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Mobile Mediated Interaction with Pervasive Displays

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ABSTRACT

With the rise of pervasive computing, technology becomes increasingly interwoven and embedded into our environments. As an effect, the number of available computing devices in our surroundings is increasing substantially. That is, a growing number of different device classes is at the user's disposal (e.g., personal devices such as mobile phones and interactive surfaces such as tabletop computers). All these device classes potentially serve as *pervasive displays* that support users to perform all kinds of tasks. Accordingly, users can apply different devices for solving tasks depending on their current context (i.e., where, with whom, and what etc.) The ensemble of these different devices in the environment span a space in which users can interact in a multitude of diverse ways, which we refer to as *pervasive interaction space*. The promise of this interaction space is highly embedded technology that blends in the environment allowing users to quickly adapt to their current context for instance, switching from a large stationary device to a small portable device or vice versa when starting to collaborate with others.

However, possibilities based on direct interaction, such as touch, are limited regarding a number of aspects including user identification, accessing and sharing personal data. Further, often physical access is required in order to interact directly with pervasive displays. In addition, direct interaction is mainly focusing on a specific device and neglects available other devices (e.g., the user's mobile phone), which is contradicting the goal of calm technology that allows users to focus on their task and not on the technology they are using.

One versatile option to address these challenges is using *mediated interaction* techniques. Mediation in this context means the application of a device that negotiates communication between a user and an interaction target (i.e., a pervasive display). For instance, handheld pointing devices allow users to bridge spatial distance in order to interact with a remote display. Using personal mobile devices as a mediator yields additional inherent advantages as users can be identified and the user's digital context (e.g., photos, messages etc.) can be accessed.

In the context of this thesis, a structured analysis of prior art was conducted. Based on this review of prior art, two general research goals were identified: *(1)* how to *interact* in pervasive interaction spaces using mobile mediated interaction. *(2)* what implication result from using mobile mediated techniques for *co-located collaboration* and *data sharing and privacy management*. Based on this work this thesis offers the following three contributions:

Mobile mediated interaction techniques can be used in a great variety of spatial combinations in space. For instance, a mobile phone can be used to bridge interaction to a distant pervasive display device, but also through physical direct contact between the mediator and a pervasive display. This thesis contributes an *anthropomorphic classification scheme* for mobile mediated interaction, in order to allow a structured investigation of these techniques.

Further, this thesis contributes novel mobile mediated techniques that extend interaction expressiveness for all spatial categories throughout the pervasive space. This includes techniques based on physical contact between mediator and pervasive display, techniques in space of the immediate vicinity of the user including manual and self-actuated semi-autonomous position control of the mediator, as well as techniques for distant interaction. These novel techniques yield original ways for colocated collaboration, data sharing and disclosure, which are investigated by means of quantitative and qualitative evaluation methods.

Finally, this thesis contributes a set of *design patterns* that are based on the findings and experiences gained throughout the work. These patterns can be used by interaction and application designers working on pervasive computing applications.

ZUSAMMENFASSUNG

Pervasive Computing Technologien ermöglichen Computersysteme, die immer stärker mit der Umgebung der Benutzer verwoben sind und in den Hintergrund treten. Damit einhergehend steigt die Anzahl der verfügbaren Geräte stetig an. Das heißt, eine immer größere Vielzahl an verschiedenen Geräteklassen steht dem Benutzer zur Verfügung. Dies schließt beispielsweise portable, ausschließlich durch den Benutzer verwendete Mobiltelefone ein sowie große, von mehreren Nutzern in Anspruch genommene interaktive Oberflächen wie interaktive Tische. All diese Geräte können der generellen Klasse der allgegenwärtigen Displaysysteme zugeordnet werden, welche Nutzer bei der Durchführung unterschiedlichster Aufgaben unterstützen können. Demzufolge können Nutzer unterschiedliche Geräteklassen, abhängig vom gegenwärtigen Anwendungskontext, einsetzen. Dies ermöglicht es dem Nutzer, andere Anwesende, die Aufgabe sowie den sich gegebenenfalls verändernden Ort zu berücksichtigen. Zusammen spannen diese allgegenwärtigen Displaysysteme in Kombination mit den Interaktionsmöglichkeiten einen Interaktionsraum auf. Der generelle Nutzen, welchen man sich von diesem Raum verspricht ist, dass Nutzer schnell zwischen verschiedenen Geräten wechseln können, um abhängig vom Anwendungskontext möglichst effizient und erfolgreich eine Aufgabe bearbeiten zu können. Dies schießt beispiel-

sweise den Wechsel von einem mobilen Gerät zu einem geteilten Gerät mit ein, um dort zusammen mit anderen Nutzern die Bearbeitung der Aufgabe fortzusetzen.

Die Interaktionsmöglichkeiten, basierend auf direkter Interaktion, wie zum Beispiel berührungsbasierte Interaktion, sind jedoch hinsichtlich einer Reihe von Aspekten limitiert. Dies beinhaltet Möglichkeiten sowohl für Benutzeridentifikation, Zugriff auf und Teilen von persönlichen Daten als auch die Notwendigkeit, in physikalischen direkten Kontakt mit dem jeweiligen Displaysystem zu treten. Darüber hinaus sind diese Interaktionsmöglichkeiten stark auf ein Gerät fokussiert und vernachlässigen die Existenz weiterer vorhandener Geräte. Dies widerspricht allerdings dem Ziel, flexibel zwischen verschiedenen Geräten wechseln zu können – abhängig vom jeweiligen Kontext.

Ein vielversprechender Ansatz zur Lösung dieser Herausforderungen ist die Verwendung von *vermittelten Interaktionstechniken*. Vermittlung in diesem Zusammenhang meint die Verwendung eines Gerätes, welches die Kommunikation zwischen Nutzer und Displaysystem unterstützt oder ermöglicht. Zum Beispiel kann ein in der Hand gehaltenes Zeigegerät die Interaktion mit einem entfernten System ermöglichen, ohne dass der Nutzer in die unmittelbare Nähe gelangen muss. Die Verwendung von persönlichen mobilen Geräten, wie beispielsweise Mobiltelefone, ergibt zusätzliche Vorteile wie die Möglichkeit, Nutzer zu identifizieren oder direkt auf ihre persönlichen Daten wie Fotos oder Nachrichten zugreifen zu können.

Im Rahmen der vorliegenden Arbeit wurde eine strukturierte Analyse der existierenden verwandten Arbeiten durchgeführt. Basierend auf den daraus resultierenden Erkenntnissen wurden zwei generelle Ziele für diese Arbeit identifiziert: *(1)* Wie können Interaktionen im gesamten Interaktionsraum stattfinden. *(2)* Welche Implikationen ergeben sich aus diesen hinsichtlich der Zusammenarbeit von Nutzern und dem Teilen von persönlichen Daten. Die darauf basierende vorliegende Arbeit leistet drei Hauptbeiträge:

Mobile vermittelte Interaktionstechniken können in vielen verschiedenen räumlichen Anordnungen von Vermittler und Displaysystem eingesetzt und verwendet werden. So kann beispielsweise ein Mobiltelefon als Zeigegerät fungieren für die Interaktion mit einem entfernten Display. Dies gilt genauso für Interaktion, basierend auf direktem physikalischem Kontakt von Mobiltelefon und Display. Die vorliegende Arbeit stellt ein anthropomorphisches Klassifikationsschema für mobile vermittelte Interaktionstechniken vor. Dieses ermöglicht die Einteilung von verschiedenen Techniken in räumliche Kategorien, basierend auf der menschlichen Gestalt des Benutzers und unterstützt somit eine strukturierte Analyse dieser Techniken.

Die vorliegende Arbeit präsentiert neue mobil vermittelte Interaktionstechniken, welche die bisher existierenden Möglichkeiten erweitern. Dabei werden Möglichkeiten für vermittelte Interaktion, basierend auf physikalischem Kontakt, vorgestellt sowie Interaktionsmöglichkeiten in der Nähe und über größere Entfernungen hinweg, außerhalb der Reichweite des Nutzers. Diese neuartigen Interaktionstechniken ermöglichen neue Formen der computergestützten Zusammenarbeit sowie erlauben es Nutzern, kontrolliert persönliche Daten preiszugeben und mit anderen zu teilen. Diese Möglichkeiten wurden in mehreren Experimenten untersucht und qualitativ und quantitativ evaluiert.

Schließlich stellt die vorliegende Arbeit eine Sammlung an Designmustern (Patterns) vor, die auf den Erkenntnissen und Beobachtungen basiert, die im Rahmen des Design, der Umsetzung und der Durchführung von Experimenten gesammelt wurden. Diese Muster unterstützten aufgrund ihrer formalisierten und abstrahierten Form den Designprozess von Anwendungen für allgegenwärtige Computersysteme.

PUBLICATIONS

Some ideas and figures have appeared previously in the following publications:

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If you want to go fast, go alone.
If you want to go far, go together.

— African Proverb

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ACRONYMS

ANOVA	Analysis of Variance
API	Application Programming Interface
AR	Augmented Reality
ATM	Automatic Teller Machine
CCTV	Closed Circuit Television
CT	Computer Tomography

DoF	Degrees of Freedom
FTIR	Frustrated Total Internal Reflexion
GPS	Global Positioning System
GUI	Graphical User Interface
HCI	Human-Computer-Interaction
ID	Identifier
IP	Internet Protocol
IrDA	Infrared Data Association
ISO	International Organization for Standardization
M	Mean (Arithmetic)
Mdn	Median
MAC	Media-Access-Control-Address
NFC	Near Field Communication
PC	Personal Computer
PDA	Personal Digital Assistant
PIM	Personal Information Management
PIN	Personal Identification Number
PSSUQ	Post Study System Usability Questionnaire
RFID	Radio Frequency Identification
SD	Standard Deviation
SDK	Software Development Kit
SMS	Short Message Service
SSID	Service Set Identifier
SUS	System Usability Scale
TCP	Transmission Control Protocol
TLX	Task Load Index
TV	Television

UI	User Interface
URL	Uniform Resource Locator
USB	Universal Serial Bus
VR	Virtual Reality
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

1

INTRODUCTION

Today, in an increasing number of different contexts one can find pervasive displays. Such pervasive displays can manifest in a large diverse variety of shapes, sizes, and other distinguishing characteristics, for instance, possibilities for interaction. To name but a few, pervasive displays turn up as *public displays*, also as *interactive surfaces* in form of tabletop computers, but also in form of personal handheld devices such as mobile phones. Depending on their inherent characteristics such as form factor or information fidelity as well as their presentation through specific placement in different locations they address varying audiences with the information provided. That is, public displays allow a large number of people to see and read information. Further, being installed in an openly accessible environment, the audience is not specified. Specific groups of users can collaborate using interactive surfaces such as tabletops or walls. Tablet computers and mobile phones in turn are targeted to individual users allowing them to carry these devices with them.

Environments of pervasive displays.

These information displays are ubiquitously available in all kinds of environments. For instance, in urban environments such as trains stations or on exposed building facades one can find public displays. Also in work environments such as office buildings and meeting rooms, but also in specific contexts such as hospitals or control rooms, pervasive displays are available. Even in domestic environments such as living rooms, one can find increasingly more pervasive displays, for instance, in the form of projected displays, interactive surfaces, and of course personal tablet computers and mobile phones.

The promise and goals of pervasive displays.

In all these aforementioned contexts the primary aim of these pervasive displays is providing access to information that facilitates the potential users' lives or increases the level of convenience. Accordingly, pervasive displays go beyond the usage context of fixed and stationary desktop computers as well as portable laptop computers. Advantages offered by this class of information displays include besides the active access of information everywhere, also serendipitous information access; for instance, stumbling across an announcement for an upcoming event on a public display. In addition, various pervasive displays are well suited to support co-located collaborative tasks. For instance, tabletop computers enable multiple users to discuss and manipulate documents simultaneously as users share the same view.

Together, these pervasive display devices span a space of opportunities for interaction, communication, and collaboration. In this thesis, *The concept of the* Pervasive Interaction Space.

this space is referred to as the *pervasive interaction space*. This terminology is directly based on Marc Weiser's vision of pervasive or ubiquitous computing,[1] respectively [285]. Weiser formulated as key characteristic of pervasive computing systems that, from a user's point of view, the computing devices should step in the background and blend with the environment. This in turn, should allow users to focus on the task they are working on instead of focusing on operating a computer system. Weiser refers to this quality as *"calm technology"*. For the implementation of this vision, Weiser identified a number of suitable devices that would support diverse aspects in this interaction space. These comprise *boards*, *pads*, and *tabs*. Boards are large interactive displays that enable a shared view and collaborative content editing. Pads and tabs are smaller, personal devices that can be carried by the user. These three classes of devices would be suitable for supporting, for instance, co-located collaboration such as a working meeting. The devices are interconnected and enable the users to share information and edit contents collaboratively.

Pervasive computing aiming for calm *technology.*

1.1 PROBLEM STATEMENT

In order to benefit from applications deployed in pervasive interaction spaces, users require effective and efficient means to solve their tasks. Accordingly, a large body of work exists that considers different interaction techniques that support users in a multitude of ways. That is, means for *mutual or reciprocal action or influence* [163]. These comprise (but are not limited to): Touch-based interaction (e.g., using the fingers, hands, or feet), tangible interaction (e.g., manipulating physical objects to control mapped functions), proxemic interaction (e.g., exploiting spatial relations between users and devices), as well as pointing interaction (e.g., based on laser pointers).

Many of these interaction techniques allow users to achieve their goals in a *natural* and *intuitive* way. That is, for instance, touch-based interactions allow users to manipulate virtual items such as documents by applying actions at the same place of their visual representation on a touchscreen. To name another example, tangible interfaces provide users with physical objects that correspond to a specific interaction possibility. The aforementioned physical objects are often designed in such a way that they communicate the manipulation options to the users. However, direct interaction techniques leave open a number of inherent issues that limit their application:

Limitations of direct *interaction techniques.*

Firstly, most of the aforementioned classes of interactions do not consider and respect the user's identity. That is, the techniques themselves

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[1] Pervasive and ubiquitous computing are equally used in the community. For the sake of simplicity, in this thesis the terminology of *pervasive computing* is used.

do not provide an inherent means for *distinguishing* and in particular *identifying* users. For instance, touch-based interaction techniques that are often applied in the context of interactive surfaces, mostly detect multiple touch-points. However, techniques based on technologies such as Frustrated Total Internal Reflexion (FTIR) are neither able to distinguish different users nor can they identify a specific user. This inherent issue limits the design possibilities of applications that involve multiple users who should have distinguished rights to access and edit data. That is, for example, if access may be granted only to specific users, an additional authentication procedure is required. This conflicts with the goal of designing 'calm technology' that blends into the background. Further, the possibilities of collaborative multi-user applications remain limited to approaches, which do not consider user identity.

Secondly, users who walk up and use large shared pervasive displays cannot take advantage of their personal digital context. That is, since shared devices cannot be personalized, individual preferences such as interface language always have to be configured by the users. Moreover, contents (e.g., documents, images, calendars, etc.) are not directly available or accessible that belong to the user's digital context. This again requires additional steps, for instance, to connect to services that would provide such personal data and contents.

Thirdly, users who use large shared pervasive displays for solving a task, for instance, in collaboration with others, face the challenge to store and save resulting data in such a way that it is accessible later. In other words, users cannot *take away* data without additional steps as for example logging on a cloud service.

A fourth limitation of many direct interaction techniques is a spatial fixed and defined relation between user and pervasive display. For instance, touch-based interaction techniques require the user to be able to approach a pervasive display so that it is within the user's arm range. However, users find themselves in situations and spatial constellations in which it is either socially inappropriate (e.g., accessing content of a slide presentation during a meeting) or impossible (e.g., a public display mounted behind rail tracks at a train station) to approach a distant pervasive display.

A further limitation of direct interaction techniques is that they do not support transitioning and interaction across multiple devices. For instance, if a user wishes to switch from a personal device to a shared interactive surface in order to continue a task in collaboration with another user, this would not be possible per se by direct techniques.

Mediated Interaction.

One versatile approach to address the discussed challenges is utilizing a *mediator* object. Such a mediator allows "acting through an intervening agency" [163], which in turn allows to leverage interaction in such a way to overcome limitations of direct techniques. An extensive body of work exists (discussed in detail in the following chapter) that show examples for mediator objects that enable an indirect connection or relation between a user and a target device include laser pointer, remote controls, or specific devices such as data gloves or electronic pens.

Based on the selection of a specific device that serves as a mediator, there is a fundamental difference in the ability to overcome the challenges regarding user identity, personal context and storage, spatial flexibility, as well as the potential to support user to transition applications between different devices.

Inherent advantages of mobile phones as mediator object.

Mobile phones and in particular smartphones are suitable candidates as universally applicable mediator object. Reasons that support this thesis are the following:

Firstly, mobile phones are virtually ubiquitously available (alone in 2013, 967 Million smartphones were sold [257]) and thus, most potential users in pervasive interaction spaces already use such a device. Hence, they can be considered to be part of the ecosystem of pervasive interaction spaces.

Secondly, mobile phones allows to distinguish and identify (e.g., via the Media-Access-Control-Address (MAC)) users when used as mediator object.

Thirdly, with their increasing capabilities, mobile phones turned into devices that cover and contain the majority of users' personal digital context. To name but a few, not only they store all Personal Information Management (PIM) related data such as calendars, messages, and contacts but also web browsing history and photos taken with the mobile phone. This capability is based on the inherent ability to store considerable amounts of data. Hence, mobile phones offer the possibility to serve as a personal storage means.

Further, mobile phones that are equipped with various networking interfaces (e.g., Wireless Local Area Network (WLAN) or Near Field Communication (NFC)) can be connected easily with other devices in a pervasive interaction space. While this alone does not enable the design and implementation of interaction techniques covering flexible and arbitrary spatial constellations, it yet is of use as technical basis.

Key challenges for mobiel mediated interaction: interaction in space, collaboration support, and privacy preserving data disclosure.

While several arguments indicate that mobile phones are well suited as mediator device for *mobile mediated interaction*, the question arises what interaction techniques are appropriate for covering the whole pervasive interaction space. That is, on the one hand how interaction is possible in situations where a user is located close to a pervasive display that is in reach allowing touch-based interaction. On the other hand, the question arises, how mobile mediated interaction techniques are possible for interaction across different spatial distances. This in turn, raises questions regarding how users benefit from mobile mediated interaction when working together with others in co-located collaborative contexts. And finally, using mobile phones as mediator objects raises concerns regarding how users would be supported when it comes to sharing and disclosing personal data in pervasive interaction space on, for instance, a shared interactive surface. In a more general sense, questions regarding possibilities and opportunities of mobile mediated interaction for supporting the management of user privacy arise.

To that end, this thesis aims to investigate and research the following aspects in a structured way in order to extend the field of Human-Computer-Interaction (HCI) and to form an understanding for them:

INTERACTION TECHNIQUES How and in what sequences are actions required in order to efficiently and effectively perform (user relevant) tasks? Further, how can mediated interaction be supported in the pervasive interaction space allowing users to bridge a range of varying distances. In addition, this thesis will assess interaction techniques under consideration of usability and a user centric perspective.

COLLABORATION How is mobile mediated interaction effecting co-located collaboration? That is, what if any benefit results from integrating multiple classes of different devices in the pervasive interaction space? And how do such mediated techniques effect accompanied social aspects such as communication behavior and decision making?

DATA DISCLOSURE & PRIVACY MANAGEMENT How can mediated interaction techniques support disclosing and sharing of personal data with others on pervasive displays? And how can mediated interaction techniques support privacy management of users?

1.2 THESIS CONTRIBUTIONS

With investigating the possibilities and implication of applying mobile phones as mediator objects for interaction in a pervasive space, this thesis aims to extend the knowledge of the field of HCI. In particular, this thesis seeks to make the following contributions:

ANTHROPOMORPHIC CLASSIFICATION FRAMEWORK. This thesis offers a novel, anthropomorphic (i.e., based on the human gestalt) classification framework. It enables a user-centered spatial categorization of mobile mediated interaction techniques.

MOBILE MEDIATED INTERACTION TECHNIQUES. This thesis presents novel interaction techniques that extend the set of possibilities within the pervasive interaction space. These techniques that apply a mobile phone as mediator cover all categories of the classification model including:

- contact-based interaction,
- contact-less interaction within the user's reach, as well as
- distant interaction out of the user's reach.

Further, within the context of these three spatial settings, different aspects are investigated in depth, which include:

- privacy management and data disclosure,
- social interaction and co-located collaborative settings, as well as
- autonomous and self-actuated movement.

These techniques can be either directly applied for application within the scope of pervasive interaction spaces or can serve as basis for adaptations and variations for novel interaction techniques.

INTERACTION PATTERN SET Based on the investigation and exploration of collaboration and privacy related concerns, this thesis derives a set of interaction patterns. Such pattern make distinct insights gained within the research context of this thesis accessible in a formalized and structured format. In particular, these generic interaction patterns facilitate reusing insights gained in this thesis in diverse applications for pervasive displays.

1.3 METHODOLOGY AND RESEARCH APPROACH

Main methodical approach: user-centered design process.

Interaction involving users and arbitrary pervasive display setups are effected by a multitude of influencing factors which yields a high level of complexity. In order to investigate aspects in that context, it is necessary to follow a methodical approach. This thesis draws on the "user-centered design process" as defined in the 9241-210 standard [123] by the International Organization for Standardization (ISO) . This process comprises four actions: context and requirements specification, solution design, and evaluation (see Figure 1), which all aims for the goal of creating findings and knowledge that is ultimately helpful beyond the scope of academic research.

In this thesis, the user-centered process is adapted for the research approach in the following two ways: on an overview level that includes the overall thesis as well as on the level of investigating specific aspects.

For the process of exploring and defining the context on high level, previous work and literature of related fields is analyzed. This leads to detailed and in depth description of explored challenges and possible conceptual as wells as implemented solutions. In addition, this analysis yields open challenges that are not, or only partly investigated. The requirements specification is reflected by the definition of the thesis scope. Solution

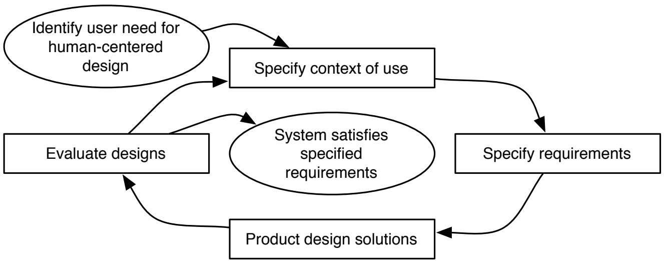

Figure 1: The human-centered design process as defined in the standard ISO 9241-210 [123]

design and evaluation corresponds to the set of specific researched aspects as well as the derived interaction patterns.

General reserach approach: specification, conceptual solution, prototyping, and evaluation.

In order to control complexity, investigation of specific aspects requires pinpointing single influence factors that can be examined isolated from each other. As for, this thesis follows the approach to tackle specific aspects in separated investigative steps. Again on this level, the thesis draws on and adapts the user-centered design process for the research. Firstly, the aspect is narrowed down to specific problems and related work is consulted and analyzed. Secondly, based on this analysis requirements are formulated that are essential for assessing the problem. Thirdly, conceptual solutions for the problem are designed. Further, prototypical implementations of the designed solutions are realized. In a fourth step, these implementations are used for evaluating the underlying concepts through user studies. It is important to note such prototypes require a sufficient level of fidelity in order to prevent misconceptions regarding what to focus on, on the users' side who participate in experiments. That is, for instance, a malfunctioning prototype of an actually well designed concept is likely to yield a low user acceptance and hence a distorted assessment of the underlying concept. However, under this conception it is legitimate to simulate certain aspects of a concept implementation given that from a user's point of view the difference is not noticeable.

Applied methods are standard in the field of HCI

For the evaluation process, this thesis applied methods that are widely acknowledged in the field of HCI (e.g., [26, 88, 142]). To name but a few, this includes quantitative methods that are based on observing objective quantifiable measures and values (e.g., error rates, completion times) as well qualitative methods (e.g., interviews, questionnaires). In addition, evaluations and user studies can be designed either as controlled laboratory studies or as uncontrolled *in situ* studies. The former ensures a high degree of internal validity as all relevant factors can be controlled (i.e., each participant is exposed to the same conditions). As mobile mediated interaction techniques require specific technical infrastructures, which can be (currently only) provided in laboratory environments, the research presented in this thesis is based on studies conducted in controlled environments such as laboratories. The resulting high internal validity supports choosing relatively small sample sizes (i.e., numbers of participants) while still statistical significant effects can be observed. Please note that the sample sizes chosen for the experiments within the scope of this thesis meet the common standards of the research field of HCI.

1.4 THESIS STRUCTURE

In order to convey main contributions of this thesis, this work is structured in the following way:

- The subsequent second chapter provides a throughout classification of the field of mobile mediated interaction with pervasive displays. This includes a characterization of related fields and the it defines the pervasive interaction space. Further, the chapter provides spatial and anthropomorphic classification scheme that serves throughout the thesis for structuring work. In addition, the second chapter provides a review and analysis of existing related research approaches in order to support and motivate the research work presented in this thesis.

- The subsequent chapter details work that investigates aspects concerning how users are affected in collaborative situations through the use of mobile mediated interaction techniques. In particular question regarding the simultaneous use of personal and shared devices are examined.

- The fourth chapter presents work on mobile mediated interaction techniques and their effect on user behavior regarding data disclosure of personal and sensitive data. Further, it investigates how privacy management can be supported through the use of the personal mobile phone as mediator object.

- The fifth chapter presents work on mobile mediated interaction techniques that are covering space close-by and in physical reach for the user. This includes work investigating manual and handheld positioning and moving the mediator object in the vicinity of a pervasive display. Further work is presented that examines possibilities for self-actuated and autonomous movement and positioning of mediator objects that aim for freeing the user from holding the mediator in their hand which is potentially tiering.

- The sixth chapter presents a structured investigation of distant mobile mediated interaction techniques which includes a design space, application examples, and evaluation results regarding the usability of such distant interaction techniques. Further, this chapter examines how such interaction techniques can be applied in the context of a domestic information and entertainment system.

- The seventh chapter presents a set of design patterns for mobile mediated interaction techniques that are derived from the investigations and finding of previously discussed aspects.
- The final, seventh chapter summarizes the contributions of the thesis and concludes with an outlook on open and further research directions.

2

CLASSIFICATION & RELATED WORK

This thesis uses the notion of *mobile mediated interaction* which refers to one opportunity to facilitate controlling applications running on *pervasive displays*. In order to classify and to develop a detailed understanding of this notion, first, this chapter discusses terms such as interaction, HCI, mobile HCI, as well as mediation and their relation to this thesis' main perspective. Further, this chapter discusses the term of *pervasive computing* and related concepts with a specific focus on the inherent aspect of space.

The analysis of the literature yields that so far, no classification framework or scheme exists that supports categorizing mobile mediated interaction techniques. Accordingly, this chapter introduces a human-centered classification scheme, which allows to categorize interaction into spatial categories. This scheme is based on a user-centric perspective from which interaction with pervasive displays is regarded. Hence, an anthropomorphic approach is followed for the classification of mobile mediated interaction techniques.

Further, this chapter illustrates related prior art and previous research, which further motivates the work presented in this thesis. To structure this overview, first general themes are discussed to provide a brief overview of the context of research. This includes *physical spatial relations* for interaction as well as *cross-device* applications and interaction. Further, this section is structured following the anthropomorphic classification scheme for mediated techniques. Therefore at first, interaction based on physical contact of mediator device and pervasive displays are discussed. Further, interaction techniques for controlling distant displays are discussed involving different approaches for mediating interaction between user and pervasive display.

Finally, this chapter discusses and relates the presented literature review in the context of this thesis' research work and targeted contributions.

2.1 CHARACTERIZATION & FRAMING OF MOBILE MEDIATED INTERACTION

This first section aims to classify the concept of mobile mediated interaction with pervasive displays by specifically first putting it in relation to the general concepts of interaction, HCI, and mediation. Secondly, the relation to pervasive computing is examined and discussed.

2.1.1 *Conceptions of Interaction*

The basic terminology of interaction.

Interaction as basic concept is defined by the New Oxford American Dictionary as *"reciprocal action or influence"* [259]. Accordingly, two or more parties must be involved, which are comprising one ore multiple entities. One of said entities may take action while another entity is being influenced by said action. This relationship between involved entities can change at any time. This most general framing of the concept of *interaction* leaves open how *interacting* entities have to be alike as well as the *action* or *influence* are not further specified.

Human-computer-interaction.

HUMAN-COMPUTER INTERACTION In the context of *mobile mediated interaction with pervasive displays*, involved entities include (but are not limited to) users, mobile devices, and pervasive displays. Accordingly, this involves humans and diverse computer systems, as for this type of interaction belongs to the field of HCI as defined by Hewett et al.:

> *"Human-computer interaction is a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them"*. [114]

While this definition by Hewett et al., which is commonly accepted and used by SIGCHI[1] [246], is specific regarding the involved entities (i.e., human users and computer systems), it leaves some room for interpretation in terms of *how* interaction should be characterized. Dix et al. proposed a complementing definition. According to Dix et al. the term of *interaction* can be described as *"any communication between a user and computer, be it direct or indirect"* [81]. This latter definition clarifies that all kinds of *communication* can be used by users and computers to realize influence or action. Further, Dix adds the terms of *direct* and *indirect* communication respectively interaction, whereas the first refers to interaction that is the immediate result of a user's action for instance, triggered by means of a

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[1] SIGCHI is a special interest group associated to the Association for Computing Machinery (ACM), which is primarily focused on human-technology as well as human-computer interaction. [246]

dialog. The latter refers to implicit control, which can be associated to other actions.

In order to enable users and computers to mutually influence each other *interfaces* are required. Such interfaces provide means for providing *feedback* and *control*, which reflects the bidirectional character of interaction. With humans being involved in the interaction process, options for designing interfaces are limited by their perceptual and motor capabilities for receiving feedback (which are factors influenced by a multitude of parameters such *age*, *fatigue*, and others; see [149, p. 3]) and performing input. Reconsidering Hewett's definition of HCI, the design of interactive systems as well as their evaluation are core aspects. As a consequence, interfaces being part of said interactive systems, are object to evaluation in regards of their *usability*, which involves for instance, assessing learnability, accuracy, and efficiency to name but a few.

Evaluating interfaces regarding their usability.

MOBILE HUMAN-COMPUTER INTERACTION With the definition of HCI, an extensive field is framed which includes all possible kinds of computing devices (e.g., mainframes, desktops, etc.). Therefore, to further approach the term of mobile mediated interaction, the term of *mobile human-computer interaction* or *mobile HCI* needs to be considered. Love defines this term as "*. . . the study of the relationship (*interaction*) between people and mobile computer systems and applications . . .*" [149, p. 2]. This narrows down the field of HCI to a specific class of devices (i.e. mobile or portable). Due to their inherent portability and the potential to use applications and services most different locations and hence, more diverse contexts of use need to be considered raising the need for mobile interaction design [131].

The field of mobile HCI.

MOBILE MEDIATED INTERACTION. In the context of both HCI and mobile HCI, users and computers interact directly or indirectly. That is, either by explicitly using a dialog providing feedback and control or implicitly through e.g., batch operations interaction is triggered. In both cases, interaction can only happen, if users can physically access and operate the interface. This thesis introduces the term *mediated interaction*, which refers to interaction with a computer device by means of a *mediator* device which acts as an agent that enables communication between user and computer. In theory, said mediator can be any kind of computing device. Yet, depending on the physicality, options for interaction can be rather limited. In the scope of this thesis, mobile devices (such as mobile and smart phones) are considered for this purpose of mediated interaction. Mobile mediated interaction provides characteristics that facilitate and leverage interaction with applications and services in a general sense. First, this is the possibility to *identify* users based on the mediator hardware Identifier (ID), given that the mobile device that is used as mediator,

The concept of mediated interaction.

is considered as *personal* device that is not used and shared with others. Second, mobile phones provide *personal digital context* in mobile settings. That is, users can easily access their personal data (e.g., PIM, photos, bookmarks etc.), share it, or add assets to this context. Mediation as general concept can be provided regarding multiple aspects. This includes bridging physical distance between user and computer, translating content, sharing and storing data, as well as authentication of personalized access rights.

2.1.2 *Relation of Mobile Mediated Interaction to other Interaction Styles*

Jun Rekimoto introduced a classification and comparison of *HCI styles* [215], which considers the *styles* Graphical User Interface (GUI), Virtual Reality (VR), pervasive computing, and Augmented Reality (AR). In the following, we develop a detailed characterization of mobile mediated interaction as one specific style for interaction by discussing its relation to aforementioned interaction styles.

Following Rekimoto's classification, GUIs for instance, running on a desktop computer, enable interaction between a user and a computer. However, during this interaction the user is isolated from the surrounding environment and the *real world*. Accordingly, a fundamental logical gap exists between environment and application used by means of a GUI and further, computer and real world are strictly separated. In contrast to mobile mediated interaction, here the user interacts directly with the GUI which requires immediate physical access.

Mediation & Virtual Reality.

In case of VR a computer creates a *virtual reality* surrounding the user [71]. Here, the user is fully detached from the environment (depending on the level of immersion reached by the specific VR setting). In contrast, with mobile mediated interaction the user interacts with a computer mediated through a personal device and is not shielded from the environment.

Pervasvie & Ubiquitous Computing.

Ubiquitous or pervasive computing in context of this classification is described as the interaction with multiple computers that are embedded in the user's environment. Again, the user interacts directly with each computer device which requires the user to be able to physically approach corresponding interfaces. Apart from characterizing the relation between user, computers, and real world, this briefest possible description neglects a multitude of various aspects that are necessary to frame this field of research.

Diversity of names for this field: in the past, several names that all refer to the same general field of research, have been established. The two most prominent and commonly used ones are *pervasive computing* and *ubiquitous computing*. According to the New Oxford American Dictionary, *pervasive* refers to *existing in or spreading through every part of something* while *ubiquitous* denotes *present, appearing, or found everywhere* [259].

Both names are often used as synonym or for the same concept (e.g., the *ACM International Joint Conference on Pervasive and Ubiquitous Computing* is the most renowned conference in this field, see [54]). For the sake of simplicity, in the course of this thesis the term *pervasive* is preferably used.

Mark Weiser's well-received article "*The Computer for the 21st Century*" can be seen as foundation of pervasive computing [285]. It introduces the concept of *calm technology* that blends in the user's environment, allowing users to focus rather on their current task than the technology that is used [286]. Want describes pervasive computing as the *third era of computing* [282]. That is, the first era of computing was defined by mainframe computers; machines used by several users. The *second era* was defined by the Personal Computer (PC); machines that are owned by one single user, who is in turn, using only one computer at a time. Now the *third era* of computing – pervasive or ubiquitous computing – is characterized by the quickly growing number of computing devices with decreasing form factors (e.g., smartphones, tablet computers, wearables, and sensors and actuators in smart homes). Accordingly, there are two oppositional trends: *(a)* the number of computing devices per user, and *(b)* the size of computing devices. As a result, users can take advantage of a growing number of devices for different tasks that are available in their environment.

