participant had to fill ten questionnaires throughout the hole study procedure. A demographic questionnaire was to be completed at the studies beginning. Subsequently, two standardized and one custom questionnaire, with five point likert scales, were handed to the participants each time they finished all tasks with an user interface. The different questionnaires are briefly described in the following. It is elucidated for which purpose the questionnaires were incorporated in the study procedure and how their results might be interpreted.

Demographic Questionnaire. The demographic questionnaire was utilized in order to gain general data about each participant, including their technical skill level as well as their level of experience in regards to large multi-touch displays ($\geq$ 30"). Further, it was used to confirm that participants had no body related constraints which might influence their behavior when working with the user interfaces. Since they were required to stand while they conducted the tasks and were supposed to manipulate a physical cloth object in reality (InformationSense), participants were asked if they had physical impairments. To complete the tasks without problems, participants needed the ability to distinguish the eight different colors, shown in Figure 5.2b. Thus, they were also queried in regards to color blindness.

NASA TLX[9]. Users *preferences*, as well as their *performance* might be influenced by the workload they experience when interacting with each of the user interfaces. To measure the participants subjectively conceived workload, they were asked to fill the standardized NASA TLX questionnaire each time they completed all tasks for one of the systems. The NASA TLX, which was developed by Hart [33], divides the measuring of the total workload in the six 20-stage subscales *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort* and *Frustration*. The questionnaire was very frequently utilized in past research [32]. It has a high factor validity and is well accepted by operators [36]. Participants received a short description for each subscale. They were requested to read it before they rated the interface they had used. While the study was designed for german speaking persons, the participants were provided with a translated version of the NASA TLX [109]. To evaluate the different questionnaires, the 20-stage scales were translated to scores between 0 (low demand) and 100 (high demand). Additionally to the six separate subscale scores, an

[9]NASA TLX: National Aeronautics and Space Administration Task Load Index

overall workload score[10] was computed for each interface which the participants used.

User Experience Questionnaire (UEQ). The standardized UEQ was utilized in order to compare the subjective user experience of participants for the different interfaces. The questionnaire was introduced by Laugwitz, Held & Schrepp [64]. Different studies, conducted for the german and english version of the UEQ indicate that the questionnaires level of construct validity and reliability is satisfactory [64, 65]. Participants received the german version of the UEQ. The questionnaire consists of 26 bipolar seven-stage scales. Each of the items scale ranges between -3 (most negative answer) and +3 (most positive answer). The items have the form of semantic differentials. One term of an opposing pair of words is assigned to either side of a scale item. The order in which the terms are placed is randomized for each item. Half of the items display the negative term left and the positive one on the right side. The other half is constructed vice versa. The UEQ provides the investigator with measures of an interfaces *Attractiveness* as well as its hedonic (*Perspicuity*, *Efficiency* and *Dependability*) and pragmatic qualities (*Stimulation* and *Novelty*). It aids the identification of strengths and weaknesses of the different interfaces. The Excel Tool, described in [89], was utilized in order to evaluate the results of the questionnaires.

Custom Questionnaire (Likert Scale). A custom questionnaire, based on five-stage likert scales, was created in order to inquire some task related issues. Participants were asked to subjectively rate how well they could keep an *overview*, how *natural* they experienced the work, how easy it was to *find* and *compare* the circle objects and how often they attempted to *memorize* the colors of circle objects, for each of the interfaces. The used scales ranged from -2 (most negative answer) to +2 (most positive answer).

Logging

For all of the systems an automatic logging was implemented. The *task completion time* in line with the participants *answers* was recorded. The interfaces based on SpaceFold additionally saved events like e.g. *create fold (vertical, horizontal or cross)*, *open fold*, *pan*, *zoom* and *fold complexity at end of task*. However, it was considered problematic to automatically log these supplementary interactions for the InformationSense interface. As result, the automatic logs which were generated by the InformationSense system contain less information than the ones of the two SpaceFold versions[11]. The created log files were evaluated in form of a quantitative analysis.

[10] To calculate the overall workload score, the subscale scores were accumulated and divided by six (number of subscales).

[11] It would have been necessary to develop some kind of classification in order to distinguish between different interactions for the InformationSense interface. Instead, the videos, which were collected while participants worked with the interfaces, were utilized to extract the related data.

Video Recording

Participants were recorded while they worked on the tasks. A Panasonic DMC-GH2 camera was mounted on a tripod and tilted diagonally downward, so that its field of view covered the Interaction Space of the filmed user interfaces. Additionally, the investigator took notes. The recordings which were created while participants worked with the InformationSense system were evaluated by video coding. A coding schema was defined (see Appendix A). It reflects the information which could be extracted from the log files for the interfaces, based on SpaceFold. However, while the InformationSense prototype also facilitates interactions which are not possible with the SpaceFold based interfaces, additional event data was coded. For example, interactions like crumpling the cloth or lifting it in the air were marked. 11.11% of the files were coded redundantly. Cohen's Kappa [18] was used to determine the inter-rater reliability. The resulting value of *0.81* reflects, according to Altman [2], a *very good* agreement. The coding, as well as the computation of the inter-rater reliability was conducted with Noldus Observer XT 10[12]. As long as a participant did not halt intermediary, navigation interactions were always coded as one event. Let's assume, for example, the case that a participant pans for 10 seconds without a break or a different interaction in between. According to the applied schema, this was coded as solely one panning interaction. If a person navigated with panning and rotation, one pan and one rotation interaction was coded. When participants folded, each fold was counted as one interaction. If a participant applied a way of folding, not supported on the touch based interfaces, the fold was logged with a separate tag. For example, in case a person pushed the cloth together and created a fold in the process, the interaction "create fold: push cloth together to fold" was coded. The log files were evaluated in a similar manner. Subsequently the gathered data was evaluated quantitatively.

Semistructured Interview

After the participants completed all tasks with each of the interfaces and had filled all of the questionnaires, a semi-structured interview was conducted. Participants were queried about their *preferences*, including *benefits* and *shortcomings* of the different systems, as well as *suggestions for improvement*. Further, it was inquired if they followed a *strategy* when solving the search & comparison tasks for each of the interfaces. In case they did, they were asked to *describe* it. The participants were also requested to give their opinion about the difference between *restricted* (SpaceFold) and *free folding* (InformationSense). Eventually, they were queried in relation to *interesting interactions* which were observed while they worked with the InformationSense interface and asked to propose *future use cases* for a system based on a deformable cloth surface.

A qualitative content analysis was applied in order to evaluate the collected statements. Mayring [73] describes the qualitative content analysis as a *"mixed methods approach"*. First text is assigned to categories as qualitative part of the process. Subsequently, the frequency of the categories might be counted. According to the author, the quantitative step is not necessarily part of the analysis, but can *"add weight"* to the *"meaning"* and *"importance* of the de-

[12] http://www.noldus.com/human-behavior-research/products/the-observer-xt

fined categories and help to generalize results. In respect to the acquired data, a qualitative analysis, followed by a quantitative processing of the categories, was carried out. In addition to the information gathered during the interviews, also notes which were taken when observing the work of participants with the different interfaces, were analyzed. Mayring [73] proposes two different ways to categorize reviewed texts. One can either utilize *deductive* or *inductive* categories. While it was not possible to predefine categories before conducting the analysis (deductive), the inductive approach was applied. While reviewing the texts the given statements were gradually reduced to categories. The resulting categories were *structured* after predefined criteria and sub criteria for later interpretation[13]. The criteria were specified based on the research questions and hypothesis elaborated in Section 5.1. These are:

- Search & comparison strategies
  (for each user interface)
- User preferences
  - Benefits & shortcomings
    (for each user interface)
  - Reasons to facilitate restricted or free folding
    (for touch and cloth based user interfaces)
- Other findings
  - Prospective improvements
    (for InformationSense)
  - Future use cases
    (for InformationSense)

5.3 Results

Various measurements where carried out in course of the study. Subjective as well as objective information was gathered. A Kolmogorov-Smirnov Test showed that the collected data was not normally distributed. Due to this, *nonparametric tests* were utilized to analyze the material further.

This section provides an overview of the studies results. Participant related information is supplied. Subsequently, the gathered data in regard to users *performance*, devised *strategies*, conducted *interactions*, participants *workload* and their *preferences* is elaborated. Also some *other findings* in relation to future improvements and prospective use cases for flexible cloth displays are presented.

[13]Mayring [73] differentiates the three fundamental forms of *summary*, *explication* and *structuring* to interpret text material. While the aim of the analysis was to extract particular aspects, related to given research questions and hypothesis, *structuring* was applied.

5.3.1 Participants

18 persons took part in the study. All of them were students, 10 male, 8 female. They were aged between 19 and 26 (M = 21.9, SD = 2.3) and mainly recruited from the two local universities (*University Konstanz* and *HTWG Konstanz*). Only two of the participants studied computer science. The others were matriculated in various different subjects, ranging from other technical majors like electronics, mechanical engineering and civil engineering to subjects like humanities, architecture, teaching and artistic sciences. None of the participants was physically impaired or color blind. 15 of them were right, two left handed and one stated that he can work with both hands equally good. While the tables, used for the systems, were for each participant of equal height, their body size was recorded to rule out undesired influences. It ranged between 157cm and 198cm (M = 176.9cm, SD = 10.2). The participants level of technical knowledge was inquired with a five-point likert scale (M = 0.2, SD = 0.9; -2 = no knowledge, 2 = high level of knowledge). Another likert scale was utilized to determine their level of experience when interacting with multi-touch displays with a screen size greater or equal 30" (M = -1.4, SD = 0.9; -2 = no experience, 2 = high level of experience). None of the participants remarked to have a lot of experience with large multi-touch devices. In case they had any, they mostly knew them from museums or exhibitions.

5.3.2 Performance

The task completion time for the interface SpaceFold without zoom (M = 21.9sec, SD = 14.9) was lower than for SpaceFold with zoom (M = 22.3sec, SD = 14.0) and InformationSense (M = 24.6sec, SD = 18.2). A Friedmanns ANOVA showed a significant main effect between interfaces (χ^2 = 7.81, p = 0.02). Posthoc, Wilcoxon Signed-Rank Tests in line with Bonferroni Correction were applied to determine effects between interface pairs. The comparisons indicated that the median task completion time for SpaceFold without zoom, was statistically significantly lower than the one for InformationSense (Z = -2.58, p = 0.03). The differences between the other interface pairs were not significant ($p > 0.05$).

Another Wilcoxon Signed-Rank Test revealed that the median task completion time for short distance tasks was statistically significantly lower than in case the objects lay far apart (Z = -19.2, $p < 0.01$). The Friedmanns ANOVA was utilized to find out if there are relevant differences in task completion time between the interfaces in regard to short and far distance tasks. The results indicated no significant effects when objects which lay close to one another, had to be compared ($p > 0.05$). On the other hand, for far distance tasks the test showed significant differences (χ^2 = 14.6, $p < 0.01$). In this case, the task completion time for SpaceFold with zoom (M = 28.4sec, SD = 14.8) was lower than for SpaceFold without zoom (M = 28.5sec, SD = 16.0) and InformationSense (M = 34.0sec; SD = 19.6). Again a pairwise comparison with Wilcoxon Signed-Rank Tests was carried out. It revealed that the median task completion time for InformationSense was significantly higher than for both versions of SpaceFold (with zoom: Z = -4.38, $p < 0.01$; without zoom: Z = -3.76, $p < 0.01$). The comparison of the two SpaceFold based interfaces indicated no significant difference ($p > 0.05$).