Consequently this fundamental computing paradigm shift raised a multitude of research challenges which were classified by Ferscha as three major trends or *generations* of research in the past [87]:

- The first generation was about *connectedness*. That is, technological foundations regarding hardware miniaturization, power consumption, as well as wireless communication technologies such as Radio Frequency Identification (RFID) were initially addressed.
- The second generation addressed questions regarding *awareness*. Reflecting Weiser's vision, technology should be calm and unobtrusive. Hence, sensors were used to capture data regarding the user, presence of other users and machines, and ongoing activities to allow technology to adapt to this *context* [78, 79].
- The third generation is focusing on *smartness*. That is, recent work *"has been attempting to exploit the (ontological) semantics of systems, services, and interactions (giving meaning to situations and actions)."* [87].

The work presented in this thesis reflects this sequence of generations as it draws on technological foundations (i.e., wireless and near field communication etc.), uses awareness information (e.g., sensors for context acquisition), and investigates how the interplay of several devices can be facilitated in various application contexts.

Mediation & Augmented Reality.

The fourth style included in Rekimoto's classification, AR, allows users to access additional information that are virtually attached to physical objects [32]. This asset information is rendered on a secondary display device that is spatially aware. Similar to mobile mediated interaction, AR provides some level of mediation: the display rendering the virtual content that augments the physical objects acts as a mediating device by providing access to otherwise invisible graphical data. Mobile mediated interaction follows a more general approach that is not limited to the graphical augmentation of physical objects but aims for general input and output mediated through the handheld mobile device. In addition, the mediator device is not necessarily considering its spatial relation as in the case of AR.

Mediation & Physical Mobile Interactions.

Rukzio et al. introduce an additional interaction style that they call *physical mobile interactions* [52, 220, 222]. This style includes *(a)* direct interaction with the *real world*, *(b)* interaction with the *real word* (e.g., smart objects) mediated through a computer device, and *(c)* interaction with a computer by means of a mediator device. According to this description, mediated interaction as focused on by this thesis, can be classified as a specific case of physical mobile interaction. That is, interaction including human-computer as well as computer-to-computer interaction is an aspect that is shared by mediated interaction as investigated in this thesis.

2.2 CLASSIFICATION SCHEME FOR MEDIATED INTERACTION

In order to ensure a structured line of action, a model or concept is required to guide the approach. One prevalent option is to make use of a *taxonomy*, a *classification framework* or *scheme*, as well as *design spaces*, which provide a clear overview of for instance, technological capabilities or limitations or other general inherent features that can be used to describe the matter of subject. In any case, such schemes seek to provide features or dimensions that have a strong discriminative power that allows to make clear distinctions between a set of existing classes. Hence, they can be used to (a) structure existing work, (b) providing an overview of approaches which (c) supports identifying novel opportunities.

In the context of interaction techniques, several approaches for classifying techniques were proposed. In the context of mobile mediated interaction with pervasive displays, the aspect of spatial relation and resulting challenges between user, mediator, and pervasive display is the main objective in this thesis. As for, first, existing classification schemes are discussed that allow structuring and categorizing interaction techniques. Second, this section introduces a spatial classification scheme that is used in the course of this thesis for structuring mobile mediated interaction techniques.

2.2.1 *Existing Classifications*

With an increasing number of diverse possibilities to operate User Interface (UI)s, the need for classifications and taxonomies was identified. As for, in 1983 Buxton introduced a taxonomy of continuous input devices [56]. In essence, this taxonomy is based on two diametrical dimensions: (a) property sensed and (b) number of dimensions. The table that is spanned by means of these dimensions, includes for each axis three levels (e.g., number of dimensions is subdivided into *1..3*). Within this coordinate system created through this table, existing work can be located which yields eventually in a visual overview which combinations of particularities of dimensions are more common or are rather rare. This overview however, also allows grouping work that is otherwise not related.

Card et al. present, based on Buxton's and others' work, a refined approach for framing the design space of input devices [57]. Their taxonomy follows the understanding that *"the design space for input devices is basically the set of possible combinations of the composition operators with the primitive vocabulary"* [57]. That is, the design space allows locating and characterizing items such as input devices or techniques. This classification is based on the primitive vocabulary, which corresponds to the basic actions a user can perform with the input device. It is important to acknowledge, that Card et al. introduce *composition operators* in the context of this classification. They use the term *composite devices* to refer to devices that incorporate multiple input primitives such as computer mouse, which consists of 2 + 3 *devices*: one slider for the x-axis and one slider for the y-axis of the mouse cursor. Further, three mouse buttons, which each corresponds to one *device*. Accordingly, this taxonomy allows a classification in regards to the action the user has to perform physically.

From a technical point of view, Card's et al. design space is again represented as two-dimensional table, which spans the space of *movement type* and *action type*. Within this space, each *device* is located within the corresponding quadrant. In addition, within these quadrants the particularity of granularity (i.e., discrete vs. continuous) is encoded through the location. To visualize the grouping of *composite devices*, lines are used.

Domain Specific Classification Approaches.

Both discussed approaches for classifying interaction are focusing on input devices and their basic capabilities. Considering these two approaches, it becomes evident that taxonomies in general are limited by the amount of dimensions they can incorporate without becoming overly complex and to remain useful. Therefore, domain specific taxonomies are a useful way to classify interaction devices or techniques that belong to a specific field. Their main advantage is, that a domain specific set of dimensions can be selected. Examples for such domain specific classification are for instance, a taxonomy for interaction with ephemeral interfaces [83], or a taxonomy for gestural interaction techniques [236]. Based on Foley's work [91], Ballagas et al. proposed a domain specific classification scheme for ubiquitous computing interaction [33]. And finally, Rukzio used this latter classification to frame mobile physical interaction techniques [220].

All these discussed approaches are serving the purpose of making sense of the sheer amount of theoretically and practically possible input and interaction possibilities and thus, they are all device or technology focused. However, none of these aforementioned classification approaches focus the user itself as a fundamental factor during the interaction. That is, in general the context of the user and more specifically, the location of the user in relation to the devices they would like to interact with. And further, even though Card et al. introduced *composite devices*, the aspect of mediated interaction incorporating multiple devices, cannot be classified properly with these existing approaches. Therefore, in order to fill this gap and to provide a classification scheme for use within the context of this thesis, a user-centered spatial classification scheme is introduced in the following.

2.2.2 *An Anthropomorphic Classification Scheme*

Interaction – that is, the mutual action or influence (see section 2.1.1) – in pervasive multi-display environments can occur in a multitude of different styles [184]. This thesis focuses on mobile mediated interaction techniques which reduces the number of possibilities considerably. However, the amount of possible combinations of operating the mobile mediator and pervasive displays in the periphery is still indefinite. Accordingly, a classification scheme is required in order to introduce a systematic which allows a categorization of interaction techniques. The main motivation for such a systematic is that existing interaction techniques can be analyzed systematically and knowledge about interaction techniques is accessible in a comprehensive way. Not only researchers benefit from such a framework, as it allows to classify existing and novel designed techniques and facilitates hence finding similar or related techniques that might be of interest for the sake of comparison. Also, application designers can use such a framework to assess similar interaction techniques offering different possibilities for a specific application.

In order to serve as valuable resource and effective means for controlling complexity and diversity, the framework needs to be granular enough to distinguish sufficient categories while remaining general enough to include all possible cases. Further, it should be extensible, allowing others to build on refine the framework.

Distance as Discriminating Feature

SUBDIVIDING THE INTERACTION SPACE. As this thesis considers mobile mediated interaction with pervasive displays (within the pervasive interaction space), the framework is chosen to consider a spatial distinction of interaction techniques. That is, the physical distance between mediator object and pervasive display is applied as discriminating feature. For selecting the spatial categories, a user-centered approach is chosen by considering the human gestalt. This *anthropomorphic* (i.e., based on the anatomic particularities of the human body) approach yields directly two spatial categories: (*1*) a space within direct reach of a user and (*2*) a space outside their reach (see Figure 2).

While in the space out of the user's reach only distant interaction (e.g., though pointing) is possible, the space within reach can to be further distinguished: here, (*a*) users can interact through directly touching the external pervasive display and (*b*) through acting in the immediate vicin-

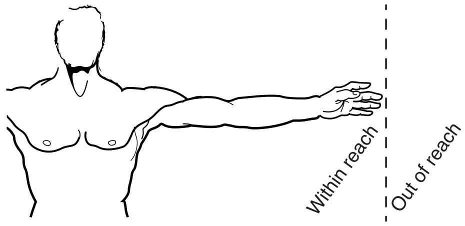


Figure 2: Anthropomorphic classification framework for mediated interaction techniques: interaction space within and out of the users' reach.

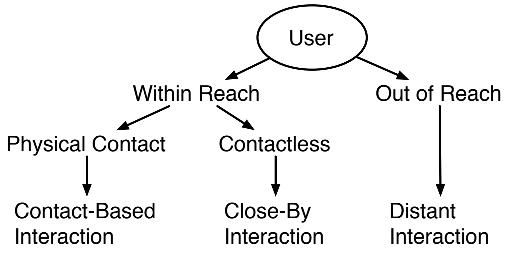


Figure 3: Classification of spatial interaction categories.

ity. In sum, this yields three generic spatial categories in which mediated interaction techniques can be classified (see Figure 3): *(1.)* contact-based interaction, *(2.)* close-by interaction, and *(3.)* distant interaction.

2.2.2.1 *Contact-Based Interaction*

Interaction techniques that can be assigned to this category require users to bring their mediator device, that is, their mobile phone, in physical contact with pervasive display in the periphery. Thus, the mediator device *touches* the other display. For instance, users could place their mobile phone on an interactive tabletop device in order to trigger an action (see Figure 4, left-hand side). However, mediator object and pervasive display can be brought in physical contact (i.e., touch each other) in most various ways.

Contact-based interaction allows placing *the mediator and* keeping *it in the hand during the interaction.*

First, placing the mediator object frees users' hands for secondary interactions. Yet, this requires a (sufficiently) horizontal surface for placing the mobile phone. Hence, this occurrence of touch-based mediated interaction works only with pervasive displays such as tabletop computers.

A second option for designing contact-based mediated interaction techniques is to require the user to keep the mediator object in their hand during the continuation of the interaction. This yields several distinctive features with respect to placing the mediator object. First, the interaction is not limited to horizontal surfaces such as tabletop computers as also vertical displays can be operated with the mobile phone remaining in the user's hand. Second, interaction can consider several different ways of how the mediator object is touching the pervasive display. For instance, in the case of a mobile phone the four corners and edges can be distinguished and used for interactions.

A third option seeks to overcome the physical boundaries of the involved mediator and display devices. This aims for creating ad hoc logical displays that span across multiple devices in order to create a larger display space. For instance, this allows to combine several devices temporarily in order to distribute a user interface on several potentially larger displays which supports jointly viewing data with other users.

2.2.2.2 *Close-By Interaction*

Interaction techniques which can be associated to this category allow users to manually or semi-manually control the mediator's position in space near a pervasive display. Thereby, the space is limited by the user's arm reach. This spatial category inherently allows users to transition to touch-based interaction when the physical facts would allow so. The spatial relation of the mediator device and the display can optionally be used for control or triggering actions. For instance, users could hold their mobile phone over an interactive tabletop device in order to control the position and size of a spatially attached visual representation on the tabletop device (see Figure 4, right-hand side).

2.2.2.3 *Distant interaction*

Interaction techniques which can be classified in this category enable users to interact over a distance with pervasive displays beyond their direct reach. This category distinguishes oneself by preventing users from approaching the pervasive display (e.g., through social or physical constraints). Similar as with close-by interaction, the spatial relation of mediator device and pervasive display is considered optionally. For instance, users can use their mobile phone as pointing device to select targets on a remote display (see Figure 4, background).

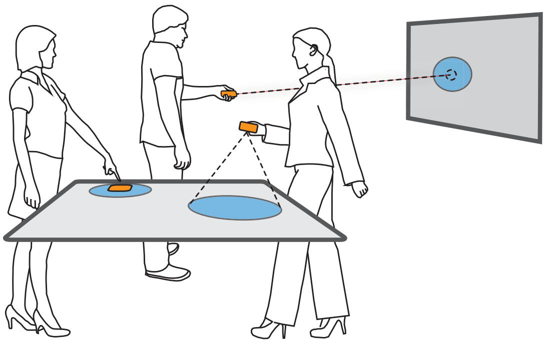


Figure 4: Interaction opportunities in the pervasive interaction space: contact-based, close-by, and distant interaction involving personal mobile phones as mediator objects on interactive surfaces.

Classifying interaction possibilities in space.

This classification scheme can be used as straightforward means for distinguishing interaction techniques. Due to its low complexity, most interaction techniques can be assigned to a specific category clearly. Yet, some techniques that allow users transitioning between different physical distances would not allow a clear classification but rather a multi-category assignment, which makes this framework rather inclusive than selective. Further, the scheme can be extended by either applying a finer grained spatial differentiation, or by considering additional discriminating features. For instance, one could use an aspect such as single-handed or bi-manual interaction in a specific application area.

For each of the three categories, this thesis offers different novel interaction techniques and applications that either present first insights for the specific domain or extend the existing state of the art. The subsequent table gives an overview of work conducted within the scope of this thesis and provides pointers to the subsequent sections in which each is discussed in detail (see Table 1).

Contact-Based	*Close-By*	*Distant*
MobiSurf (3.1)	MobiZone (5.1)	PointerPhone (6.1)
MobIeS (3.2)	Hover Pad (5.2)	Hover Pad (5.2)
MoCoShoP (3.3)	projecTVision (6.2)	projecTVision (6.2)
projecTVision (6.2)		
TreasurePhone (4.2)		
Smart ATM (4.3.2)		
Shield&Share (4.1)		

Table 1: Overview and classification of work conducted within the scope of this thesis.

Table 1 shows the short names of research activities and projects that were conducted within the scope of this thesis. It is noticeable that the column representing work regarding contact-based work is filled with considerable more entries compared to the two other columns. The reason for this proportion is that by means of contact-based interaction techniques several aspects have been investigated. That is, with MobiSurf, MobIeS, and MoCoShoP aspects of co-located collaboration have been investigated. Further, the work TreasurePhone, Smart ATM, and Shield-&Share were mainly focused on privacy aspects. The fields of close-by and distant interaction were investigated with a strong focus on the interaction options. Please note that several items appear multiple times in the table, which is due to the covered aspects in the respecting work. In particular the work projecTVision covers all three distant categories as this work aimed for investigating a continuous interaction space.

2.3 PRIOR ART & RELATED WORK

In this section, we summarize the review and analysis of the body of related existing work, which has been considered in the context of this thesis. The two main goals are, on the one hand, to illustrate the state of the art and work related to this thesis' main theme of mobile mediated interaction. On the other hand, this analysis aims to identify and frame open issues. The offered perspective in this section focuses on a higher level analysis, which is complemented by additional and specific background discussions in the context of subsequent chapters.

This section discusses prior art that can be considered as predecessor approaches that motivate the work of this thesis. First, direct interaction with pervasive displays is analyzed, which illustrates the need for mediated approaches in general. In addition, the specific aspects of co-located collaboration as well as tangible and embodied interaction are examined in particular. Second, earlier approaches for connecting personal devices with shared device resources is discussed. In this context, approaches that serve rather as augmenting information display are discussed as well as privacy issues that potentially arise when connecting personal and shared devices. Further, the aspect of space and spatial relations is discussed. This includes in particular the aspects of spatially aware display systems as well as extending and augmenting displays. Finally, this section discusses prior art that can be categorized as mediated interaction by first analyzing contact-based and then distant mediated interaction approaches. This section closes with a general discussion and summary of prior art and its meaning for the research of this thesis.

2.3.1 *Direct Interaction with Pervasive Displays*

Pervasive displays can occur in a large variety of physical particularities. These range from static passive displays (e.g., in form of an NFC augmented poster [110]) to all kinds of (horizontal or vertical) interactive surfaces [50, 67, 80, 105]. Also very large displays such as media facades [94] as well as small, embedded, and ambient displays [206] such as the dangling string [286] belong to this larger category of pervasive displays. In order to enable direct interaction with these displays the user and display need to be sufficiently close to each other to allow users to either *touch* the display, or to use gestures (e.g., to control a distant Television (TV) set [175]) or voice commands to communicate with the system (e.g., to control a public display [179]), which are the general options for direct, non-mediated interaction. This however, requires the corresponding display system to support any of these kinds of communication. For instance, the *Diamond Touch* interactive surface allows for direct touch [80], while a passive static display such as a poster [110] cannot support direct interaction.

Prior work on direct interaction with pervasive displays mainly focuses on touch-based interaction using hands and fingers.

Fails and Olsen emphasize that users wish to interact immediately with these pervasive and partly embedded displays, for instance, by directly touching them using some kind of widgets or interactive areas [85].

Early work by Wellner et al. focused on fusing interactive surfaces in the user's environment to augment these. For instance, a tabletop device enabled users to place physical sheets of paper on a projection-based interactive surface, which were augmented with additional information [290, 291]. A similar approach was followed by Underkoffler et al., who investigated the *luminous room*, which allowed users to place physical widgets on a surface, which were augmented through top-projected contents [273]. This concept of turning existing everyday surfaces into displays was picked up by Pinhanez et al. who proposed the *everywhere display* [205]. They investigated how using projection all kinds of surfaces within a given room could be transformed into an interactive surface. A prototype by Pinhanez et al. provided already basic touch-input capabilities. Harrison et al. leveraged this work and presented OmniTouch, a wearable camera-projector system that allows rendering interactive surface on all kinds of surfaces in the user's environment [111]. Direct touch-based interaction most often refers to a user who brings one of her fingers in physical contact to a touch-sensitive interface. In cases that two or more touch-points can be distinguished, the term of *multi-touch* is used as characterized by Han [105]. In addition to using the fingertips, other touch-based options have been realized including whole hands [231, 303], edge of the hand [135], and knuckles and fists [293].

Large interactive surfaces allow multiple users at the same time to collaborate.

CO-LOCATED COLLABORATION SUPPORTED THROUGH INTERACTIVE SURFACES. Pervasive displays can occur in most diverse form factors which can be radically different from desktop computers. For instance, interactive surfaces in form of horizontal tabletop computers do not only introduce a new interaction paradigm (i.e., mostly touch-based interaction), but also in terms of form factor they enable new forms of interaction regarding cooperative work of multiple users. That is, a tabletop allows multiple users to gather around and work for instance, on a shared tasks by means of the shared surface. Accordingly, a large body of work focuses on the potential advantages of shared interactive surfaces for co-located collaborative work.

Relatively early work by Scott et al. presented guidelines for the design of co-located, collaborative work based on shared interactive surfaces [238]. These guidelines, while designed for purely surface-centric interaction, are highly relevant also for the design of mediated interaction techniques. The guidelines demand systems to support for instance, *"natural interpersonal interaction"*, *"transitions between personal and group work"*, *"transitions between tabletop collaboration and external work"*, and *"simultaneous user interactions"* [238]. Also Yuill and Rogers present findings regarding requirements and use of multi-device environments and their impact on collaboration [307]. In particular, they emphasize that in situations when users have access to personal and shared devices at the same time, individual and shared phases should be supported through corresponding devices. That is, aspects that are rather performed during individual work, should be supported on the personal device and vice versa, shared activities should be supported on a shared device such as an interactive surface.

Territoriality: users split the surface space into shared *and* private *spaces.*

Considerable effort has been invested in researching the potential of shared surfaces for group tasks that are related to searching pieces of information (e.g., [27, 177, 178, 268]). These works however, did not consider additional devices such as personal laptops or tablet computers, which forced users of these approaches to arrange their activities on the shared surface. Hence, the use of space and territory is crucial to understand for the design of such collaborative applications. Scott et al. observed during their study that people distinguish three different types of space on a shared interactive surface: *personal, group,* and *storage* areas [237]. These areas are based on the users' behavior and their *social conventions*. Such conventions however, tend to be only weak rules which can result in interference of users' actions [204]. Tse et al. emphasize that *"there is risk of interference: when two people are interacting in close proximity, one person can raise an interface component [...] over another person's working area..."* [266]. In their study, Tse et al. found that *"spatial separation and partitioning occurred consistently and naturally across all participants"*. Marshall et al. who designed and studied a collaborative planning application for tourists for a *walk-up and use* scenario in a tourist office, hence designed clear areas for each user [161]. Wigdor et al. present the *WeSpace* which addresses the limited space issue by connecting a large wall-mounted display with a shared tabletop computer [294]. Shen et al. presented the *UbiTable*, which combines a shared interactive surface with two laptop computers for two possible users [241]. This setup allows users to share data using the common surface while content located on the connected laptop remains private. Also the system *Carreta* by Sugimoto et al. follows the concept of using personal devices to allow users to work individually while a shared surface enables working on the common task. While there have been approaches for leveraging collaboration through additional personal devices, the setting was only static and did not support dynamically adapting to different collaborative situations.

TANGIBLE & EMBODIED INTERACTION. The majority of pervasive displays is based on rendering visual output based on modulated light. While this has several advantages such as flexibility and speed, one major disadvantage is that interfaces based on such displays are rather indirect as they do not allow to grasp displays' virtual artifacts. This immanent shortcoming of conventional graphical UIs motivated the exploration of tangible interfaces that allow users to physically grasp and manipulate the interface.

The system *mediaBlocks*, which features small wooden tangible items, which was presented by Ullmer and Ishii is an early example for a *tangible UI* [272]. The tangible items serve as containment, for transport, and manipulation of corresponding virtual objects. That is, such mediaBlocks can be assigned to a file, which can be carried from one computer to another. Based on this concept, Waldner et al. presented *Tangible Tiles*, a system comprising a top-projected interactive surface and said tiles, which allow to interact with digital contents that are associated to them [279]. Weiss et al. introduced with *SLAP* tangible widgets such as sliders, buttons, and dial wheels which can be placed freely on an interactive surface, which senses user input performed with these widgets [289].

Tangible interfaces add the dimension of physicality to communicate the state of a virtual model.

From a technological point of view, mainly two approaches have been investigated: in case of Ullmer's *mediaBlocks*, the tangible items had to be placed on dedicated reader devices (i.e., so called *"slots"*), which used Dallas Semiconductor iButtons™ to read the stored IDs. The implementations of *Tangible Tiles* and *SLAP* however, rely on an optical tracking approach. Waldner et al. used 2D markers for tracking tiles while Weiss et al. used the widget's geometric characteristics to track position and states. These two general approaches (radio-frequency based, and optical tracking) have been combined by Olwal et al. who presented *SurfaceFusion*, an interactive surface system that tracks tangible items not only using their shape but also by means of attached RFID tags [194].

These aforementioned tangible interfaces enable users to grasp an interface physically and manipulate it directly. However, the corresponding system is not capable of rendering changes that have been applied to the underlying virtual model. Ishii et al. propose the vision of *radical atoms* that foresees computationally controlled artifacts that can autonomously change their physical appearance [122]. For instance, the work *inFORM* by Follmer et al. illustrates this concept of a dynamically changing physical appearance by featuring a shape changing interactive surface [92]. Much earlier work in this field investigated small individual motorized objects that can move freely on an interactive surface, which allows to provide also physical output [219]. This idea has been picked up by Pederson and Hornbæk, who presented small *tangible bots* that enable bidirectional tangible input and output on a UI [203] as well as by Nowacka et al. who miniaturized the motorized tangible agents to the form factor of bugs [190]. Weiss et al. investigated even finer grained and miniaturized forms of actuated output and presented self-actuated widgets on interactive surfaces [287, 288].

More recent work investigated how self-actuated tangible interfaces can encounter also space beyond flat surfaces. Marshall et al. used ultra sound to move light weight balls over a small defined surface [160]. Alrøe et al. utilized controlled air streams in order to place small balls that hover in mid-air to visualize a sound scape installation [24]. This rather artistic work, however, explores how interfaces can take advantage of self-actuation in mid-air. *TouchMover* by Sinclair et al. uses actuation in space (along one axis) of a large scale (24”) touch screen in order to provide a tactile interface that allows to explore pseudo physical characteristics of virtual items (e.g., weight or shape) [247]. In summary, there are little insights so far investigating how interaction can be designed to control self-actuated interfaces that move self-actuated in space.

Self-actuated and autonomous movement for physical interfaces to leverage displaying model changes.

2.3.2 *Integrating Personal & Shared Devices*

For the integration of *personal* and *shared* devices several phases and iterations were passed through on the way to mobile mediated interaction with pervasive displays. In general, two major advantages for the user can be derived from connecting these two classes of devices: accessing and sharing data. That in turn, enables their manipulation and control and thus interaction across devices.

PERSONALIZED OUTPUT USING HANDHELD DEVICES. Early work investigated at first the potential of using a personal device for accessing information that is, for instance, not visible for the human sight. Bier et al. presented the concept of the *magic lens*: a handheld display device reveals information that are not visible before [43]. Fitzmaurice adapted this concept for the *Chameleon*, a handheld display device that senses its spatial relation to an external display (in particular a large paper map) and provides corresponding additional content [89]. Rekimoto and Nagao also used a handheld device that provided a display and a camera to track the user’s environment, in order to reveal virtual data content that are spatially registered with real world objects [215]. Similar settings, with devices that reveal virtual content that is attached to physical objects, has been intensively investigated within the field of augmented reality [32]. In particular handheld devices such as smartphones with their built-in camera and sensors have been used in augmented reality settings [228]. More recent work by Spindler et al. investigated handheld *paper lenses*, that serve as magic lens for exploring the space over an interactive tabletop [254]. Here, the user manually moves this lens through space and corresponding content is projected on the handheld display.

Personal output through a handheld device without interaction.

SHARING PERSONAL DATA ON EXTERNAL DEVICES. Personal devices have not only been *connected* or associated with external devices and displays to serve as personal output but also the other way around, to share data via the connected display. For instance, Robertson et al.

designed a real estate sales support application that is running on the Personal Digital Assistant (PDA) of the sales officer [218]. On the PDA the officer could access data related to sales objects. In order to share and show specific data to clients, the PDA was connected to an external TV. An example for similar work, yet in a different application domain is work done by Ratib et al., who designed an application for hospital staff, who could display data, stored on a personal PDA, on an external display that was located in the hospital environment [210]. Work by Nichols et al. introduced the concept of the *personal universal controller* as a generic controller device for any external complex appliances [185, 186]. Through a generic description language that expresses each appliance's capabilities, interfaces for the personal universal controller can be generated and such appliances can be controlled. For instance, a stereo set could be controlled remotely using a PDA.

PRIVACY ISSUES WITH SHARED DEVICES. Privacy in general and information privacy in particular are essential aspects that need to be considered when designing mobile mediated interaction techniques with pervasive displays. On the one hand, while using a shared device with other users, all actions can be observed by others which might expose sensitive data (e.g., a password). On the other hand, connecting the personal mobile device with shared infrastructures and using them for sharing could cause unintended and accidental disclosure of sensitive data from the personal device.

Identifying and distinguishing users.

Within this context, the aspect of user identification has been addressed by a large body of work. That is, while interacting with interactive surfaces, from the system and application side it is hardly possible to distinguish between users nor to identify them when using e.g., standard FTIR technology. Dietz and Leigh presented a first technology – called *DiamondTouch* – that allowed user distinction which extended the design space for multi-user applications considerably [80]. Kim et al. presented privacy protecting input techniques that allowed users to securely authenticate them on the shared surface [135]. With the system *IdWristbands*, Meyer and Schmidt introduced a wrist-worn token device that allowed implicit authentication on a shared surface [164]. Holz and Baudisch introduced the technology *FiberIO*, which allows to implicitly identify users by the fingerprints while they touch the interactive surface [118].

Controlling how personal data is shared.

In addition to the question who can access or manipulate a data item, the question was addressed how to manage the disclosure of data. When connecting a personal mobile device with a public terminal in order to use cross-device or multi-display applications, privacy issues arise regarding the way information can be displayed [240]. In particular a challenging issue is regarding the choice *where* or on which device information may be displayed without harming the user's privacy. Sharp et al. present a filter-based approach, which makes sensitive data unreadable on public displays by simple obfuscation [240]. A more elaborate approach was presented by Shoemaker et al. who used shutter glasses to provide a personalized view on a shared surface [244]. Users can simultaneously work but see different contents on the surface (through time sequential displaying). Similar also Lissermann et al. used shutter glasses to enable private input and output [148]. An alternative approach was presented by De Luca et al. who used the mobile phone which was connected to a public terminal, to enter a secret Personal Identification Number (PIN) on the phone [75]. Similarly, also Schmidt et al. used a connected mobile phone as device for secretly entering a password in order to prevent other users to observe the input [16].

Personal mobile devices as privacy risk.

Privacy related aspects are highly relevant in the context of personal devices such as mobile phones. Stajano emphasized that said devices with their capabilities (i.e., access to services) and stored data bear a high risk when the user loses control over them [256]. For instance, mobile phones have been used as authentication token for an access control system [38]. Boyd et al. even proposed the *wallet phone*, which not only would provide access to the user's data, but would also serve as payment device [49]. Event though most mobile phones do not provide such sensitive applications, people do not like to share their mobile phone (i.e., hand it over to another user), in order to show some pieces of information (e.g., an image) [134]. Accordingly, one can argue that connecting a personal device with a shared device can address this problem. For instance, using the *Phone Touch* technique introduced by Schmidt et al., users can share data using a pick-and-drop technique [230]. However, said technique was not investigated in regard to its effectiveness of preventing users from accidentally disclosing data.

2.3.3 *Ambiance & Spatial Relations in Pervasive Spaces*

In the context of mobile mediated interaction techniques with pervasive displays the aspect of ambiance, that is, the spatial relation of users, and personal and shared devices is of high relevance for the possibilities how interaction can happen. Due to the amount of influencing parameters (i.e., users and different devices each with specific spatial relations), the resulting complexity demands models for controlling and managing it.

Dey and Abowd propose and define the concept of *context* [22, 79] which is "*. . . any information that can be used to characterize the situation of an entity*" [78]. An entity here means either an artifact or a person and hence, applies to the aforementioned parameters that are relevant to mediated interaction. With location and space being parameters that *characterize* the relation of different entities, they are promising parameters to model their relations. Beigl et al. developed a location model that allows to describe the context of objects [41]. While one of the advantages of their model is the relative low complexity, Schmidt emphasized the aspect in accordance to Dey and Abowd that location can only approximate actual context [229].

Further, more recent work by Marquardt and Greenberg et al. explores *proxemic interactions* [154–158] which are defined as *"the relationships of people to devices, of devices to devices, and of non-digital objects to people and devices."* [35], whereas the characterizing features are relative *distance*, *orientation*, and *movements* to each other. Based on this concept, Marquardt et al. explore for instance, how interfaces can adapt to users while they are approaching an interactive surface (the finger before and finally touching the surface) [159]. With focusing in particular on the transitioning between the spatial configurations, this research on proxemic interaction is closely related to the area of mediated interaction with pervasive displays.

SPATIALLY AWARE DISPLAY SYSTEMS. Through exploiting relative spatial relations of multiple displays to each other, three categories of spatial reference systems can be identified: *(1)* world-centric, *(2)* display-centric, and *(3)* body-centric reference systems.

Using the explicit change of spatial relation between handheld display and environment to control output.

Yee presented *peephole displays*, which are based on the metaphor of a small window into a larger virtual world [306]. Here, the window is provided through a handheld display (PDA), which is connected to a location tracking device that senses the display's movement in space. Relative to this movement, the displayed content on the handheld is adapted (i.e., deferred). Another world-centric spatially aware display system was presented by Tsang et al. who introduced the *Boom Chameleon*, a spatially aware display mounted to a boom which allows users to manually control the display's position within a defined space [264]. The joints of the boom are equipped with sensors to track the movement that the user performs with the display. The *iCam* system by Patel et al. enables tracking of location in relation to the user's environment (via a camera) and allows thus creating and reading virtual content that is attached to physical items [200]. A different approach for tracking the spatial particularities is *KinectFusioin* by Izadi et al. [126]. It utilizes a depth camera to create a detailed model of the environment which was used for instance, by Wilson et al. to render geometrically aligned graphical content in the environment using the *Beamatron* system [301].

Display-centric spatially aware approaches are based on an secondary large screen that serves as reference for the handheld display. Sannebald and Holmquist implemented this approach for their *ubiquitous graphics* system [224]: a handheld tablet computer is moved manually in front of a large projected screen. Depending on the location, a spatially aligned high-resolution version of the projected background is displayed on the tablet.

Izadi et al. presented an interactive surface, equipped with a switchable diffuser which allows to project through the surface onto a handheld paper display, which is held by the user [125]. Conceptually similar, yet technically differing, are the approaches by Spindler et al. [251, 253] and Steimle et al. [258] who used top-projection for rendering content on handheld displays that are spatially related to the underlying surface.

Body-centric approaches are independent from the user's environment and do not consider other displays. Thus, this direction is just remotely related to mobile mediated interaction. Yet, in order to give one example, Chen et al. applied the peephole metaphor for a mobile phone that allows users to access data that is placed in space relative to them [64].

EXTENDING & AUGMENTING DISPLAYS. Mobile devices are being used for virtually all kinds of computing tasks. This however, raises challenges regarding the possibilities for visualizing information on their small screens. One obvious approach is to optimize the mobile information visualization as advocated by Chittaro [65]. This approach is limited through, as specific types of spatial data (e.g., images) require screen space in order to be displayed. Hence, an alternative is to temporarily connect two or more devices to create a logical larger screen.

One first approach is using *hybrid user interfaces* as presented by Feiner et al. [86]: a head mounted display renders additional interfaces around a screen and thus enlarges the available space. This concept raises issues, for instance, head mounted displays used for augmenting standard displays require users to focus their eye-sight on two different focal planes, which can be tiering. Hence, a different approach is to connect portable devices through ad-hoc interaction as presented by Hinckley et al. with the *stitching* system [117]. Here, users place tablet computers next to each other and their displays get logically merged. This required sensing of the *placement* through accelerometer sensors as well as through a *stitching gesture* performed across the touchscreens of the two devices by the user. A similar concept for a *dynamic composed display* was used by Lyons et al. [153], who implemented a system that enabled to create one logical display consisting of four tablet computers.

Most approaches for dynamic composed displays consider only homogeneous devices.

Further work by Grolaux et al. investigated possibilities of automatically distributing UIs across multiple available displays [103]. More recent work investigated how mobile phones can be used to create dynamic composed displays: for instance, Lucero used mobile phones as display tiles that could be composed freely to create a larger screen [151]. Further, Lucero researched possibilities for loosely coupled mobile screens that facilitate in particular content sharing between multiple users [150].

Integrated multi-display devices.

A rather different concept was followed by Hinckley et al. who presented a dual-display device called *Codex* [116], which allows diverse display configurations as the two displays can be folded in a number of different ways. Also Winkler et al. presented a mobile dual-display device, the *Penbook* [14]. This however, uses a pico-projector to render the secondary screen, which offers the advantage of small hardware in relation to a relatively large projected display. Also Kane et al. used projection in order to augment the display space, yet in their case for a laptop computer device called *Bonefire* [133]. This allows users for instance, to place widgets and windows literally in the periphery while the main display is used for the primary task. Winkler et al. use mobile projection to create a display space that can dynamically switch between floor projection and personal projection on the user's hand [302]. While this latter approach requires the user to switch between two modes of displaying information, it allows users to adapt to the content that is currently viewed.

This overview shows that little to no work has investigated the use of different device classes to create larger logical screens composed by multiple devices. The projection-based approaches such as *Bonfire* use the projection rather es built-in feature than as a dynamic extension.

2.3.4 *Mediated Interaction Techniques*

The review of related literature and prior art reveals that a number of work has been done that can be classified as mediated and even mobile mediated interaction. Following the earlier introduced classification scheme, this section first summarizes the work on contact-based interaction.

CONTACT-BASED INTERACTION. One of the first examples of an contact-based interaction technique that includes a device for mediating bi-directional interaction, is the *Pick-and-Drop* technique by Rekimoto [214]. Here, the user is provided with a digital pen, which can be used to pickup a data item for instance, on a personal handheld device and can be dropped subsequently on a shared interactive surface. Please note that here the mediator object is not the personal display device itself but an additional device.

Rukzio et al. present first mobile mediated interaction including *touching* and *scanning* for interaction with smart objects and to control them [221, 222]. Based on these techniques, several concepts followed, whereas NFC as underlying technology for sensing *touch* or *physical contact* of mobile phone and external appliances was used primarily. For instance, Hardy and Rukzio implemented the *Touch & Interact* technique based on NFC [109], which allowed basic interaction with NFC augmented displays. Further work that draws on this approach investigated NFC augmented laptop displays [239] as well *dynamic* and *static* displays [110]. While NFC as a technology has multiple advantages such as low costs or short reading range, the main disadvantage for mediated interaction is the low resulting input resolution which requires workarounds such as zooming or detail on demand.

Multiple technological concepts were presented previously that enable contact-based mediated interaction.

A quite different technological approach for implementing mobile mediated interaction with an external pervasive display has been followed by Wilson et al. who presented *BlueTable* [300]. Using this technique, users can place their Infrared Data Association (IrDA) enabled mobile phone on a surface. Via Bluetooth, the phone is triggered to send a connection sequence via the IrDA, which is tracked to either identify a phone and to further sense its location and orientation. This technology allows for instance, to share data such as photos on the surface in a similar way as presented by Microsoft to demonstrate their *Surface* device [173], which however, raises privacy related issues such as how data should be selected for disclosure.

Hutama et al. equipped a mobile phone with two *touch prongs*, which need to be brought into physical contact with an external display and use *tilt-correlation* of the touch-points on the display as well as the sensed tilting of the phone to match and distinguish different phones [120]. This allows for personalized interaction mediated through a mobile phone. Schmidt et al. demonstrated with their *Phone Touch* technique a pixel-precise contact-based interaction technique for mobile phones in connection with FTIR-based interactive surfaces [230]. As physical contact between mobile phone and surface can be tracked with high precision, as well as different phones can be identified, this technique allows to use the mobile phone as general input and output device [16] for mobile mediated interaction based on physical contact. Hence, technology-wise this technique answers most questions raised by previous technology approaches. Yet, regarding the interaction and in particular, regarding social interaction and accompanied privacy aspects open questions remain unanswered.

CLOSE-BY INTERACTION The second category of mediated interaction technique that is considered in this thesis, is close-by interaction. That is, contact-less interaction which however, would allow users to transition to contact-based interaction since the corresponding pervasive display is located within the user's reach.

Marquardt et al. provided a theoretical analysis of the *continuous interaction space* that is spanned by an interactive surface or tabletop computer and the immediate space above it [159]. Within this space for instance, Hilliges et al. applied hand-gestures such as *pinch* for picking up and placing items from the underlying tabletop computer [115]. Through adding the space above the surface the semantics of graphical content on the surface can be extended (e.g., an item cannot be dragged and dropped into a bowl but needs to be picked up and dropped). A first mediated approach was presented by Subramanian et al., who explored how to extend the interaction space above the surface by using a tracked stylus that is moved manually by the user in mid-air above a tabletop surface [260]. This setup allows users to interact with applications on the surface that provide multiple layers which allow accessing different data. The *metaDesk* by Ullmer and Ishii [271] features a display that serves as a magic lens which is mounted on a boom. This lens can be moved relative to a connected surface and reveals additional information. Interaction in this case is limited to just displaying information.

Kray et al. investigated users would naturally connect their mobile phones an interactive surfaces such as a public display or tabletop computer [139]. The resulting user defined gestures involve a mobile phone and a pervasive display and thus, can be classified as one early mobile mediated technique. And further, Jeon et al. explored how users can use their camera-equipped mobile phone to extend their interaction capabilities while interacting with a large tabletop computer whereas the phone allowed contact-less interaction with contents such as photos [127]. One interesting aspect is the use of bi-manual interaction: while using the phone as mediation device users can interact with the other hand with the surface.

DISTANT REMOTE-LIKE INTERACTION. The third category of mediated interaction distinguished and considered within the scope of this thesis is distant interaction. That is, interaction where the user is not able to transition immediately to contact-based interaction.

An early example for mediated interaction across the distance is the work by Greenberg et al. who addressed the problem how users can easily switch between individual work, for instance, on their personal devices (PDAs) and share work results with others on a public display [102]. The personal devices are not aware of their spatial relation to the distant screen. Also Izadi et al. investigated possibilities to support group work through connecting personal and shared devices. They presented the *Dynamo* system which combines, for instance, laptops and PDAs with large interactive surfaces [124]. This theme of *multi display group-ware* occurred also in work by Myers et al. [180, 182].

Multi-display group-ware systems.

Another theme that can be found repeatedly in the literature, is the adaptation of the metaphor of *throwing* data from a personal device to a shared surface [63, 73, 226]. That means, that users perform an arm-gesture which is similar to throwing an object in the direction of the shared screen. However, the user actually does not throw anything but holds a mobile phone in her hand while performing the gesture. In contrast to the previously discussed work, here a spatial relation is already considered. Yet, this approach is limited to that end that transferring items in the other direction requires a metaphorically different approach.

BASIC DISTANT INTERACTION WITH SIMPLE POINTING DEVICES. Early work that can be classified as distant mediated interaction with pervasive displays, which considers the spatial relation is based on using simple pointing devices. In fact, a large body of work exists that uses laser pointers in order to visually point to content on the remote screen and trigger some interaction. One of the earlier projects in this domain has been conducted by Kirstein et al., who explored ways for interaction with an external pervasive display by using a laser pointer [136]. Similar to Kirstein et al. other work also relied on a camera-based sensing of the location of the laser pointer (e.g., [40, 74, 202]). Pure *pointing* cannot be used without further ado for interaction. Therefore, using *dwell times* for triggering an action [193] as well as additional hardware buttons attached to the laser pointers which send wireless signals to a server have been explored [59]. Further, in order to enable multi-user settings, in particular time-encoded patterns (i.e., a *blinking patterns*) of the involved laser pointers are used to distinguish them [192, 278].

Using laser pointers as input device for distant displays.

DISTANT INTERACTION WITH COMPLEX POINTING DEVICES. While using laser pointers as pointing device for direct interaction with distant displays is a relatively straightforward approach, several limitations regarding the possibilities for interaction (e.g., triggering an action, copying data to a personal device) suggest using more complex devices for distant interaction.

Accordingly, Ringwald et al. combined a laser pointer with a PDA which enabled pointing and selecting *everyday objects* (e.g., a stereo set) in the user's environment and the PDA provided a corresponding interface to interact with the selected object [217]. Yet, using a direct pointing device such as a laser pointer has the inherent limitation of low pointing accuracy because it depends heavily on the distance to the target object (which amplifies for instance, hand tremor of users holding the pointing device) [181]. One alternative to direct pointing was presented by Wilson and Shafer, who presented the *XWand*, which is a relative pointing device [296, 297]. The XWand uses internal sensing for determining its orientation in space and vision based tracking of the location. It serves as a general input and control device in a *smart environment*. The main disadvantage of this approach is the use of a dedicated hardware which is not integrated into for instance, the user's personal mobile phone.

In fact, using the mobile phones provides the key advantage that this device is already used and carried by many people at virtually all times. Hence, a considerable amount of work has been invested in exploring mobile phones as interaction devices for distant pervasive displays. For instance, Shirazi et al. followed a conceptually similar approach as the laser pointer-based work; yet, instead of a laser pointer they used the mobile phone's camera flashlight in order to control the relative movement of a distant cursor [242]. The *C-Blink* system by Miyaoku et al. [172] follows also a visual communication transmission approach: here, the user turns the mobile phone so that its display faces the distant display, where a camera tracks the content of the phone's display. The display is used to transmit hue encoded control commands to the distant display which enables basic interaction with content on the distant display.

Camera-based motion tracking for remote cursor control.

The previously discussed concept requires the user to hold the mobile phone in a rather untypical way, which can be a disadvantage in particular, when often switching between different control modes (which requires to turn the phone, selecting another mode, and turning it back again). Hence, a more convenient way for the interaction is using the phone's camera to track the interaction, which allows users to hold the camera equipped mobile phone in a more natural way. Ballagas et al. presented for instance, the *sweep* interaction technique that is based on the optical flow of the phone's camera stream [34]. The flow data is mapped to cursor movements on the remote display. Similarly, Jiang et al. tracked the relative position of a cursor displayed on the distant screen, which was computed in a closed feedback loop to apply relative movement to the cursor [128]. Boring et al. investigated and compared different options to control a remote cursor using optical flow and accelerometer data [48], which revealed that optical flow is highly efficient.

Camera-based tracking of the distant display position.

Another technical approach that was investigated intensively was tracking image features on the distant screen, which allows to calculate the position of a target. For instance, Maunder et al. presented an interaction technique where users took a photo of a desired target with the mobile phone, which is send to a server that analyzes the content and returns a corresponding answer (e.g., a media file) [162]. The main downside of this approach is low granularity due to the low feature density. A much more elaborate approach was presented by Boring et al. [47]. Their system *Touch Projector* allows users to interact via touch-input with content on displays. To do so, the user holds the mobile phone in such a way that the distant display is visible in the camera view of the mobile phone where the user now can touch the distant display. This however, requires to compute image features not only on the mobile phones side but on the remote display's side as well, which can be compared and matched. This concept allows all kinds of interaction styles as for instance, *virtual projection* by Baur et al. where the distant display is used as virtual projection screen for the handheld mobile phone [39].

From a technological point of view, many versatile solutions for interacting with distant pervasive displays have been explored. However, in particular regarding the more complex pointing and interaction devices for distant control the user-centered aspects such as collaboration support were rather neglected so far. Further, a comprehensive set of interaction possibilities and building blocks that can be used for the design of applications is missing.

2.3.5 *Discussion of Literature Analysis*

The preceding sections provided a detailed overview of prior art and related research encounters. Thereby, technological aspects were detailed and further interaction techniques enabled through them as well as usage aspects that are related were discussed. Note that in the following chapters additional background is provided where necessary for the characterization of specific work. This analysis aimed in particular for two main goals which are closely related to the motivation of the research questions addressed by this thesis. First, a detailed characterization of the state of the art work, which provides insights on *(1)* what has been done, *(2)* what technologies feature which specific particularities, and also *(3)* which methodologies are considered as best practice in the fields. The second goal was the identification of open issues, challenges, and shortcomings that were not considered by previous work, which allows to carefully establish a border between existing work and results presented in the scope of this thesis.

Considering these analyzed technologies and interaction techniques from a higher level point of view, three themes or general shortcomings emerge: *(1)* collaboration support, *(2)* data disclosure and sharing, as well as *(3)* interaction techniques across the pervasive interaction space.

The analysis of direct interaction techniques with pervasive displays revealed that there is great potential for supporting co-located collaborative work scenarios. However, by considering only the shared pervasive displays (e.g., interactive tabletops and surfaces), an important aspect of the original vision, on which the field of pervasive computing is based, is neglected: technology should be designed in such a way that it appears as blended into the environment which should allow users to focus on the task at hand and not on the technology they are using. In the context of collaboration, this means for instance, that users should be able to easily transition between individual and group work phases as noted by Scott et al. [237]. This aspect has been only sparsely investigated in existing work and thus leads to the question: *how can co-located collaboration be supported through mobile mediated interaction techniques?*

A second aspect that can be identified when considering the work that investigated how personal and shared devices can be combined for instance, to enable mediated interaction, is data privacy and security. The latter results from the fact that distributed computing demands high measures of network security for instance, to prevent unauthorized access to personal devices. Note that security is closely related, yet beyond the scope of this thesis. The other aspect regarding privacy focuses on the user who is willing to manage and control if and which data is disclosed to others. For instance, the work *Blue Table* by Wilson et al. clearly illustrates this issue: by placing the personal phone on an interactive (presumably shared) surface, the system starts transferring all pictures from the phone to the surface. This creates the risk of disclosing private or inappropriate photos to bystanders. This issue is representative for the general need for means that allow users to control data disclosure. The literature analysis provided a multitude of approaches that seek to support sharing, yet none addressed the issue of privacy support. This motivates the general question: *how can mobile mediated interaction techniques protect user privacy through supporting controlled data disclosure?*

A third aspect that arises from the consultation of prior art is regarding the expressiveness of mobile mediated interaction techniques. That is, previous work introduced examples and solutions that enable mediated interaction throughout the pervasive interaction space. In particular regarding the contact-based interaction considerable advances and numerous techniques have been introduced. Yet, this raises the question how the set of possibilities for mobile mediated interaction can be extended? And further, *how should mobile mediated interaction be designed for all three categories of spatial relation between user and pervasive display?*

	Contact-Based	*Close-By*	*Distant*
Collaboration	MobiSurf (3.1), MoCoShoP (3.3), projecTVision (6.2)	MobiZone (5.1), projecTVision (6.2)	PointerPhone (6.1), projecTVision (6.2)
Data Disclosure	Shield&Share (4.1), TreasurePhone (4.2), Smart ATM (4.3.2)	MobiZone (5.1)	PointerPhone (6.1), projecTVision (6.2)
Interaction	MobIeS (3.2), Shield&Share (4.1)	MobiZone (5.1), Hover Pad (5.2)	Hover Pad (5.2), PointerPhone (6.1), projecTVision (6.2)

Table 2: Overview of work addressing core issues and corresponding spatial dimensions. Note: numbers next to short names refer to the containing section.

The review of the prior art also indicates that the commonly adopted methodological research approach is based on empirical investigation of conceptual or theoretical solutions. That is, issues or challenges within this context of mediated interaction need to be broken down and focused to a highly specific aspect. This allows creating a conceptual solution which can be implemented and subsequently used for empirical data collection (e.g., by means of an experiment). Therefore, in this thesis the previously identified general issues and challenges are broken down into specific aspects that could be investigated through actual designs, prototypes, and corresponding experiments. Table 2 extends the table 1 and gives an overview of the projects conducted within the scope of this thesis and which of the aforementioned and identified general challenges are addressed by them. Accordingly, supporting *co-located collaboration* through mobile mediated interaction techniques is investigated within the category of contact-based, close-by, and distant interaction each through a number of projects. Similar, *data disclosure* and privacy management is addressed by a number of projects that target all three spatial categories. And further, the set of options for interacting using mobile mediated techniques has been addressed in the context of all three categories yielding novel mobile interaction techniques.

Part

CONTACT-BASED INTERACTION

3

COLLABORATION & SOCIAL INTERACTION SUPPORT

This chapter deals with mobile mediated interaction that is based on physical contact of mediator and pervasive display. In particular, it focuses on the aspect of co-located collaboration support, realized through the application of such mobile mediated interaction techniques. That is, how and in what ways can multiple users benefit from using such techniques in an environment as the pervasive interaction space. In this effect, this chapter first examines the influence of mobile mediated interaction on dyadic co-located decision making processes. Further, it discusses possibilities for creating and interacting with ad hoc cross-device interfaces that span across mediator and external pervasive displays in order to support joint viewing and discussion of data such as images or maps. In addition, the chapter details two case studies in form of application examples that illustrate possibilities for collaboration support based on mobile mediated interaction techniques.

This chapter is based on previously published work which includes the following refereed conference papers:

[4] J. Seifert, D. Schneider, and E. Rukzio. "Extending Mobile Interfaces with External Screens." In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 722–729

[5] J. Seifert, D. Schneider, and E. Rukzio. "MoCoShoP: Supporting Mobile and Collaborative Shopping and Planning of Interiors." In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 756–763

[7] A. L. Simeone, J. Seifert, D. Schmidt, P. Holleis, E. Rukzio, and H. Gellersen. "A Cross-device Drag-and-drop Technique." In: *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*. MUM '13. Lulea, Sweden: ACM, 2013, 10:1–10:4

[8] J. Seifert, A. Simeone, D. Schmidt, P. Holleis, C. Reinartz, M. Wagner, H. Gellersen, and E. Rukzio. "MobiSurf: Improving Co-Located Collaboration through Integrating Mobile Devices and Interactive Surfaces." In: *ITS '12: Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*. Cambridge, Massachusetts, USA: ACM, 2012, pp. 51–60

In addition, the following partially related theses were supervised by the author:

- "Einsatz von NFC-Technologie und Multi-Touch-Oberflächen in Einkaufsumgebungen" (Application of NFC-Technology and Multi-Touch Surfaces in Shopping Environments). Dennis Schneider. Diploma thesis. 2011. (*Parts of this thesis contributed to [5]*).
- "Ad-hoc Cross-Device Interfaces for Mobile Applications". Dennis Schneider. Bachelor's thesis. 2012. (*Parts of this thesis contributed to [8]*).

3.1 SUPPORTING CO-LOCATED COLLABORATION THROUGH MOBILE MEDIATED INTERACTION

This section is based on the work:

[8] J. Seifert, A. Simeone, D. Schmidt, P. Holleis, C. Reinartz, M. Wagner, H. Gellersen, and E. Rukzio. "MobiSurf: Improving Co-Located Collaboration through Integrating Mobile Devices and Interactive Surfaces." In: *ITS '12: Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*. Cambridge, Massachusetts, USA: ACM, 2012, pp. 51–60

It is envisioned that the tables in our domestic environments will turn into interactive surfaces once the price per square meter is in the region of a few hundred Euro. One of the key reasons for buying and using them is the natural support for co-located collaboration, such as information visualization and retrieval or joint planning and decision making [28].

MobiSurf aims for supporting co-located collaboration through mobile mediated interaction.

So far, it has been widely assumed that users in such a setting will focus almost exclusively on the interaction with the interactive surface. However, this neglects the number of existing personal devices people currently have in use at home such as laptops, tablets, or smart phones and use them for co-located collaboration tasks. This section introduces the novel *MobiSurf* concept, which draws on touch-based mobile mediated interaction techniques (e.g., [120, 230, 16, 248]). It establishes a seamless integration of personal mobile devices and an additional shared interactive surfaces for co-located collaboration (Figure 5) extending existing interaction concepts and technologies. Using this approach, the mobile devices facilitate interaction in private while the interactive surface constitutes a shared space that is equally accessible to everyone (e.g., for placing information). This also turns mobile and personal devices at home into tools that support collaboration although they are primarily designed for a single user and usually relegate people nearby to mere observers.

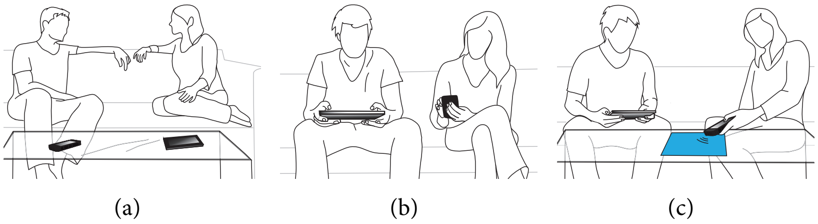

(a) (b) (c)

Figure 5: MobiSurf supports co-located decision making through integrating personal devices and a shared surface. a) Users discuss their goals. b) They can decide to work on the surface or their personal device. c) Information can be shared easily for discussion on the surface.

Application Scenario.

The following scenario illustrates how MobiSurf supports collaboration: Kim and John want to buy a new camera. After an initial discussion and joint web search on the interactive surface, they know what they want and what their needs are (Figure 3.5(a)). Then they start searching for offers individually using their personal devices (Figure 3.5(b)) as they would like to use different web sites, have differing ways of searching, want to check personal discounts, etc. As soon as they find interesting offers, they share them by dropping the web page on the common surface (Figure 3.5(c)). Now they can jointly view and discuss their options or go back to individual browsing.

The main contributions of the research presented in this section are the results from a study which compared MobiSurf with the current practice of using individual and separated laptops for co-located collaboration in a domestic environment. When using MobiSurf, the participants interacted with the mobile devices twice as long as with the interactive surface itself. Furthermore, none of the groups in our study exclusively used the interactive surface or the mobile devices. This shows that the suggested combination of devices through mobile mediated interaction provides distinct advantages to the user which are not possible when considering individual and separated devices. Furthermore, participants of the user study exchanged two to three times more content during the study tasks using MobiSurf than with the laptop-based approach, which further supports the validity of the MobiSurf approach.

3.1.1 *Background of Interaction for Co-Located Collaboration*

MobiSurf mostly builds on work in co-located search in general as well as the combination of personal and shared displays and the way information is transferred between them.

Co-located collaborative search.

Collaboration in information seeking is very common. A recent web survey found that 97% of 204 respondents had already engaged in a collaborative web search activity [174]. Further, 88% of those who searched the web collaboratively reported doing so in a co-located setting. Similarly, in a diary study with 20 participants, Amershi and Morris observed 38 co-located collaborative web search sessions within one single week of which 45% occurred at home [28].

This motivates why there has been considerable research on supporting small-group co-located collaboration. Most of this has focused on the use of a single large interactive display. We basically follow this as it has been shown to support teamwork activities [280] and improve collaboration in general [55]. While Schneider et al. summarize advantages of using multi-touch tables for collaboration with respect to other systems [235], the successful integration of tabletop systems in the home has been frequently demonstrated (e.g., [269]).

Morris et al. have extensively studied tabletops for collaborative browsing and provide an overview of several projects using Microsoft Surface for collaborative search tasks, discussing the design space and challenges [176]. For instance, WeSearch has been designed for collaborative web search to leverage the benefits of tabletop displays for face-to-face collaboration [178]. A user study showed that tabletop displays facilitate collaborative web search. Furthermore, it revealed that they enhance the awareness of group members' actions and artifacts such as search criteria and allow fluent transitions between tightly- and loosely-coupled work styles.

A few studies have been conducted comparing collaboration when each user has a personal device to using a tabletop system only. Heilig et al. in [113], e.g., found that, with respect to a setting with synchronized laptops, their tabletop version fostered more simultaneous interactions, people were more likely to interrupt and engage in other users' actions, and they needed less short interruptions to notice and interpret "nonverbal expressions of the other group members". Yet, their study focused on a special tangible, physical token as an additional UI element on the tabletop and also did not incorporate cross-device sharing.

In the last years, some projects have begun to extend collaborative systems with several devices, especially multi display environments. These systems, however, usually involve high cost for acquisition, setup, and maintenance. They are thus mostly targeted at specific groups at a professional level and not suitable for home use (e.g., combining large vertical displays with a multi-touch tabletop to support scientific exploration of large data sets in teams [294]).

Combining personal and shared displays

A major theme in combining mobile and shared devices is that a personal screen can keep private documents or data such as passwords invisible and unreachable to other users. For example, Döring et al. used a tabletop as digital poker table while the cards of each users show up only "in their hands" on the mobile phone [82]. Other projects have shown additional promising uses of mobile displays in combination with large displays, e.g. the ability to present additional information [241, 294], enhance mobility of the overall system [133], improve control and security (e.g., for authentication [210]), leverage group discussions [261], and share information across different classes of displays [216].

Wallace et al. provide a comprehensive overview of projects that integrate heterogeneous devices [280]. Other research working with a combination of devices mostly focused on systems limited in some sense or concentrated on a specific issue. For example, the CoSearch system employs mobile devices mostly for cursor control and download of material [27]. Twidale also integrated phones into his system to upload images onto a shared display [269]. However, no further sharing or synchronization functionality has been envisioned.

Mobile data disclosure & sharing interaction

With respect to how data can be shared between a mobile device and an interactive surface, many approaches have been proposed: placing the phone on the table [300], using the phone's camera to detect its location with respect to a tabletop [72], using stereo microphones [95], or detecting dragging gestures across displays [117]. Also, gesture-based systems for moving data between screens have been implemented (e.g., [152]). In order to provide an easy to understand, quick interaction style for transferring data from a mobile device to the surface and back that requires little effort, we chose to employ *PhoneTouch* which is based on direct touch interaction between mobile and surface [230]. In order to transfer data using this technique, users simply touch the surface with their phone and selected data items are transferred and appear at the touch location on the surface. The technique allows users to transfer data from the surface to their phone (*picking them up*) through touching the corresponding item with their phone.

3.1.2 *Concept for Collaboration Support*

The MobiSurf concept has been developed along the lines of various guidelines retrieved from related systems and projects: Amershi and Morris conducted a set of interviews leading to seven limitations of current co-located collaborative web search practices [27]; the last three (*Referential Difficulties*, *Single-Track Strategies*, and *Information Loss*) have also been stressed in the context of remote collaboration [177]. Besides these, Scott et al. identified three more guidelines for co-located collaborative tabletop systems [238] and Twidale et al. empirically derived guidelines for media surfaces in domestic environments [269]. Yuill and Rogers created a mechanism framework of factors for collaboration including *Awareness, Control,* and *Availability* [307]. Finally, studies with their WebSurface system lead Tuddenham et al. to a set of design goals for a tabletop-based co-located collaborative systems [268].

The majority of those issues and guidelines can be classified into five groups (G1-G5). The following list shows how the MobiSurf concept is built on top of them:

G1 The issues of *Difficulties Contributing* and *Pacing Problems* [27] as well as the feature *Independent Work* [268] are implemented by *giving each user a personal device*

G2 The issues of *Referential Difficulties* [27] and *Lack of Awareness* [27, 177, 268, 307] as well as features *Designing Activity Centers* and *Coordinate Displays* [269] are implemented by *using a shared device for all users*

G3 The issue of *Information Loss* [27, 177] is implemented by *using a tabletop as storage device for (intermediate) results*

G4 The features *Single-Track Strategies* [27, 177], *Flexible User Arrangements* [238], *Combining and Linking Heterogeneous Devices* [269], and *Transitions between Working Independently and Closely Together* [268] are implemented by allowing *easy switching between personal and shared device*

G5 The features *Natural Interpersonal Interaction* [238] and *Seamless Sharing of Results* [268] are implemented by an *easy to use cross device information sharing technique*

Thus, MobiSurf is based on the observation that collaborative searching and planning tasks often consist of individual and shared phases. Users need to be able to follow their own strategies (*G1*) while at the same time be able to easily share their results with each other (*G2*). Accordingly, the concept includes one large, shared interactive surface (*G3*) and personal mobile devices for each user. For a seamless integration and supporting shifting between individual and joint work (*G4*), it is important, especially for ad-hoc meetings that often happen in the home, that information can be easily transferred from one device to another through a simple interaction technique (*G5*). This is provided by using a simple touch-based interface.

3.1.3 *MobiSurf Application Design*

From the user's perspective, the system consists of two main components: a web browser application running on the shared surface (Figure 6) and a web browser application running on the personal mobile device.

The web browser application on the interactive surface allows users to open any number of browser windows on the surface which can be arranged freely using a corresponding handle at the top of the window (Figure 3.6(b)). Browser windows support touch-based interaction with the web page content and controls (e.g., links, buttons, or scrolling) and a virtual keyboard is available for text input. Users can control the zoom level using corresponding buttons on the left of each browser window. Accordingly, the application on the surface can be controlled fully independently from additional for instance, connected personal devices.

The web browser application on the mobile devices (implemented for Android devices) allows standard web searching and browsing tasks. Hence, the application can be used fully independently from the available and connected interactive surface.

Approach for seamless data sharing and disclosure.

Users can exchange web pages with the interactive surface and other mobile devices through transferring a Uniform Resource Locator (URL)

(a) (b)

Figure 6: MobiSurf application overview: (a) Two users jointly viewing and interacting with information on the shared surface. (b) The shared browser application on the interactive surface.

of the respective web page (this implementation is limited to websites that encode session information in the URL). For instance, when a user wishes to transfer a web page from the mobile device browser (Figure 7) to the surface to share it with other users, the user simply touches the surface with the mobile device at the desired location (Figure 3.7(b)). The touch event gets detected, the URL of the page is transmitted in the background via WLAN, and the web page is loaded and displayed on the surface (Figure 3.7(c)). For picking up web pages from the surface, for instance, in order to further review them on the personal device, the user just touches a displayed browser window on the surface with their phone. After the touch event is detected, the page URL is transmitted, and the web page is loaded and displayed on the mobile device.

(a) (b) (c)

Figure 7: Transferring data from a mobile device to the surface. The web page shown in the mobile browser (a) is transferred to the surface using PhoneTouch [230], causing the system to create a new browser window (b). The received web page is then immediately loaded (c).

In addition, users can exchange web pages directly between mobile devices. In order to do so, the *sending* device needs to display the web page which is to be shared (Figure 3.8(a)). The *receiving* device displays the home screen. As the users hold both device close to each other (Figure 3.8(b)), the web page is transferred and displayed on the receiving device (Figure 3.8(c)). For MobiSurf, we used NFC to implement this functionality.

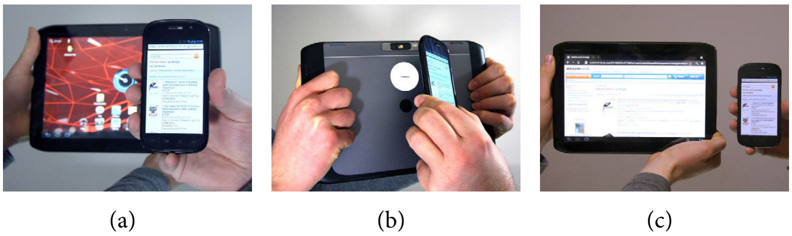

(a) (b) (c)

Figure 8: Transferring data between mobile devices. (a) The phone displays a web page (sender); the tablet shows the home screen (receiver). (b) Users hold their devices together for reading the NFC tag information. (c) The page is transferred from phone to tablet.

3.1.4 *Evaluation of Collaboration Support*

The following section reports on the design and execution of a user study which aims for gaining in depth insights of how users interact with MobiSurf in comparison with current practice. The general objective of the study was to investigate to what extent MobiSurf facilitates collaboration. In doing so, this study focuses in particular on its abilities to seamlessly integrate personal mobile devices and a shared large interactive surface to support varying collaboration styles. Also, how and to what extend are users taking advantage of different classes of devices offered simultaneously. Further, how does the provided shared space support information sharing and discussion as basis for joint decision making

3.1.4.1 *Current Practice*

To guide the design of a the system which reflects current usage realistically, an initial web-based survey was conducted about current practices and reasons for collaboration when performing planning or shopping tasks on the web. This questionnaire was advertised via a department email list (ca. 250 recipients) and posted on a departmental discussion board. As incentive, participants could win one of five gift vouchers for 10 EUR each. In total, 54 persons (13 female), aged between 19 and 34 (M =

24) completed the questionnaire. The majority of participants reported to *always* (18.5%) or *often* (40.7%) collaborate with others for online shopping. When planning holiday trips 35.2% reported to collaborate *always*, 24.1% *often*, and 31.5% *sometimes*. In general, 83.3% reported to be co-located with their collaborators. Laptop computers were most often used (90.7%) followed by desktop computers (57.4%), smart phones (46.3%), and tablet computers (11.1%). In response to the question whether they would share a single device with others during collaborative tasks, 13% stated *never*, 25.9% *rarely*, and the majority (42.6%) *sometimes*. Based on these results as well as on related settings reported in the literature (e.g., [27, 174]), we choose to compare MobiSurf with participants working side by side at a table using their individual laptop computers and allow for message exchange via instant messenger.

3.1.4.2 *Practical Tasks*

Initial training with both systems.

To familiarize participants with the systems, training tasks before working on the collaborative tasks were arranged. These tasks were system specific and covered all features that were available for performing the tasks. In case of MobiSurf, participants were asked to "Use the surface browser to look up your current location (use Google Maps)", "Use the mobile device and search your favorite movie DVD on Amazon. Then, share the results on the surface", and "Share a URL with the other participant using the 'beam' feature". Participants were told that they were allowed to move around the interactive surface. Further, the investigator pointed out that they were free to use the surface or the mobile devices. Participants were also told that they could switch their personal devices if they want to do so.

In case of the laptop-based approach, the training tasks included "Look up your favorite music album and share the link with the other participant by instant messaging". Participants were told that they are allowed to talk, to move and to share their laptop screens as they would like to do.

Two simple tasks were designed, yet typical for domestic environments, that allow people to easily relate to in order to investigate co-located collaboration with both systems. Inspired by Morris who found travel planning and shopping to be the most common tasks for collaborative web browsing [174], we also chose these categories for our study.

Realistic tasks based on initial interview findings.

The first task (T1) required participants to plan a weekend trip to London. Participants had to find options for flights, hotels, and museums they wanted to visit. In addition, participants were told that they had a budget of 700 EUR. The task was finished when they found a configuration they agreed on. The second task (T2) was to find a birthday present for a friend, which should cost not more than 40 EUR. Additional information about the friend was given (playing volleyball and badminton). In this task, participants were asked to make suggestions for presents, collect corresponding offers, and come to a final decision on how to spend the money.

In both cases, participants were free to decide by themselves when they were finished with the task. No goals were defined such as short completion time or money they spend. Accordingly, no quality criterion for the outcome of the group collaboration was defined.

3.1.4.3 *Session Structure*

Eight pairs of volunteers were recruited (i.e. 16 participants in total; seven female) for a repeated measures study design. Participants received 10 EUR as compensation for participation. In each study session two participants worked together. We omitted to include additional group sizes (e.g., triads or small groups) to avoid increasing the study complexity. The session was organized in three parts: 1) introduction, 2) tasks with the MobiSurf and laptop-based approach, and 3) post-hoc questionnaires.

Initially, the participants were introduced to the study and gave their consent that recorded data may be analyzed and published. In the second phase, participants were asked to perform two tasks. One task using MobiSurf and another task using the laptop approach, preceded by training tasks with both systems. While working with the laptop approach, participants were sitting at a table and were free to change their position. During the MobiSurf condition, however, participants were standing at the interactive surface device as this makes it easier to reach for distance items on the surface. The order in which participants used the two systems was counterbalanced as well as the task assignment. All task instructions were read by the investigator. After giving the instructions, participants had the opportunity to clarify open questions with the investigator. Participants were allowed 10 min per task after which the investigator asked them to finish their discussion (which was not necessary in any case).

3.1.4.4 *Apparatus*

The hardware of the MobiSurf implementation consists of a custom-built interactive multi-touch surface able to support an arbitrary number of connected mobile devices. The mobile devices which were used, were a Samsung Nexus S and a Motorola Xoom tablet. The former has a 4 inches screen with a resolution of 480×800 pixels. The latter has a 10.1 inches screen with a resolution of 1280×800 pixels. The interactive surface is based on FTIR technology using a rear-projected screen (1280×800 pixels on 65×105 cm). The whole system is controlled by a PC (Windows 7 (64), Xeon dual core 2.4 GHz, 4 GB RAM) that runs both the multitouch server, which is responsible for touch detection (i.e., *finger touches* and *device touches*) and the browser application.

Communication between the interactive surface and the mobile devices was implemented based on the PhoneTouch technique [230]. Mobile devices and the interactive surface are connected via (wireless) network to a central server receiving events. Based on time correlation, the server matches accelerometer events from the mobile devices and corresponding visual events from the surface. Matching pairs of events are considered as *phone touch*. Depending on where the mobile device touches the surface a *picking up* (touch on open browser window on the surface) or *dropping* (touch free area on surface) action is performed. In this implementation of MobiSurf only URLs of web pages are transferred which are loaded on the receiving devices. Accordingly, only websites that encode session information in the URL are supported.