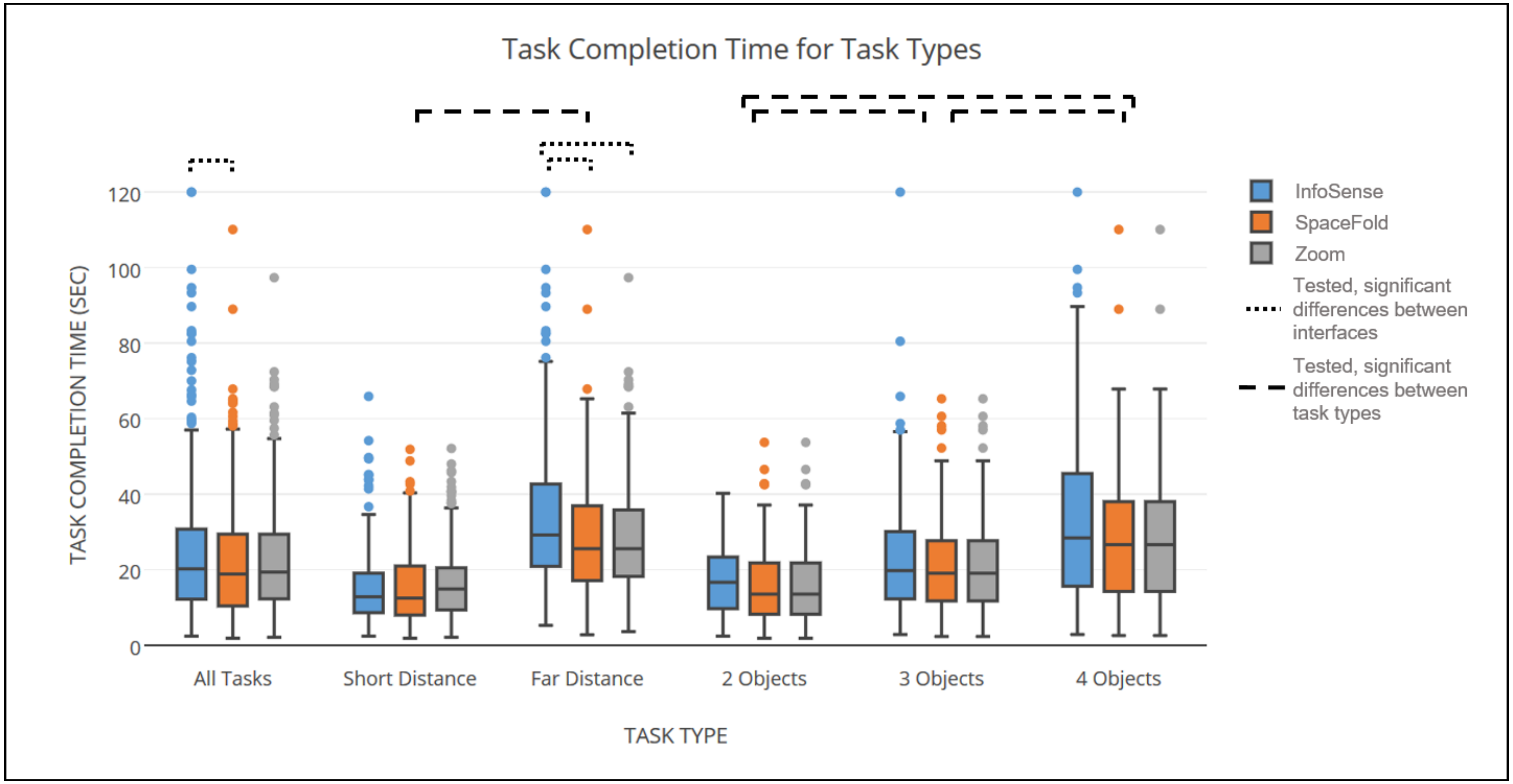


Figure 5.12: Task Completion Time for Task Types. Task completion time for the three different interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)* in relation to different task types. Tested, significant differences are highlighted with dotted lines.

Eventually the impact of the tasks complexity in relation to participants completion times was examined. A Friedmanns ANOVA showed that there is a significant difference in task completion time for different amounts of circle objects ($\chi^2 = 236.69$, $p < 0.01$). The task completion time for two objects was lowest ($M = 16.1$sec, $SD = 9.0$), while tasks with three ($M = 22.3$sec, $SD = 13.8$) and four circles ($M = 30.5$sec, $SD = 19.3$) took participants longer. Post hoc conducted Wilcoxon Signed-Rank Tests revealed that the differences between all three conditions are significant (all $p < 0.01$).

Figure 5.12 illustrates the task completion times in regard to the different task types.

5.3.3 Search & Comparison Strategies

During the interview, it was inquired if participants utilized different strategies for solving the search & comparison tasks when working with each of the three user interfaces. In case they did, they were asked to describe them stepwise. Table 5.1 depicts the different approaches they named. In brackets, the amount of participants who stated the strategy is provided. Some participants applied more than one strategy for the same interface. For these cases, the count, reflecting the number of participants which worked with an approach, was raised for both strategies. For each interface a main strategy, which was utilized by at least 50% of the participants, could be identified. It is always the topmost strategy in a systems listing (highlighted in light blue).

	search & comparison strategies	
InfoSense	• search (corners) by moving cloth, fold, compare	(11)
	• chaotic: deform cloth so that circles are visible, compare	(3)
	• search one "start circle" by moving cloth, than search the remaining by folding, compare	(2)
	• search by moving cloth, memorize circle colors, (almost) no folding	(2)
	• search by moving cloth, memorize circle positions, (center cloth on table), fold, compare	(2)
	• no strategy, sometimes memorizing	(1)

Table 5.1: Identified Search & Comparison Strategies. Different search & comparison strategies were identified for the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*. The number of participants which named the strategy is given in brackets behind each statement. For each interface a main strategy was identified. It is highlighted in light blue.

	search & comparison strategies	
SpaceFold	• search by panning, fold, (adjust), compare	(9)
	• fold a lot at the beginning, search in folds, (adjust folds), compare	(4)
	• search one "start circle" by panning, than search the remaining by folding, compare	(2)
	• search by panning, memorize circle positions, (center map), fold, compare	(2)
	• search by moving cloth, memorize circle colors, (almost) no folding, move map forward and backward to compare remaining circles with memorized colors	(2)
	• chaotic: just fold/unfold (based on luck), compare	(1)
	• search (corners) while folding, compare	(2)
Zoom	• zoom out, (think about folding strategy), fold, zoom in, compare	(13)
	• zoom out, search cluster of circles, zoom in, memorize circle colors, (almost) no folding, pan forward and backward to compare	(2)
	• fold a lot at the beginning, search in folds, (adjust folds), compare, (almost) no zooming used	(1)
	• zoom out, search circles, zoom in, fold, compare	(1)
	• search, fold, compare	(1)

Table 5.1: Identified Search & Comparison Strategies. Different search & comparison strategies were identified for the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*. The number of participants which named the strategy is given in brackets behind each statement. For each interface a main strategy was identified. It is highlighted in light blue.

5.3.4 User Interactions

The analysis of video recordings and log files revealed information in regard to interactions which were utilized by participants while conducting the search & comparison tasks. The amount of interactions was highest for InformationSense (M = 6.1, SD = 5.4). Participants interacted less when working with each of the SpaceFold interfaces (without zoom: M = 3.4, SD = 2.9; with zoom M = 4.0, SD = 2.8). A Friedmanns ANOVA indicated a significant main effect between the interfaces ($\chi^2 = 72.1$, $p < 0.01$). Posthoc, Wilcoxon Signed-Rank Tests revealed a significant difference between all three conditions ($p < 0.01$). Figure 5.13 displays the total amount of interactions which were conducted with each user interface.

In relation to the sub research question SQ3, described in Section 5.1, it was deemed of interest if participants made use of the cloth surfaces real world properties or if they mainly applied interactions which are also facilitated by

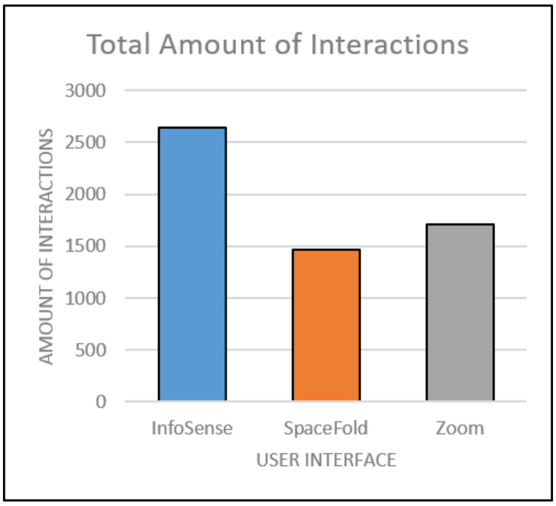


Figure 5.13: Amount of Interactions between Interfaces. The total amount of interactions which was carried out by all participants for each of the three interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*. With SpaceFold (1461) a lower amount of interactions was conducted than with Zoom (1714) or InformationSense (2639).

the restricted SpaceFold based interfaces. On this ground, the interactions were divided in the following categories for further analysis:

- Navigation interactions:
    - Pan / move cloth: hand on top of cloth
    - Zoom
    - Supported only by InformationSense (e.g. lift cloth in the air)
- Deformation interactions
    - Supported by SpaceFold / Zoom
    - Supported only by InformationSense (e.g. crumple cloth)
- Fixation interactions (only one interaction type: temporary pin cloth with hand, e.g. by holding it)

Figure 5.14 illustrates the frequency of interactions from each category for the three user interfaces.

Table 5.2 supplies a more fine grained listing. It provides the information how frequently the interactions of the different categories were applied by the participants. The color coding used for the table can be related to the coloring in Figure 5.14.

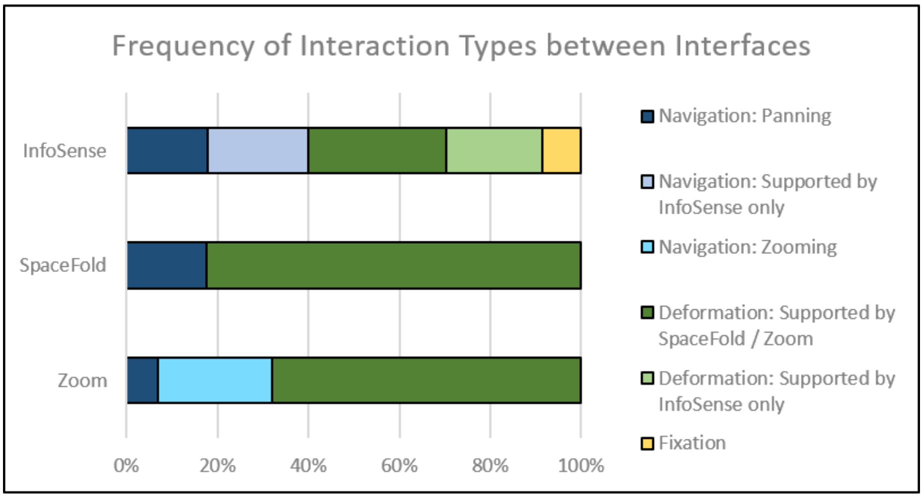


Figure 5.14: Frequency of Interaction Categories between Interfaces. The frequency with which interactions from each of the six categories were utilized for every one of the three user interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*.

		frequency of interaction (%)		
		InfoSense	SpaceFold	Zoom
Navigation	pan / move cloth: hand on top of cloth	17.89	17.59	6.83
	zoom	-	-	25.26
	rotate	15.57	-	-
	move cloth: grab cloth border	3.22	-	-
	move cloth: one hand grab cloth border, one hand on top of cloth	2.80	-	-
	lift cloth in air	0.53	-	-

Table 5.2: Frequency of Interactions between Interfaces. The frequency with which each interaction from the six categories was utilized for every one of the three user interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*.

		frequency of interaction (%)		
		InfoSense	SpaceFold	Zoom
Deformation	create fold: vertical	3.52	16.29	14.76
	create fold: horizontal	0.76	7.19	7.70
	create fold: cross	-	7.46	4.67
	modify fold	5.95	23.75	18.61
	unfold	20.05	27.31	21.94
	merge	-	0.41	0.23
	create fold: diagonal	10.69	-	-
	create fold: push cloth together from two sides	2.99	-	-
	create fold: on top of existing fold (stack folds)	1.36	-	-
	create fold: put hand under cloth and fold	0.53	-	-
	create fold: fold cloth under itself	0.49	-	-
	crumple cloth	2.31	-	-
	look under existing folds (fold them over)	1.78	-	-
	grab circle and place it somewhere else	1.10	-	-
Fixation	hold cloth in position	8.45	-	-

Table 5.2: Frequency of Interactions between Interfaces. The frequency with which each interaction from the six categories was utilized for every one of the three user interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*.

As can be observed in the table, nine different interactions for navigation, deformation and fixation, which require the high degrees of freedom provided by the InformationSense system, were identified. Figure 5.15 gives an overview, how often these real world interactions were utilized in contrast to interactions which are in general facilitated by the SpaceFold based interfaces, as well. The total amount of interactions from each category in relation to the different task types is visualized. One can see that participants utilized the high degrees of freedom supplied by the textile interface, independent of the task type. Further, it is possible to perceive that the number of fold interactions decreased when the task complexity rose.