The touch-based transfer of web-pages between two mobile devices was implemented using NFC, whereas one device needs to be equipped with an NFC reader and the other device is equipped with an NFC tag on its back (see Figure 8(b)). For communication between the mobile devices the surface server is used to transfer web page URLs.

The compared laptop-based approach consisted of two laptop computers (IBM ThinkPad, 15", 1400×1050 pixels) running Windows. As a web browser we installed Mozilla Firefox. To allow users to share information (e.g., a URL) not only verbally, Skype was installed and configured with a corresponding account to allow sharing via instant messaging.

3.1.4.5 *Data Collection*

During the study sessions the investigator took notes and recorded videos for a post-hoc multi-pass analysis. For post-hoc video analysis (i.e., coding and annotation), the *ChronoViz* software environment was used [284]. Repeated analysis passes ensured that both, both high-level trends as well as subtleties of ongoing interactions between participants and devices were identified.

After performing the practical tasks with each system, participants answered questions concerning the systems' ability to support collaborative task performance and selected, appropriate questions from the NASA Task Load Index (TLX) questionnaire [112]. As the last part of the user study, participants had to fill in a questionnaire about the two systems and their experiences with them. Participants were also asked to compare the two systems and to share any thoughts and observations they made.

3.1.5 *Evaluation Results*

The 16 participants were aged between 21 and 26 years (M = 24). Three of the pairs were couples. Participants of two pairs were sharing an apartment while the remaining pairs were friends. Three were graduate students and the others were undergraduate students. The kind of relation between participants of each pair did not have any significant effects and no correlations to aspects such as verbal communication or sharing of information could be found.

All participants reported that they had prior experiences in collaborative tasks for which computers were used together with other users to achieve the common goals. Reasons for collaboration were ranging from gaming to working on course assignments together with other students. All participants had experiences with planning a trip or buying a product together with others. Each study session lasted for about one hour including the introduction, the tasks, and the completion of the questionnaires.

3.1.5.1 *User Feedback*

Initial semi-structured interview results.

Concerning previously applied practices of the participants for collaborative shopping two themes were reoccurring: Eight participants reported that they used one personal computer together with others (sharing mouse, keyboard, and a single screen). Four participants pointed out that only one person is controlling the computer while the others are sitting nearby and participate in the discussion. In another approach that was described by six participants each user controls their individual device (e.g., the laptop) for searching offers online and discussing their search results with the others simultaneously.

One participant emphasized that using one computer that is shared with the others is quite comfortable because one can point at particular items in a web page. Another participant reported that he experienced the planning of a trip with friends where they set up a projector so that all could see comfortably the web browser while one person was controlling the computer.

Quantitative feedback.

After completing the two tasks with both systems, participants answered questions from a post-hoc questionnaire. The first part focused on aspects of collaboration support. Participants answered the questions on a five points Likert scale (1 = very poor; 5 = very good; Figure 9). Differences were tested for significance using the Wilcoxon signed ranked test.

Rating results indicate a preference towards the MobiSurf system concerning collaboration, discussion, *and* visual *support.*

Answers to (Q1) "How well does the system support collaborative shopping or planning?" and Q2 "How well did the system support switching between individual and collaborative work phases?" indicate both a preference towards the MobiSurf (Median (Mdn) = 4.0) over the laptop-based approach (Mdn = 3.5). Yet, differences are not statistically significant. Question Q3 ("How well did the system support you to discuss particular information with the other user?") resulted in a significantly higher rating ($z = -2.37$; $p = 0.018$; $r = -0.53$) in favor of MobiSurf (Mdn = 4.5)

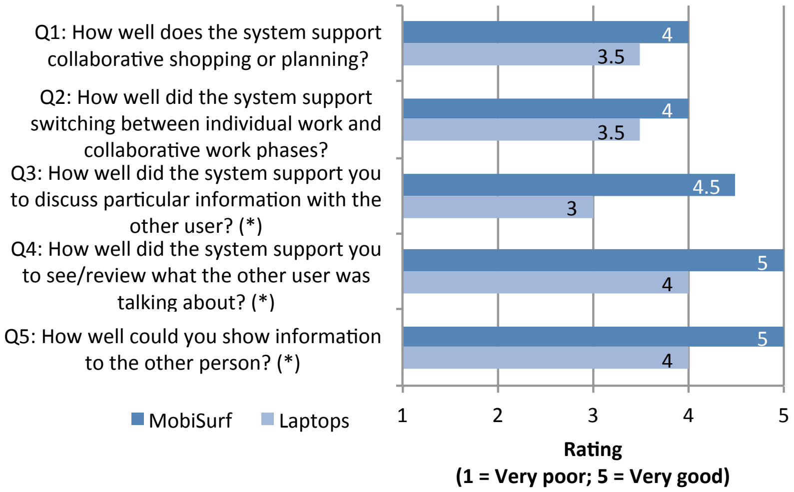


Figure 9: Results of the participants rating the tested systems regarding collaboration support ((*) indicate significant differences).

compared to the laptop-based approach representing current practice (Mdn = 3.0). Also Q4 (“How well did the system support you to see what the other user was talking about?”) resulted in significant higher ratings for MobiSurf (Mdn_{MS} = 5.0; $\text{Mdn}_{\text{Laptop}}$ = 4.0) (z = -2.83; p = 0.005; r = -0.63). Accordingly, users rated MobiSurf significantly higher (Mdn_{MS} = 5.0) in Q5 (“How well could you show information to the other person?”) than the ($\text{Mdn}_{\text{Laptop}}$ = 4.0) (z = -2.7; p = 0.007; r = -0.60). The large effect sizes (r) for Q3, Q4, and Q5 were expected considering that MobiSurf provides a shared display for shared reviewing of information.

MobiSurf is experienced as physically more demanding.

Participants rated both systems using selected questions from the NASA TLX questionnaire [112]. The results for one question show significant differences: ratings of “How physically demanding was the task using this system?” show that participants perceived MobiSurf as physically more demanding (Mdn = 2.0) than the laptop-based approach (Mdn = 1.0) (z = -2.109; p = 0.035; r = -0.52). One probable reason for this different rating is while using MobiSurf, many participants held the mobile device in one hand and did the typing with other one. In particular, participants who used the tablet computer often placed their device on the rim of the surface partially due to the weight of the device. Also, direct touch interaction between mobile devices and interactive surface could be perceived as physically demanding as most users were very careful not to hit the surface too hard with the mobile device. Anther factor that influenced this rating is that users were standing while using MobiSurf and sitting during the laptop-based condition. However, we believe that this factor is rather small as none of the participants gave feedback indicating that standing while using MobiSurf was straining. In fact, standing while interacting with MobiSurf is of advantage as it is easier to reach for distant items on the surface.

Results of the remaining TLX questions do not show significant differences: on average the mental demand was rated to be equally moderate low (both systems with Mdn = 2.0). Also the level of effort for accomplishing the level of performance was rated for both systems low (Mdn = 2.0) and the success of accomplishing the tasks was rated equally for both systems (Mdn = 4.0). The latter aspect indicates that MobiSurf allows participants to reach the collaboration task in to a satisfying level, event though participants were not familiar to use it,

Finally, we asked the participants to compare the two approaches they were using in the study with each other directly. 12 participants answered that in general they would prefer to use MobiSurf. 13 participants answered that MobiSurf allowed them to have a more active conversation and discussion with the other user. In addition, 15 decided that MobiSurf was more fun to use.

QUALITATIVE FEEDBACK. To complement the quantitative data we collected qualitative feedback from the study participants, thereby drawing a more detailed picture of the user experience.

Highlighted aspects appreciated by participants: joint view on workspace that support discussion and communication.

Seven participants emphasized that they liked the shared large display as one could show some information to the other user. For instance, P12 pointed out that "you could easily point at specific items on a website". Another aspect that was perceived as positive by three participants was how the system is supporting the discussion and conversation of the collaborators. For instance, P10 stated "the discussion is very direct", and "both had the same information available". Further, four participants identified as a positive aspect that users can start searching individually using the personal mobile device and collect valuable information on the shared screen. One participant highlighted that it was very easy to transfer information between different devices.

Concerning the laptop approach, seven participants indicated that they liked it because they were already familiar with it and have used it before. Four highlighted that exchanging links to webpages containing relevant information was something they liked. For instance, P1 emphasized that "one could share information by turning the screen towards the other person or simply send the link" via instant messaging. However, six participants expressed that the discussion support is not sufficient using individual laptops. For instance, P12 stated that "you cannot show what you are talking about, so one has to turn the screen and point to that piece of information". Also, three participants indicated that sharing of information using instant messaging did not suit their needs. For instance

P9 expressed: “I did not know which link I should open and what the other one was talking about.”

3.1.5.2 *Video Analysis*

Table 3 exhibits the results of the video analysis which are described in detail in the following.

Total duration	**MobiSurf**: 8:11		**Laptop Approach**: 8:49	
Conversation	27.6%	2:15 (1:26)	29.2%	2:34 (0:41)
Joint viewing	28.5%	2:20 (1:28)	5.45%	0:29 (0:30)
Mobile interaction	51.3%	4:12 (3:08)		
Surface interaction	26.1%	2:08 (0:41)		
Pointing		2.5 (2.0)		0.9 (1.4)
Dropping		5.4 (2.7)		
Picking up		0.8 (2.1)		
Instant messaging				1.0 (1.5)

Table 3: Video analysis results (times in minutes, SD in parenthesis): Device interaction, communication, and information exchange in both conditions.

Observations concerning device interaction.

To complete the tasks, participants took on average 8:11 min with the MobiSurf, and 8:49 min with the system representing current practice. The number of average interaction phases that were observed was similar with the mobile device (M = 3.6 phases/session) and with the surface (M = 3.7 phases/session). Interaction phases included all kinds of touch interactions (e.g., typing, scrolling) interrupted by reading information performed on one device. When a participant changed focus, the phase was considered to be ended. It was observed that users interacted about twice as long with their mobile devices (4:12 min, or 51.3% of the average session length) compared to interactions with the surface (2:08 min, or 26.1%) in the MobiSurf condition. In the remaining time (1:51 min, or 22.6%) when participants did not actively interact with one of the two device classes, users mostly discussed with and observed the other participant’s interaction. Moreover, participants frequently switched between mobile and surface interaction.

This difference in interaction time of the personal mobile and the shared device results from diverse reasons. First, in all study sessions, participants divided the task and decided to search for offers in parallel. Most participants started searching using the personal mobile device. Two participants decided right from the beginning to use the surface. The main reason appeared to be that the participants preferred to use the larger keyboard on the surface application. As they found satisfying offers they shared and collected them on the surface. When they had collected a set of selected web pages on the surface, the discussion about which option to chose was much shorter as all information were at hand and no time consuming typing was necessary. Second, during the discussion often only one participant interacted with the contents presented on the shared surface, while the other one followed the actions on the surface.

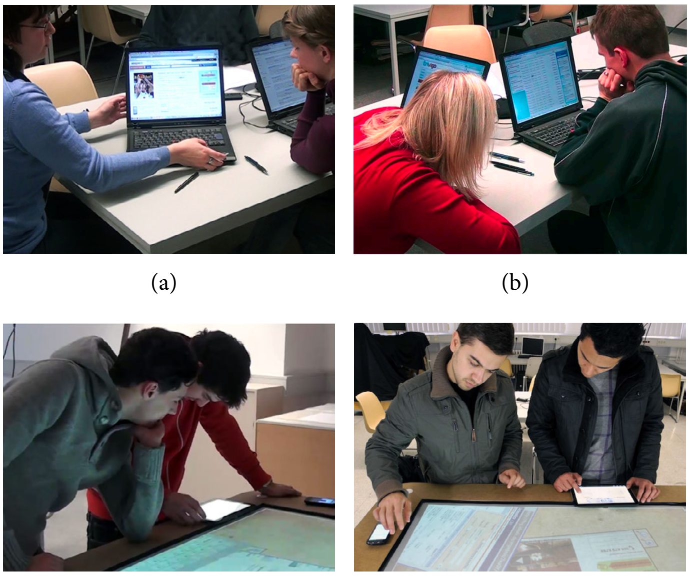

(a) (b)
(c) (d)

Figure 10: Using the mobile and surface system and using the laptop approach, users reviewed information together. (a) Participant actively sharing the laptop screen. (b) Participant leaning over to get a view on the screen of the other participant's laptop. (c) Participant looking at the screen of the mobile device used by the other participant. (d) Two participants reviewing a web page together on the surface.

Using MobiSurf, it was observed that participants spent 2:20 min or 28.5% of a session to *jointly* view and interact with shared information on the surface. In contrast, joint information viewing accounted for 0:29 min or 5.45% in the laptop-based condition. This required either actively sharing the screen by turning the laptop towards the other participant (six instances, Figure 3.10(a)), or leaning over to get a view on the other screen (12 instances, Figure 3.10(b)).

Regarding mobile device usage, in total 11 occurrences of participants depositing their devices on the surface rim (Figure 11) were observed. Reasons were to free both hands for typing on the tablet (Figure 3.11(a)) or interacting with the surface (Figure 3.11(b)), for example. Two times, both

(a) (b)

Figure 11: Users often put their mobile devices aside: (a) for typing with both hands and (b) for interacting with the surface.

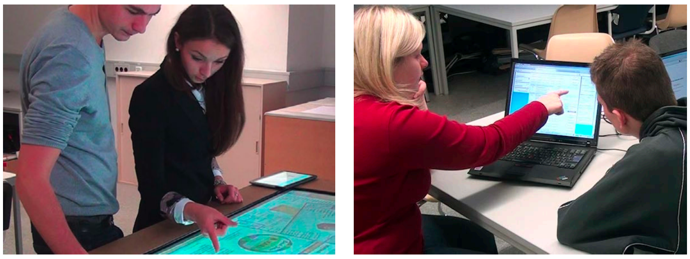
users deposited their mobile devices simultaneously while discussing their search results. In nine cases, the time period of depositing the mobile device was less than a minute and succeeded by further interaction using the mobile device. In two cases, participants decided not to use the mobile device as they felt more comfortable using the surface application. Therefore, they placed their mobile devices on the surface rim after a short interaction period and continued to interact with the surface application.

COMMUNICATION. Each participant spent on average 2:15 min for conversation using MobiSurf and 2:34 min in the laptop-based condition. This corresponds to roughly the same amount when compared to the mean session lengths, namely 27.6% (MobiSurf) and 29.2% (laptops). In both systems, the verbal communication was dominated by dialogs between users. Participants frequently articulated information they were looking at or commented on their current actions. For example, one participant stated "I found one [offer] for only 25.99" (MobiSurf). Another said "I just sent you a link", before actually doing so (laptop approach). We also observed an instance of reading out loud the entire text of an offer in the laptop-based condition for comparison with the other participant.

In addition, participants repeatedly used their hands to point out information in both conditions (Figure 12). This happened more frequently using MobiSurf than using the laptop computers, which required screen sharing or leaning over as discussed above.

Using MobiSurf users are more likely to share information.

INFORMATION EXCHANGE. Both systems supported directly exchanging web links either by touching the surface with a mobile (MobiSurf) or by sending instant messages (laptop-based). In total, participants shared through *dropping* 43 web pages (on average 2.7 per participant) but picked up only six with MobiSurf. Turning to the laptop-based



(a) (b)

Figure 12: For discussing information, users point to them on the surface (a), and while using laptop computers (b).

approach, a total of 16 instant messages were exchanged (on average 1.0 per participant).

Analyzing the other participants' reaction to a drop interaction, we found that in 18 cases (41.9%) they were already focused on the surface. Another 10 sharing or dropping events (23.2%) interrupted the other participant's ongoing interaction with the mobile and drew their attention towards the surface. In 14 cases, no reaction at all could be observed (32.5%).

A percentage of 81.3% of sent instant messages resulted in immediately opening the included link on the other side. Two pairs of participants did not use instant messaging at all. Sharing links using instant messaging was accompanied by different actions. For instance, P6 sent a link to P7 to then lean over and discuss the content of the shared web page. In another case, sharing multiple links caused confusion since the receiver was uncertain as to what link the sender referred to in a subsequent conversation.

3.1.6 *Discussion*

The study results derived from user feedback and observations indicate that MobiSurf improves on a comparable laptop-based approach which represents current practice and which was identified in a preceding online survey.

MobiSurf supports transitioning between personal and the shared device, while personal devices were used twice as long as the share device.

MobiSurf successfully supported interleaving individual and group work as participants used both mobile devices (roughly 50% of the time) and interactive surface (roughly 25% of the time) to complete the tasks. Mobile devices were mainly used for individual searching while the surface was predominantly used for the shared discussion which was less time-consuming. They also made frequent use of the possibility to switch between those devices, strongly supporting the previously formulated design decision *G5*. Especially notable here is that the usage of the mobile devices has been considerable thus confirming *G1* and marking the importance of the differences of MobiSurf to other systems. This is in line with the observation by Marshall et al. that collaborators often start with individual work phases and shift to shared work phases [161].

Users are likely to share more frequently information when using MobiSurf.

In particular, participants exchanged digital information more frequently in the MobiSurf condition (43 dropped and 6 picked up webpages) compared to using instant messages in the laptop-based approach (16 exchanged links) which confirms *G4*. Dropping information frequently caused the other participant to interrupt ongoing individual interaction on their mobile and switch the focus to the shared surface, leading to a better understanding of what the other user was engaged with. These findings suggest that users interacting with MobiSurf have a higher awareness of the current state of the workspace compared to the using individual laptops which is what *G2* asked for.

The shared surface creates a joint workspace awareness supporting discussion.

MobiSurf's interactive table proved indeed to be an effective area for shared storage and interaction (see *G3*). In particular, participants jointly looked at the surface for about one fourth of the overall task completion time. They were also substantially more likely to accompany their words with pointing gestures when using MobiSurf. Consequently, the *awareness* (c.f., [307]) of the other user's actions on the shared surface and presentation of information changes the quality of how users collaborate. Transitions between individual work phases and shared work phases are supported through the awareness of the shared surface as users can quickly decide whether they continue with their individual work or join the other user. While participants spent about the same time with verbal communication in both conditions, the majority felt that MobiSurf facilitated more active conversations and provided better support for discussions. This may be attributed to the availability of a common basis for discussion, as provided by the content shown on the shared surface. Further, the shared device creates a higher degree of *control* (c.f., [307]) compared to using individual laptops. As both users have access to displayed information and optionally picking them up with their mobile device allows them to interact with the corresponding web pages individually.

Participants rated MobiSurf to be more physically demanding compared to the laptop condition. The main factor appears to be holding the mobile device with one hand while typing with the other one. Also the direct touch interaction of dropping or picking up information from the surface seemed to be physically straining. Further, participants were standing while using the MobiSurf system as this allowed reaching for distant items more easily. No feedback was received that indicated that users perceived the standing as unpleasant or tiring, yet, it cannot be fully ruled out that this as a factor.

Another interesting finding is that none of the participants used the device-to-device information sharing feature even though all participants were introduced to it during the training phase. It seems that the shared surface already provided an adequate place for sharing information without the direct and quite intrusive and especially interruptive means of pushing content to the other person's mobile device.

Even though MobiSurf was unfamiliar to participants they assessed it as easy to use.

Although MobiSurf and particularly its integration of mobile devices with an interactive surface is novel and thus unfamiliar, participants were able to effectively use its features after a brief introduction. A few participants highlighted that they liked the laptop-based approach due to its familiarity, but MobiSurf was still rated as easy to learn and use with low mental demand required. This is also reflected in the similar average completion times and the throughout effortless interaction that we observed. As users were allowed to freely decide when they were finished with a task, objective measures for the collaboration outcome could not be applied. However, participants rated their successes of accomplishing their task when using MobiSurf equally high as in the laptop condition. When asked to state a preference, most participants favored MobiSurf and consistently rated it superior to the laptop-based approach with respect to information exchange and shared viewing.

3.1.7 *Conclusion and Future Work*

As technology matures and prices fall, interactive surfaces are expected to become more pervasive in people's homes. In this paper we introduced MobiSurf which integrates an interactive surface into the interaction with people's own personal and mobile devices using existing interaction technologies and techniques.

In the presented study, it was observed that even though participants used the mobile devices twice as long as the shared surface (e.g. for searching), the shared surface proved to be an integral part of the overall interaction. Using MobiSurf, participants shared more links and spend more time jointly viewing web pages compared to the laptop-based alternative. This shows that the mobile devices become central interaction devices and that the interactive surface is primarily used to share information for common discussions or later use.

This observation is very much in line with current situations at home when people discuss based on paper (e.g. holiday planning using various holiday catalogs or brochures) at a table in the kitchen or living room. People are used to take the material in their own hands to read it, show it to others by turning it towards them, place it on the table for discussion, and arrange it on the table to organize previously discussed aspects. People have different strategies and preferences when working in such a way. Some, for example, may prefer to read while holding a paper in their hands while others might prefer placing it on the table to read it. These types of familiar behavior have been taken into account during the design of MobiSurf and the results of our study confirm the need for adding and integrating shared interactive surfaces into interaction with personal mobile devices. Hence MobiSurf provides an environment allowing a user to seamlessly switch between individual and group work and easily share information between devices. As we have shown, these features made users more engaged in the task and helped them to have a better understanding of the current situation.

The study design featured two specific tasks in a scenario of domestic environments. Although not investigated as yet, it is envisioned that MobiSurf also facilitates co-located collaboration in office or educational situations (e.g., to support collaborative problem solving tasks in schools or planning meetings at work). In addition, surfaces in semi-public settings can serve as walk-up platforms for ad-hoc collaboration. For example, to schedule a meeting, the mobile devices can contribute personal appointments while the surface displays a joint calendar, hence facilitating finding a joint time slot. Besides using mobile devices for separate and private input, they also serve as source for personal data (e.g., documents or photos) that can readily be brought into the shared space.

3.2 EXTENDING MOBILE INTERFACES ON EXTERNAL SCREENS

This section is based on the work:

[4] J. Seifert, D. Schneider, and E. Rukzio. "Extending Mobile Interfaces with External Screens." In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 722–729

Today's mobile phones enable users to perform a large variety of tasks in mobile contexts. Given the increased computing power, battery capacity, and data connectivity, users can perform the same tasks as by using traditional personal computers (e.g., browsing the web, viewing and editing photos). However, one of the mostly limiting factors is the screen size of the mobile devices [65]. The screen size affects users mainly in two ways: First, only a limited amount of information can be displayed on the screen at once. Hence users often have to change the view (i.e., zooming in or out, switching between different screens). Second, collaboration with co-located persons is inherently limited, as only a certain amount of people can comfortably view the information.

MobIeS: Mobile Interfaces on External Screens.

In this second section of this thesis' chapter focusing on how mobile mediated interaction can enable or facilitate collaborative tasks and user activities MobIeS is introduced. MobIeS is a system that allows users to extend mobile application interfaces through temporarily spanning the user interface across multiple screens. In short, the technique requires users to touch the border of an available external screen (e.g., a public display, TV, or desktop screen) with their phone during the interaction. The system detects this event of getting in spatial proximity and initiates the distribution of the user interface across the mobile and the external screen (See Figure 13). Subsequently, users benefit from the extended screen space which facilitates tasks such as viewing a map on much larger scale together with other users, browsing the web, or showing and exchanging pictures to, and with other users. When the phone is removed from the border of the external screen, the user interface returns to the original mobile mode.

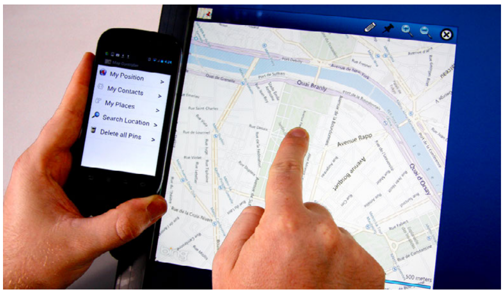


Figure 13: Spanning a mobile user interface across the mobile phone and an external display, here showing a map application.

That is, users can take advantage of existing screens in their environments without the need to carry additional hardware.

In order to investigate how effective this approach is, a comparative user study with 16 participants was conducted. The main aim was to investigate how smartphone users perceive this technique and to gain insights regarding the system's usability. The results show that the majority of participants rated MobIeS considerable higher in terms of information clarity which results from the larger screen space available for the application user interface. The main contributions of this work are the concept of MobIeS and the findings of a user study investigating a system based on this concept.

3.2.1 *Background of Cross-Device Extended Interfaces*

Early work on seamlessly connecting devices of different classes investigated how users can share information from their PDAs with others on a large shared device to support collaboration [102]. Integration of personal mobile devices with pre-installed devices in the environment has also been explored [216]. Ullmer et al.'s *mediaBlocks* showed how data attached to mobile tokens can be transferred to external devices [272]. Hinckley et al. demonstrated how multiple devices with touch screens allow users to drag-and-drop items from one device to another using the *stitching* technique [117]. Connecting large screens to mobile phones has been investigated [209] while other work focused on creating larger logical screens by combining several devices such as tablet computers [153] and considering the spatial relation of devices and users to each other [150]. NFC has been used to detect the relative position of mobile devices to larger displays (e.g., [109, 211]). Yet no work considered placing NFC tags around an external display which allows a novel way of interaction by using the displays of both devices together. Baur et al. present *virtual projection* which enables users to transfer data (e.g., pictures) from their phone to a large screen and display it thereon [39]. This approach allows users to take advantage of existing displays in their environment. However, the user's interaction is limited to the mobile device. Another approach is to distribute application interfaces on different devices and associated displays [103]. For instance, using mobile devices and large shared displays at which the phone is used as tool by touching the shared display in order to execute actions [16]. Our approach enables users to interact simultaneously with the phone and the extending display. In contrast to the discussed work, MobIeS focuses on mobile situations in which the users have the need for more screen space to perform a specific task. The distribution of the user interface of the mobile application onto both devices - both allowing for interaction - increases the user's capabilities.

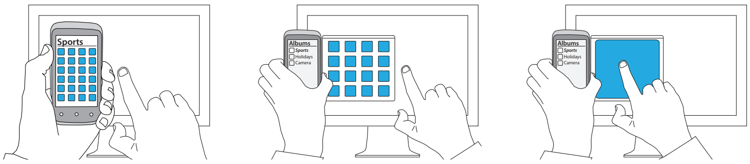
3.2.2 *Concept of MobIeS*

The concept of MobIeS is based on users temporarily creating a physical and spatial connection between their mobile device and an external screen to create a larger logical display that consists of the *mobile interface* and an *extended interface* on the external screen. For this concept, a necessary requirement which is assumed to be given is that displays in the users' environments can temporarily be used (e.g., public displays, kiosk terminals, TV sets, interactive surfaces, and even screens in cars or airplane seats). User interfaces of mobile applications can display only a limited amount of information due to the small screen size (see Figure 3.14(a)). By connecting the phone with an external display in order to create a larger logical screen, more space is available as this allows to distribute the user interface across two screens (see Figure 3.14(b)). The larger screen space on the external screen facilitates for instance, jointly viewing of content with a spatial dimension such as images (see Figure 3.14(c)). Existing work that investigated connecting mobile phones and external screens, for instance, through using mobile mediated interaction techniques, did not consider the potential of using the mobile and the external screen simultaneously for displaying information.

Creating a logical larger screen be spanning interfaces across devices.

The event of connecting the phone with the display can be sensed, for instance, by using NFC tags that are placed around the external display which is a novel way to use NFC tags for device location detection.

Sensing the touch of devices yields interaction possibilities.



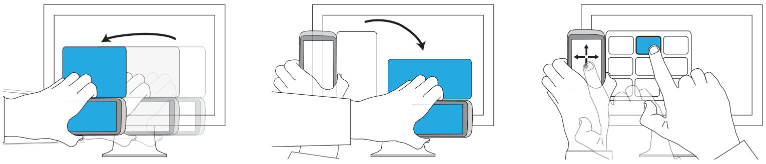
(a) (b) (c)

Figure 14: MobIeS allows users to distribute application interfaces across multiple screen ((a) and (b)). This allows to view for instance, images on a lager scale than on the mobile phone alone (c).

The MobIeS concept, which involves a handheld mobile phone and a stationary external display, allows users to perform input operations with this system in the following ways (see Figure 15).

- *Translation.* Relative movement of the mobile phone along the border of the external display can be sensed (via the same mechanism that detects the event of physical contact of mobile phone and external screen) and used as input (see Figure 3.15(a)). For instance, this action can be mapped for *skimming* or scrolling through a large document that comprises multiple pages.

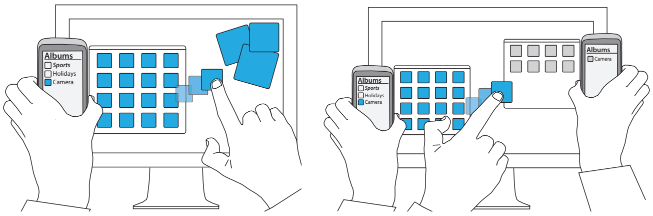
- *Rotation.* Rotation around the mobile phone's center can be sensed (through the mobile phone's internal accelerometer sensor) and used as input command (see Figure 3.15(b)). For instance, rotating the phone to the right could be mapped to increasing a continuous value, and vice versa rotating the phone to the left.
- *Touch input.* Touch input can be performed on the phone's display, and on the external display in cases a touch-sensing layer is provided (see Figure 3.15(c)).



(a) (b) (c)

Figure 15: Input options: (a) Translation of the phone. (a) Rotation of the phone. (a) Touch based input.

While the phone is connected with an external display, sharing and exchanging data such as pictures, documents, or contact cards can be performed in a straightforward way. Given that the external display supports touch-based interaction, users can simply drag-and-drop items from the external part of their mobile application to the public space of the external screen (see Figure 3.16(a)). For instance, this can be used in order to leave a message on a bulletin board. In addition, two users can exchange data by both connecting their devices to the same display and drag-and-dropping items from one phone to another (see Figure 3.16(b)).



(a) (b)

Figure 16: Data sharing options: (a) If the external screen provides touch input, data items can be dragged and dropped on the public space outside the application interface. (b) Data items can be shared with others via drag-and-drop to another connected mobile device.

3.2.3 *Implementing the MobIeS prototype*

The MobIeS prototype is based on standard technologies and products.

The prototype of MobIeS comprises two main components. First, a server application running on a PC connected to a host application that is displayed on the stationary touch screen (Dell ST2220T, 22" screen (1920×1080 px)). Second, a mobile client (for Android) running on the user's phone (Nexus S; 4" screen (800×480 px)). The server and the client manage the communication (via Transmission Control Protocol (TCP) over a WLAN) between the distributed application parts. Each application (e.g., a photo album) consists of a mobile component implemented as an Android application and a matching remote part implemented using the Microsoft Surface Toolkit. Depending on which application is active on the mobile phone when it touches the rim of the large display, the server launches a matching instance of the remote part of the application in the host application.

(a) (b)

Figure 17: External display border equipped with NFC tags (a). Tags are covered with tape to prevent accidental removal (b).

NFC tags are used to detect when a mobile phone is placed on the border of the large display. Thereby, the mobile phone actively detects the tag and reads stored information. NFC is supported by a large number of different mobile devices (e.g., Samsung Nexus and Nokia devices). Every 50 millimeters, an NFC tag is placed on the display rim (see Figure 17). When a phone equipped with an NFC reader is placed on the rim, it reads the tag content. This includes the position on the border, the display server's Internet Protocol (IP) address, and the Service Set Identifier (SSID) of the used WLAN. If the phone is not connected to the server application, the phone client establishes the connection with the wireless network and connects to the server. Finally, the phone client sends back the tag position and the ID or the currently active mobile application to the server which then launches the remote part of the application.

Using NFC tags allows for the extension of any existing screen to support MobIeS interactions by relatively low costs. This includes non-touch-enabled displays (e.g., public displays), as users can perform input on the phone while the external display simply extends the screen space.

3.2.4 *Evaluation of MobIeS concept*

In order to evaluate if the MobIeS concept provides benefits compared to using mobile phones in a stand-alone mode, a comparative user study was conducted. The goal was to investigate to what extent MobIeS supports users in performing typical mobile tasks. It was of particular interest to gain insights concerning usability and how participants perceive this extension of the user interface through holding the phone next to the extending screen compared to the familiar practice of using only mobile phones.

STUDY APPARATUS. For the experiment, three applications were implemented that allow users to experience the MobIeS concept. These include a *photo album*, a *map*, and a *web browser* application. All applications could be used with an additional external display or as a *stand-alone* mobile application using only a mobile phone. Using only the mobile phone without the extension of the user interface on an external display was used as a comparative condition for the practical tasks (in the following referred to as the *mobile-only* or *MO* option). The features of the applications cover standard functionalities inspired by existing Android applications.

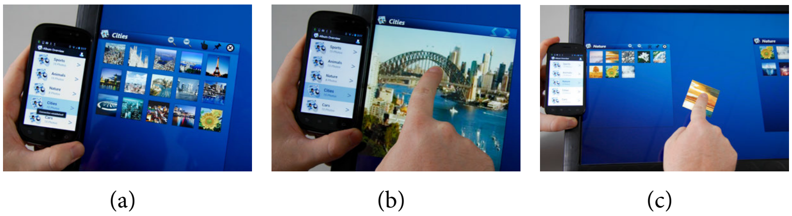

(a) (b) (c)

Figure 18: The photo sharing application: (left) extended overview; (middle) focus on a single image; (right) sharing images with another user by dragging an image from one extended interface to another.

The photo album application for MobIeS.

In the mobile mode, the photo album application enables users to organize photos taken with the phone in different albums. After selecting an album, contained items are displayed as small thumbnails. Touching a thumbnail activates the full screen mode. When the user launches the extended interface by holding the mobile phone next to the display border, the phone displays the album list and the extended interface shows an overview of picture tiles (Figure 3.18(a)). Which album is displayed can be selected using the list on the mobile interface. Selecting an item in the overview magnifies the picture to fill the application window on the extended interface (Figure 3.18(b)). For the transfer of pictures from one mobile phone to another, users drag-and-drop items from one extended interface to another (Figure 3.18(c)).

(a) (b) (c)

Figure 19: The web browser application: (left) extended web page view; (middle) selecting bookmarks; (right) browser tab overview.

The web browser *application for MobIeS.*

The web browser application provides a history overview and supports tabbed browsing and bookmark management (in both modes). As the user connects the phone to the external display, the mobile phone display shows a menu containing options (e.g., History, Open Tabs) and the extended interface shows the corresponding content such as the list of bookmarks (see Figure 3.19(a)). When the user selects the bookmark overview from the menu list, the interface on the external display provides a comprehensive list of saved links which can be open through selecting one by touching it (see Figure 3.19(b)). Similar, the user can open an overview of open browser tabs by selecting the corresponding menu entry. In addition, for typing in text, the user can use a virtual software keyboard either on the phone or on the external display.

The map *application for MobIeS.*

The map application allows users to take advantage of a larger screen area to display map contents. That is, when a user has opened a specific view on the mobile phone (see Figure 3.20(a)), the available screen size is limited by the mobile phone's dimensions. Through bringing the mobile phone and an external screen into physical contact, the user interface automatically gets distributed across the two devices: the mobile phone is used to display a menu (e.g., contact addresses, points of interest, or favorites) and the larger interface on the external display shows the map content that was previously visible on the mobile phone (see Figure 3.20(b)). In order to facilitate inspecting map content, which can take some time, the MobIeS maps application allows users to *pin* the external interface to the corresponding screen. This allows for instance, to type in a search query string using the mobile phone virtual keyboard (see Figure 3.20(c)). In addition, this facilitates also collaborative discussion of how to get to some place with others, as the user is not forced to hold the phone constantly which might prevent others from viewing the maps properly.

Pinning *interfaces to an external screen allows users to remove the phone without closing the logical connection of distributed interfaces.*

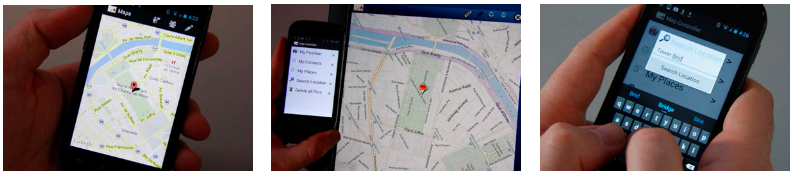

(a) (b) (c)

Figure 20: The MobIeS map application: asdfadsfasdf

PRACTICAL STUDY TASKS Participants were asked to perform a number of tasks using one time MobIeS and another time the comparative MO option while using a pre-configured mobile phone on which all required data (e.g., pictures or contacts) were available. With the *photo album* application, participants performed the following tasks:

- *Show the investigator pictures showing people from three different albums.*
- *Search for the picture showing the {Eiffel Tower, stones} in the albums and delete it.*
- *Take a picture and transfer it to the investigators phone and receive a picture.*

With the *map* application, participants performed another set of three tasks:

- *Find the Eiffel Tower / the Tower Bridge on the map and show it to the investigator.*
- *Show the investigator the addresses of two contacts from the address book as a pin on a map.*
- *Show the investigator on a map how to get to the main campus from the faculty building.*

And finally, participants were asked to perform a third block of tasks using the MobIeS web browser application comprising the following points:

- *Open the test web page and look up the contact information of the author and tell the investigator.*
- *Add the test web page to the bookmarks and check if the URL was added.*
- *Show the investigator which pages are loaded in the open browser tabs.*

The tasks were selected in that sense that it should involve several times the aspect of sharing information with another person (i.e., the investigator), which is an important characteristic of collaborative interaction which MobIeS seeks to facilitate and to support.

STUDY PROCEDURE. The investigator introduced MobIeS and the MO option and participants were asked practiced using them until they subjectively felt that they were comfortable to use it. Then the participants performed the series of practical tasks, once using MobIeS and once as a comparative approach using mobile phones only (MO). The order of systems was counterbalanced and the task order was randomized. Participants filled in a questionnaire regarding usability, including the computer system usability questionnaire [145], after performing the tasks with each system.

PARTICIPANTS. 16 participants (5 females) were recruited, aged between 20-33 (M = 26). All participants were students with diverse fields of studies. All of them used smartphones with a touch screen and 14 reported having experience with large multi-touch displays. They received 10.00 EUR after the study session which lasted an average of 45 minutes.

3.2.5 *Evaluation Results*

On average, each system condition was used for 20 minutes. After each trial, they filled in a questionnaire and rated the system (1 = Strongly disagree; 7 = Strongly agree). We used the non-parametric Wilcoxon signed-rank test to evaluate differences.

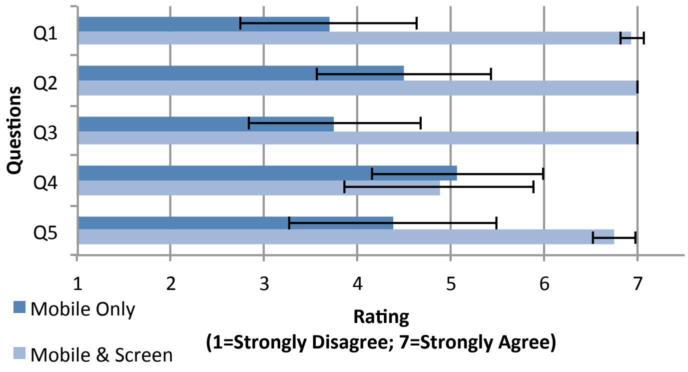


Figure 21: Average ratings of question Q1-Q5.

Regarding the statement (Q1) "Using the system, I could easily show information to other persons" participants rated the MobIeS system significantly higher (Mdn = 7.0) than the MO condition (Mdn = 3.0) (z = -3.3, p = .001). Similarly, participants rated MobIeS (Mdn = 7.0) significantly higher than MO (Mdn = 5.0) regarding (Q2) "The system supported sharing of information well" (z = -3.3, p = .001). Further, participants rated MobIeS higher (Mdn = 7.0) than MO (Mdn = 3.5) in regards to (Q3) "The system supported jointly viewing of information well" (z = -3.4, .001). Yet both conditions were rated equally concerning (Q4) "Using the system, I often had to change my focus" (z = -.4, p = .72). One likely reason is that the larger screen space provided by MobIeS spanned across two devices and thus required users to change their focus, much as using only the mobile phone requires switching between different views. Regarding (Q5) "Transferring information to another device was easy using the system", participants rated MobIeS significantly higher (Mdn = 7.0) when compared to MO (Mdn = 5.0) (z = -2.9, p = .004).

Regarding showing, sharing *and* transferring *as well as* jointly viewing *MobIeS was significantly higher rated by participants.*

Regarding focus shifts *MobIeS was rated equally with the baseline.*

Participants rated both conditions using the IBM Post Study System Usability Questionnaire (PSSUQ) (1 = Strongly disagree; 7 = Strongly agree) that allows calculating four scores: OVERALL (the overall satisfaction score), SYSUSE (system usefulness), INFOQUAL (information quality), and INTERQUAL (interface quality) [145]. All score results are higher for MobIeS: OVERALL (MobIeS: 6.37; MO: 5.08), SYSUSE (MobIeS: 6.37; MO: 5.25), INFOQUAL (MobIeS: 6.30; MO: 5.18), and INTERQUAL (MobIeS: 6.34; MO: 4.58). Using Wilcoxon signed-rank test shows that the MobIeS was rated significantly higher in 15 of the 19 questions. Statements that were not rated significantly different covered *system capabilities*, *documentation or help*, and *recovery from mistakes*.

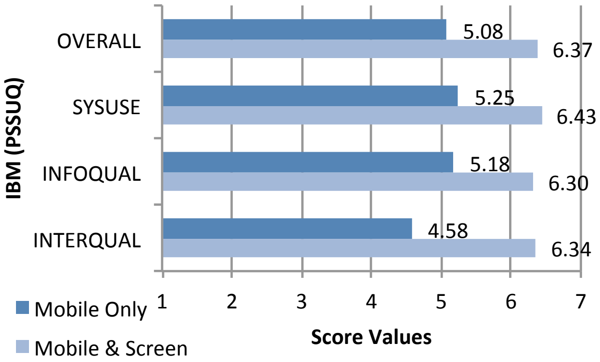


Figure 22: System scores based on IBM PSSUQ.

The statements with the largest differences in the ratings cover the issues of system interface and task efficiency (see Figure 23). S1 and S2 both indicate that participants appreciated the extended interface spanning across two screens as it was perceived as significantly more *pleasant* to use (z = -3.2, p = .001) and the organization of information was rated to be more clear (z = -2.6, p = .01). S3, S4, and S5 show that participants perceived MobIeS as significantly more effective (z = -2.7, p = .007), more efficient (z = -2.4, p = .01), and faster to use (z = -2.6, p = .008).

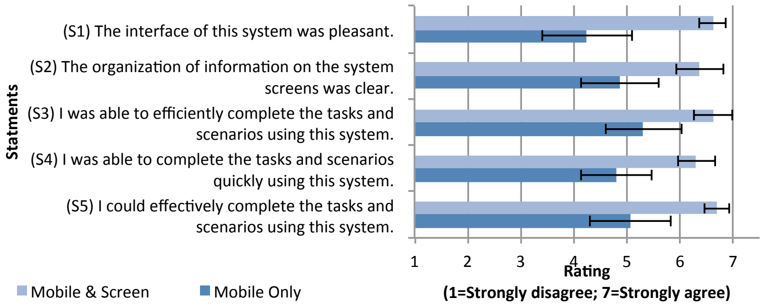


Figure 23: Questionnaire statements with the largest differences in ratings.

Qualitative feedback and obersvations.

Six of the participants emphasized that they liked the level of clarity achieved through the larger screen space. Also, participants pointed out that extending the interface of mobile applications would be helpful to show or share information with others. One user suggested a holder for the mobile phone to leave both hands available for interaction. Several (four) participants pointed out that they liked the ease of use of the system. For instance, P8 stated "It is very easy to switch between using only the mobile phone and using the additional display." Few participants pointed out that they initially had to look for information after the user interface spanned across two displays. Yet all participants learned how to use the system quickly after a short introduction. Other participants highlighted that they liked the extension but expressed doubts whether an external display would be available when needed.

14 participants stated that in general they would prefer to use MobIeS over the standard mobile option. 15 stated that it is easier to use and all stated that MobIeS provides more clarity of information.

3.2.6 *Discussion of findings on MobIeS*

MobIeS addresses the issue that mobile users temporarily have the need for more screen space in selected situations. For instance, to gain more clarity when viewing large images or maps, or when sharing information with others. The results of our laboratory study strongly indicate that users benefit from using this approach. Parameters that could not be mapped through an experimental setting, such as availability of matching external screens, as well as possible privacy and security concerns need to be considered when deploying such a system. The presented approach is based on a novel application of NFC technology that allows extending existing displays at very low costs. It enables users to take advantage of displays in their environments in order to extend the user interfaces of their mobile applications when needed. In a user study, we compared MobIeS with the standard mobile phone option. The results indicate that participants appreciated the degree of information clarity, perceived their task performance to be faster, and highlighted that the system is easy to use.

3.3 COLLABORATIVE APPLICATION CASE STUDY

This section is based on the work:

[5] J. Seifert, D. Schneider, and E. Rukzio. “MoCoShoP: Supporting Mobile and Collaborative Shopping and Planning of Interiors.” In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 756–763

This subsequent section introduces and discusses a case study on how collaboration can be supported in a specific application context through mobile mediated interaction techniques: a mobile shopping assistant application that facilitates activities in a retail environment. The main goal of this case study was to investigate how different mobile, mediated, and direct interaction techniques can be integrated in application context.

The motivation to choose this application context is the observation that online shopping is more popular than ever and recent numbers indicate that this trend is continuing [147]. Reasons for this success are a high flexibility for customers who wish to compare prices of products, access to detailed information on products (e.g., availability, possible configurations, dimensions), and social aspects such as easy access to other customers' ratings and reports on experiences with a product.

Many types and groups of products are well suited for online shopping. For instance, previews on media files such as music or movies can be provided and thus, customers get a clear idea of what they are going to purchase. However, other artifacts cannot be previewed in an adequate way due to their specific physicality or other inherent aspects that cannot be communicated. Accordingly, many customers prefer visiting retail stores as they allow the touching, testing, and experiencing of a product. This is in particular the case for pieces of furniture that must fit into an existing setting of other previously acquired pieces of furniture. Additionally, they need to meet the customer's personal criteria such as taste or comfort. In retail stores, customers can check these criteria and gain hands-on experience with products. On the downside, retail stores have different drawbacks compared to online shops: detailed product information such as prices, available configurations, etc. are difficult to access. Also, planning how different products would fit into a room with existing pieces of furniture is difficult.

The MoCoShoP application seeks to explore benefits of contact-based mobile mediated interaction in the context of retail environments.

Based on this motivation MoCoShoP[1] was designed, a system that allows customers to experience the advantages of retail stores (e.g., physical and hands-on experiencing of products) and combines these with the benefits of online shopping (e.g., information access, social shopping). MoCoShoP provides a mobile client application that runs on the cus-

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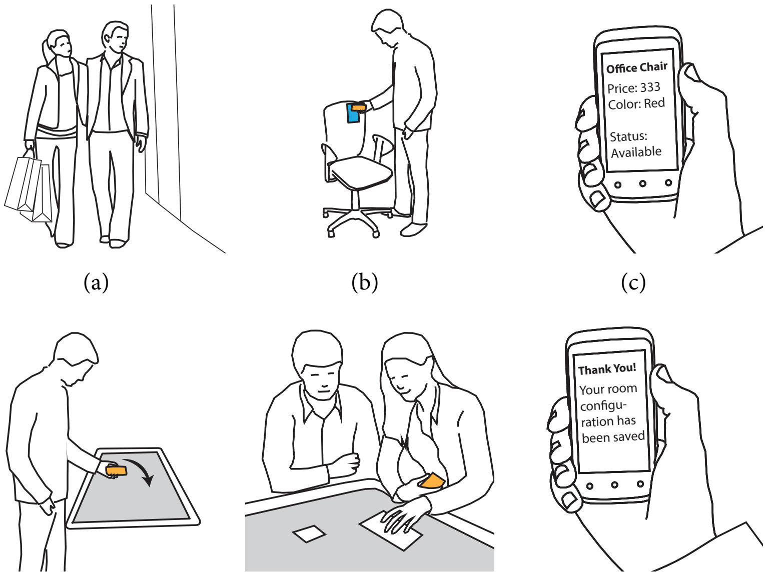
[1] MoCoShoP: *Mobile Collaborative Shopping and Planning.*

tomers' mobile phones, which allows for access of product information via network and provides a shared shopping cart (e.g., with family members) if desired. Further, the system provides an interactive planning desk which supports collaborative creating of product arrangements and floor plans containing the collected products. In the following, we illustrate the usage of MoCoShoP with a usage scenario.



(a) (b) (c)

(d) (e) (f)

Figure 24: Usage scenario for MoCoShoP: Multiple users go shopping together (a). Users pick up information by scanning labels (b) and (c). Users transfer collected items to a planning desk (d) and create plans containing interesting products (e). Finally, they save a planning arrangement and purchase items (f).

Application and usage scenario of MoCoShoP.

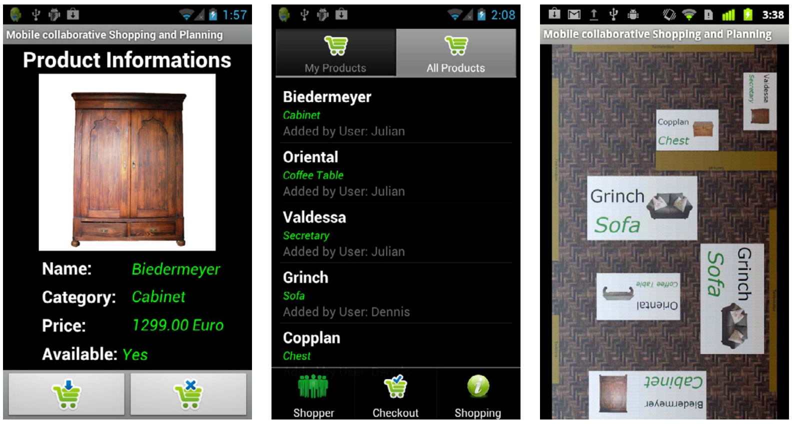
Alex and Kim are planning to buy additional pieces of furniture for their office. In order to look for possible items, they go to a furniture retail store (see Fig. 3.24(a)). Both Alex and Kim use the MoCoShoP mobile client on their mobile phones to scan and check out prices and available settings of products (Fig. 3.24(b) and 3.24(c)). When they have collected and added enough items to their cart, they approach the collaborative planning desk and transfer the items to the desk through a touch gesture (Fig. 3.24(d)). On the planning desk, Alex and Kim try different configurations and floor plans with selected products (Fig. 3.24(e)). When they agree on a configuration including which items to buy, they save the configuration back to their mobile phones (see Fig. 3.24(f)) allowing for further item collection or for the purchase of the selected items.

This section provides details on the application design of MoCoShoP as well as a first prototype implementation. This prototype was used to set up an evaluation environment in which a first qualitative evaluation of the concept was conducted. This section further, details the insights regarding the application concept on the background of a comparison with the current practice of taking notes using pen and paper in retail environments. Finally, this section discusses the research background and discusses the findings.

3.3.1 *MoCoShoP Application*

The design goals of MoCoShoP are (a) supporting quick information access in retail environments, (b) providing awareness of other users actions to support collaboration, (c) support for collaborative planning and reviewing of potential room plans including purchasable furniture items.

In order to meet these design goals, MoCoShoP includes two components for interaction: a personal mobile client application for each user and a shared interactive planning desk.



Name: Biedermeyer
Category: Cabinet
Price: 1299.00 Euro
Available: Yes

Biedermeyer
Cabinet
Added by User: Julian

Oriental
Coffee Table
Added by User: Julian

Valdessa
Secretary
Added by User: Julian

Grinch
Sofa
Added by User: Dennis

Copplan
Chest

(a) (b) (c)

Figure 25: The MoCoShoP mobile application: (a) Product details screen after scanning a product label. (b) Shared shopping cart overview. (c) A floor plan of a configured room including arranged pieces of furniture.

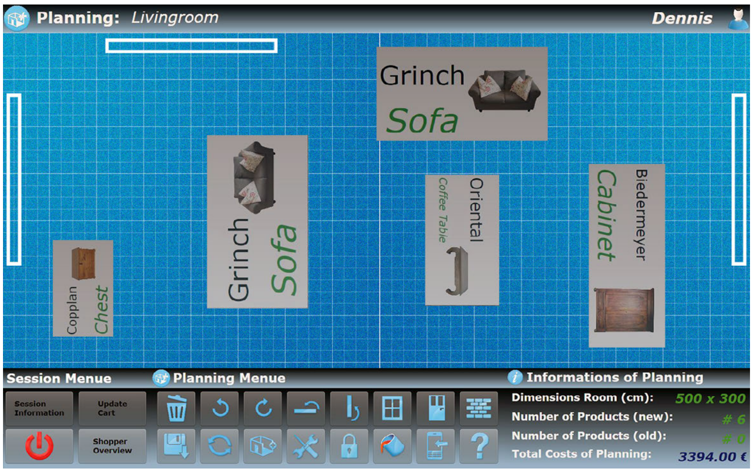
Personal mobile client is implemented as Android application.

The mobile client runs as an application on the user's mobile phone. It allows users to scan product labels in order to access related detailed information. In order to scan a product ID, the user holds the phone close to the corresponding label which allows the phone to read a NFC tag that is integrated into the label. NFC is based on the Radio-Frequency Identification technology and allows storing of data on a chip that is powered via a capacitive field created by the reading device. This technology is included recently in an increasing number of smartphones (e.g., Nexus

4). As an alternative, printed bar-codes could be used to include a larger number of potential smartphones which are not equipped with an NFC reader (e.g., the iPhone). When a product label has been scanned, the application retrieves product details and provides an overview (see Fig. 3.25(a)). Users can choose to add the product to their shopping cart or simply reject the product. Multiple users can create a joint shopping session which allows them to add products to a shared shopping cart (see Fig. 3.25(b)). By selecting an item from the product list in the shopping cart, users can inspect the corresponding product information or delete the item. The mobile client also allows the storage of product lists and floor plan configurations that were created on the shared planning desk (see Fig. 3.25(c)).

The shared collaborative planning desk is implemented as Windows Surface application.

When users have added potentially interesting products to their shopping cart, they can transition their shopping activity towards a planning activity which is supported by MoCoShoP through the collaborative planning desk. The planning desk is an application that is running on an interactive multi-touch surface, allowing multiple users to work together. First, one user of a group touches the planning desk on the device border with their mobile phone. The mobile phone reads a specific NFC tag which initiates the transfer of collected product IDs to the planning desk application.



Dimensions Room (cm): 500 x 300
Number of Products (new): # 6
Number of Products (old): # 0
Total Costs of Planning: 3394.00 €

Figure 26: The collaborative planning desk application provides a touch-based interface.

The planning desk application provides a large canvas which represents a floor plan of the room which the user would like to configure, and thereby plan which pieces of furniture would fit into it (see Fig. 26). The application allows users to quickly rearrange and configure such a floor plan. The interface provides information such as how much money the items cost that are included in the current configuration. In addition, the application provides a number of tools that support the users throughout the planning task. For instance, buttons which rotate items, align, or delete them are provided. Finally, when users are satisfied with their design, the store, the floor plan, and the data are transferred back to their mobile devices.

3.3.2 *Concept Evaluation*

We conducted an initial user study in order to gain insights on if and how users would appreciate such a collaborative shopping and planning system such as MoCoShoP. In particular, our aim was to gain an understanding of how the system would support collaboration during the shopping and the planning process of furnishing when compared to the current practice of using pen and paper in order to collect information and plan during the shopping process.

SESSION ORGANIZATION. Initially, participants were introduced to the aim of the study. Then, participants performed two practical task in counterbalanced order. Once they used the MoCoShoP system and once they used only pen and paper. This pen and paper condition was selected for comparison as it represents an approach most users are familiar with. In order to investigate the collaboration support by MoCoShoP, participants would perform these tasks as pairs of two. After finishing each task, participants were asked to fill out a questionnaire regarding their experiences with the used approach.

PRACTICAL TASKS. Participants performed one task with each condition (MoCoShoP; pen and paper). The tasks required participants to select, collect, and plan furniture items for a room (a living room and a bedroom). Both tasks were similar in terms of the actions required: first, users were given instructions such as how much money they could spend and what pieces of furniture should be included. Second, the two participants started walking through the study shopping environment. We equipped two laboratory rooms with 69 labels attached to the walls representing available furniture items (see Fig. 3.27(a)). There, participants looked for items suitable for their planning task. Whenever participants found interesting items they could add them to their shopping lists. When using MoCoShoP, they used smartphones which were provided with the mobile client application installed. In the pen and paper condition, participants were required to take notes manually (see Fig. 3.27(c)). Further, participants should plan a room layout including the selected pieces of furniture one time with the MoCoShoP planning desk (see Fig. 3.27(b)) and one time using pen and paper (see Fig. 3.27(d)).


(a) (b) (c) (d)

Figure 27: Interaction during evaluation tasks. (a) Using the personal mobile client to collect product information. (b) Collaboration on the planning desk. (c) and (d): Collecting information and planning a room outline using pen and paper.

APPARATUS IMPLEMENTATION. In order to allow running a concept evaluation in form of a user study, a prototype of MoCoShoP was implemented. The mobile client application was developed for the Android platform running on a Samsung Nexus S (4" screen, 800×480 px) mobile phone that provides an NFC module for the scanning of product labels. The collaborative planning desk (Dell ST2220T, 22" screen (1920×1080 px)) was developed based on the Microsoft Surface 2.0 Software Development Kit (SDK) which provides support for multi-touch interfaces. For the storage and management of product information, a web server provided an interface for the retrieval of corresponding information. Further, a session management server was implemented to store information related to shopping sessions (e.g., list of items in a shared shopping cart).

PARTICIPANTS. In total 14 participants were recruited who worked during the study sessions in pairs of two. Participants were aged between 23 and 33 years old and seven of them were female. Most of them were undergraduate students; two were employees.

3.3.3 *Evaluation Results*

All participants expressed that they liked how fast it was to access product information by scanning a label. Several users expressed that a shared shopping cart is helpful in situations when collaborators split up to search for different products by creating a kind of awareness for the other users' activity or location. As expected, most participants appreciated the flexibility provided by the planning desk application which allows users to create many different confections easily.

13 participants stated that shopping and planning furniture items is a collaborative activity they perform together with other people. This reinforces the identified design goal that collaboration support is needed for shopping for furniture items.

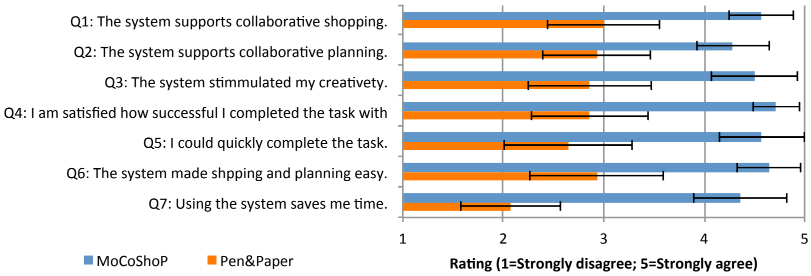


Figure 28: Post-hoc questions comparing MoCoShoP and the pen and paper condition (Error bars indicate the standard deviation).

Participants rated MoCoShoP significantly higher (on a 5-point scale; 5 = best; tested using the Wilcoxon Signed Ranks test) compared to the pen and paper condition regarding the support for collaborative shopping (z = -3.13; p = .002), collaborative planning (z = -2.87; p = .004), and perceived creativity stimulation (z = -3.1; p = .002) (see Figure 28). Further, participants rated MoCoShoP significantly higher in terms of successful task completion (z = -3.22; p = .001), time required to complete the task (z = -3.21; p = .001), support to make the task easy (z = 3.21; p = .003), and the perceived system ability to save the user time (z = -3.33; p = .001).

3.3.4 *Discussion of MoCoShoP*

BACKGROUND. The concept and interaction techniques applied for MoCoShoP are grounded in a number of existing and related works. Early work by Rekimoto investigated the pick and drop interaction technique [213]. The touch and interact technique advances the touch-based interaction to mobile phones based on NFC technology [109]. PhoneTouch generalizes cross-device (touch-based) interaction [16] as adopted by MoCoShoP.

Mobile phones have been demonstrated to be suitable devices for mobile recommendation systems to overcome the limitations of traditional retail stores [212]. Additionally, mobile phones have been used [51] for the visualization of customer-specific information on products (e.g., a diabetes shopping assistant). Similar to MoCoShoP, the system SoloFind allows users to collect information on products in a retail store for further inspection on a kiosk computer [292]. In contrast, MoCoShoP incorporates different classes of devices for specific tasks, allows information access via the mobile device, and supports collaboration on the shared planning desk.

DISCUSSION & CONCLUSION. This case study presented MoCoShoP, a system that aims to support customers in retail stores during the process of collecting information on potentially interesting pieces of furniture, and further, during the process of planning how the collected products could fit into their devised layout. While the personal mobile devices are used for information collection, the large interactive surface is used for collaboration and shared discussion.

Our prototype implementation of MoCoShoP demonstrates that the effort for deploying such a system is moderate and existing environments can be easily augmented: product labels with either integrated NFC tags or simply printed bar-codes are low-cost factors and interactive surfaces to be used as planning desks will be relatively cheap as technology matures. MoCoShoP combines the benefits of e-commerce and traditional retail stores to improve the user experience by providing digital access to information using the mobile application which is used directly in the retail environment. Feedback of participants in the evaluation highlighted the benefits of flexible and straightforward information collection. In addition, several participants highlighted that a shared surface in form of a planning desk is of particular use and supports the collaboration during a planning activity.

4

DATA DISCLOSURE & PRIVACY MANAGEMENT

This chapter focuses on aspects regarding how users cope with sharing and disclosing personal data in pervasive interaction spaces and how mobile mediated interaction techniques can be used for managing privacy related aspects. The main motivation for investigating this point is the inherent characteristic of mobile mediated interaction techniques that they aim for integrating and seamlessly connecting the user's personal mobile phone with other pervasive displays in the environment. While it is on the one hand a desired goal to allow straightforward sharing of data that are stored on a personal device, users must be prevented and protected from accidental or unintended disclosure of personal data on a pervasive display.

The decision of which pieces of data are intended for sharing depends on a multitude of diverse factors which are not fix as these can change over time. The sociologist Erving Goffman described the decision process of how people present themselves towards their environment as a negotiation activity [96]. In particular, the *audience* effects a person's willingness to disclose specific information. Accordingly, depending on who is present, a user needs to be able to adjust what data is potentially disclosed when using shared interactive pervasive displays. In case this process of deciding and adjusting which data is appropriate in a given situation, is not sufficiently supported, users risk to disclose information which can result in disadvantages for the user. For instance, disclosing personal photographs in a working context could be perceived awkward.

The second aspect on which this chapter focuses on is how mobile mediated interaction techniques can be used to facilitate privacy management. One fundamental aspect of *privacy* is "the right to be left alone" [283]. This characteristic applied not only to physical aspects such a *territorial privacy* [225] but also to *information privacy* [195]. From this it follows that the process described by Goffman of negotiating what information should be disclosed about oneself applies also to users' digital information. While users can easily and naturally adapt their disclosing behavior constantly this negotiating process requires in the context of digital information disclosure actively changing settings. This privacy *managing* process is essential for mobile mediated interaction techniques as personal mobile phones that are used as mediator devices potentially store sensitive data that must be protected in specific contexts. This chapter presents investigations regarding how users mange their privacy when exposed to mobile mediated interaction techniques (see section 4.2) as well as how such techniques itself can support this process (see section 4.1).

Privacy is a highly complex research field that involves diverse points of view in order to gain a holistic picture. That includes for instance, cryptography, network security, and corresponding communication protocols. In this work however, the investigative work followed the approach to abstract aforementioned aspects and to focus fully on the aspect of interaction and thus on a user-centric view.

This chapter is based on previously published work which includes the following refereed journal and conference papers:

- [2] J. Seifert, D. Dobbelstein, D. Schmidt, P. Holleis, and E. Rukzio. "From the private into the public: privacy-respecting mobile interaction techniques for sharing data on surfaces." In: *Personal and Ubiquitous Computing* 18.4 (2014), pp. 1013–1026
- [9] J. Seifert, A. De Luca, and E. Rukzio. "Don't Queue Up!: User Attitudes Towards Mobile Interactions with Public Terminals." In: *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia*. MUM '12. Ulm, Germany: ACM, 2012, 45:1–45:4
- [7] A. L. Simeone, J. Seifert, D. Schmidt, P. Holleis, E. Rukzio, and H. Gellersen. "A Cross-device Drag-and-drop Technique." In: *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*. MUM '13. Lulea, Sweden: ACM, 2013, 10:1–10:4
- [10] J. Seifert, A. D. Luca, B. Conradi, and H. Hussmann. "TreasurePhone: Context-Sensitive User Data Protection on Mobile Phones." In: *Pervasive Computing*. Ed. by P. Floréen, A. Krüger, and M. Spasojevic. Lecture Notes in Computer Science 6030. Springer Berlin Heidelberg, 2010, pp. 130–137

In addition, the following partially related thesis was supervised by the author:

- "Privacy Zone: Privacy Preserving Concepts for Dynamic Sharing of Photos on Interactive Surfaces" . David Dobbelstein. Bachelor's thesis. 2011. (*Parts of this thesis contributed to [2]*).

4.1 SUPPORTING DATA SHARING THROUGH MEDIATED INTERACTION

This section the is based on the work:

[2] J. Seifert, D. Dobbelstein, D. Schmidt, P. Holleis, and E. Rukzio. “From the private into the public: privacy-respecting mobile interaction techniques for sharing data on surfaces.” In: *Personal and Ubiquitous Computing* 18.4 (2014), pp. 1013–1026

Interactive horizontal surfaces enjoy large popularity for all kinds of usages such as sharing and viewing of media, planning trips, browsing, or gaming. The constant increase in terms of technical features and the decrease of the price for such surfaces will eventually lead to their pervasive usage for example at home, in offices, in hotels, in lounges, or in public buildings such as schools, universities, or libraries within the next decade. Their large size and multi-touch capabilities support in particular co-located collaborative interactions (e.g., [124, 241]). However, this also raises various privacy related questions when considering the information that could be displayed or stored on them. In contrast to mobile phones, interactive surfaces are shared public or semi-public devices and anyone nearby can see what is displayed.

The use of interactive surfaces for displaying, discussing and sharing private media (e.g., pictures) or information stored on the user’s mobile phone (e.g., contacts, address information, or documents) is a frequently discussed scenario [168, 173, 239, 300]. Here, a mobile phone needs to first establish a connection to the interactive surface and then, for instance, all pictures stored on the device [168, 300] or a thumbnail view of the pictures [173] can directly be shown at the table. Another possibility is that the user remotely selects information in private on the mobile phone before it is shown on the surface [62].

It is likely that most users store information on their mobile devices that they do not wish to show or share with others in all situations. This depends on the location in which the interactive surface is placed, the current situation, the relationship to the bystanders and the information to be shared. This might range from settings at home where one wants to share holiday pictures with close family members to public settings in a hotel lobby where one wants to share only pictures of recently visited sights. Therefore, as users decide depending on the current context which data are appropriate for sharing with the current audience, effective means are required for selecting which data is to be shared. In particular, smart phones and their camera feature allow users to create large numbers of photos in diverse contexts. Interaction techniques are required that allow users to select from a large number of photos what they wish to share within a specific context.

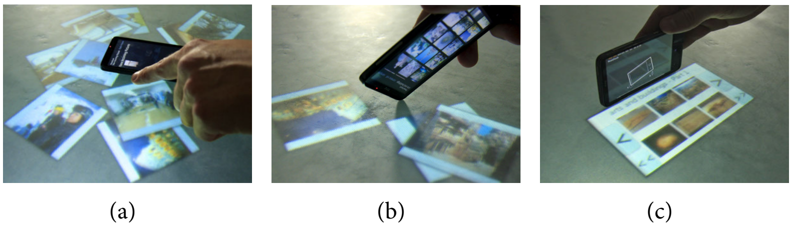

(a) (b) (c)

Figure 29: Interaction techniques for privacy preserving sharing of data on interactive surfaces. (a) Select&Place2Share. (b) Select&Touch2Share. (c) and Shield&Share.

To address this, Select&Place2Share and Select&Touch2Share were developed. Both techniques enable pre-selection of information on the mobile phone before showing it on the table (initiated by touching or placing the phone on the table as shown in Figure 4.29(a) and 4.29(b)). In a third technique, Shield&Share, the user touches the surface with the side-edge of the phone so that the phone is placed like a viewing shield (see Figure 4.29(c)). On the phone's screen, the user can see a high-resolution preview of the selected file. At the same time, on the area right in front of the mobile phone facing the user, thumbnail views with navigation controls are displayed. For sharing a photo, the user simply drags the corresponding thumbnail from the menu bar at the bottom of the phone onto the public surface area. There, the photo is displayed visible for everyone around the surface.

This section contributes three novel interaction techniques Select&Touch2Share, Select&Place2Share, and Shield&Share that draw on previous work in this area, and the results gained from a comparative user study. The results indicate that users highly appreciate and require interaction techniques that support protecting their privacy through allowing them to specify which items to share.

4.1.1 *Background on Data Disclosure Techniques*

The related research can be classified into following categories: (1) Integration of personal devices (e.g., mobile phones) and shared displays (e.g., interactive surfaces and public displays). (2) Extending and augmenting displays through connecting multiple devices. (3) Direct touch interactions of mobile phones on interactive surfaces. (4) Privacy issues that arise from using personal devices in collaborative settings.

In order to complement the explanations in the classification chapter of this thesis, additional work regarding sharing personal data in pervasive interaction spaces is given in the following.

Users interacting on shared surfaces face challenges regarding privacy issues. Wu and Balakrishnan introduce the usage of the non-dominant hand to shield information displayed on the table from others while using the dominant hand to perform interactions in the shielded area [303]. Kim et al. showed that shielding a small area on the surface from the view of other users supports entering private information such as personal identification numbers [135]. Another privacy relevant issue arises from combining personal mobile phones of users with shared displays as users store large amounts of data on their personal devices [10]. Therefore, users should be in control of what data are shared. Shoemaker and Inkpen addressed the challenge of displaying private information within the context of a shared display by making certain information only visible to users with the corresponding access rights [244]. This approach requires users to wear shutter glasses that are connected to the display which allows displaying an individual view to each user. In contrast, Shield&Share does not require users to use additional hardware but their mobile phones. With Ubitable, Shen et al. presented a system that allowed users to share and exchange data on an interactive surface [241]. Users could decide on a personal device (a laptop computer) which data should be transferred to the surface. The data appeared first in the private area on the surface, which could only be accessed by the user itself. Thus, the user is in control of what information is disclosed at all times.