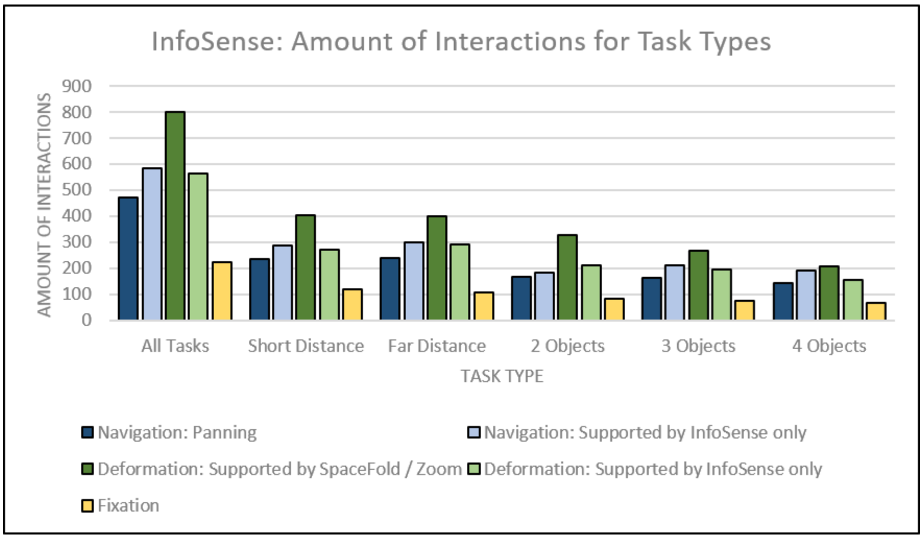


Figure 5.15: InformationSense - Amount of Interactions for Task Types. The amount of interactions from each category in regard to the different task types is supplied. It is possible to see that the participants made use of the cloth surfaces high degrees of freedom for interaction, independent of the task type. Additionally, the diagram shows that the number of folds, participants created with the InformationSense system, decreased for a higher task complexity.

5.3.5 Workload

Figure 5.16 depicts participants subjective workload rated with the the NASA TLX. The overall workload as well as the scores for the six separate dimensions is illustrated. The Friedmanns ANOVA was applied to find out if there are significant differences between the interfaces for any of the questionnaires dimensions. The tests solely suggested significant effects for the scales *Temporal Demand* (χ^2 = 11.2, p < 0.01), *Effort* (χ^2 = 9.1, p < 0.02) and the *Overall Workload* (χ^2 = 9.0, p < 0.02). All other dimensions indicated no relevant differences (p > 0.05). Posthoc pairwise comparisons were carried out. The Wilcoxon Signed-Rank Tests revealed that SpaceFold with zoom was scored significantly better than InformationSense for all three dimensions which showed an effect (all p <0.01). All other pairwise comparisons indicated no significant effects (p > 0.05).

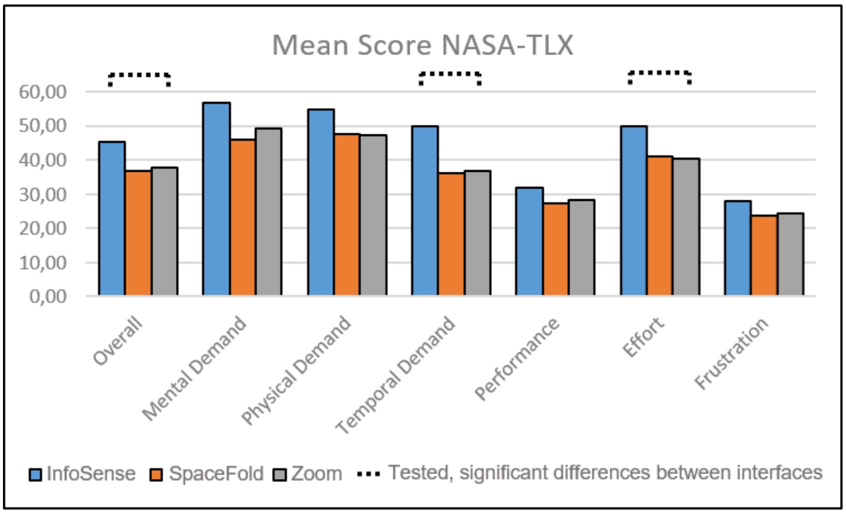


Figure 5.16: Mean Score NASA TLX. The NASA TLX mean score for the different dimensions in regard to the three interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)* is displayed.

5.3.6 User Preferences

In the following the studies results in regard to users preferences between the three different *interfaces*, as well as their subjective opinions about *folding restrictions*, in relation to the touch based systems and the InformationSense interface, are elaborated.

Preferences between Interfaces

Friedmanns ANOVA was utilized to determine effects between the different user interfaces for each of the UEQs dimensions. The *Attractiveness* scale showed no significant effects ($p > 0.05$). On the other hand, Friedmanns ANOVA indicated significant differences for the ratings of the pragmatic qualities *Perspicuity* ($\chi^2 = 12.7$, $p < 0.01$), *Efficiency* ($\chi^2 = 10.8$, $p < 0.01$) and *Dependability* ($\chi^2 = 6.1$, $p = 0.48$). Post hoc comparison with Wilcoxon Signed-Rank Tests revealed that SpaceFold with zoom was rated significantly better than the InformationSense interface for all three dimensions. SpaceFold without zoom was only for the scale *Efficiency* scored significantly higher than InformationSense. Between the two touch based interfaces solely the dimension *Perspicuity* showed a significant difference. The system which supports zooming was rated higher. When looking at the hedonic qualities, the Friedmanns ANOVA also indicated significant effects between the interfaces for the dimensions *Stimulation* ($\chi^2 = 13.6$, $p < 0.01$) and *Novelty* ($\chi^2 = 15.6$, $p < 0.01$). Post hoc pairwise comparisons showed that InformationSense was rated significantly better for both scales when compared to SpaceFold with and without zoom. The results of the Wilcoxon Signed-Rank Tests are displayed in Table 5.3. Figure 5.17 provides an overview of the rated mean scores for *Attractiveness*, *Pragmatic Qualities* and *Hedonic Qualities* between interfaces.

		Pragmatic Qualities			Hedonic Qualities	
	Attrac-tiveness	Pers-picuity	Efficiency	Depend-ability	Stim-ulation	Novelty
$M_{InfoSense}$	1.7	1.4	0.7	0.4	2.0	2.7
$M_{SpaceFold}$	1.4	1.8	1.4	1.2	1.0	1.3
M_{Zoom}	1.5	2.1	1.5	1.1	1.1	1.4
InfoSense - SpaceFold		Z = -1.74 $p > 0.05$	Z = -3.00 $p < 0.01$	Z = -2.24 $p > 0.05$	Z = -3.22 $p < 0.01$	Z = -2.90 $p < 0.02$
InfoSense - Zoom		Z = -3.00 $p < 0.01$	Z = -3.13 $p < 0.01$	Z = -2.78 $p < 0.01$	Z = -3.22 $p < 0.01$	Z = -3.19 $p < 0.01$
SpaceFold - Zoom		Z = -3.00 $p < 0.01$	Z = -0.29 $p > 0.05$	Z = -0.03 $p > 0.05$	Z = -0.93 $p > 0.05$	Z = -1.12 $p > 0.05$

Table 5.3: Wilcoxon Signed Rank Test - UEQ. Pairwise comparison of the UEQs dimensions for which a Friedmanns ANOVA indicated significant effects. The combinations which showed a significant difference, for two of the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*, are highlighted in light blue.

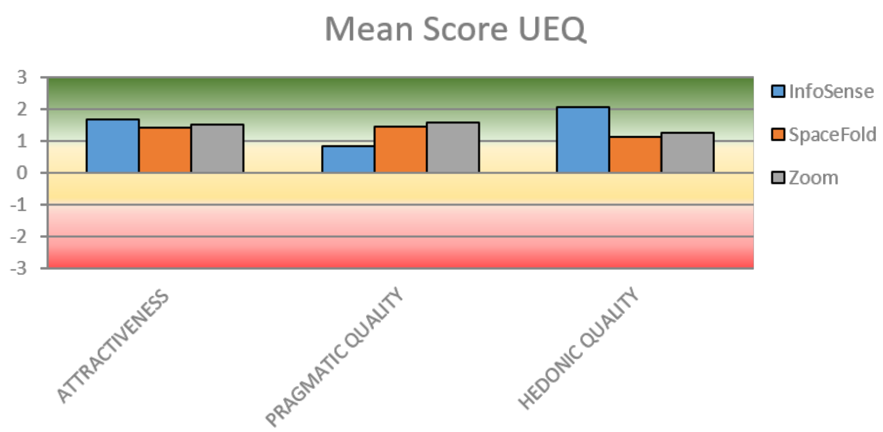
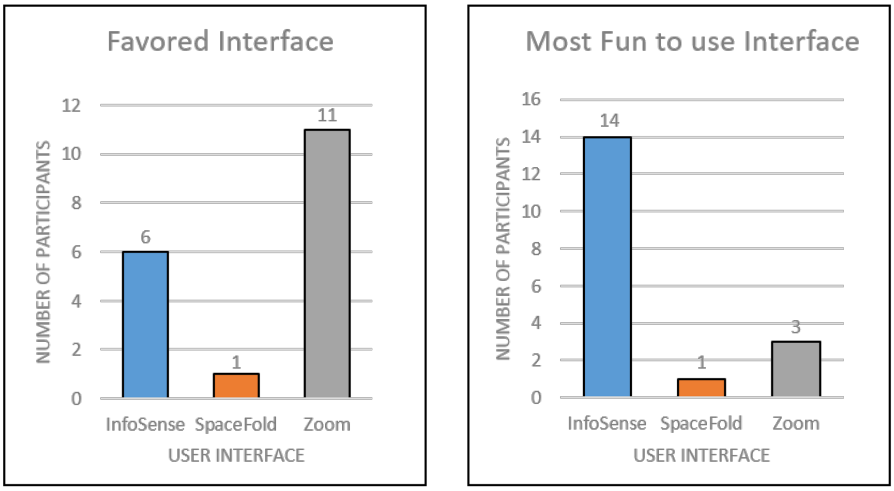


Figure 5.17: Mean Score UEQ. Provides an overview of the mean score, the three interfaces, *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*, received for the UEQs three main scales *Attractiveness*, *Pragmatic Quality* and *Hedonic Quality*.

In course of the semistructured interviews, participants were asked to name the interface they favored for the completion of the tasks (measure, related to pragmatic qualities). Figure 5.18a illustrates that most participants preferred SpaceFold with zoom. Subsequently, it was inquired which interface the participants determined the most fun to use (measure, related to hedonic qualities). In this case, the InformationSense system scored highest (see Figure 5.18b).



(a) (b)

Figure 5.18: Preferences User Interfaces. (a) Amount of participants which rated each of the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)* as their favored. (b) Amount of participants which scored each of the interfaces the most fun to use.