4.1.2 *Data Sharing Concepts*

Two aspects are of particular relevance when designing privacy respecting interaction techniques for sharing data between mobile phones and shared interactive surfaces. First, the ability for users to select ad-hoc what data to share is crucial. In particular, it may not be sufficient to priori classify data as *public* versus *private* since the changing usage context determines what is considered sensitive and worth protecting. Second, it is important to consider the phone's location during the sharing process; it can remain in the user's hand or may be placed on the interactive surface. Which interaction techniques users prefer and how well they support users to protect their privacy are open questions and need to be investigated. Therefore, these interaction techniques are compared in a comparative study. In the following, first a technique is discussed that is commonly found in the literature to serve as baseline for this comparison. Further, three original touch-based interaction techniques are described that enable novel ways of sharing data stored on mobile phones on interactive surfaces.

The Place2Share interaction technique serving as baseline in the context of this work.

The interaction technique Place2Share (c.f., [2]) draws on the concept presented with *BlueTable* [300] which has been adopted in many different contexts (e.g., [29, 168]). Place2Share consists of only one step: users place

Figure 30: Place2Share allows users to share all their data stored on the phone (a) by placing it on a surface. As the phone is placed, the data is transmitted to the surface and displayed around the phone (b).

their mobile phones on the interactive surface. As soon as the event of placing the mobile phones is detected by the system, all data (e.g., images) stored on the mobile phone is transmitted to the surface. There, data is displayed around the mobile phone (see Figure 4.30(a)). Users can select items to interact with through direct touch-based interaction. In the opposite direction, users can transfer data from the surface to the phone by dragging a picture very close to the phone.

The Select&Place2Share interaction technique supports previous data selection.

Place2Share is a comparably straightforward approach, yet it does not support controlling which data is intended for sharing.An adapted and modified version which is more sophisticated to that end is called Select-&Place2Share. It allows users to make a selection of data items which are intended for sharing on the surface beforehand. The selection is made on the phone by marking items as *public* through touching them (see Figure 4.31(a)). Touching marked items again changes the state back to *private*. When the user places the mobile phone on the surface the items that are contained in the public folder are transmitted to the surface and displayed around the phone (see Figure 4.31(b)). In the opposite direction, the user can transfer data from the surface to the phone by dragging a picture very close to the phone.

This interaction technique provides basic support for users to protect their privacy as they have to explicitly define what data is to be shared. The selection is made while the phone remains in the hand of the user. Thus, others cannot observe what is selected and it is not possible to assess how much data is stored on the user's phone. The phone is then placed on the surface which, again, allows two-handed interactions on the surface.

The Select&Touch2Share technique supports previous data selection while device remains in the user's hand.

The interaction technique Select&Touch2Share draws on such direct touch interactions between the mobile phone and the interactive surface previously reported (e.g., [213, 230, 239]). In order to apply this interaction technique, the user first makes a selection of data on the mobile phone (see Figure 4.32(a)); then the user performs a touch with the phone on the

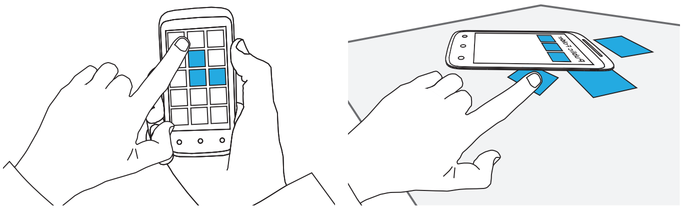

(a) (b)

Figure 31: Select&Place2Share allows users to select items that are intended for sharing (a). Then users place their phone on the surface and selected items are displayed around the phone (b).

interactive surface (see Figure 4.32(b)). As this event occurs, the selected data is transferred to the surface and displayed around the touch location (see Figure 32). For transferring data back from the interactive surface to the phone, users touch the corresponding item on the surface with the phone.

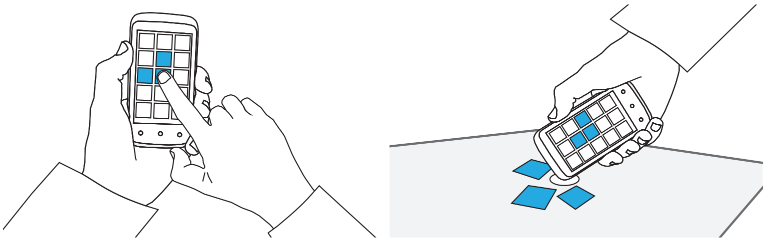

(a) (b)

Figure 32: Select&Touch2Share allows users to make a selection of items that are intended for sharing (a). Then they touch the surface with their phone and selected items are displayed around the phone (a).

The selection of data that is intended for sharing is done through marking items as public by touching them on the phone screen beforehand. As a result, the selection can be made in private without risking to disclose any private data. In contrast to the previous techniques, the phone remains in the hand of the user throughout the whole interaction process. As a consequence, users can interact only using one hand with the surface while the other one holding the phone is occupied. Yet, the phone remaining in the hand of the user additionally supports the protection of the user's data as the phone cannot be viewed or accessed by others.

The Shield&Share interaction technique.

Another, novel interaction technique called Shield&Share draws as well on previous work [16, 303]. It allows the user to share data on an interactive

Shield&Share provides a cross-device interface allowing for sequential data disclosure.

surface while the phone is placed like a viewing shield on the surface (see Figure 33). The concept of shielding private information with the non-dominant hand is well-known and used in other areas such as typing in a code when interacting with an Automatic Teller Machine (ATM). As the user places the phone on the surface, a menu bar appears at the bottom of the phone (see Figure 4.33(a)), containing small thumbnails representing data items. The phone itself prevents other users from seeing details of the thumbnails behind the phone (see Figure 4.33(b)). When the user touches a thumbnail in the menu bar displayed on the interactive surface, a detailed preview of the data is displayed on the phone's screen (see Figure 4.33(c)). In case of photos, a high-resolution preview is displayed. For sharing data with others, the user drags the corresponding thumbnail out of the menu bar onto the public surface area (see Figure 4.33(d). For transferring data from the surface to the phone, the user drags items from the surface into the menu bar displayed on the interactive surface at the bottom of the mobile phone.

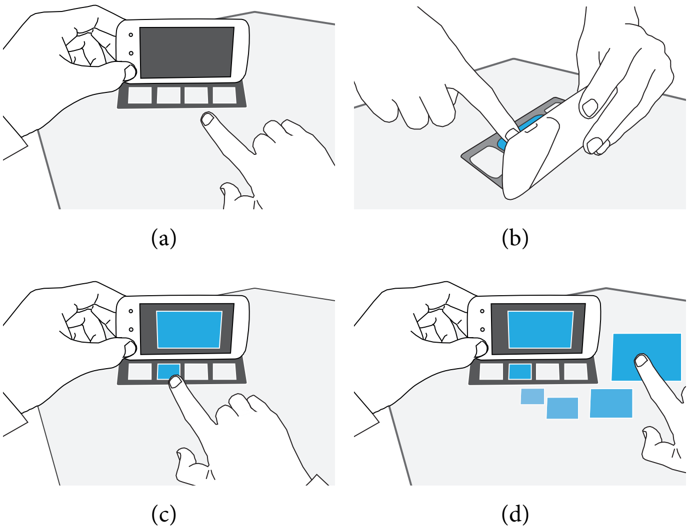

(a) (b) (c) (d)

Figure 33: Shield&Share requires users to place their phone on the surface like a viewing shield ((a) and (b)). For sharing data, the user drags the item out of the bar onto the surface ((c) and (d)).

Browsing through the data and selecting an item takes place while the phone remains in the hand of the user, but is connected with the surface at the same time. The user's privacy is protected as only data items explicitly dragged onto the surface are shown to others. However, depending on the location of bystanders, the phone might shield only parts of the menu bar. Therefore, the thumbnails need to be rendered in a low resolution in order to additionally prevent others from seeing details of private data.

4.1.3 *System Implementation*

The discussed interaction techniques were implemented within the context of a sharing application that allows users to view and exchange photos. As interactive surface, a tabletop computer based on FTIR was used [105]. The interactive surface has a resolution of 1280 × 800 pixels and is operated through a computer running Windows 7 (64 bit). The graphical user interface on the surface is implemented using the Microsoft Surface 2.0 SDK. As mediator device an HTC HD7 smartphone was used, running the Windows Phone 7 (WP7) operating system. A client-server model was applied, whereas phones and the surface applications were connected to a surface-server managing communication and data transfer (via TCP) between connected clients and detection of direct touch events. When the phone client is started, the connection to the surface server is automatically established and remains open until the user exits the phone application. The hardware ID of the mobile phone allows the system to distinguish between connected phones which enables multiple users to use the system simultaneously. For touch-based interaction between mobile phone and interactive surface, a time correlation-based touch detection was applied as presented by Schmidt et al. [230]. The mobile phone's microphone and accelerometer are used for detecting the bump event that occurs when touching the interactive surface. On the surface-side, visual blobs are detected. Both, the mobile phone and the surface, send detected events to the connected server for inspection. When the time difference between these events remains below a defined threshold, a successful *phone touch* is detected and the system infers where the surface has been touched by which mobile phone and corresponding images are transferred to this location. Images transferred from the mobile phone to the surface application remain there after the connection of the phone to the surface server is closed. Alternative options are removing them automatically after the connection is closed or allowing users to explicitly leave behind selected images.

Cross-device interactions were implemented based on the Phone Touch *technique as presented by Schmidt et al. [230]*

Each interaction technique makes specific demands for the implementation of the photo sharing application. In the following, these specific aspects for each of the implemented techniques is illustrated.

4.1.3.1 *Implementation of Place2Share*

The first, baseline concept (Place2Share) requires users to place their mobile phone on the surface (see Figure 34). Before doing so, the user touches the surface with the mobile phone's corner. The resulting phone touch event is detected and a proxy appears on the surface that is associated with the mobile phone. Then, the user places the phone on this proxy. The phone's accelerometer sensor is used for detecting that it has been placed

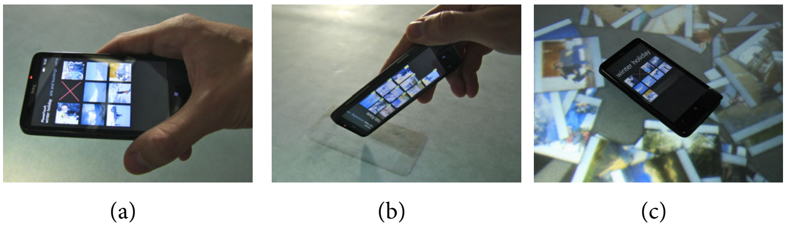

(a) (b) (c)

Figure 34: Place2Share allows the user to place the phone on the surface. Once the phone is lying on the surface, all photos are copied from the phone to the surface.

on the surface (the values of the z-axis have to reach a specific threshold and remain above this value for a defined period). Then all photos are sent to and displayed on the surface around the phone.

This approach was selected as base line as it appears in different particularities in the literature and in demo applications for interactive surfaces (e.g., [165, 300]). With Place2Share, users can transfer photos from the surface to their phones. This can be achieved by dragging photos on the surface close to the phone (see Figure 35). When the photo is downloaded, the phone displays the folder containing incoming photos. When photos are transferred to the phone, the folder *Incoming Photos* is displayed including the new photos.

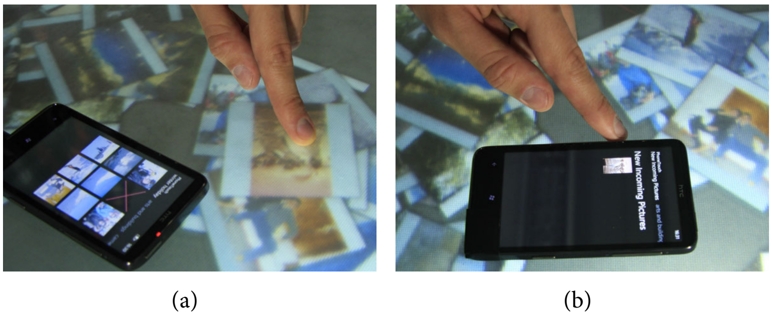

(a) (b)

Figure 35: Users can transmit data from the surface to their mobile by dragging items close to the phone (a). Added files are stored in an *incoming* folder (b).

4.1.3.2 *Implementation of Select&Place2Share*

The concept of Select&Place2Share allows the user to select the photos to be shared before the phone is placed on the interactive surface. Therefore, the implementation offers an interface to mark photos as *public* (see Figure 36). References to these photos are displayed in the *Public Folder*. The

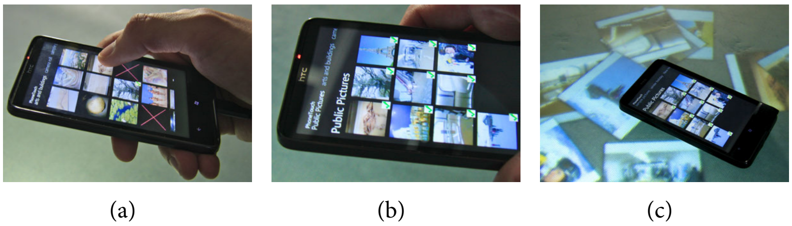

(a) (b) (c)

Figure 36: Using Select&Place2Share, the user first marks photos as public. These can be reviewed using the *Public Folder*. When the phone is placed on the surface, only public photos transferred to the surface.

user can deselect images that are not intended for sharing anymore. For placing the phone on the surface, the user performs a phone touch to create a proxy and places the phone on the latter. Transferring photos back from the surface to the phone works in the same way as with Place2Share illustrated previously.

4.1.3.3 *Implementation of Select&Touch2Share*

The implementation of Select&Touch2Share also allows the user to specify which photos should be shared. Similar to Select&Place2Share, users touch the tiles representing the photos they wish to share (see Figure 37). Once finished with the selection, they touch the surface with the phone to start transmitting the photos to the surface.

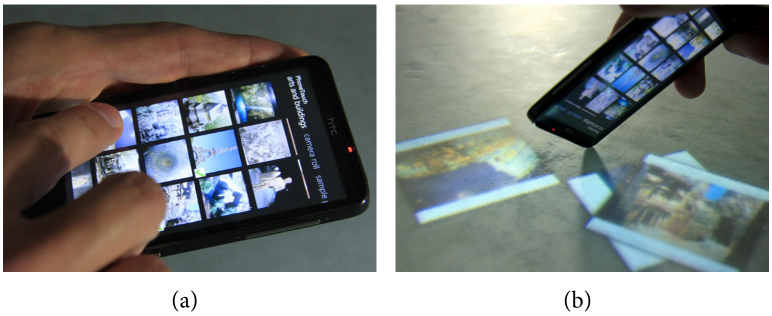

(a) (b)

Figure 37: Select&Touch2Share allows users to first select a number of photos (a). When they touch the surface with their phone, the photos displayed around the touch location on the surface (b).

The user can place photos at a specific location on the surface as they are displayed around the location where the phone touched the surface. The user can upload photos from the surface to the phone by touching the desired photos displayed on the surface with the phone.

4.1.3.4 *Implementation of Shield&Share*

In order to make use of Shield&Share, the user first needs to pair the mobile phone with the interactive surface. To do so, the user touches the surface with one corner of the phone; then the user rotates the phone towards the surface until its side fully touches the surface (see Figure 38). This sequence of steps was chosen as the shape of the edge of the phone could not be detected in a reliable way by the surface. The main reason is that buttons placed on the edge of the phone touch the surface in different ways depending on the angle of phone.

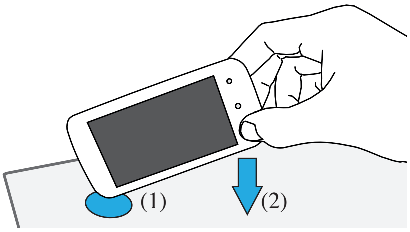
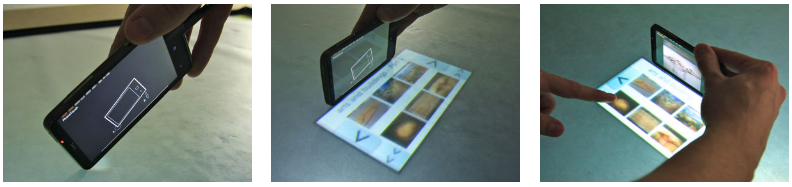


Figure 38: To start the Shield&Share interaction, first, the user has to touch the surface with the corner of the mobile phone. Then the phone is moved down on the surface so that the edge touches the surface.

When the physical connection between phone and surface is successfully detected, the menu bar interface is displayed at the bottom of the phone on the surface. In our implementation, the orientation where the menu bar is displayed is determined based on the shortest distance to the edge of the surface screen. That is, the interface is displayed on the side of the phone that points towards the nearest surface border.



(a) (b) (c)

Figure 39: Shield&Share is initiated by touching the interactive surface with a corner of the phone. When the phone edge is touching the surface, the interface is displayed. Touching a thumbnail in the menu bar will start a preview on the phones display.

Figure 39 shows how to set up the menu bar interface of Shield&Share. The menu bar displays two rows of photo thumbnails with a low resolution (50 × 50 pixels per thumbnail). In addition, the menu bar contains two buttons on each side. One button is for switching to the next photo album, the other for selecting the next subset of photos from the current album. When the user touches a thumbnail, a high-resolution preview of the photo is displayed on the phone screen.

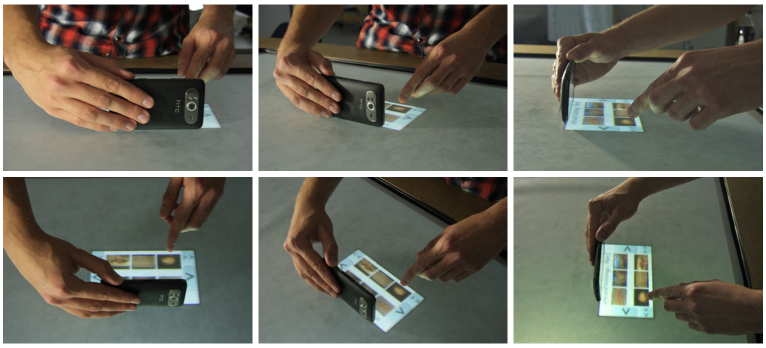


Figure 40: Shield&Share and how well it protects the user's privacy is depending on the angle and the height of view. This image series shows the use of Shield&Share from two different heights and viewing angles.

The size of the menu bar (225 × 133 pixels, which corresponds to 17.5 × 10.3 cm) was chosen to be large enough to contain at least six photo thumbnails. Due to the relatively low resolution of the interactive surface (1280 × 800 pixels) the thumbnails could not be smaller. Figure 40 shows the implementation of Shield&Share from three different viewing angles: from a height of 160 cm and from a height of 190 cm. It appears that only in one case the phone is capable of shielding the menu bar completely from the observers view. Users can share photos by dragging a thumbnail out of the menu bar onto the surface. Vice versa, photos from the surface can be added to the phone by dragging them over the menu bar and dropping them there (see Figure 41).

4.1.4 *Comparative Study*

A user study was designed and conducted in order to compare the three discussed privacy preserving interaction techniques (Select&Place2Share, Select&Touch2Share, and Shield&Share) and to gain in-depth insights in how users experience them. The interaction technique Place2Share served as baseline as it does not support users to protect their privacy since no pre-selection option is provided. In particular, the evaluation aims for providing insights about the effectiveness of support for privacy respecting data sharing, user acceptance, and usability aspects. The study also focused on aspects such as perceived effort or task completion time to investigate potential effects of the new privacy preserving interaction

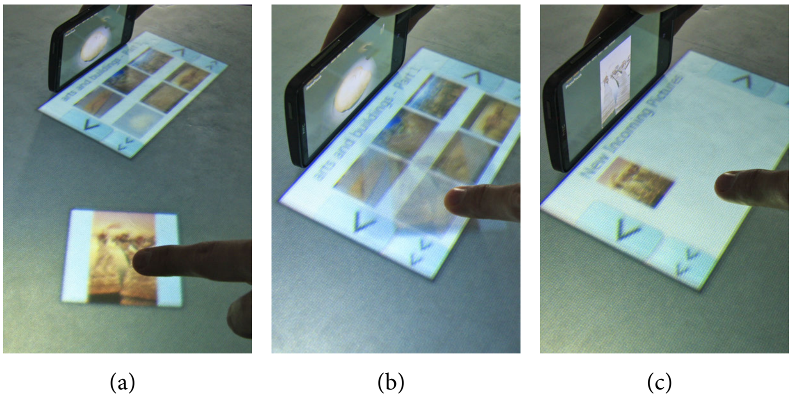

(a) (b) (c)

Figure 41: Adding a photo from the surface to the mobile phone using the interaction technique Shield&Share.

techniques on the overall interaction task. The study did not include a *phone only option* as a further comparative system as an interactive surface supports effective and efficient co-located collaboration and as phone based solutions suffer from the small screens designed for a single user.

For evaluating the interaction techniques a photo sharing situation was selected as context where participants would share specific photos with another person. This context was primarily chosen as people related to and understand easily in what ways photos can be regarded as private or sensitive.

EVALUATION PROCEDURE The participants took part individually. The study was organized in three phases.

1. The participants filled out a questionnaire regarding their general experience and usage of mobile phones and their photo sharing behavior.

2. They performed a series of practical tasks with all four interaction techniques preceded with a training phase. We used a within-subjects design so that each participant evaluated each interaction technique. The order in which the interaction techniques were selected was counterbalanced using Latin square. The order of the tasks was randomized. No time was required for transmitting the images between surface and phone in the study as they were already stored on those devices beforehand. After finishing all tasks with the respective technique, the users completed a questionnaire.

3. In the third phase, users ranked all tested interaction techniques with regards to interaction speed, privacy protection, and general

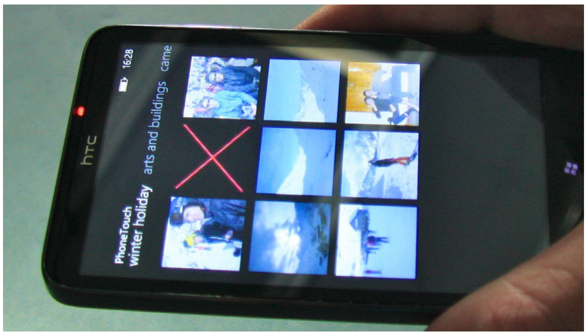


Figure 42: Photos that were to be considered as private were represented by black images with a red cross.

preferences in a second questionnaire. We decided to use a photo sharing scenario for the user study in order to give the participants a well-known context for the practical tasks.

Participants were introduced to the practical tasks they were about to perform. During these, they had to search and show a number of photos that were stored on the provided mobile phone to the experimenter. In total, a set of 69 photos was prepared and stored on the mobile phone for the user study. These were organized in four photo albums (arts and buildings, winter holiday, camera roll, and the pre-installed sample photos). They also contained seven special images which the participants should not disclose to the investigator. The participants could recognize them easily as this were black images with a large red cross (see Figure 42). It was considered to asking the participants to provide own public and private photos for the study but this would have been rather unrealistic as truly private pictures would not have been chosen by the participants and further, behavior of the participants would be influenced by different conditions. Considering that privacy is a very subtle notion depending on many factors such as context and audience, this experimental condition can only simulate a sharing situation. However, it allows comparing the selected interaction techniques in terms of support to disclose a defined set of images.

In a training phase before the practical tasks, participants had time to familiarize themselves with the albums. Also, they were told to look up the photos that were to share in the upcoming tasks, to make sure that those interaction technique tested first would not strongly be affected.

In the following, participants were asked to perform the following sequence of tasks with each interaction technique.

1. “Please show me your photos of the Eiffel Tower and the Colosseum.” (two photos).

2. “Could you please show me the photos you took of the train station that was water-flooded lately?” (four photos).
3. “Last winter we were skiing. Can you show me photos with me wearing this yellow helmet?” (two photos).
4. “Could you please add these photos to you phone, so that you can show them to our other friend?” (three photos).

A video camera mounted under the ceiling above the interactive surface recorded all sessions for capturing the interactions of the participants. Also, on the interactive surface, all events and interactions were logged.

In total, 16 participants were recruited. Seven of them were female and their average age was 23 years (21–27). The majority of the participants were students (11 undergraduates, 4 graduates). One participant was an employee. Six of the participants had a computer science background. The others had a background in humanities or economics.

4.1.5 *Study Results*

All participants used mobile phones with a photo camera for several years. Ten of them used smartphones as their personal mobile phone. The participants reported to store a variety of different data on their phones such as music, messages (email, text), calendars, appointments, and photos. In particular, they stored in average 174 photos (Standard Deviation (SD) = 271) on their phones they brought with them to the study. These great differences in the number of stored photos are also reflected by the importance the participants attach to this feature of their mobile phones. On a five point Likert scale (5 = very important), they rated the camera feature on average at 3.51 (SD = 1.40), while four rated it with 1 or 2.

Participants reported to regularly share photos with others using different channels.

Participants assessed the frequency (5 = very often) of showing photos they have on their mobile phones to other people with 3.20 (SD = 1.43). Similarly they rated the frequency how often they share photos with others (Mean (Arithmetic) (M) = 2.51; SD = 1.40). They reported to use Bluetooth, email, Universal Serial Bus (USB) cable to PC, Facebook, and Dropbox channels for sharing photos with others, with Bluetooth sharing being named most often (6 times). Ten of the participants stated that they would hand their phone to other persons in order to show them certain photos. However, some added that they would hand their mobile phone only to friends. Four of the participants stated that they would not give their phone to other persons under any circumstances.

After each trial, participants rated the tested interaction technique using selected questions from the NASA TLX [112]; as questions before on a five point Likert scale (1 = very low; 5 = very high). Selected questions for

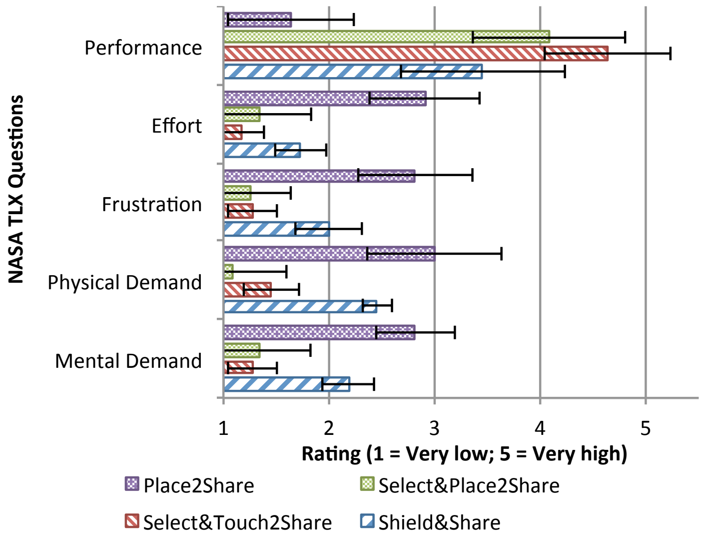


Figure 43: Participants' estimations of the four evaluated interaction techniques based on the NASA TLX questions. Bars show the mean values; error bars indicate standard deviation.

comparison of interaction techniques were: *Performance*: How successful were you in accomplishing what you were asked to do? *Effort*: How hard did you have to work to accomplish your level of performance? *Frustration*: How insecure, discouraged, irritated, stressed, and annoyed were you? *Physical demand*: How physically demanding was the task? *Mental demand*: How mentally demanding was the task?

With Friendman's Analysis of Variance (ANOVA) differences between the techniques were tested for significance (level $\alpha = 0.05$) and Wilcoxon's signed-rank test with Bonferoni correction was used for pairwise comparison where appropriate. Concerning the perceived level of *performance* the ratings were significantly different ($\chi^2(3) = 20.81$, $p<0.001$). Pairwise comparison showed that participants rated Select&Touch2Share (z=-1.9, p=0.003) and Select&Place2Share (z = -1.81, p = 0.006) significantly higher compared to Place2Share. In regards of *effort* the ratings were found to be significantly different ($\chi^2(3) = 15.62$, $p < 0.05$). Pairwise comparison showed that the perceived effort was higher with Place2Share compared to Select&Place2Share (z = 1.54, p = 0.03) and Select&Touch2-Share (z = 1.77, p = 0.008). Concerning the *perceived frustration level* the ratings differ significantly ($\chi^2(3) = 15.50$, $p < 0.05$). Pairwise comparison showed that the frustration level for Place2Share was rated significantly higher than for Select&Place2Share (z = 1.72, p = 0.01) and Select&Touch-2Share (z = 1.45, p = 0.03). Also, ratings concerning the physical demand differed significantly ($\chi^2(3) = 16.35$, $p < 0.05$) It appears that the physical

Place2Share was as expected rated worst regarding all aspects (e.g., performance, frustration, physical demand).

demand for using Select&Place2Share was rated significantly lower than Shield&Share (z = 1.45, p = 0.04) and Place2Share (z = 1.9, p = 0.003). Ratings for the perceived mental demand differ significantly ($\chi^2(3) = 18.66, p < 0.05$). Pairwise comparison showed that Place2Share was rated to be significantly more mentally demanding as Select&Touch2Share (z = 1.86, p = 0.004) and Select&Place2Share (z = 1.9, p = 0.003).

These results show (see Figure 43) that Place2Share was consistently rated worst (e.g., least performance, highest effort etc). Main reason was a delay caused by the demand to render the 69 images after placing the phone on the surface. Furthermore, participants had to browse and search for the pictures which were spilled on the surface. Also, the phone was perceived as disturbing lying on the surface together with such a large number of photos.

Shield&Share yields high physical demand and effort during interaction.

Further, the results indicate that Shield&Share required a higher effort, caused more frustration as well as a higher physical and mental demand compared to Select&Place2Share and Select&Touch2Share. One reason was the setup of the connection between phone and surface, which did not always work on the first attempt. Second, holding the connection between phone and surface was perceived as exhausting as users could not move the phone without risking disconnecting phone and surface. In addition, Shield&Share allowed users to interact with only one hand. Select&Place2Share and Select&Touch2Share received the best results in terms of performance, effort, frustration, physical demand, and mental demand.

For each interaction technique, participants rated how time consuming they felt the interaction technique was and how much the corresponding technique caused interruptions in the flow of interactions (5 = very much). The results indicate a tendency that Select&Place2Share was perceived as the fastest interaction technique (M = 1.98; SD=1.16). Select&Touch2Share was rated with an average of 2.75 (SD = 0.95) and Shield&Share with 3.0 (SD = 0.81). Place2Share was rated as the most time consuming technique (M = 3.25; SD = 1.70).

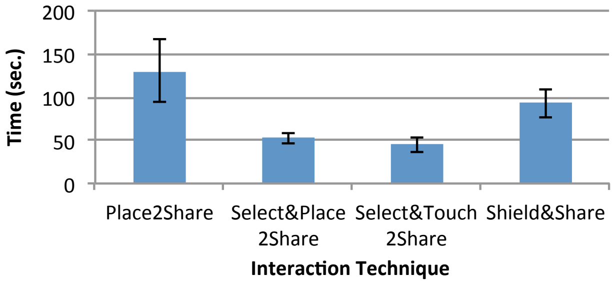


Figure 44: Task completion times of the four interaction techniques.

The feedback from the participants match the results from the measured task completion times. Figure 44 shows the mean task completion times of the different interaction techniques. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the difference in mean task completion time was statistically significant (at a significance level of $\alpha = 0.05$) for the four tested interaction techniques ($F(1.50, 22.52) = 16.33$, $p < 0.001$). Pairwise comparing through post-hoc tests using the Bonferroni correction reveals that the mean task completion time using the interaction technique Select&Place2Share is significantly shorter than with Place2Share $p = 0.005$). Also, Select&Touch2-Share allows for significantly faster interaction times than Place2Share ($p = 0.002$). Yet, interaction with Shield&Share was not significantly faster as with Place2Share ($p = 0.217$). The difference between the two fastest techniques, Select&Place2Share and Select&Touch2Share, is not significant ($p = 0.09$). However, Select&Place2Share ($p = 0.008$) and Select&Touch2Share ($p = 0.001$) are both significantly faster than Shield-&Share.

Fastest interaction was supported by Select&Touch2Share and Select&Place2Share.

After completing the practical tasks, the participants ranked the four tested interaction techniques regarding which technique they considered as the fastest one in direct comparison to the others. They gave four points for the best and one point for the least preferred interaction technique. The best average score was reached by Select&Place2Share (3.44 points), followed by Select&Touch2Share with 3.25 points. Shield&Share reached a score of 1.69 and Place2Share a score of 1.63 points.

Participants ranked on average Select&Touch2Share (3.50 points) and Select&Place2Share (3.44 points) as the best techniques for hiding private photos when sharing with other people. Shield&Share reached a score of 2.06 points in this ranking and Place2Share only 1.00, which means that all participants ranked this technique to be the least suitable for protecting their privacy. Further, we asked the participants to rank the techniques regarding their suitability to be used for sharing single photos. The majority ranked Select&Touch2Share as the best technique (in average 3.44 points) and Place2Share as the least suitable technique (1.06 points). Select&Place2Share and Shield&Share scored 2.75 and 2.13 points.

The ranking results of the interaction techniques' ability to support sharing of several photos in a sequence are more diverse. Select&Place2-Share (in average 3.44 points) and Select&Touch2Share (2.75 points) were ranked as the best techniques. While Place2Share reached 2.13 points Shield&Share received 1.69 points in this ranking.

USABILITY AND EASE OF USE. Participants gave diverse feedback regarding how well they perceived the interaction techniques supported them in sharing photos on the surface. For instance, several participants stated that they liked how easy it is to transmit photos to the surface when

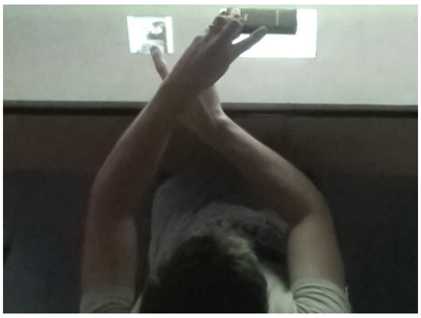


Figure 45: Participant using Shield&Share. The hand holding the phone is interfering with the interacting hand.

using Place2Share. One participant stated "I like that you don't need to configure anything before sharing images". Another pointed out that it is positive that "you can see all images on the surface right away". On the other hand, other feedback indicates issues of Place2Share: "It takes long until all photos are uploaded to the surface". In fact, it took around 5 seconds until all images were displayed on the surface. In practice, Place2Share would suffer from additional delays as all the images have to be transferred (e.g., via Bluetooth or Wi-Fi) between the devices once the phone is placed on the surface. Additionally, it was commented that "it is hard to find a specific photo amongst the others on the surface". One participant even pointed out that "after searching all the photos on the surface, my finger was burning". Also several participants criticized the fact that uploading all photos to the surface causes the screen to be cluttered.

Main critique regarding Shield&Share: physical demand of holding the phone in a tiering posture.