The participants were also queried about the benefits and shortcomings they saw in working with the different user interfaces. Their statements are listed in Table 5.4. The number of participants which mentioned a property is provided in brackets.

		benefits			shortcomings	
InfoSense	+	large degree of freedom, e.g. rotation	(11)	-	technical limitations, e.g. detection errors	(16)
	+	modern, new	(11)	-	cloth is to inflexible, e.g. to thick, desired folds sometimes not possible	(9)
	+	haptic	(8)	-	no zoom	(5)

Table 5.4: Benefits & Shortcomings of User Interfaces. The number of participants which named the advantageous or disbeneficial property, for each of the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*, is given in brackets behind every statement.

	benefits		shortcomings	
InfoSense	+ human, real	(7)	- complex, exhausting	(4)
	+ beautiful, fascinating	(5)	- cloth is to heavy	(3)
	+ practical, e.g. easy to estimate if a circle gets invisible when folding	(5)	- long training period required	(2)
	+ playful	(4)	- difficult to use, e.g. "I have only two hands"	(2)
	+ good orientation, e.g. spatial relation to cloth border	(3)		
	+ feels good	(3)		
	+ faster panning than with touch	(1)		
	+ faster folding to bring circles closer together than with touch	(1)		
SpaceFold & Zoom	+ circles visible in folds	(6)	- technical limitations, e.g. fingers not detected	(9)
	+ concept familiar, e.g. tablets or smartphones	(5)	- no rotation	(6)
	+ simple to use, e.g. easier to create many folds than with InfoSense	(2)	- feels "technical", no haptic experience	(3)
	+ fluent	(2)	- tiring, uncomfortable	(2)
	+ crossfolds	(1)	- hard to estimate if circles are "swallowed" when creating a fold	(2)
SpaceFold	+ simple	(1)	- no zoom	(5)
	+ pleasant	(1)	- complex, high mental demand, e.g. hard to fold in correct way	(3)
			- weakest system	(2)
Zoom	+ zoom, e.g. overview, faster search	(18)	- min distance between fingers to fold	(2)
	+ best usability	(3)	- feels high pressure to deliver a result	(1)

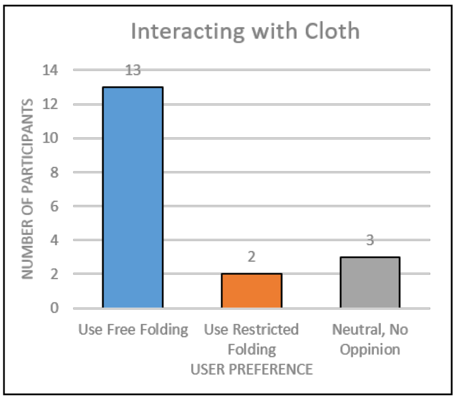
Table 5.4: Benefits & Shortcomings of User Interfaces. The number of participants which named the advantageous or disbeneficial property, for each of the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*, is given in brackets behind every statement.

	benefits	shortcomings
Zoom	+ faster, takes fewer steps to arrive at the goal than with the other interfaces (3) + low mental demand (2) + highest feel of success (1)	

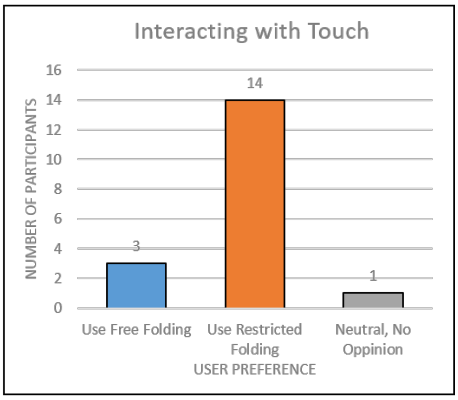
Table 5.4: Benefits & Shortcomings of User Interfaces. The number of participants which named the advantageous or disbeneficial propert, for each of the interfaces *InformationSense (InfoSense)*, *SpaceFold* and *SpaceFold with zoom (Zoom)*, is given in brackets behind every statement.

Free Folding and Restricted Folding

During the interviews the participants were also asked if they would have wished that the InformationSense interface only facilitates restricted folding[14] or if they liked it more to fold the cloth freely. Like shown in Figure 5.19a most participants stated that they want no fold restrictions when interacting with the textile surface. Further, it was inquired if the participants missed the possibility to fold freely with the SpaceFold based systems or not. Most of them stated that they liked the restricted folding on the touch table and do not wish to fold freely with the interface (see Figure 5.19b). The reasons the participants gave for their answers are depicted in Table 5.5.



(a)



(b)

Figure 5.19: Free Folding or Restricted Folding? (a) Amount of participants which preferred free, respectively restricted folding with the *cloth* or had no opinion. (b) Amount of participants which preferred free, respectively restricted folding with the *touch based interfaces* or had no opinion.

[14] As an example, a grid of plates, weaved inside the textile, which limits the fold freedom to solely horizontal or vertical folds, was mentioned.

	use free folding	use restricted folding
Cloth	• no restrictions, more possibilities, e.g. diagonal folds or small partial folds (4) • faster, less worksteps necessary (3) • intuitive, natural (2) • low mental demand, less need to think about "how to fold" (1) • better for persons with a good spatial imagination (1)	• restrictions make interacting easier (2) • free folding causes a loss of overview (1) • free folding is slower, takes more time (1) • better for persons with a bad spatial imagination (1)
Touch		• free folding problematic on touch, e.g. might result in accidental diagonal folds, unexpected shifts of circles, overstretch users or feel unintuitive (3) • easily keep an overview (2) • low complexity, simple to understand (2) • the display is "only 2d" (1)

Table 5.5: Reasons to use Free respectively Restricted Folding. Reasons the participants gave for free, respectively restricted folding with the cloth and touch based interfaces. The number of participants which named a property is given in brackets behind each statement.

5.3.7 Other Findings

As part of the interviews, participants were queried about improvements for the cloth based interface and future use cases for flexible displays. Their replies are summarized in Table 5.6 (improvements) and Table 5.7 (future use cases). The number of participants who suggested an improvement or use case is provided in brackets behind the statements.

improvements for cloth based interfaces	
• provide overview, e.g. zoom	(4)
• touch	(3)
• write on cloth	(3)
• use reverse of cloth to display information	(2)
• visible cues, e.g. to find offscreen circles	(2)
• rubber grip on table or magnetic surface, e.g. to build "high" folds respectively fixate the textile somewhere	(2)
• show info if circles lie in folds	(1)
• overblend measurement scale when folding, to know how far one folds when interacting with a map which uses a specific scale, e.g. 10 kilometers	(1)
• voice input for search	(1)
• loops on cloth to facilitate lifting	(1)

Table 5.6: Improvements for Cloth based Interfaces. The number of participants which named the improvement is given in brackets behind each statement.

future use cases for cloth based interfaces	
• maps, e.g. city plan, animated construction plan	(6)
• games (for kids), e.g. pong (control by movement) or strategic games	(5)
• creation and construction of landscapes, e.g. architecture	(3)
• dynamic whiteboard, e.g. presentations or meetings	(2)
• replacement of smartphones, tablets	(2)
• fashion design, e.g. directly write on cloth	(1)
• teaching	(1)
• picture gallery	(1)
• military strategies	(1)
• span it over objects and adjust texture dynamically, e.g. over a car to change the paint dependent on a customers wishes	(1)

Table 5.7: Future Use Cases for Cloth based Interfaces. The number of participants which named the future use case is given in brackets behind each statement.

5.4 Discussion

In the previous section of this chapter, the studies results were elaborated. This section discusses the presented data concerning users *performance*, *search & comparison strategies*, *interactions*, *workload* and *preferences*, in order to determine answers for the specified research questions and verify the stated hypothesis. At the end of the section a *conclusion* is provided.

5.4.1 Performance

Solely two participants stated that InformationSense was faster in relation to some specific interactions than the other interfaces. One argued it was preferable in terms of panning performance (S03) and the other that it facilitated faster fold interactions to bring circles closer together (S02). Like shown in Section 5.3.2, when *all tasks* are considered, there was a significant difference in performance between the two interfaces SpaceFold without zoom and InformationSense. Participants were faster when they interacted with SpaceFold without zoom. In regard to *far distance tasks* the measured task completion times indicated that participants worked significantly quicker when utilizing any of the touch based interfaces in comparison to InformationSense. Three of the participants explicitly stated that working with the zoomable version of SpaceFold was *fastest* (S03, S06, S09). One of them reasoned that it took her *fewer steps* to arrive at her goals than with the other interfaces (S03). All participants remarked that the zoom functionality was advantageous (S01-S18). It supplied them with an *overview* and supported *quicker searching* than feasible with the other systems. One commented during her work:

> *"That is now really an advantage that I can zoom. I can see them [the circles] faster!"* (S01, observation)

Another benefit of both SpaceFold interfaces was that circles, situated in folds, were displayed in an abstract form (S02, S04, S09, S11, S15, S17). Especially the work on far distance tasks, which require more searching, was highly facilitated by the additional computational power.

The results in terms of subjective workload indicated that participants perceived the *Temporal Demand* closely aligned to the task completion times which were measured for far distance tasks. Both touch interfaces were deemed quicker than InformationSense. However, participants solely rated the zoomable version of SpaceFold significantly faster than the InformationSense interface.

As can be expected, participants speed decreased significantly when the amount of objects was raised. This was the case when moving from two to three and from three to four circles per task.

One of the research interest was to determine how performance is affected by trading computational power against realism and vice versa, when designing interfaces. The hypothesis was that the more powerful SpaceFold interfaces would outperform the InformationSense system.

The hypothesis was confirmed for *far distance tasks*. Participants had a significantly lower task completion time when conducting these tasks with the touch based interfaces than in case they worked with the less powerful InformationSense system. Participants statements in the interview indicated that the digital functionalities, to zoom the interface for an overview and to perceive circles lying in folds, facilitated their workflow and especially sped up their search for the round objects. However, in regard to *short distance tasks* the hypothesis was disproved. No significant amount of performance was gained through the additional digital power. A likely reason is, that these tasks often did not require participants to get an overview by zooming or to carry out much folding. All of the circles were positioned within a smaller region in the virtual data space. This might made search interactions in many cases unnecessary.

5.4.2 Search & Comparison Strategies

As mentioned in Section 5.3.3 it was possible to identify different strategies which participants applied in order to complete the search & comparison tasks. For each interface a *main strategy*, which was utilized by at least 50% of the participants, could be determined. These are:

- **InformationSense:** Search (corners) by moving cloth, fold, compare.
- **SpaceFold without zoom:** Search by panning, fold, (adjust), compare.
- **SpaceFold with zoom:** Zoom out, (think about folding strategy), fold, zoom in, compare.

Upon comparison of the three main strategies one can easily see that the approach participants utilized for InformationSense is nearly equal to the steps they took when working with SpaceFold without zoom. The third strategy also solely differs in terms of search. The panning was exchanged against the zoom functionality. Figure 5.14 suggests that participants used zooming as a very frequent navigation interaction[15].

Another interesting finding is that, although users sometimes interacted chaotic, most strategies indicate a structured work process for either of the interfaces. Even when participants interacted with the cloth they tried to organize their workspace. This is also reflected by the extracted interactions. Structured folding was observed far more frequently than chaotic behavior like e.g. crumpling. Participants often applied vertical respectively diagonal folds or organized the cloth with interactions like "stacking" folds on top of other existing ones.

The research question related to this topic was, how strategies to pursue search & comparison tasks differ between interfaces which facilitate interactions in reality and systems which solely simulate such behavior.

The conducted study provided a set of strategies for each of the utilized interfaces. The main strategies which were applied by participants were determined to be nearly equal. Overall, although the interactions conducted with

[15]The interaction was even logged more often than panning. However, it has to be considered that multiple movements of the digital landscape were evaluated as one pan interaction when no other interactions were in between. In case the pan interactions would have been counted each time separately when a participant changed the direction while moving the digital landscape, the result might differ.

the touch based systems were often different from the ones used with InformationSense, the utilized strategies seem closely related. Only for SpaceFold with zoom, the described steps vary stronger while users frequently utilized the additional functionality of zooming to facilitate their search process.

5.4.3 User Interactions

Users conducted significantly more interactions with InformationSense than when working with the other interfaces. Figure 5.15 depicts the amount of interactions for each of the defined interaction categories in relation to the different task types (all tasks, far distance, short distance, two objects, three objects, four objects). The bar chart reveals that especially the number of fold interactions decreased when the task complexity was raised. In the interview multiple participants stated that the cloth was to inflexible (S02, S03, S06, S07, S09, S10, S13, S15, S16). This problem in line with the technical limitations might made folding more complex when the amount of circles was higher. After an unsuccessful fold attempt with four circles, one participant stated:

> *"Now I might have to memorize them [the circle positions], yet."*
> (S01, observation)

The graphic also shows that participants made use of the physical properties provided by the cloth and that they did so independent of the task type. Although the participants wished themselves an even more flexible cloth surface, eleven of them mentioned in the interview that they already appreciated the high degrees of freedom they could use when manipulating the given textile object *in* reality (S02, S07-S10, S12-S15, S17, S18). One participant said:

> *"With this material [cloth] I have it [the ways to interact with it] in my own hands. Thats because I can manipulate and deform it as I want and my interactions are transfered one to one."*
> (S18, interview)

Many of the interactions which were applied by participants are familiar from the real world. They utilized their pre-existing knowledge. For example, most humans are aware of the possibilities to push a textile together to create a fold in the middle, crumple it, lift it in the air, grab it on its border(s) for movement or flip existing folds over to look under them. The last of the mentioned interactions shows how power was traded for reality in regard to the InformationSense system. Instead of instantly perceiving circles in folds, participants had to physically flip them over to determine if one or multiple of the round objects lie hidden below. One participant proposed to add more power to the InformationSense system and show circles which are situated in folds more directly in the future (S09). Another interaction which made use of the textiles physical properties was the temporary fixation of the cloth or parts of it by participants through pressing it on the table or grabbing it with their hand(s). Like shown in Table 5.2, the interaction was very frequently utilized (8.45% of all interactions were fixations). However, one of the participants mentioned the problem that he had only two hands to work with the cloth surface (S14). When one hand was used to fixate part of the textile, participants were limited in their capabilities to conduct further interactions. Two of them suggested to fixate the cloth temporarily by applying a rubber grip on the table (S10) or making the textile magnetic (S17). This would free both hands for subsequent interactions.

One of the posed research questions addressed the issue, if humans make use of interactions which are only supported by an interface which facilitates high degrees of freedom for manipulation in the real world or if they utilize such a system in a similar manner as restricted, less physical interfaces.

The studies results indicated that participants frequently manipulated or moved the textile interface *freely* in reality. According to their statements, they welcomed the high degrees of freedom which were provided by the cloth. Multiple of their interactions were based on humans pre-existing knowledge from the real world. Nevertheless, the analysis also showed that the participants deemed the used textile to inflexible. It might be beneficial to utilize a different material in the future. Further, the results revealed that it could be advantageous to enhance the textile interface with more digital power. Although this would probably make the interface slightly less realistic, it might facilitate users work greatly if they could directly perceive content situated in folds or fixate parts of the cloth temporarily to use both hands for further interactions.

5.4.4 Workload

The subjective overall workload of InformationSense was significantly higher than for the zoomable SpaceFold interface (see Section 5.3.5). In regard to *Temporal Demand* participants scored both SpaceFold interfaces better than InformationSense, while only SpaceFold with zoom was rated significantly higher. As mentioned in Section 5.4.1 this confirms the results of the tasks completion time measurements for *far distance tasks*. Participants performed for these tasks significantly faster when they worked with the touch interfaces. The identified likely reason for this is that the SpaceFold systems provide users with more digital powers, which especially can speed up their search process. The interface with zooming was deemed even more powerful than the version without. Participants also subjectively perceived the *Effort* for working with InformationSense significantly higher than with the zoomable SpaceFold interface. This result relates to the outcome of the UEQ. The participants rated the *Pragmatic Quality* for SpaceFold with zoom significantly better than for InformationSense. Four of the participants stated during the interview that they found interacting with the textile complex or exhausting (S03, S05, S14, S16). Their main reasons were that the cloth could not be fixated without loosing one hand for further interactions (S14) and that technical limitations had a negative impacted on their workflow (S03, S05, S16). The issue of technical limitations was also mentioned by various other participants (S01, S02, S04, S05, S07-S13, S15, S17, S18).

The discussed factors relate to the research question, how subjective workload might be affected by the support of interactions in the real world, in contrast to the sole emulation of realistic processes. The assumption was that users perceive the subjective workload for all of the three interfaces equally high.

The hypothesis was disproved. Participants felt a significantly higher workload when interacting with InformationSense. The main identified reasons are that the touch interfaces are more powerful, the cloth lacks an option for temporary fixations and problems which occurred due to technical limitations.

5.4.5 User Preferences

One of the defined research questions was, if users prefer interfaces which are based on interactions in or like the real world when they conduct search & comparison tasks and what they perceive as disadvantages and benefits. Four related hypothesis were defined. They concern the interfaces pragmatic and hedonic qualities, as well as the difference between free and restricted folding on the touch screen respectively with the cloth based system. The different hypothesis are discussed in the following.

Pragmatic Quality

Related to the interfaces pragmatic quality, most participants declared the system SpaceFold with zoom as their favorite for the conduct of the search & comparison tasks. The results of the UEQ also showed that participants rated the pragmatic quality for SpaceFold with zoom significantly higher than for InformationSense, in all three of the questionnaires related dimensions (*Perspicuity*, *Efficiency*, *Dependability*). Further, the answers to the NASA TLX confirmed that SpaceFold with zoom was perceived as very efficient. According to the UEQ Handbook the scale *Efficiency* states if *"users can solve their tasks without unnecessary effort"* [95]. The dimension *Effort* of the NASA TLX was scored significantly better for the zoomable touch system than for InformationSense. The main reason that the interface was rated highest in regard to pragmatic quality, is probably that the zoom functionality, as well as the possibility to directly see content situated in folds, is very powerful. Like described in Section 5.4.1 the digital functionalities aided participants especially when they searched the circle objects. Further, participants mentioned that SpaceFold with zoom required a low mental demand (S11, S14). One person even stated that he had the highest feeling of success when working with the system (S13).

SpaceFold without zoom was also rated significantly better in terms of *Efficiency* than InformationSense. Although the interface facilitates no zooming (S01, S03, S07, S09, S11), it was still more powerful while people could perceive circles which lay inside of folds in an abstract form (see Section 5.4.1). Two participants said that they conceived the interactions with both touch interfaces as fluent (S11, S14). Others argued the work felt familiar from their experiences with smartphones and tablets (S05, S10, S11, S13, S16).

Even though most participants stated that SpaceFold with zoom was their favored interface, still one third of them preferred InformationSense. Five participants mentioned that some of the InformationSense systems properties were practical (S02, S03, S05, S06, S18). Three said that the interface supplied a good orientation[16] (S01, S03, S15). However, participants also found the cloth not sufficiently flexible (see Section 5.4.3) and missed the possibility to zoom (S01,

[16]For example, while it was possible to relate the textiles border to positions on the cloth.

S07, S09, S10, S13). A few even deemed the interface complex or exhausting (see Section 5.4.4).

The related hypothesis was that users would prefer SpaceFold with zoom in terms of pragmatic qualities.

The assumption was verified as correct. Participants rated the pragmatic quality for the interface SpaceFold with zoom significantly higher than for InformationSense. They did so when asked after their favorite to conduct the task, as well as when they answered the UEQ and the NASA TLX (*Efficiency*). The main identified reasons are that the functionalities to zoom and to perceive circles in folds were very powerful and improved users efficiency. Further, the interface felt fluent and participants were already familiar with the operation of touch systems. Nevertheless, the InformationSense interface was the favorite system of six participants. To enhance the textile with further digital power in the future might lead to an increase of the cloth surfaces pragmatic quality.

Hedonic Quality

Most of the participants mentioned InformationSense when asked which of the interfaces was the most fun to use. One participant exclaimed during her work with the system:

> *"Thats really cool. I think that [to use InformationSense] is a lot of fun!"*
> (S17, observation)

Another one said:

> *"That [to use InformationSense] was just the most fun for me. It was something new. "*
> (S09, interview)

These statements confirm the results of the UEQ. The hedonic qualities *Stimulation* and *Novelty* were rated significantly better for InformationSense than for the touch based interfaces. Participants argued that they liked the high degrees of freedom provided by the cloth surface (see Section 5.4.3). They also found the interface modern and new (S02-S05, S09, S10, S13-S17), valued its haptic qualities (S02, S05-S08, S13, S17, S18) and described it as natural, human, real or direct (S02, S05, S08, S10, S13, S15, S17). One of them said:

> *"Everything you did with your hands actually happened."*
> (S17, interview)

Further, some participants mentioned that the system was beautiful, refreshing, interesting or fascinating (S07-S09, S13, S14), that it feels good (S01, S06, S08) or that it had a playful character (S01, S09, S10, S13).

In contrast, when looking at the two touch based interfaces, participants argued that the systems felt technical (S08, S12, S13) and tiring respectively uncomfortable (S02, S10). They missed the possibility to rotate the digital data

(S05, S09, S10, S12, S15, S18). Only one participant described the SpaceFold interface without zoom as simple and pleasant (S10).

The hypothesis, that users prefer InformationSense in terms of hedonic quality, was defined before the study was carried out.

The hypothesis was clearly approved. Most participants deemed the textile interface the most fun to use of all three. Also, participants rated the hedonic quality for InformationSense significantly better than for the touch based systems. Further, they mentioned various advantageous properties of the interface which confirmed the results of the UEQ in relation to hedonic quality.

Folding with Cloth

Most people liked it that they could fold the cloth freely when working with the InformationSense system. They appreciated the high degrees of freedom, supplied by the interface (see Section 5.4.3). They argued that free folding provided them with more possibilities like e.g. the creation of small partial folds (S01, S08-S10). Three participants said that they needed fewer worksteps when they deformed the cloth without restrictions (S03, S10, S15). Other arguments to keep the high degrees of freedom were, that it felt intuitive and natural (S04, S05) and that the mental demand was lower while one did not need to think so much about how to place the folds (S10).

Only two participants stated that to restrict the folding would possibly make the interactions easier (S11, S16). Others mentioned the issues that to fold freely can cause a loss of overview (S09) when interacting with the textile and consumes more time (S02).

One participant suggested to utilize free folding for people with a good spatial imagination and restricted folding in case users are less creative (S18).

It was expected that users will not want to restrict folding for the InformationSense system.

The hypothesis can be acknowledged as correct. Most participants valued it that they could fold freely when they worked with the digitally enhanced cloth surface. Only very few argued that restrictions might simplify the operation of the interface.

Folding with Touch

The majority of the participants did not think that free folding would work well in combination with the touch based interfaces. Most of them stated that they would prefer it to keep the restrictions intact. They argued that free folding might result in problems when implemented in the SpaceFold interfaces (S03, S05, S17). According to them it could easily happen that users place diagonal folds by accident or that it feels unintuitive to them to fold freely in a 2 dimensional environment. The participants said that it is easier to keep an overview when folding restricted (S15, S16). They further deemed folding on the touch surface less complex and simpler to understand when only a limited set of possible interactions is supplied (S07, S14). One of them explicitly emphasized that the touch display is only a 2 dimensional surface (S15).

Before the study, the assumption that users will not miss the possibility to place folds freely when working with the SpaceFold interfaces, was established.

The hypothesis was confirmed. Most participants did not state that they would have liked to use free folding with the touch based interfaces. Instead they argued that high degrees of freedom for the placement of folds would probably cause more problems than advantages. Additionally, they appreciated the simpleness of a limited set of interactions when working in 2 dimensional space.

5.4.6 Conclusion

Five sub research questions and six hypothesis were established in Section 5.1. The results of the study were discussed in order to answer the posed questions and verify the hypothesis. In the following, the discussions outcome is summarized and the studies main findings are elaborated. Further, based on the results, it was possible to give four recommendations for the future design of flexible cloth displays.

- **H1:** Users perform *faster* when working with *SpaceFold (with and without zoom).*

  This hypothesis was confirmed for *far distance tasks* and rejected for *short distance tasks.* The task completion times for far distance tasks were significantly lower when participants worked on the touch based interfaces. It was reasoned that the SpaceFold systems computational powers, to gain an overview by zooming and directly perceive circles positioned in folds, strongly facilitated participants when they needed to search for circle objects and thus increased their performance. For short distance tasks often no searching was necessary.

- **H2:** Users perceive the *subjective workload* for all three interfaces *equally high.*

  The assumption was disproved. Participants felt a significantly higher workload when they worked with the cloth based system. It was seen likely that the SpaceFold interfaces additional power probably facilitated users workflow. Also, participants could not fixate part of the textile temporarily and keep interacting with two hands. Another problem were technical limitations. Some participants argued that the technical shortcomings made the work with the augmented cloth complex or exhausting.

- **H3:** Users prefer *SpaceFold with zoom* in terms of *pragmatic quality.*

  This expectation was verified as correct. Participants scored the pragmatic quality for SpaceFold with zoom in the UEQ significantly higher than for the other two interfaces. The interview data in line with the results of the NASA TLX confirmed the UEQs results. Nevertheless, six of the participants rated InformationSense as their favored system for solving the search & compare tasks. The interface was perceived as practical by some participants, but lacked in terms of computational power.

- **H4:** Users prefer *InformationSense* in terms of *hedonic quality*.

  The hypothesis was acknowledged as correct. For most participants it was the most fun to work with InformationSense. They also scored it significantly better in terms of hedonic quality than the other interfaces and appreciated the textiles physical properties, as well as the systems playful character.

- **H5:** Users will *not* want to *restrict* the process of *folding* for the *InformationSense* system.

  This assumption was approved. Most participants liked it that they could fold the cloth freely. Only very few stated that restrictions might have simplified their work with the textile.