Participants indicated that they liked the high-resolution preview on the phone screen when using Shield&Share. Also the navigation through the photo albums using the controls on the surface were perceived as positive as well as the sharing and collecting of photos through dragging them out of (or into) the thumbnail bar onto the surface area. One participant highlighted that "this technique is great for sharing several photos spontaneously as I can make a selection and drag the photo on the surface". On the other hand, participants criticized that it was burdensome and tiring to hold the phone constantly in one hand. Some indicated that they did not like the low-resolution thumbnails on the surface so they often had to use the preview function on the phone screen. One major issue that came up is that the hand holding the phone can interfere with the interacting hand, see Figure 45.

Concerning Select&Touch2Share, participants highlighted that they liked that the selection of the photos to share is done while the phone is in the hand of the user. They indicated that is was easy to share and to pick up photos from the surface. One participant stated "it is fast and the phone does not occlude on the surface". On the downside, one participant criticized that this technique requires touching the surface often with the phone which might damage the phone over time. Also, one participant criticized that "holding the phone in the hand all the time is positive but also a problem at the same time", indicating that only one hand is available for interacting with the photos on the surface.

Participants pointed out that it is positive that Select&Place2Share allows the selection of photos to share before the phone is placed on the surface. They also appreciated having two hands available for interacting with the photos on the surface. One participant reported that "it is great that one can easily add photos from the surface to the phone", also applying to Place2Share which follows the same approach.

PRIVACY SUPPORT. Participants also gave rich feedback concerning the ability of each interaction technique to support the user protecting their privacy. With respect to Place2Share, participants gave exclusively negative feedback. For instance, one participant stated "photos that I did not intend to share were visible on the surface and others knew how many photos I have stored on my phone". Several participants indicated that they were missing a means for showing and sharing only selected photos.

Participants appreciated the ability of Shield&Share to protect the user's privacy. For instance, one participant stated that "the low resolution thumbnails on the surface do not really reveal private information". They also highlighted that the preview on the phone screen allows for private access to photos. On the other hand, other participants criticized that the thumbnails can be seen by other users that are standing very close by. For instance, one participant criticized that "people standing around can see thumbnails of my private data easily". On the other hand, another participant stated that "the thumbnails in the menu bar are very blurry. I often had to use the preview on the phone to check what photo it actually was".

Participants mentioned regarding Select&Touch2Share that it is great that the selection of photos is done in private while the phone is held in the hand. One participant stated "it was easy and fast to use. Others cannot see how many photos I have stored on my phone and I could decide whether I share one or more photos at a time" and "this technique is ideal for selecting specific photos from a set of personal photos". Concerning the effectiveness of Select&Touch2Share to support the user's privacy one participant pointed out that "private photos are not revealed to others at all. I can check my selection before I transmit the photos to the surface". The feedback concerning Select&Place2Share contained similar aspects. Users liked the selection of photos beforehand and the good privacy protection support. However, they pointed out that it is a problem when placing the phone on the surface when a photo album containing private photos is visible on the phone: “you have to be careful that the public folder is visible on the phone when placing it on the surface. Otherwise private photos can be visible to others”. This aspect was not considered in the implementation but could be improved easily. For example, the screen could be turned off automatically as the phone is placed on the surface. With respect to how effective Select&Place2Share supports the user’s privacy, users stated that they liked the “silent” selection of photos that is made in private. However, one user criticized that using Select&Place2Share would not support to share several photos after another: “using this technique it makes more sense to select all photos that you want to share otherwise you have to pick up the phone each time you want to share additional photos”.

Most of the participants indicated with their feedback that they were aware of privacy issues in the context of photo sharing and that privacy is important to them. For instance, one participant stated “if I could not hide my private photos, I would not share any”. In addition, participants pointed out that sharing selected photos is more usable: “it is very annoying to search on the surface for certain photos!”

4.1.6 *Discussion of Data Sharing Techniques*

Interactive surfaces are promising devices for collaborative work as multiple users can view and interact with contents simultaneously. For personalization, personal devices such as mobile phones can be integrated enabling seamless access to personal data. Users can then easily share and exchange photos, contacts, and other kinds of data or files. However, users often store large amounts of data on their personal mobile devices. Considerable parts of the data can be regarded private and even highly sensitive, for instance, specific pictures, text messages, or notes. Therefore, interaction techniques for sharing and exchanging data from the personal mobile phone need to support the users and protect their privacy. That is, they need to be privacy respecting.

An increasing number of social networks enable users to share their photos with their friends and communities. For instance, Facebook [84] or Twitter [270] support quick sharing of photos through different mobile application. Vice versa, users have access to a constantly growing amount of photos that were uploaded by their contacts. When accessing photos from social network sources for sharing them in a face-to-face context from the mobile phone on an interactive surface, users require even more effective means for selecting which photos are displayed on the shared interactive surface. The main difference to accessing photos stored on the personal device is that users cannot control which data is shared and appears in the stream of photos. As a result, the amount of shared photos that are potentially irrelevant in the current sharing situation increases. Also, photos that are not appropriate in the current situation could be uploaded to the social network media streams. Therefore, when accessing photos from social networks and sharing them with present persons, users benefit from means provided by the presented interaction techniques that allow users to select which data they want to disclose. The necessity of filtering data in the context of social networks is reflected, for instance, by the concept of *Circles* in Google+ [101].

This section investigated three interaction techniques (Select&Place2Share, Select&Touch2Share, and Shield&Share) which allow users to select and control which data they share with others on an interactive surface and thus support users to protect their privacy. In addition, the interaction technique Place2Share was considered that has been reported and demonstrated previously, which enables straightforward data sharing but does not provide any kind of privacy support.

	Item Selection Time	Location of phone	Sequential Sharing
Place2Share	—	On surface	– –
Select&Place2Share	Before	On surface	–
Select&Touch2Share	Before	In hand	+
Shield&Share	During	In hand & on surface	+ +

Table 4: Comparison of sharing interaction techniques Select&Place2Share, Select&Place2Share, Select&Touch2Share, and Shield&Share

These interaction techniques differ in particular regarding the time of data selection, the phone location during interaction, and to what extend they support users in sharing multiple data items sequentially one after another (see Table 4). Place2Share does not support selecting items for sharing and due to the phone being placed on the surface, interaction with the phone is difficult to perform. Accordingly, sequential sharing of different data items is only possible in terms of pointing out different items. Yet, all items are transferred at the same time. However, this technique can be suited in application context where the data items that are to be shared is determined through additional logic. For instance, in a card game context (see [82]), the mobile phone could be used for displaying the user's cards. For showing the cards to other players, the phone could simply placed on the shared surface and corresponding cards are displayed around the phone. However, this technique appears to be not suitable in application contexts in which no logic can determine the selection of items, which will be disclosed. Hence, Select&Place2Share is better suited in application contexts when large numbers of potential items are available such as the case of photo collections. Yet, this technique requires, as the previous, to place the phone on the surface, which makes it difficult to interact with the phone. For instance, when selecting additional items for sharing them on the surface. Therefore, the technique Select&Touch-2Share, which allows the users to keep the mobile phone in her hand throughout the interaction is more suited for application scenarios, in which users share multiple items sequentially as it might be the case when for instance, giving report on a journey. In contract to the previous techniques, Shield&Share allows making the selection continuously as the user holds on the phone that is touching the surface. On the downside, one hand of the user is constantly blocked for interaction which might result in fatigue. Hence, mobile phones that are equipped with a stand (e.g., the HTC HD7) which allows the phone to remain in an upright position without the user's help, are potentially more suited. This would enable not only sharing items such as photos but also applications such as giving presentations to customers sitting around an interactive surface.

The four interaction techniques were evaluated in a comparative user study, with a focused on how users perceived the tested interaction techniques in terms of interaction speed, usability, and in particular how well each of the techniques supports users to disclose only specific selected photos.

The main findings from the evaluation are that (1) users demand interaction techniques that enable making a selection of what data are to be shared. (2) Users prefer selecting the data before touch-based interaction with the interactive surface starts. (3) The ability to easily share several photos in a sequence and not all at the same time is important to users. The interaction techniques Select&Place2Share and Select&Touch-2Share allowed participants in this study with 16 participants to perform significantly faster compared with Shield&Share and Place2Share. Select-&Touch2Share requires users to often touch the surface with their mobile phone, which was reported to be something they would not like to do too often with their own mobile phones. Therefore, Select&Place2Share can be seen as a suitable alternative as it supports protecting privacy at a similar level. Shield&Share turned out to be hard to use and tiring because users had to hold the phone constantly with one hand while performing the interaction with the other. We can conclude that Shield&Share is not ideal in the setting as applied in the user study, yet it could have a positive impact in other areas of application such as gaming.

In this work, the implementation and evaluation focused on sharing of photos as one example. Different kinds of data place specific demands in terms of privacy and access rights, hence, it is open to question how other kinds of data (e.g., documents, calendars, or contacts) affect the way how users want to share them with others using surfaces. For instance, when arranging a meeting using an interactive surface, it is likely that users do not want to display all their calendar entries on the surface. Based on the given situation and context, users should be able to control what information is displayed and at what level of detail. Accordingly, the presented findings apply rather to a specific domain and request for further investigation steps in this filed.

4.2 SUPPORTING PRIVACY MANAGEMENT THROUGH MEDIATED INTERACTION

This section the is based on the work:

[10] J. Seifert, A. D. Luca, B. Conradi, and H. Hussmann. “TreasurePhone: Context-Sensitive User Data Protection on Mobile Phones.” In: *Pervasive Computing.* Ed. by P. Floréen, A. Krüger, and M. Spasojevic. Lecture Notes in Computer Science 6030. Springer Berlin Heidelberg, 2010, pp. 130–137

Current mobile phones support the creation and storage of all kinds of data ranging from contacts and e-mail to photos and text documents. At the same time, the amount of stored data is growing enormously which increases the need for securing the privacy of this data [256]. For instance, the integration of mobile phones into enterprise environments for mobile handling of e-mail, contacts and other data is enjoying increasing popularity. However, mobile phone users still use a simple privacy/security model that only distinguishes between *locked* and *unlocked* state of the mobile phone [134].

Users experience highly individual contexts in their lives such as *family* and *work* each with a corresponding need for privacy [144]. This makes privacy management of the data stored on their mobile phones practically impossible. That is, a user who has a single mobile phone for her working context as well as for private use cannot hide data belonging to one context while being in the other one. When working for companies that have high security standards, a user might face additional usage restrictions to avoid exposing business data to third parties by using the business mobile phone for private use as well.

Different usage context demand for different data security levels.

One solution for this challenge would be to use more than one mobile phone. Users might have a mobile phone for their work as well as a personal one. From a usability perspective this solution is not satisfying as there are usually more contexts than only *work* and *personal*. Therefore, users would need to use one mobile phone for each context they have.

The concept of Spheres *for context specific privacy protection.*

Privacy protection should be an essential part of the mobile device’s operating system and should be addressed during the design of mobile systems. This section presents *TreasurePhone*, which supports context-sensitive protection of the user’s data by allowing the user to define so called *spheres*. TreasurePhone uses *locations* for automatic activation of spheres and supports interaction with the user’s environment to activate appropriate spheres on the go in order to facilitate privacy management. TreasurePhone enables users to secure their data in each context in a sophisticated way using a mobile phone. Hence, TreasurePhone reduces the risk of unwillingly disclosing sensitive and private data.

The background and prior work regarding privacy management and TreasurePhone can be generally classified into three categories: conceptual work about data privacy for mobile devices, authentication mechanisms for cell phones, and context-dependent adaptive mobile devices.

Stajano addresses privacy issues that arise from sharing (willingly or unintended) a PDA with others [256]. He describes a system for PDA which is based on the observation that some data and applications could be used by anybody who gets access to the PDA. However, other applications and data should be accessible only by the legitimate owner of the device. Accessing these *private areas* or "hats" would require authentication and thus secures the privacy of the user. In their work, Karlson et al. conducted interviews to find out basic requirements of data privacy on mobile phones. Their results suggest to use *usage profiles* that correspond to different contexts of the user [134]. These would allow sharing the mobile phone to others without risking disclose of private data. They showed that users would appreciate a security model for mobile phones that is based on usage profiles enabling privacy management. However, the concept of usage profiles was not implemented. Nevertheless, this work, suggesting a role based access model, strongly influenced the design of TreasurePhone. The system SecurePhone is designed to enable multi-modal biometric authentication [138]. For instance, it allows the user to authenticate by face and voice recognition, allowing secure data exchange between involved parties. Furthermore, this system combines different biometric authentication mechanisms with promising results. SecurePhone is rather focusing on the authentication process than on a general security model.

TreasurePhone draws on the concept of context specific privacy profiles.

With *SenSay* Siewiorek et al. present a mobile phone that adapts its behavior in a context-based way [245]. This system processes data captured by several sensors and determines the user's current context based on the results. SenSay adapts the ringer volume, vibration and alerts to the current context. It can further provide remote callers with the ability to communicate the importance of their call which optimizes the availability of the user. Another contribution with its focus on context-based adaptation is presented by Krishnamurthy et al. [140]. Instead of using various sensors to determine the current context of a user, this system makes use of NFC. With NFC, the context can be determined on a fine grained base. This system as well as SenSay manage to determine the context of the user, but use a different approach. Both systems do not focus on privacy issues or data security.

Sensing context for automatic adaptation.

TreasurePhone provides a first implementation of a usage profile based system for mobile devices as suggested by Stajano and Karlson et al. The prototype applies findings presented by Krishnamurthy and Siewiorek and combines them to provide an advanced security model.

4.2.1 *Concept of Implicit Privacy Management*

THREAT MODEL. In this work, two main threats are modeled against which the described system is resistant.

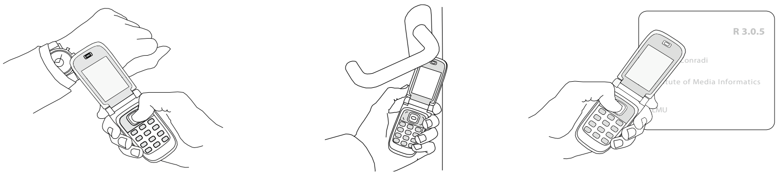
TreasurePhone prevents unwilling disclosure of sensitive *data and unauthorized access.*

The first threat consists in unwillingly disclosing private or inappropriate data to the "wrong" people. Mobile phones are often borrowed to friends and other people, mostly to help them by providing a possibility to make phone calls, browse the Internet, etc. While interacting with the phone, the borrower might accidentally gain access to data that the owner of the mobile phone might want to keep private (e.g. when browsing the photos on the mobile device). Using TreasurePhone, a special sphere could be used that grants access to the call application only to avoid such problems.

The second threat are attackers that willingly try to steal information (e.g., business data) from a user. By disabling access and encrypting data of other contexts, TreasurePhone limits those kind of attacks. For instance, business data can only be stolen while the device is set to the business sphere.

CONCEPTION Privacy cannot be seen as a fixed state. It rather means dynamically controlling the disclosure and use of personal information [129]. The dynamic character of privacy is stressed by its context-depended nature [144]. Furthermore, the user's grasp of what kind of personal data is considered as private is highly individual [76]. In the field of sociology and psychology, the concept of *faces* exists that was proposed by Goffman [96]. According to Goffman, people use different faces depending on their current context; a face defines what information a person reveals to a specific audience.

The concept of TreasurePhone is based on the hypothesis that users are willing to protect and manage the privacy of their private data stored on their mobile phones. Based on Goffman's faces we propose the concept of *spheres* that allow users to protect their data privacy. A sphere represents the user's privacy requirements for data on her mobile phone in a specific context. That is, the user can define which applications such as e-mail clients, address books, photo viewers etc. are available in a specific sphere and furthermore, what exact data is accessible and which is not. One can imagine a sphere as a filter that lets pass only data that are not private in this sphere. This way, users could create spheres for their home, family and friends as well as work context – each providing only as much access to data as desired. The spheres concept includes one special sphere that allows exclusive administrative actions such as creating, editing or deleting spheres as well as deleting or changing access rights of data. This sphere is called *Admin Sphere* (*AS*) and requires the user to authenticate before accessing it. Usually this sphere will only be active when the user wants to perform administrative work. All other spheres do not allow deleting data or editing access rights of data. Besides the *AS*, TreasurePhone contains three spheres by default: *Home*, *Work* and *Closed*, which serve as examples of typical configurations that are not bound to certain contexts but can be applied in various matching situations. While *Home* provides access to all services, *Closed* denies access to all of them. This set of default spheres was compiled based on the results of a small study with five participants who used diaries to collect the contexts for which they would use spheres.



(a) (b) (c)

Figure 46: (a) Authentication using a personal token that is integrated into a wristband. (b) Controlling a lock using actions. (c) Reading a location that is based on an NFC tag integrated in a nameplate.

In order to protect the data, the user chooses the appropriate sphere depending on the current context. However, to prevent any person other than the legitimate owner from accessing private data, the activation of other spheres requires the user to authenticate to the system if the current sphere is not the *AS*. Fast and secure methods for authentication that do not require manual entry of a PIN minimize the effort for the user [256]. The TreasurePhone prototype supports authentication using a personal token that contains an NFC tag (see Figure 4.46(a)). It has to be noted here, that the benefit of the personal token comes with a security flaw. If an attacker can steal both, the token and the mobile device, full access to the device will be granted. To minimize the effort of spheres even further, context-dependent activation of spheres by *location* is supported by the system. A location in TreasurePhone is a configuration that is associated with a sensor value such as Global Positioning System (GPS) coordinates, a wireless network identifier, a Bluetooth identifier or an RFID tag (see Figure 4.46(c)). Whenever a location is recognized, the corresponding sphere is activated. Besides locations, TreasurePhone supports interaction with the user's environment by *actions*. For example, electronic locks could be controlled using a mobile phone. With the two actions that are applied to simple locks (locking and unlocking) the user could associate the activation of certain spheres. For example, the lock of the the apartment door could correspond to actions *unlocking* which activates the *home* sphere and *locking* which activates the *closed* sphere (see Figure 4.46(c)).

Context sensitive activation of spheres.

An example could be a Metro Network (like the Tokyo Metro system) that supports the use of NFC-enabled mobile phones to handle payment. When a user leaves the metro network at his work place, touching the gate mechanism with the phone would activate the *Work* sphere. Entering the metro network at his work location on the other hand could switch back to the *Closed* sphere.

EXAMPLE SCENARIO. Using TreasurePhone implies initial effort for configuring the system. However, this is not mandatory because of the set of default spheres that are available. The configuration effort consists of creating individual spheres according to the user's needs and contexts in addition to the default spheres. For example, Bob could create a new sphere named *Friends*, which he intends to use while he is with friends, for instance at home or in a pub. He configures this sphere to allow access to messages, the address book and the photo service. Now Bob can start to create and manage data. After a while the configuration of Bob's TreasurePhone looks like the illustration in Figure 47. In the spheres *Home*, *Friends* and *Work* some contacts and other documents are visible. The spheres *Friends* and *Home* overlap and both allow access to the data in the intersection. The *Admin Sphere* encloses all data and Bob can access all data while this sphere is active.

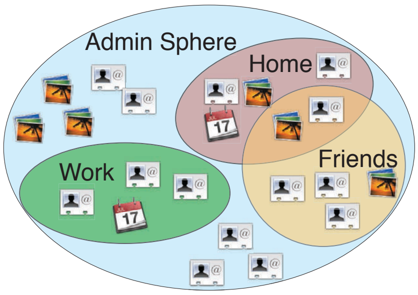


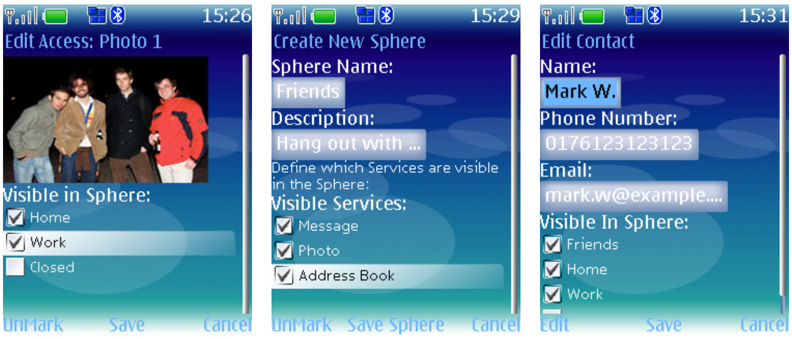
Figure 47: The sphere model: The *Admin Sphere* allows access to all data; other spheres limit access and might overlap.

When Bob turns on his mobile phone the *AS* is initially activated. After checking if there are new messages and having a look at today's appointments at work, Bob activates the *Home* sphere. Thereby personal data like photos, messages and contacts are accessible, however, all business related data are hidden now. When Bob leaves his apartment he locks the RFID based lock of the door using his TreasurePhone, which is also usable as a key (See Figure 4.46(b)). This requires the configuration of corresponding *actions* for the lock. Bob configured the action *Locking Door* to activate the *Closed* sphere when finished. By using this action Bob does not have to think of changing the sphere. As Bob arrives at his office, his mobile phone detects the Bluetooth identifier of his desktop computer, which is associated with the location *My Office*. The sphere *Work* gets activated automatically. Now Bob has access to his calendars, documents, messages and all other data that is work-related. However, photos of his family and friends are now hidden.

4.2.2 *Prototype Implementation*

The TreasurePhone prototype is written in Java ME and implements the fundamental concepts: spheres, locations, actions and services as well as an abstraction for data. A sphere management subsystem controls which sphere is activated and what data and services are accessible. Activation is based on context information such as sensor data that correspond to locations and actions. The implementation also contains interfaces for applications which allows access management of applications that are registered as services.

The TreasurePhone prototype provides basic functionalities of standard mobile phones such as call, Short Message Service (SMS), address book, camera, and a photo viewer. The user interface changes or grants access depending on whether the AS or another sphere is activated (see Figure 48). Editing access rights for data is only available while the *AS* is activated.



Edit Access: Photo 1
Visible in Sphere:
☑ Home
☑ Work
☐ Closed

Create New Sphere
Sphere Name: Friends
Description: Hang out with ...
Define which Services are visible in the Sphere:
Visible Services:
☑ Message
☑ Photo
☑ Address Book

Edit Contact
Name: Mark W.
Phone Number: 0176123123123
Email: mark.w@example....
Visible In Sphere:
☑ Friends
☑ Home
☑ Work

(a) (b) (c)

Figure 48: Screens of TreasurePhone (*AS* activated): (a) Editing access rights for a photo. (b) Creating a new sphere named "Friends". (c) Editing contact details.

The default assignment of data access rights follows the basic rule: data is accessible in the sphere in which it was created. For instance, if the sphere *Home* is activated while the user makes a photo, this picture is accessible by default in this sphere. In case of the *AS* being activated, the image would not be accessible in any of the normal spheres.

We chose the Nokia 6131 NFC mobile phone as platform for the first prototype, which comes with a built-in NFC reader. The prototype allows the user to authenticate via a personal token, which contains an NFC tag or by entering a PIN. NFC is also used for locations. The physical correspondence of a location in TreasurePhone is an NFC tag attached to an object (see Figure 4.46(c)).

4.2.3 *Concept Evaluation*

20 participants; within subject design.

We conducted a preliminary evaluation of TreasurePhone to study two basic questions. First, will users accept the increased complexity of handling the mobile device required by the privacy features? Second, will the use of automatic sphere switching by context (locations and actions) have a positive effect on the usability of the system? We recruited 20 volunteers; 8 female and 12 male. Participants were undergraduate and PhD students with a technical background and aged between 23 and 32 years. They indicated they had all used mobile phones for at least six years. Half of the subjects use profiles (like silent, vibrate etc.) of their mobile phone on a daily basis; the others only occasionally or not at all. 19 of the subjects use PIN authentication when they turn on their mobile phone while only 3 use PIN authentication after each period of inactivity. During the study we first explained the system and then a training phase with the prototype was conducted by the participants. For training, each feature of the system was explained to them and tested with a small task. Next, practical tasks were carried out. Finally the users filled out a questionnaire regarding the system. Answers were given on a five point Likert scale (1 = worst, 5 = best). Overall the procedure took around 40 minutes, up to one hour.

Practical tasks included: configuring spheres as well as creating and editing permission of files.

The practical tasks started with a system configuration, in which users had to create and configure a sphere. This was followed by a series of five tasks in randomized order, which covered all actions that are specific for the concepts of TreasurePhone (see Figure 49). For instance, participants created a contact in the address book and set the access rights for this contact to 'visible in sphere x'. Other tasks required the participant to activate different spheres in order to hide or get access to data. These five tasks were repeated two times in randomized order. One time participants used a prototype that did not integrate context information and a second time they used a system that supported context information integration. That is, one time the participants could make use of token based authentication (a wristband with an integrated NFC transponder), locations, and actions and the other time they could not. The context free prototype used an assigned PIN to activate the *Admin Sphere* and to switch between spheres.

Results of the study show that on average, users consider the system easy to understand (M = 4.4, Mdn = 4, SD = .5). They appreciate the support given by integrated context and 19 out of 20 participants stated that they would prefer using a system that implements locations, actions, and token based authentication. Users rated the general system's capabilities to secure privacy as 4.2 (Mdn = 4, SD = .8) and the usefulness of spheres for privacy protection as 4.6 (Mdn = 5, SD = .5). However, users estimated their willingness to store more sensitive data on their mobile phone, if this was running TreasurePhone, with 3.2 (Mdn = 3, SD = 1.1). Nevertheless, users stated that on average (4.1) they would feel more secure when sharing their TreasurePhone secured mobile phone with others (Mdn = 5, SD = 1).

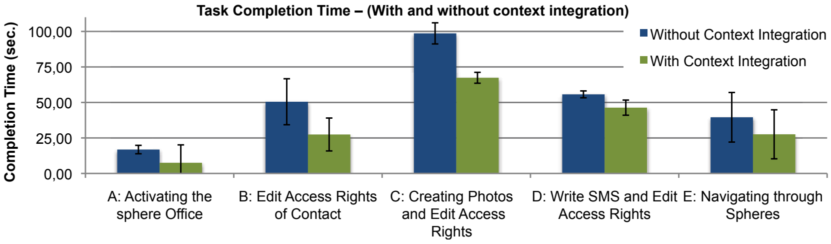


Figure 49: Task completion times of the practical tasks with and without context information integration (error bars display the standard deviation).

Because this is a laboratory experiment, our results should be handled with care. However, they suggest user acceptance of the security features, and a preference for the context integration. Users did not mind increased complexity (and even did not consider it that complex). Also they agreed that their data would be more secure on such a phone. One user confirmed this by stating "I wouldn't need to be concerned about my data so much when I want to share my mobile phone with a friend or when I just leave it at some place". One user was especially happy that this system would provide her the possibility to limit the access to specific applications as well: "I like that I can even define access policies for facilities such as camera and address book". The results are already quite encouraging, even more since none of the participants was in a business that requires carrying around sensitive data on a mobile device. We expect business users to be even more concerned about their data privacy.

Context information for supporting supporting managing and switching spheres leads to significantly shorter interaction times.

A detailed analysis of task completion times shows that, not surprisingly, tasks were completed significantly faster with the prototype that uses context information for task switching (see Figure 49). The data was analyzed using paired-samples t-tests. For each task the prototype using NFC was faster than the PIN version. The results for task A ($t(18)=7.26$, $p<.001$), B ($t(16)=4.15$, $p<.003$), C ($t(15)=5.91$, $p<.001$) and D ($t(18)= 3.85$, $p<.003$) were highly significant while the difference in task E was significant ($t(17)=2.89$, $p<.05$). The positive results for the context version are supported by the users' opinion. One user explicitly stated "it makes changing the profiles fast and easy".

4.2.4 *Discussion of TreasurePhone*

This section presented TreasurePhone, an approach toward a mobile phone operating system which supports context dependent data privacy for users based on spheres. Supporting locations and actions for changing spheres makes adapting to the users' current context easier. Accordingly, the users are supported during the process of privacy management. The results of the user study show that integrating context and fast authentication makes the system significantly faster in use and is favored by the users over a system that requires manual authentication and manually switching spheres.

4.3 CASE STUDIES OF DATA SHARING & PRIVACY MANAGEMENT

Subsequently, this chapter offers two case studies that provide a deeper insight how sharing and privacy management can be implemented using mobile mediated interaction techniques. The first case study illustrates how sharing information across physical boundaries of devices can be supported through adapting a *drag-and-drop* metaphor. The second case study investigates if and how mobile mediated interaction techniques can increase the privacy and thus, the security level in the context of operating an ATM.

4.3.1 *Data Sharing through Cross-Device Drag-and-Drop Actions*

This section the is based on results presented in:

[7] A. L. Simeone, J. Seifert, D. Schmidt, P. Holleis, E. Rukzio, and H. Gellersen. "A Cross-device Drag-and-drop Technique." In: *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*. MUM '13. Lulea, Sweden: ACM, 2013, 10:1–10:4

The author contributed to this work substantially regarding the conception of the interaction technique, the evaluation design and experiment execution, as well as the documentation.

The growing number of available personal and shared devices increases the need for efficient and straightforward possibilities to transfer data from one device to another. For instance, in order to show a photo to others which was taken with a mobile phone that only features a small screen, a user needs to the photo to a large tabletop computer.

Many existing data sharing concepts are based on classic messaging.

Numerous approaches exist that enable transferring data from one device to another. For instance, many users use e-mail services to send files from one device to another. This approach facilitates in particular sharing data with other people which do not need to be co-located. On the downside, this approach requires users to take several secondary steps (i.e., selecting an email address, composing the email, and attaching a file). A more direct approach which involves less preparation steps is sharing data via Bluetooth: a user just initiates the sharing process for a selected file. Further, the user selects from a list of available Bluetooth devices to which the file shall be send. Given that the user knows the *hardware name* of the target device and that both involved devices are already paired, this approach facilitates the sharing in comparison to the use of e-mail services. Nevertheless, often device names are ambiguous and thus it is difficult to decide to which device the file should be sent to. Further, the pairing process can be unpleasant and cumbersome. A third option that should be considered in this context is the use of cloud-based sharing services: in case a user has configured two devices to access a shared could service, files are easily accessible from each device. However, this requires the previous configuration which not always possible as for instance, shared or public interactive surfaces should not be connected to a private cloud storage repository.

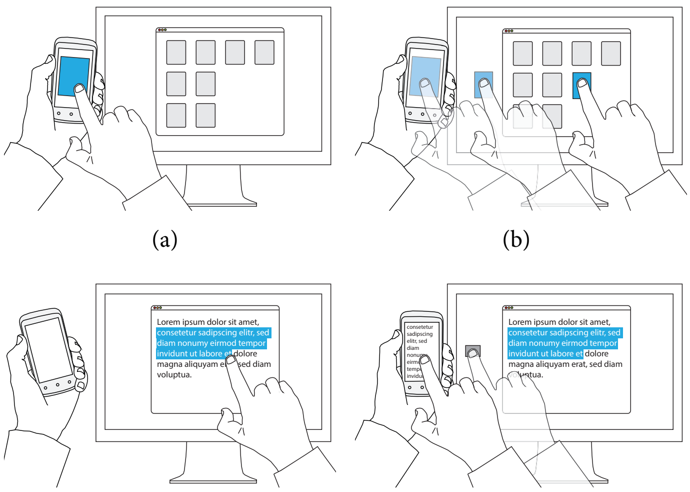
In addition, in many application contexts the process of sharing requires a specific piece of data to be at a specific target. That is, in order to further use a file after transferring it to another device, it must be imported or loaded to a specific application context. For instance, when a user wishes to attach a photo to an e-mail, the photo first must be transferred and than added to the e-mail attachments.

Extending the concept of drag-and-drop for cross-device interaction.

CONCEPT In order to address this requirement that data not only need to be transfered but also be directly available for further use, the *cross-device drag-and-drop* technique was developed [7]. This technique is based on the concept of an adaptation of the drag-and-drop metaphor: users can drag-and-drop data items from one device to another. For instance, for copying an image from a mobile phone to a specific folder on a desktop computer with a touch screen, the user simply starts dragging the image from the mobile phone (see Figure 4.50(a)) to the desired folder and drops it there (see Figure 4.50(b)). Vice versa, a user can transfer a piece of information such as a text string by first selecting the text (see Figure 4.50(c)) and dragging and dropping it on the mobile phone application where the text is needed (see Figure 4.50(d)).

PROOF OF CONCEPT IMPLEMENTATION In order to proof the applicability of the concept, a prototype was implemented. Based on time-correlation of *exiting* and *entering* dragging events, the logical connection between devices is established. That is, if the time-difference between exiting one device display and entering anther one stays below a defined threshold, these events are defined as cross-device drag-and-drop event. As prerequisite all involved devices (i.e., mobile phones, tabletop computers, or personal computers) need to be connected with a shared WLAN. Each device runs a custom service application in the background: the mobile phone (the prototype was developed for Android) runs a service, the bridge application, that accepts sharing intends from other applications running the phone or from external device. Devices such as personal computers run a background service as well which manages the drag-and-drop event on their side.

This prototype allows users for instance, to drag-and-drop an image from a personal computer to the phone (see Figure 51). This application requires the user (a) to select an image on the PC display. Then it is possible to drag it across the display into the red activated sharing zone (b). By continuing the dragging-gesture to the phone, an icon next the

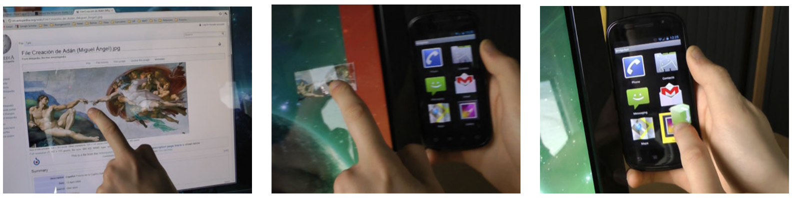


(a) (b)

(c) (d)

Figure 50: Cross-device drag-and-drop: (a) a user holds the mobile phone next to the desktop screen and selects a data item. (b) The user starts dragging the data item on the mobile phone and continues on the desktop screen. (c) In the other direction, a user selects data on the PC and (d) drops it on the phone. [7]

the finger indicates the attached data item (c). On the phone, the *bridge application* allows to select a target application where the data is submitted to.

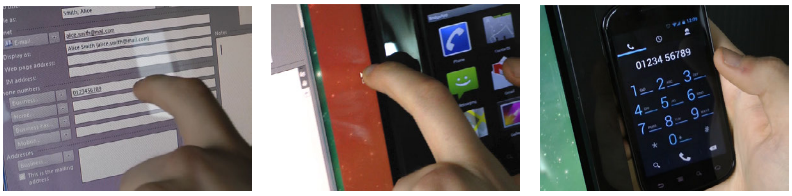


(a) (b) (c)

Figure 51: Using cross-device drag-and-drop for transferring an image to the mobile phone [7].

Another example for using this cross-device drag-and-drop technique is transferring a phone number from a PIM application on the PC to the mobile phone (see Figure 52): The user selects the number (a). When getting close to the screen border, the sharing zone is activated (b). Using the bridge application, the user can select which application the number shall receive, e.g., the calling application (c).

INITIAL USER FEEDBACK & EVALUATION In order to gain first insights how users would assess this interaction technique an initial qual-



(a) (b) (c)

Figure 52: Transferring a phone number to the phone from the PC [7].

itative study was performed. 15 participants performed first a number of practical tasks with the prototype and were secondly interviewed regarding their usage experience.