- **H6:** Users will *not* miss the possibility to place folds *freely* when they work with the *touch based interfaces*.

  This expectation was deemed accurate. The majority of the participants stated that free folding would probably cause more problems than benefits when applied in context of a 2 dimensional touch surface.

Besides supplying answers to the defined hypothesis, the study results gave insights into strategies and interactions which participants applied when utilizing the different interfaces. For each system a set of approaches was extracted and a main strategy was identified. It was determined that participants approaches for all three interfaces were closely related and that they mostly tried to structure their workspace. Only the strategies for SpaceFold with zoom varied stronger from the ones for the other systems. The reason is that zooming was frequently used by the participants, but not supplied by the other interfaces.

The results of the study indicate that more computational power could improve the InformationSense system strongly in the future. For example, three participants proposed to support *input modalities* like touch (S01, S09, S13). When considering users suggestions in line with the other findings of the study, it was possible to extract four *design recommendations* (DR) for the creation of prospective flexible cloth displays which facilitate the navigation of digital information spaces:

- **DR1:** Use materials which support *high degrees of freedom* for deformation in reality.

  Participants welcomed the high degrees of freedom which were provided by the textile surface. They frequently applied interactions which were based on their pre-existing knowledge of the real world. They also often utilized the physical properties of the cloth and conducted interactions which were not feasible with the touch based systems. They did this independent of the task distance and complexity. The participants even stated that they would have liked the textile to have a *higher degree of flexibility* than the one supplied by the given cloth.

- **DR2:** Facilitate users *orientation* through computational power.

  Only few participants said that they could orientate themselves well when they worked with the cloth object. They mentioned that it was an advantage to know where digital information was positioned in relation to the textiles border. Nevertheless, all of the participants argued that it would have been beneficial for their orientation if they could zoom the virtual data in order to get a *quick overview*. Further, during the interviews, two of the participants suggested to provide additional clues about *offscreen content* (S06, S10) to improve users orientation.

- **DR3:** Provide information about *content situated in folds* through computational power.

  To *directly* supply participants with *information which lies in folds* can facilitate their search for objects in the digital data space. Participants argued that they missed the possibility to perceive content situated in folds when they worked with the InformationSense system. It is considered beneficial to provide users with such additional information in the future.

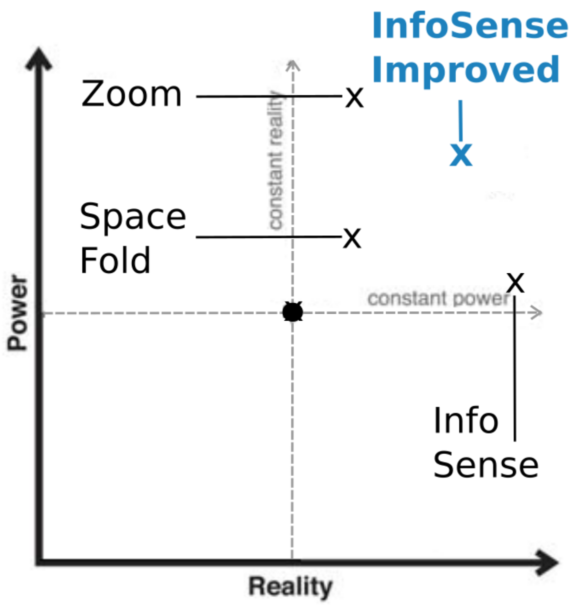


Figure 5.20: Power vs. Reality Tradeoff - Proposed Improvements for InformationSense. It might be beneficial to enhance the InformationSense system by trading a bit of realism for additional computational powers like *a better overview*, the reflecting of *information situated in folds*, *temporary fixations* of the cloth (e.g. through magnetism), the display of hints about *off-screen content* or by facilitating *input modalities* (e.g. touch). The graphic illustrates the estimated placement of the improved cloth based system in the coordinate plane defined by Jacob et al. [46]. For comparability the original position of the three interfaces which where utilized in course of the study is also displayed.

- **DR4:** Allow *temporary fixations* of (parts of) the flexible display through computational power.

  Many participants made use of the possibility to fixate the cloth temporarily with their hands. Some of them suggested to enhance the textile with more computational power in the future. They proposed to facilitate *temporary fixations* which allow user to pin part of the cloth somewhere and keep both hands free for further interactions, e.g through magnetism. This might enable new ways to work with flexible cloth displays.

Three of the four proposed design recommendations suggest to add more computational power to flexible displays in the future. However, to do so might lower the interfaces degree of realism slightly. Figure 5.20 shows were an improved version of InformationSense might be placed in regard to the tradeoff between computational power and reality.

In regard to all of the provided recommendations, further research is necessary to determine how they might be implemented in order to facilitate users work best. Although past scientific work addressed topics like *methods to provide an overview* or *offscreen content visulization* in the context of rigid 2 dimensional devices, it is unclear if the findings are directly applicable to the interaction with deformable screens. Section 6.2.1 provides examples for possible future enhancements of the InformationSense interface.

5.5 Limitations

Multiple participants complained about the technical limitations of the InformationSense system, elaborated in Section 4.3. They were sometimes irritated or annoyed when the projection did not adapt as expected. For example, one of them stated:

> *"Is that an error? [irritated when a circle was not shown due to a detection error]"*
> (S16, observation)

Another participant had the problem that the folded region was to small and thus no data could be mapped. After slightly jolting the textile multiple times, he exclaimed:

> *"Thats always getting black!"*
> (S15, observation)

The touch systems also showed some small technical problems. For example, sometimes the unfolding with doubletap did not work or participants fingers were not detected instantly. However, these shortcomings might be corrected in the future.

Besides the technical limitations, there are also some other factors which restricted the study. They are explained in the following:

- **Realism of task:** Although this lowered the tasks degree of realism, the decision was made to keep it rather easy. According to Hornbæk [39], simple tasks can help to *"capture the essence of what is being investigated"*. The main interest was to determine what the differences are when people work with systems which support interactions in or like the real world. The focus lay on navigation and deformation interactions. Thus, a task, which motivated participants to move and fold the digital data space, was selected. To keep some external validity, it was decided that participants can choose by themselves at what point in time they open all or some previously created folds in the digital landscape. They could also reuse existing folds in subsequent tasks.

- **Validity of performance measures:** The time which participants required to compare the circles before providing their answer was not equal for each of them. Some participants were slower, some faster. This influenced the task completion times. Another factor, which had an impact, was to supply participants with the option to decide by themselves if and when they like to open created folds in the digital landscape. Participants had different starting points for each task. It could sometimes happen that they were "lucky" and the cloth was already folded in the right way from the previous task. If this occurred, their task completion time might be much shorter than the one of other participants. However, to measure performance was not the focus of the study. The aim was to investigate users strategies, interactions and preferences in regard to systems which facilitate interactions in or like the real world. Thus, a higher external validity was preferred over more accurate task completion times.

- **Coding of interaction durations:** Like described in Section 5.2.4, when a participant e.g. panned the interface for a longer duration of time without another interaction or a break in between, solely one pan interaction was coded. No information about how long the different interactions took was considered when evaluating the results.

Chapter 6

Conclusion & Outlook

Section 2.3 introduced six requirements for a system which facilitates the navigation of virtual data in reality. This chapter provides a *conclusion* to which degree the *desired criteria* were *fulfilled* (see Section 6.1). Further, an *outlook*, including future work and use cases, is given in Section 6.2.

6.1 Conclusion - Requirements Fulfilled?

Figure 6.1 illustrates which of the defined requirements are fulfilled by the current implementation. The topmost two desired criteria are fully supported by

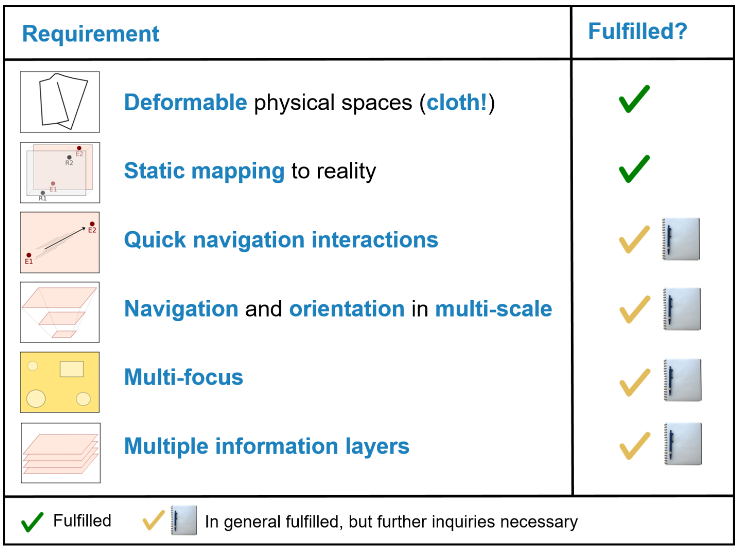


Figure 6.1: Requirements Fulfilled? The two topmost of the listed desired properties are fulfilled. The remaining four requirements are also supported in general. However, further research is needed to determine how fast navigation interactions really are and if the other three properties really fulfill users expectations and facilitate their work.

the implementation. A *deformable* cloth surface was utilized for interactions and visualized output is *statically* mapped on the textile. However, the results of the study indicated, that although participants appreciated the supported high degrees of freedom for deformation, they would have preferred it to have an even more flexible cloth. Thus, it might be of advantage to exchange the textiles material against a more deformable surface in the future. It is in general also feasible to pursue *quick navigation interactions* with the system by physically moving the cloth. Zooming is supplied by the lenses. However, it is unclear how fast user can really navigate through digital data content with the deformable cloth surface and the rigid lens objects, in contrast to other interfaces. In regard to the textile, the study indicated that the overall performance for searching virtual spaces might be improved when users are provided with a better overview (see Section 5.4.1). Nevertheless, to make a clear statement in regard to performance for navigation interactions, it is necessary to research the matter further. The three remaining requirements, to support *navigation and orientation in multi-scale*, *multi-focus* and *multiple information layers*, are also in principal fulfilled through the lenses with buttons. Still, until now, the features were solely implemented. To verify that they really benefit users work and match their expectations, it is necessary to review them in more detail.

6.2 Outlook

As a result of the conducted user study it was suggested to enhance the InformationSense interface with additional computational power in the future (see Section 5.4.6). In relation, four recommendations for the design of prospective flexible displays were given. In the following, some examples for future improvements of the created InformationSense interface are introduced. Also, some prospective use cases for a digitally augmented cloth surfaces are elaborated in this section.

6.2.1 Future Work

Like stated in Section 5.4.6, even though the systems realism might be slightly reduced, it seems beneficial to enhance InformationSense with additional digital functionalities. Five main areas which could be improved in the future were determined. They are illustrated and briefly described in the following. Four of the mentioned ideas are related to the in Section 5.4.6 introduced design recommendations:

- **Provide an overview (related to DR2):** To supply users with a functionality for gaining an overview might benefit their orientation. Nevertheless, to apply zooming with touch was deemed disadvantageous in context of the cloth surface (see Section 3.3.2). It is far from reality and would continuously break the static mapping of digital information. Thus, two other approaches are proposed for the future. One possibility would be to utilize the rigid lenses. Users can zoom very far out with a lens and thus get an overview of the hole digital data space like shown in Figure 6.2a. Another way to provide an overview is illustrated in Figure 6.2b. It would

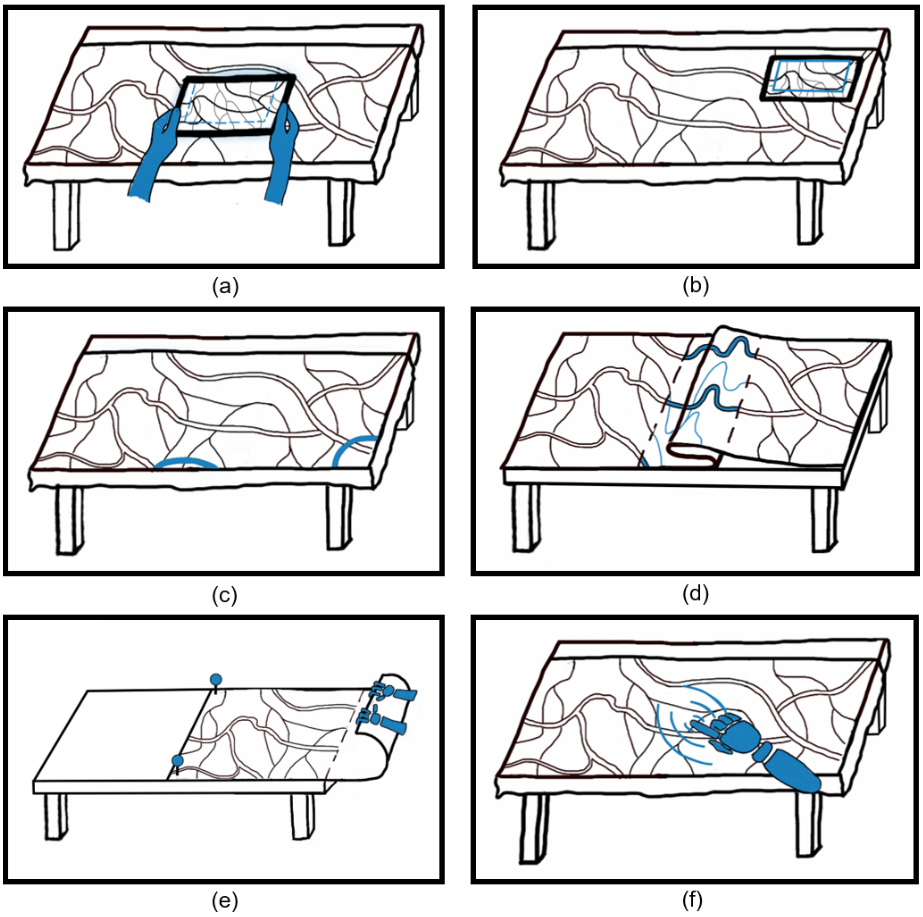


Figure 6.2: Future Work (a) Overview by using a lens and zooming far out. (b) Overview region projected on the cloth. The surfaces part which lies within the Interaction Space is highlighted by a border. In the example the border is depicted in blue. (c) Clues for offscreen content might be provided, e.g. in form of halos [5]. (d) A region is shown around a fold. It displays information which lies within the fold line in a distorted form. (e) Temporary fixation of cloth. In the sketch pins are displayed to stick the textile to the table surface. In reality one may use e.g. magnetism instead. (f) Touch as input modality.

be possible to project a small rectangle on the top right corner of the textiles part which currently resides in the Interaction Space. Within this rectangle the hole Exploration Space might be reflected. The part of the digital data which is currently projected on the cloth could be highlighted with a border.

- **Support clues about offscreen content (related to DR2):** According to Baudisch & Rosenholtz [5]:

  > *"The clipping of locations, such as relevant places on a map, can make spatial cognition tasks harder."*

  The authors suggested the use of halos, small rings on the border of the space which displays information, in order to make offscreen locations visible. Figure 6.2c provides an example. Of course one might also utilize a different kind of offscreen visualization. A more detailed analysis and review of existing work would be required to propose a specific technique.

- **Show information situated in folds (related to DR3):** The user study revealed, that it can benefit users search behavior to display information about parts of the Exploration Space which are situated in folds (see Section 5.4). Figure 6.2d gives an example for a possible implementation. One might use a small region surrounding a fold line to overlay a distorted visualization of the data which resides in the fold.

- **Allow the temporary fixation of cloth (parts) (related to DR4):** The participants of the user study frequently fixated the cloth for short durations by grabbing it or pressing it on the table (see Section 5.3.4). Nevertheless, they were not able to carry out such a temporary fixation without keeping one of their hand on the textile. The disadvantage of this was that they lacked one hand for further interactions. Figure 6.2e illustrates a possible solution. One might also use e.g. magnetism instead of pins.

- **Facilitate input modalities:** The current implementation lacks functionalities which support the manipulation of the digital content which is projected on the cloth or the lenses. One could, for example, supply users with touch in the future (see Figure 6.2f). The created textile surface might be enhanced by the concept introduced by Parzer et al. [84]. Another related work, which could provide interesting ideas for future developments, is Googles project Jacquard[1].

6.2.2 Future Use Cases

Various participants of the conducted study proposed different future use cases for flexible cloth displays (see Section 5.3.7). For example, they suggested to use them in the areas of maps, games, construction, architecture, fashion design, teaching or as replacement of technical devices like smartphones and tablets. In the following, three possible scenarios for the prospective utilization of deformable, digitally augmented textiles are elaborated:

[1] https://atap.google.com/jacquard

- **Flexible display prototyping:** Like shown in Figure 6.3a, cloth surfaces could be used for the fast creation of flexible display prototypes in different shapes and sizes. This might allow the research of interactions which will facilitate users work with deformable screens when these are available in the future.
- **Cloth prototyping:** Figure 6.3b illustrates another possible prospective use case. People might utilize the textile in order to build cloth prototypes. The cloth objects might be worn by models and projected with digital content to quickly test different design ideas. Further, like one study participant mentioned, drawing or writing on the textile could be supported in the future. These functionalities might additionally aid the work of fashion designers.
- **Physics simulations:** During the interview, one of the study participants talked about the idea to utilize the cloth display in schools for teaching. A real textile could support pupils in their understanding of properties from our physical world. A simple example is provided in Figure 6.3c. A person might lift the textile and, depending on its deformation, a digitally projected ball moves over the surface with different levels of speed.

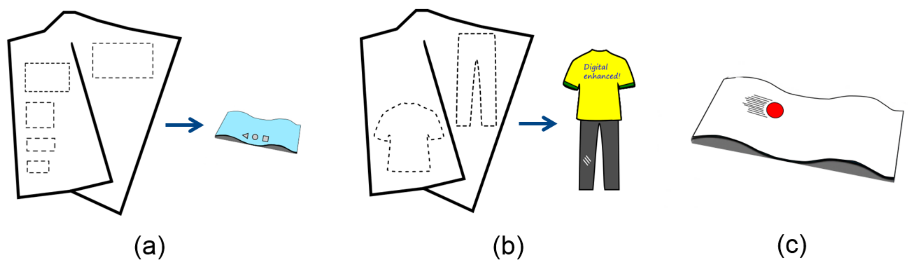


Figure 6.3: Future Use Cases (a) Flexible display prototyping. (b) Cloth prototyping. (c) Physics simulations.

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Appendix A

Documents User Study

Different documents were created in order to conduct and evaluate the user study. These include:

- **Introduction (Welcome Letter)**
- **Declaration of Consent (Video Recording)**
- **Demographic Questionnaire**
- **NASA TLX Questionnaire**
- **User Experience Questionnaire**
- **Custom Questionnaire (Likert Scales)**
- **Script, Semistructured Interview**
- **Coding Schema (Video Coding, InformationSense)**

An example of the utilized texts and forms is presented in the following. While all participants spoke german, the documents which were utilized for the conduct of the study were crafted in this language.

Einleitung zur Studie

Hallo,

vielen Dank, dass Sie sich bereit erklärt haben mich bei meiner Master-Thesis zu unterstützen.

In der Studie wird es darum gehen drei Systeme miteinander zu vergleichen. Während der Sitzung werden ich Ihnen für jedes der Systeme Aufgaben stellen, Sie bitten Fragebögen auszufüllen und am Ende ein kurzes Interview mit Ihnen durchführen. Die Studie wird ungefähr 90 Minuten dauern.

Ich will, bevor wir anfangen, ganz deutlich festhalten, dass nicht Sie, sondern die Systeme getestet werden. Sie können hier keine Fehler machen. Sie können nur Vor- und Nachteile der verschiedenen Systeme aufzeigen!

Falls Sie sich nicht wohlfühlen sollten, können Sie zu jeder Zeit die Studie abbrechen oder eine Pause machen. Ich bitte Sie mir dies im gegebenen Fall einfach kurz mitzuteilen.

Wenn Sie während der Studie irgendwelche Fragen haben, dann stellen Sie diese bitte einfach. Es kann jedoch möglich sein, dass ich sie Ihnen nicht sofort beantworten kann, weil ich in manchen Fällen daran interessiert bin was passiert, wenn Ihnen niemand als Hilfe zur Verfügung steht.

Mit Ihrer Zustimmung werde ich den Verlauf der Studie aufzeichnen und mitprotokollieren. Die Aufzeichnungen und Notizen werden ausschließlich zur Auswertung, Dokumentation und Präsentation im wissenschaftlichen Rahmen verwendet.

Wenn Sie nichts dagegen haben, werde ich Sie bitten ein einfaches Formular zum Einverständnis zu unterschreiben.

Zu guter Letzt würde ich es sehr schätzen, wenn Sie in den nächsten **drei Wochen** nicht mit anderen Personen über den Aufbau der Studie und die getesteten Systeme sprechen. Es könnte sonst zu einer Verfälschung der Testergebnisse von nach Ihnen eingeladenen Probanden kommen. Vielen Dank!

Haben Sie zum weiteren Ablauf noch Fragen?

Basiert auf Vorlage aus: Krug Steve. Web Usability - Rocket Surgery Made Easy. Addison-Wesley, 1. Auflage Edition, 2010.

Formular für die Zustimmung zur Aufzeichnung und Verwendung von Teilnehmerdaten

Vielen Dank, dass Sie mir bei meinen Untersuchungen zum Thema *Navigation in digitalen Datenräumen* behilflich sind.

Ich werde diese Sitzung mit Ihnen aufzeichnen, um den Test im Nachhinein besser nachvollziehen zu können. Die Aufzeichnung wird sich aus Bild, Ton, Notizen und der automatisierten Protokollierung durch die getesteten Systeme zusammensetzen. Vor und während der Studie werde ich Sie bitten mehrere Fragebögen auszufüllen. Weiterhin würde ich am Ende der Studie gerne ein kurzes Interview mit Ihnen durchführen.

Ihre Daten, werden ausschließlich im Rahmen meiner Master Thesis sowie eventueller weiterer wissenschaftlicher Arbeiten ausgewertet, dokumentiert und präsentiert. Die Daten werden keinem weiteren Zweck zugeführt. Ebenfalls werden Sie an keiner Stelle namentlich genannt. Es ist möglich das Teile der Aufzeichnungen zur Präsentation des Studienaufbaus und der Ergebnisse, im wissenschaftlichen Rahmen, eingesetzt werden.

Bitte lesen Sie die folgenden Aussagen durch und unterschreiben Sie dann.

Ich bin darüber informiert worden, dass meine Studiensitzung aufgezeichnet wird (Bild, Ton und automatische Protokollierungen durch die getesteten Systeme) und während der Sitzung Notizen durch den Studienleiter angefertigt werden.

Ich erlaube hiermit Herrn Maximilian Dürr oben genannte Aufzeichnungen, im Rahmen der Studie ausgefüllte Fragebögen, sowie Aufschriebe in Bezug zu durchgeführten Interviews, zum Zweck der wissenschaftlichen Untersuchung, Dokumentation und Präsentation zu verwenden.

Proband:

Unterschrift: ____

Name in Blockbuchstaben: ____

Ort und Datum: Konstanz, ____

Studienleiter:

Unterschrift: ____

Name in Blockbuchstaben: MAXIMILIAN DUERR ____

Ort und Datum: Konstanz, ____

Basiert auf Vorlage aus: Krug Steve. Web Usability - Rocket Surgery Made Easy. Addison-Wesley, 1. Auflage Edition, 2010.

Fragebogen: Demografische Daten   ID: __________

Alter: ______________

Geschlecht: ☐ männlich ☐ weiblich

Job/Studienfach: ____

Physische Beieinträchtigung: ☐ ja, welcher Art? ______________________ ☐ nein

Farben Blindheit: ☐ ja ☐ nein

Primäre Hand: ☐ links ☐ rechts

Körpergröße: ______________

Wie *hoch/gering* schätzen Sie Ihre *Kenntnisse* im Umgang mit *Computern* und *verwandten Systemen (z.B. Smartphones)* ein?

sehr gering ☐ ☐ ☐ ☐ ☐ sehr hoch

Wie *hoch/gering* schätzen Sie Ihre *Erfahrung(en)* im Umgang mit *großen Multitouch-Dsiplays* (größer 30“) ein?

sehr gering ☐ ☐ ☐ ☐ ☐ sehr hoch

Falls Sie Erfahrung(en) haben sollten: Mit welcher Art von Multitouch-Display(s)?

____

____

____

Erläuterung zum Fragebogen: Beanspruchungsstruktur (NASA TLX)

Durch die eben absolvierten Aufgaben erfuhren Sie eine gewisse Belastung. Bitte lesen Sie sich die Erläuterungen zu den folgenden Aspekten der Belastung durch:

Aspekte	**Erläuterung**
1) Geistige Anforderungen	Wie viel geistige Anstrengung war bei der Informationsaufnahme und bei der Informationsverarbeitung erforderlich (z.B. Denken, Entscheiden, Rechnen, Erinnern, Hinsehen, Suchen, ...)? War die Aufgabe leicht oder anspruchsvoll, einfach oder komplex, erfordert Sie hohe Genauigkeit oder ist sie fehlertolerant?
2) Körperliche Anforderungen	Wie viel körperliche Aktivität war erforderlich (z.B. ziehen, drücken, drehen, steuern, aktivieren, ...)? War die Aufgabe leicht oder schwer, einfach oder anstrengend, erholsam oder mühselig?
3) Zeitliche Anforderungen	Wie viel Zeitdruck empfanden Sie hinsichtlich der Häufigkeit oder dem Takt, mit dem Aufgaben oder Aufgabenelemente auftraten? War die Abfolge langsam und geruhsam oder schnell und hektisch?
4) Ausführung der Aufgaben	Wie erfolgreich haben Sie Ihrer Meinung nach die vom Versuchsleiter oder Ihnen selbst gesetzten Ziele erreicht? Wie zufrieden waren Sie mit Ihrer Leistung bei der Verfolgung dieser Ziele?
5) Anstrengung	Wie hart mussten Sie arbeiten, um Ihren Grad an Aufgabenerfüllung zu erreichen?
6) Frustration	Wie unsicher, entmutigt, irritiert, gestresst und verärgert fühlten Sie sich während der Aufgabe?

Fragebogen: Beanspruchungsstruktur (NASA TLX) ID: _________

Geben Sie jetzt bitte an, wie hoch die Beanspruchung in den einzelnen Aspekten war. Markieren Sie dazu bitte auf den folgenden Skalen, in welchem Maße Sie sich in den sechs genannten Aspekten von der Aufgabe beansprucht oder gefordert gefühlt haben:

Beispiel:

gering X hoch

Geistige Anforderungen

Wie viel geistige Anstrengung war bei der Informationsaufnahme und bei der Informationsverarbeitung erforderlich (z.B. Denken, Entscheiden, Rechnen, Erinnern, Hinsehen, Suchen, ...)? War die Aufgabe leicht oder anspruchsvoll, einfach oder komplex, erfordert Sie hohe Genauigkeit oder ist sie fehlertolerant?

gering hoch

Körperliche Anforderungen

Wie viel körperliche Aktivität war erforderlich (z.B. ziehen, drücken, drehen, steuern, aktivieren, ...)? War die Aufgabe leicht oder schwer, einfach oder anstrengend, erholsam oder mühselig?

gering hoch

Zeitliche Anforderungen

Wie viel Zeitdruck empfanden Sie hinsichtlich der Häufigkeit oder dem Takt, mit dem Aufgaben oder Aufgabenelemente auftraten? War die Abfolge langsam und geruhsam oder schnell und hektisch?

gering hoch

Ausführung der Aufgaben

Wie erfolgreich haben Sie Ihrer Meinung nach die vom Versuchsleiter oder Ihnen selbst gesetzten Ziele erreicht? Wie zufrieden waren Sie mit Ihrer Leistung bei der Verfolgung dieser Ziele?

gut schlecht

Anstrengung

Wie hart mussten Sie arbeiten, um Ihren Grad an Aufgabenerfüllung zu erreichen?

gering hoch

Frustration

Wie unsicher, entmutigt, irritiert, gestresst und verärgert fühlten Sie sich während der Aufgabe?

gering hoch

Erläuterung zum Fragebogen: User Experience

Bitte geben Sie Ihre Beurteilung ab.

Um das Produkt zu bewerten, füllen Sie bitte den nachfolgenden Fragebogen aus. Er besteht aus Gegensatzpaaren von Eigenschaften, die das Produkt haben kann. Abstufungen zwischen den Gegensätzen sind durch Kreise dargestellt. Durch Ankreuzen eines dieser Kreise können Sie Ihre Zustimmung zu einem Begriff äußern.

Beispiel:

attraktiv	○	⊗	○	○	○	○	○	unattraktiv

Mit dieser Beurteilung sagen Sie aus, dass Sie das Produkt eher attraktiv als unattraktiv einschätzen.

Entscheiden Sie möglichst spontan. Es ist wichtig, dass Sie nicht lange über die Begriffe nachdenken, damit Ihre unmittelbare Einschätzung zum Tragen kommt.

Bitte kreuzen Sie immer eine Antwort an, auch wenn Sie bei der Einschätzung zu einem Begriffspaar unsicher sind oder finden, dass es nicht so gut zum Produkt passt.

Es gibt keine „richtige“ oder „falsche“ Antwort. Ihre persönliche Meinung zählt!

Fragebogen: User Experience

ID: __________

Bitte geben Sie nun Ihre Einschätzung des Produkts ab. Kreuzen Sie bitte nur einen Kreis pro Zeile an.

	1	2	3	4	5	6	7		
unerfreulich	○	○	○	○	○	○	○	erfreulich	1
unverständlich	○	○	○	○	○	○	○	verständlich	2
kreativ	○	○	○	○	○	○	○	phantasielos	3
leicht zu lernen	○	○	○	○	○	○	○	schwer zu lernen	4
erfrischend	○	○	○	○	○	○	○	einschläfernd	5
langweilig	○	○	○	○	○	○	○	spannend	6
uninteressant	○	○	○	○	○	○	○	interessant	7
unberechenbar	○	○	○	○	○	○	○	voraussagbar	8
schnell	○	○	○	○	○	○	○	langsam	9
neu	○	○	○	○	○	○	○	alt	10
unbedienbar	○	○	○	○	○	○	○	bedienbar	11
gut	○	○	○	○	○	○	○	schlecht	12
kompliziert	○	○	○	○	○	○	○	einfach	13
abstoßend	○	○	○	○	○	○	○	anziehend	14
veraltet	○	○	○	○	○	○	○	modern	15
unangenehm	○	○	○	○	○	○	○	angenehm	16
vorhersagbar	○	○	○	○	○	○	○	unvorhersagbar	17
abwechslungsreich	○	○	○	○	○	○	○	eintönig	18
zuverlässig	○	○	○	○	○	○	○	unzuverlässig	19
ineffizient	○	○	○	○	○	○	○	effizient	20
übersichtlich	○	○	○	○	○	○	○	verwirrend	21
stockend	○	○	○	○	○	○	○	flüssig	22
aufgeräumt	○	○	○	○	○	○	○	überladen	23
schön	○	○	○	○	○	○	○	hässlich	24
sympathisch	○	○	○	○	○	○	○	unsympathisch	25
unauffällig	○	○	○	○	○	○	○	auffällig	26

Fragebogen: Arbeitsweise ID: _________

Wie *gut/schlecht* konnten Sie beim Arbeiten mit dem System die *Orientierung* / den *Überblick* behalten?

sehr schlecht				sehr gut
☐	☐	☐	☐	☐

Wie *natürlich/unnatürlich* empfanden Sie die *Arbeit* mit dem System?

sehr unnatürlich				sehr natürlich
☐	☐	☐	☐	☐

Wie *einfach/schwer* empfanden Sie das *Finden* der Kreise mit dem System?

sehr schwer				sehr einfach
☐	☐	☐	☐	☐

Wie *einfach/schwer* empfanden Sie das *Vergleichen* der Kreise mit dem System?

sehr schwer				sehr einfach
☐	☐	☐	☐	☐

Wie *häufig/selten*n haben Sie versucht sich *Farbkombinationen* von Kreisen zu *merken*?

sehr selten				sehr häufig
☐	☐	☐	☐	☐

Leitfaden: Semi-Strukturiertes Interview ID: __________

1. Präferenzen

Sie haben während der Untersuchung 3 unterschiedliche Systeme gesehen.

1.1 **Favorisiertes System:** Welches System ist Ihr persönlicher Favorit?

☐ InfoSense ☐ SpaceFold ☐ Zoom

1.2 **Höchster Spaßfaktor:** Mit welchem der Systeme hat das Arbeiten am meisten Spaß gemacht?

☐ InfoSense ☐ SpaceFold ☐ Zoom

1.3 **Vor-/Nachteile und Verbesserungsmöglichkeiten**

Vorteile: ____

____

____

____

____

Nachteile: ____

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____

____

____

Verbesserungsmöglichkeiten: Haben Sie Ideen wie man eines oder mehrere der Systeme in der Zukunft verbessern könnte / was man anders machen sollte und WARUM? (Option bieten direkt am System zu Zeigen, bzw. zu Sketchen)

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____

____

____

WARUM ist etwas ein Vor-/Nachteil?
Weitere Vor-/Nachteile?
Gibt es sonst noch etwas das Ihnen aufgefallen ist bzw. gut/schlecht funktioniert hat?

ID: __________

2. Strategien für Such- und Vergleichsaufgaben

Haben Sie sich während oder vor der Durchführung der Such- und Vergleichsaufgaben mit den unterschiedlichen Systemen, Gedanken über eine Vorgehensweise (Strategie) gemacht? Wenn ja, welche? (Wenn möglich bitte **Schrittweise** beschreiben!)

InfoSense: ____

____

____

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____

____

____

SpaceFold: ____

____

____

____

____

____

____

Zoom: ____

____

____

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____

Hat sich die Vorgehensweise mit mehr/weniger Kreisobjekten geändert? WARUM? Inwiefern?
Haben Sie aktiv über Ihr Vorgehen nachgedacht?
Hat sich die Strategie während dem Arbeiten verändert? WARUM?

ID: __________

3. Interaktionen

3.1 Wahrnehmung Faltrestriktion: Haben Sie es wahrgenommen das die Faltung mit den Systemen auf dem Touchtisch eingeschränkt ist und Sie nur horizontal und vertikal Falten konnten?

☐ Ja ☐ Nein

3.2 Freies vs. restriktives Falten:

Fanden Sie das restriktive Falten hilfreich oder nachteilhaft im Verhältnis zu dem frei faltbaren System mit dem Stoff? Für welches der Systeme würden Sie sich welche Art des Faltens wünschen?

Freies Falten (Stoff): ____

____

____

Restriktives Falten (Touchtisch): ____

____

____

3.3 Beobachtete Interaktionen: Ich habe gesehen Sie haben … (z.B. den Stoff häufig geknüllt). Aus welchem Grund? Besondere Vorteile/Nachteile? Probleme?

____

____

____

Hätten Sie gerne noch etwas Anderes gemacht was nicht unterstützt wurde?

4. Zukünftige Anwendungsfälle: In welchem Bereich des (täglichen) Lebens könnten Sie sich vorstellen in Zukunft ein flexibles Stoffdisplay zu nutzen? Welche Anwendungsfälle fallen Ihnen ein?

____

____

____

Warum genau in diesem Bereich? Weitere Ideen? Sonst noch etwas? Wie meinen Sie das genau?

Coding Schema (InformationSense)

Timestamps:

- Start of first task in video
- Task interaction span (start and end timestamp of the span in which a user interacts)

Navigation Interactions:

- Move cloth: hand on top of cloth
- Move cloth: grab cloth border
- Move cloth: one hand grab cloth border, one hand on top of cloth
- Rotate
- Lift cloth in the air

Deformation Interactions:

- Create fold: vertical
- Create fold: horizontal
- Create fold: diagonal
- Create fold: push cloth together from two sides
- Create fold: on top of existing fold (stack folds)
- Create fold: put hand under cloth and fold
- Create fold: fold cloth under itself
- Modify fold
- Unfold
- Crumple cloth
- Look under existing folds (fold them over)
- Grab circle and place it somewhere else

Other Interactions & States:

- Hold cloth in position
- Reset (open all folds on the cloth)
- Unspecified interaction
- Number of folds at end of task

Appendix B

Content USB Drive

The attached USB drive contains:

- **Digital Version of Thesis**
- **Documents User Study:**
    - **Introduction (Welcome Letter)**
    - **Declaration of Consent (Video Recording)**
    - **Demographic Questionnaire**
    - **NASA TLX Questionnaire**
    - **User Experience Questionnaire**
    - **Custom Questionnaire (Likert Scales)**
    - **Script, Semistructured Interview**
    - **Coding Schema (Video Coding, InformationSense)**