The practical tasks comprised transferring (1) a phone number from the PC to the phone, (2) a vCard was to store on the phone, and (3) transferring an address to the map application on the phone and start the navigation app there. The interview framework consisted of 13 questions regarding the participants' prior experiences with data transfer between devices, current practices, and their assessment regarding the potential of the system to be used in real world settings.

All participants indicated that if the interaction technique will be integrated into future (mobile) operating system that they would like to use it. Also, they were all positive about using the system for interacting with public screens and terminals (e.g., at a train station to pick up a virtual copy of a time table). The main reason (stated five times) why they liked to use it was that it simple to use. For instance, P4 emphasized that "it felt really natural". Two participants stated that drag-and-drop across the screen's outer frame is rather difficult to do. One suggested using a smartphone and a tablet computer would probably work better. Two participants did not perform a continuous dragging gesture but lifted their finger and jumped from the touch screen to the mobile. They explained that it felt more comfortable and natural to perform the transfer this way. Three participants indicated that interaction with the large touch screen felt awkward. In particular, dragging data over longer distances across the touch screen was reported to be straining.

4.3.2 *Mediated Interactions with Public Terminals*

This section the is based on the work:

[9] J. Seifert, A. De Luca, and E. Rukzio. “Don’t Queue Up!: User Attitudes Towards Mobile Interactions with Public Terminals.” In: *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia*. MUM ’12. Ulm, Germany: ACM, 2012, 45:1–45:4

Public terminals are a very convenient tool for all kinds of services. They allow for service execution at any time while reducing costs for the service provider and increasing benefits for the users. For instance, they can be used to buy snacks, drinks, tickets, or even gold. Users can benefit from interacting with these machines in many ways. However, two main challenges can be identified: (1) at times, users have to wait in line before they can start interacting with the machine and (2) public terminals are prone for manipulations by attackers or shoulder surfing attacks.

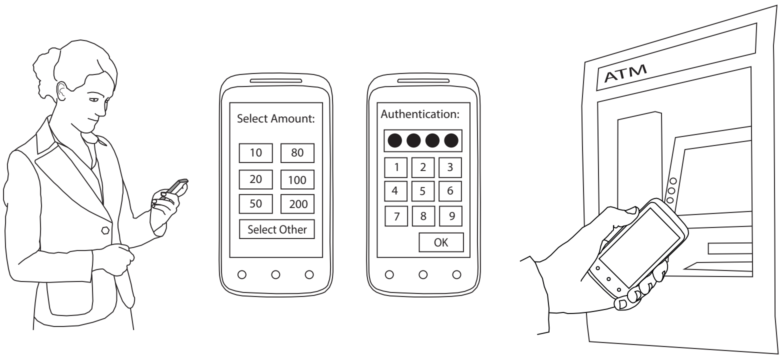
One option to address the first challenge is to increase the number of terminals. However, this comes at considerable costs for the service provider. Thus, another versatile option is to provide mobile services based on the personal smartphone of the user. For instance, users can purchase flight tickets, perform online check-ins and even present their boarding pass, all by using their smartphone. This way, both issues are addressed, as users do not have to wait in line and shoulder surfing attacks are significantly harder to conduct. This approach is only applicable if the corresponding service does not require connection to physical objects. Thus, it is for instance, not an option for withdrawing cash from an ATM. A connection between the physical service (thus the terminals) and the mobile service has the potential to provide the desired convenience and solve the previously mentioned problems.

Mobile services have the potential to replace kiosks as long the service provided does not include a physical artifacts.

Various approaches for mobile interactions with public terminals for payment, transportation, ticketing and access control have been investigated recently and are already commercially available. This concept is very popular in Japan where circa 60 million “Osaifu-Keitai” (mobile phones with wallet function) can be used for payment in more than 1 million shops or as membership cards or keys [49, 191]. Another example is the recent launch of Google’s smartphones, which have a NFC module that allows users to pay through touching terminals with their phone [97, 281]. Furthermore there is a large body of research which investigated architectural [31], security [38, 199] and user interface aspects [75, 240] within the given context. In particular, efficient and effective solutions can be found that protect information stored on the mobile phone and communicate them in a secure way as can be seen in the large number of available mobile banking applications and contact-less payment solutions (e.g. [42]). However, no research has analyzed the behavior and opinion of users when performing such mobile interactions with public terminals and in particular where and how much in advance they might start the interaction on their mobile device.

The concept of hybrid *mobile interaction.*

In order to run a real world user study, an interaction concept was developed, which combines the advantages of mobile services on the smartphone and stationary service machines, such as ATM. In short, the user creates a transaction token using the smartphone which contains all information about the service transaction. Then, this token is transmitted to the public terminal and the service items are delivered. For instance, if a user wants to withdraw cash from her bank account, she uses her mobile phone to prepare the transaction (see Figure 4.53(a)). After specifying the amount of money and authenticating (Figure 4.53(b)), the user goes to the ATM terminal and transmits the transaction token (e.g. by means NFC). By doing so, the withdrawal is triggered (see Figure 4.53(d)). In addition, the whole transaction can also take place at the terminal only.



(a) (b) (c) (d)

Figure 53: Illustrating the concept of mobile transaction preparation. (a) The user starts the interaction on the mobile phone and prepares the transaction by (b) selecting the amount of money and (c) entering the personal PIN. (d) The user starts the payout through transmitting the transaction token to the automatic teller machine.

4.3.2.1 *Concept of mobile service use*

The concept of mobile interaction with terminals is based on splitting the process of the service into two parts: preparation and execution. The advantages from the user's point of view are flexibility and reduced interaction times with the terminal which leads to shorter waiting times. Flexibility in terms of location and time allows users to perform the preparation in individual contexts. Thus, the preparation can happen during downtimes of the user such as during bus rides. At the same time, users can perform the preparation in a secure environment of their choice which prevents attackers from spying on the user's PIN. Here one has to rely on the user to choose a secure and private context as many already do when using one of the popular banking apps offered by many banks.

SCENARIO. Alice is in the metro heading downtown where she is going to meet friends in a coffee shop. She needs to withdraw cash firstly. As she is late and does not want to wait in line at the ATM, she starts the banking application on her smartphone and prepares the transaction. That is, she selects from a list of favorites the amount of money and authenticates to finish preparation. When she arrives at the station, she goes to the special express ATM, touches it with her mobile phone and picks up the money.

In case the mobile phone is lost after preparation, firstly the finder does not know the authentication code to unlock the phone, secondly most ATMs have Closed Circuit Television (CCTV) that will record an illegal withdraw and thirdly the user can lock all financial transactions with the mobile phone by calling her bank. A mobile service as suggested in this paper does not have a higher security risk compared with existing mobile banking and payment solutions such as Google Wallet or the widely deployed "Osaifu-Keitai" phone in Japan.

To start the payout, the user in the scenario performed a touch gesture with the phone on the terminal. This can be implemented using different technologies. For instance, NFC allows for fast and secure exchange of information [281]. It should be noted here that this work is not aiming for a novel and optimal solution for the implementation of such a hybrid approach but about gaining insights on if and how hybrid approaches would be used in a (semi-)realistic scenario.

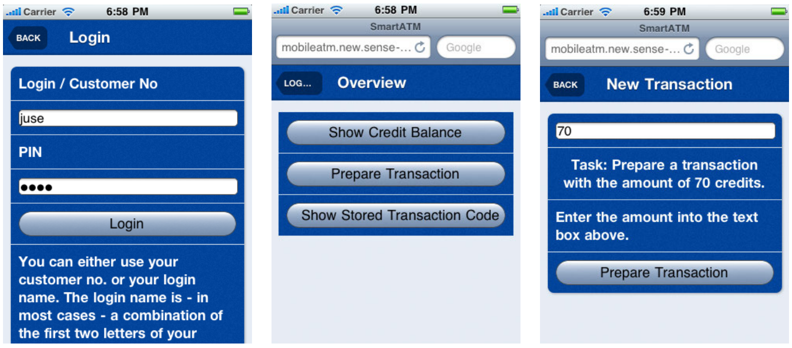
4.3.2.2 *User Study Design*

Study goal: what benefits do users see in hybrid interaction?

A user study was conducted in order to investigate the following questions. (1) Do users exploit downtimes for configuring transactions? (2) Do users prefer to perform the interaction mobile or on a terminal and what are reasons for using either of the two options? (3) Where and when are users preparing transactions? (4) How do users perceive this system from a usability perspective and (5) how do they feel in terms of security?

In order to investigate these questions, the study was structured in two phases. In the first phase, participants used the systems for four weeks. In the second phase, participants filled in a post-hoc questionnaire concerning their experiences with the systems.

The test system for the first study phase allowed participants to perform transactions. Users were instructed that a transaction is similar to the process of withdrawing money from an ATM: Firstly, participants have to configure the transaction (typing in a given amount of money). Secondly, they get a virtual payout at the terminal. In this study, participants received 50 Cents credit for each successful transaction as an incentive (up to a limit of 20 transactions). Further transactions were counted as a lot for a lottery after the study, where participants could win gift vouchers.



You can either use your customer no. or your login name. The login name is - in most cases - a combination of the first two letters of your

Task: Prepare a transaction with the amount of 70 credits.

Enter the amount into the text box above.

(a) (b) (c)

Figure 54: Graphical user interface of the mobile transaction configuration system.(a) Login screen, (b) service overview, (c) transaction preparation for creating a transaction code.

In this study, users could create transactions in two different ways:

HYBRID: Preparation on the mobile phone and execution by entering the transaction code at the terminal. For this, they opened a mobile web page on their own mobile phone, logged in, and performed the preparation (see Figure 54). When the configuration was finished, they received a text message and an email with a five-digit transaction code. In order to execute the transaction, the participant entered this code at a public terminal that served as an ATM dummy (see Figure 55).

TERMINAL ONLY: The second option was to perform all steps directly at the terminal.

The terminal (see Figure 55) was set up on a university campus in a highly frequented faculty building near a coffee shop. It could be easily accessed by all participants at all times during the study. All participants were students, therefore, they all were nearby the terminal anyway which was close to their lecture theaters, labs, cafeteria, learning zones and offices of their lecturers. No participant had to come to the campus only to execute a transaction.

Following the observations by De Luca et al. ([77]), waiting times were simulated at the terminal by displaying a counter that showed the number of seconds until the user could start interacting with the terminal.

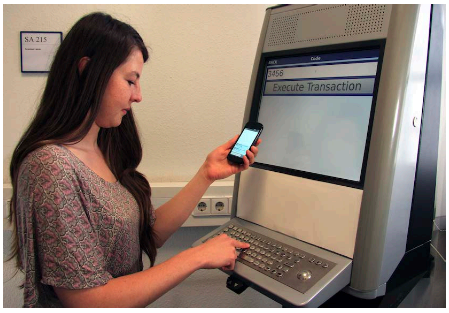


Figure 55: A study participant completing a transaction on the terminal computer by entering the five digit transaction code that she received after preparing the transaction.

Waiting times at the kiosk were modeled following the empirical observations c.f., [77]

The waiting times for terminal-based transactions were modeled with $t_{ATM} = \sum_{i=0}^{Q} 28s + (30s * r_i)$. Q models the number of persons waiting in line and is a random variable with values $\{0, 1, 2, 3\}$ whereas the distribution is {0=70%; 1=24%; 2=5%; 3=1%} (cf. [77]). r is a random variable ranging from $\{0.0..1.0\}$. A pretest for measuring the average time for performing a transaction with the study ATM terminal (M=43s, SD=15s) was performed. As users, who prepared a transaction on their mobile phone can also experience waiting times before executing the transaction by entering the transaction code at the terminal, waiting times for this situation were modeled with $t_{Mobile} = \sum_{i=0}^{Q} 9s + (5s * r_i)$. As additional temporal regulation, participants were allowed to perform only one transaction within 60 minutes in order to motivate them to perform the transactions in a broader variety of contexts and to prevent participants executing multiple transactions in a row while remaining next to the ATM.

4.3.2.3 *Study Results*

13 participants were recruited who performed transactions either with the hybrid or with the terminal only version of the system (four female) and filled in the post-hoc questionnaire. Their average age was 24 years (22-29). All were students (computer science, economics, and humanities), used mobile phones for several years (M=9.2; SD=2.2) and were using a smartphone (e.g. Apple iPhone, HTC Desire, Samsung Galaxy S) at the time of the study in combination with an unlimited data plan. They reported that they withdraw money 1-2 times a week (max. 3). In average, they estimated the maximum waiting time they would be willing to wait with 220s (SD=157.6 seconds). In total, the participants performed 320 transactions in the four weeks of data collection. The great majority was performed using the hybrid version (254). Only a few times users performed the configuration of transaction on the ATM terminal (36). The remainder of recorded transactions was invalidated by the users by

creating new transaction codes while old codes were not entered at the ATM yet. Nine participants performed a transaction at the terminal at least once (M=3.54; SD=4.18). The other participants used the mobile version exclusively.

The mobile web page, which allowed participants to prepare transactions with their mobile phones, also recorded the current location through accessing the GPS-coordinates (using the Webkit Application Programming Interface (API) [263]). Analyzing these locations shows that participants were 4.7 km away from the ATM terminal on average (SD=11.4 km). Summarizing the distances into a limited number of classes reveals that the distance varies strongly (see Figure 56). Only few transactions were prepared within a distance of 100 m. Due to GPS aberrations that occur especially when trying to determine the current position while being indoors, we can assume these transactions to be performed inside the university building, where the ATM terminal was located. Most transactions (42.4%) were prepared within a distance of 400 m to 800 m.

Most transactions were prepared within a distance of 400 m to 800 m, which corresponds to the distance between terminal and university main campus.

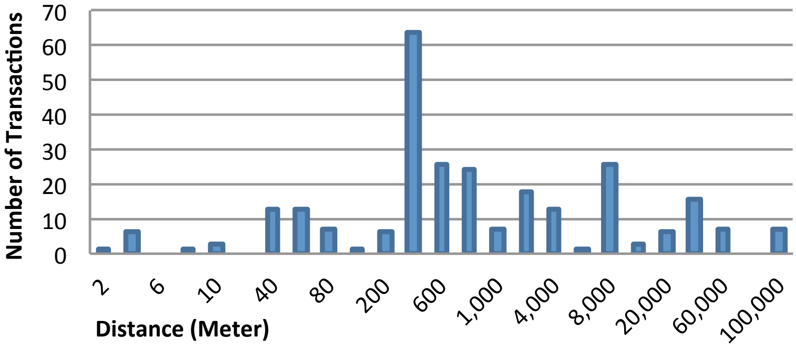


Figure 56: Distribution of distances between the location where the users prepared the transaction on the mobile phone and the ATM.

Looking at the time duration between mobile preparation and terminal interaction shows that the majority of transactions were prepared and executed within three hours (83.9%). In 41% of all cases, the users went to the terminal within 5 minutes after preparing the transaction. Figure 57 shows how much in advance they prepared the transactions.

Evaluating which version of the system the participants preferred reveals three usage patterns.

- Four participants used both options throughout the study in arbitrary and randomized order.
- Four participants used the hybrid version only.
- Four participants used the terminal at the beginning of the study and used the hybrid version for the rest of the time.

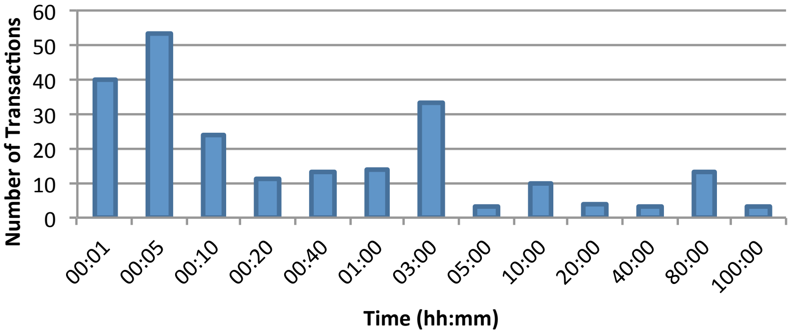


Figure 57: Distribution of durations between starting the transaction on the mobile phone and interaction with the ATM.

After using the system for four weeks, participants filled in a post-hoc questionnaire. As reasons for using the hybrid version, participants indicated that they liked the flexibility to prepare the transaction anywhere. Participants reported that they performed the mobile transaction preparation during downtimes, for instance, while they were using the local public transport. Others reported to perform preparation at home before they left, in coffee shops or on the way to the terminal. One participant reported to having prepared the transaction on the mobile device while standing next to terminal because another participant was occupying it. Participants stated that the hybrid version is faster and more comfortable to use. For instance, one statement was that 'I spend less time at the ATM as I can prepare the transaction e.g. on the train.'

One participant addressed the security aspect by stating that it would be impossible for an attacker to observe the interaction since the user can do this, for instance, at home. Reasons for performing the interaction using the terminal only version were that the battery of the mobile phone ran out of power, or that they arrived at the terminal without previously preparing the transaction. Also, participants indicated that they were performing transactions on the terminal out of curiosity. One participant emphasized that the terminal only version is more failure-resistant as it cannot run out of power, get lost, or get damaged.

The post-hoc questionnaire included also questions of the System Usability Scale (SUS) questionnaire for comparing the hybrid and the terminal version regarding general aspects such as *appreciation, system complexity,* and *ease of use* [53]. The results for both systems were similar for all but one statement. Users agreed on average with 4.2 (SD=0.6) (on a 5-point Likert scale: 5 = fully agree) with the statement 'I think that I would like to use this system frequently' for the hybrid version. For the terminal only version the average was 2.7 (SD=0.6). Comparing the two system versions directly, all of the participants indicated explicitly that they would prefer to use the hybrid version of the system if they had the choice.

4.3.2.4 *Discussion of Hybrid Interaction with Terminals*

Usage shift towards the hybrid interaction.

The number of transactions prepared on the mobile phone is much larger (79.3%) than those that were performed at the terminal only. The behavior of initially using the terminal only and then shifting to the hybrid version can be seen as a strong indicator for the hybrid version. In addition, none of the participants switched from the hybrid version to the terminal as the preferred option. These results come with two major benefits. Firstly, they indicate that service providers can reduce their costs as the number of terminals could be reduced and secondly, potential customers can save waiting time as they can prepare the transaction in advance.

Hybrid interaction increases complexity for shoulder surfing attacks.

At the same time, such a hybrid solution could increase the security when withdrawing money as fixed installations to spy on the users' PIN are not working anymore and the risk for shoulder surfing attacks at the ATM is reduced. This advantage is partially compensated by the potential of shoulder surfing attacks when the user is interacting with the mobile application in an inappropriate context. However, it seems that most users are aware of this and use those applications only in relatively safe settings as the intensive usage of mobile banking applications shows. The great advantage of the hybrid approach lies in the aspect that nobody knows whether a certain person interacting with a mobile phone somewhere is currently using a mobile banking application. This argument is supported by our study which shows that the preparation of the transaction on the mobile phone was often conducted relatively far away from the terminal (81.0% with a distance greater than 400m) and well in advance (82.1% at least 5 minutes in advance). This is different to the concept of an ATM where people interact directly to withdraw money.

The study was designed with goal of a very high external validity which we achieved through aspects such as a real physical terminal accessible at all times, a realistic prototype and a study duration of 4 weeks. It was, however, a limitation of our study that the participants didn't deal with significant amounts of their own money which might have had some impact on their usage behavior. A further much more sophisticated field trial (e.g. conducted by a major bank) would be required to investigate such possible effects.

Part

CONTACTLESS INTERACTION

5

CLOSE-BY INTERACTION WITH PERVASIVE DISPLAYS

This first chapter in the context of *contactless* mobile mediated interaction focuses on options and possibilities that enable users to interact beyond and in the direct vicinity of pervasive displays. Within the introduced anthropomorphic classification framework, interaction in this spatial sector allows users to transition and switch between touch-less and touch-based mobile mediated interaction.

Through detaching the mediator device and the pervasive display throughout the interaction process, several additional features and options for designing interaction are available. For instance, distance of the mediator device to the pervasive display can be used as a controlling feature. Also, users can interact simultaneously with the pervasive display (e.g., through finger touch) and the mediator device.

While using the spatial relation of mediator and external displays yields several novel and additional options for the design, it requires at the same time that users constantly manually position the mediator object in space. That is, the user has to hold the mediator device constantly in their hand and needs to remain in a straining position at times.

This section first introduces work that investigates handheld approaches for mobile mediated interactions that exploit the spatial relationship of mediator and pervasive display device. Results of this research suggested the second direction of research presented in this chapter: autonomous and self-actuated movement and position control of mediator devices.

This chapter is based on previously published work which includes the following refereed conference papers:

[1] J. Seifert, S. Boring, C. Winkler, F. Schaub, F. Schwab, S. Herrdum, F. Maier, D. Mayer, and E. Rukzio. “Hover Pad: Interacting with Autonomous and Self-Actuated Displays in Space.” In: *ACM Symposium on User Interface Software and Technology*. UIST ’14. New York, NY, USA: ACM, Oct. 2014, pp. 139–147

[6] M. Rader, C. Holzmann, E. Rukzio, and J. Seifert. “MobiZone: Personalized Interaction with Multiple Items on Interactive Surfaces.” In: *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*. MUM ’13. Lulea, Sweden: ACM, 2013, 8:1–8:10

This section draws on the work:

[6] M. Rader, C. Holzmann, E. Rukzio, and J. Seifert. “MobiZone: Personalized Interaction with Multiple Items on Interactive Surfaces.” In: *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*. MUM ’13. Lulea, Sweden: ACM, 2013, 8:1–8:10

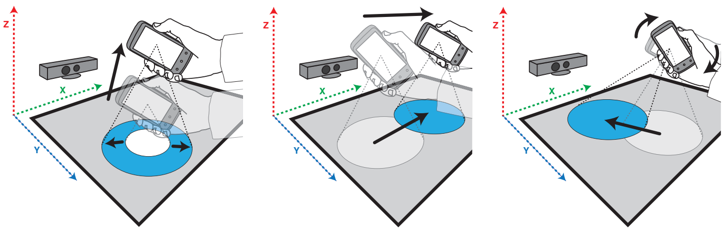
The author contributed to this work substantially with the conception of the interaction technique, the evaluation design and subsequent statistical data analysis, as well as the documentation and publication.

Mobile mediated interaction based on direct touch restricts the number possible Degrees of Freedom (DoF) that are involved for controlling and interacting with an application. For instance, when *placing* the mobile phone on an interactive surface, only rotation around the device center is possible. As a consequence, interaction with the mobile phone in the immediate vicinity of a pervasive display enables a maximum of flexibility in terms of exploiting available DoF for interaction.

The FlashLight&Control technique facilitates interacting with multiple itmes simultaneously on an interactive surface.

One task that can be in particular cumbersome to perform with touch-based interaction is the simultaneously selection of multiple items on an interactive surface. With standard touch-based approaches only one item is selected at a time, which requires time consuming sequential selecting. This section introduces FlashLight&Control, an interaction approach for supporting personalized interaction with multiple items represented on interactive surfaces. FlashLight&Control provides users with a *spatial zone* displayed on the surface, which is spatially linked to the user’s mobile phone. FlashLight&Control allows users to control the position and size of the spatial zone by holding the mobile phone in their hand and moving it over the interactive surface (inspired by the behavior of the light spot of a flashlight). The movement is tracked using a depth camera (i.e., a Microsoft Kinect camera). To control the size, the movement of the phone along the Z-axis in the 3D space over the surface is tracked and mapped to the zone size (see Figure 5.58(a)). The X/Y position of the zone can be controlled by moving the phone in parallel to the surface plane (see Figure 5.58(b)).

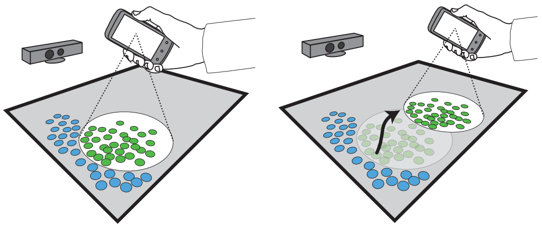
The concept of using a zone as cursor is motivated through the observation that sometimes users have the need to select and manipulate multiple items on an interactive surface simultaneously (e.g., two-handed transport as introduced by North et al. [189]). At the same time, user identification for managing or restricting access to items on the surface is a key requirement in many application contexts such as collaborative settings (e.g., [164]). To address both requirements, the user first has to connect the personal mobile phone to the surface. The mobile phone serves as a token that allows for identification to the surface, thus enabling



(a) (b) (c)

Figure 58: Using the FlashLight&Control interaction technique to (a) control the size of the spatial zone as well as its position by (b) translating or (c) rotating the mobile phone.

personalized access to specific items. At the same time, the phone is used as a tool to perform different kinds of actions that can be customized via the phone. For instance, items such as photos that are located within the spatial zone on the surface, can thus be selected and moved to another position simultaneously (see Figure 59).



(a) (b)

Figure 59: (a) FlashLight&Control enables the selection of multiple items by placing and resizing the zone over the items. (b) Selected items are bound to the zone for interaction, e.g., to move them to a new position.

IMPLEMENTATION OF FLASHLIGHT&CONTROL. The technical realization of FlashLight&Control is based on a distributed architecture comprising three main components: a server component running on the interactive surface, a mobile client component running on the mobile phone, and a Microsoft Kinect depth-sensor that is connected to the server component. The depth-sensor tracks the user and provides the potion of the user's hand above the surface. The mapping of the hand's coordinates in space above the surface to the screen coordinate system is handled by the server component. In addition, the server component runs the surface side of applications. That is, a program based on the Surface SDK provides the user interface on the surface. The mobile client application is based on the Windows Phone 7.5 SDK.

The mobile phone position is mapped to cursor control.

5.1.1 *Evaluating Handheld Close-By Interaction*

Benefits of spatial mapping for cursor control.

In order to investigate the potential and effectiveness of FlashLight&Control to support users during tasks that involve handling multiple items (e.g., images) simultaneously an initial users study was designed and conducted. In general, the aim was to investigate the usability and effectiveness of handheld mobile mediated interaction close-by a pervasive display. In particular, the goal was to investigate to which extend the spatial relation of phone and surface is of benefit for the user. Therefore, two alternative approaches for handling multiple items (based on the concept of using a spatial cursor such as the *zone*) were identified and implemented for a comparison. These alternative interaction techniques are presented in the following.

THE PLACE&CONTROL INTERACTION TECHNIQUE. The first alternative approach for comparison, Place&Control, allows users to control the size and position of the zone while the mobile phone is place on the interactive surface. Initially, the user needs to connect the mobile phone with the interactive surface and then place it. The phone has a visual marker (i.e., a Byte Tag) attached to its back for identification, and the zone appears next to the top of the phone when it is lying on the surface. To change the size of the zone, the user applies a *pinch gesture* on the surface (see Figure 5.60(a)). To change its position, the user moves the mobile phone (either by picking it up and placing it on the surface at a different position, or by dragging it along the surface). The zone follows as long as the phone is lying on the surface (see Figure 5.60(b)).

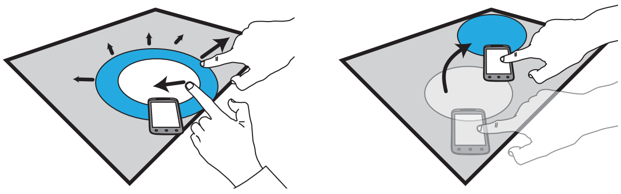

(a) (b)

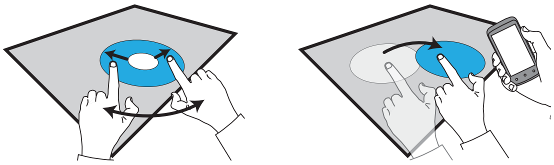
Figure 60: (a) Place&Control allows to control the spatial zone by placing the phone on the interactive surface; its size can be adapted with a pinch-gesture. (b) The position of the zone is bound to the mobile phone and follows the device.

THE REMOTE&CONTROL INTERACTION TECHNIQUE. In contrast to the previous, the interaction technique Remote&Control discards the spatial relation of phone and zone on the surface. Therefore, after initially establishing a connection between mobile phone and interactive surface to start a session, the zone appears at a random position on the surface.

The Remote&Control technique discards the spatial relation of devices.

Similar to Place&Control, the user can change the size of the zone by using a *pinch* gesture (see Figure 5.61(a)), while the mobile phone may either be placed on the rim of the surface or remain in the user's hand. To control the position of the zone, the user can drag it to a new position and release it there (see Figure 5.61(b)).

Accordingly, in order to move items to a new position on the surface, the user first makes a selection by positioning and resizing the zone over the desired items. Afterwards, the user pushes a *hold* button on the mobile phone to bind the selected items to the zone. Finally, the user drags the zone to its new position and releases the button. Throughout the interaction, the position of the mobile phone in relation to the surface is of no relevance.



(a) (b)

Figure 61: Users can (a) resize the zone using gestures and (b) drag-and-drop it to a new position.

EVALUATION DESIGN The users study was designed as repeated measures within subject experiment. Each participant performed a series of three practical tasks with the interaction techniques FlashLight&Control, Remote&Control and Place&Control. The order of the techniques was counterbalanced. During performing the tasks, task completion times and error were logged. After each trial with an interaction technique, participants filled in a questionnaire in order to collect their subjective assessment. In total, 12 participants were recruited aged between 16 and 27 years (M = 25).

PRACTICAL TASKS In total, three tasks were designed and used for testing each interaction technique.

1. *Transferring items from the mobile phone to the interactive surface.* The tasks requires participants to connect the mobile phone with the interactive surface. Once the connection is established, a red

hair-cross appears on the surface, which had to be positioned on a designated target zone where items had to be placed.

2. *Moving multiple item on the interactive surface simultaneously.* This task required users to first place the zone cursor on a selection of specific files, which further were to move to a second target zone.
3. *Searching specific items among many items on the interactive surface.* This third task required users to place the zone cursor on items. As an effect, these items could be inspected on the phone display.

5.1.2 *Evaluation Results & Discussion*

Regarding the task completion times, a slight advantage of FlashLight&-Control and Remote&Control over Place&Control could be observed. One reason is that placing the phone on the surface, while using the Place&Control interaction technique, requires users to perform more physical movements in order to finish the tasks compared to the tow techniques in which participants keep the mobile phone in their hand.

In terms of errors (e.g., transferring accidentally wrong items, placing items at wrong position etc.) no significant differences could be observed. Also regarding the subjective rating of usability aspects (using the PSSUQ questionnaire), no substantial differences could be identified. In addition to the questionnaires, participants had the opportunity to highlight any aspect regarding the techniques which they particularly liked or disliked.

FlashLight&Control was perceived as imprecise and physically tiering.

Six of the participants emphasized that they experienced FlashLight&-Control as a *novel* and *interesting* technique that "enables natural interaction" while controlling the spatial zone on the surface. Further, two participants highlighted that they found that FlashLight&Control enables efficient task completion. The qualitative feedback regarding FlashLight&-Control has to be handled with care due to the possibility of *novelty bias* towards this technique. However, the majority of participants (8) expressed that the position tracking of the hand lacks accuracy and needs to be more robust. This resulted in prolonged interaction using this technique while users had to hold the mobile phone in their hand at a given position in space which causes substantial fatigue.

Regarding Place&Control, four participants emphasized the positioning of the zone through placing the phone on the surface. For instance, P8 stated "moving items is fast" using Place&Control. Additionally they stated that the interaction technique was easy to use and could be a nice add-on for current mobile phone applications. As a downside, several participants criticized that controlling the exact position of the zone can be difficult in situations when working close to the surface rim, which could collide with the phone.

Concerning the Remote&Control technique, five participants praised the concept as easy to understand. Four participants expressed that they liked this interaction technique best. For instance, Remote&Control is "most intuitive, and best performing overall" (P6). In particular the aspect of precise positioning of the zone was highlighted several times (e.g., "It was easier to move the zone with the hand." P12).

In summary, handheld mobile mediated interaction close-by a pervasive display extends the space of design options for interaction techniques by another dimension. Existing work highlighted that handheld mobile displays can support exploring and investigating volumetric data that are anchored to an interactive surface (e.g., [125, 250–255, 264, 265]). However, handheld interaction that is spatially related to a pervasive display did not result in significant advantages regarding speed and error as show by the initial evaluation of FlashLight&Control. However, holding the mobile mediator device that provides the spatial display causes fatigue over time and is heavily depending on the technical infrastructure provided for hand and mobile phone tracking.

5.2 INTERACTION WITH AUTONOMOUS & SELF-ACTUATED DISPLAYS

This section is based on the work:

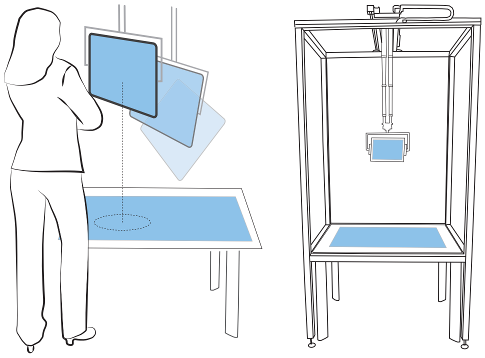
[1] J. Seifert, S. Boring, C. Winkler, F. Schaub, F. Schwab, S. Herrdum, F. Maier, D. Mayer, and E. Rukzio. "Hover Pad: Interacting with Autonomous and Self-Actuated Displays in Space." In: *ACM Symposium on User Interface Software and Technology*. UIST '14. New York, NY, USA: ACM, Oct. 2014, pp. 139–147

With their mobility, handheld displays such as tablets can be used for spatial exploration of information spaces. They provide a digital window into a much larger three-dimensional information space (see Figure 62). This approach can help users to explore and understand complex volumetric data sets. This space is either centered around the user's body [64, 306], or anchored to larger displays in the environment [125, 137, 254, 258]. Previous research has assumed that people move the display manually (may it be a tablet computer or a sheet of paper with projection) using their hands. While in motion, the display content changes continuously according to its position and orientation in space.


Figure 62: Handheld spatially aware displays allow to explore volumetric data.

Manually controlling the display's position and orientation empowers users to navigate to a desired location in that space. This approach, however, has its shortcomings: (1) users hold the device continuously (occupying at least one hand) which may increase fatigue; (2) exact positioning becomes difficult due to the natural hand tremor [251]; and (3) users search for information within the space which might be time-consuming and error-prone (i.e., missing important aspects in the data as users focus on finding a specific item instead). In summary, handheld displays are tied to the user's physical input (here: moving it in space) in order to change their content.

This section presents work that aims for *freeing handheld displays* from the user's physical input constraints. That is, displays can autonomously move within the information space of a volumetric data set. Unlike previous systems (e.g., [125, 137, 254, 258, 306]), users do not have to hold the tablet in their hands; instead the display can move autonomously and maintain its position and orientation (see Figure 5.63(a)). This autonomous actuation can further be combined with manual input by users, e.g., a user moving the display to a position where it then remains. To investigate this new class of displays, *Hover Pad* was built – a self-actuated



(a) (b)

Figure 63: Self-actuated and autonomous displays free handheld displays from this requirement (a). The *Hover Pad* prototype is a first realization of a self-actuated display that can autonomously move and hold its position (b).

mobile display mounted to a crane (see Figure Figure 5.63(b)). This setup allows for controlling five degrees of freedom: moving the tablet along its *x*-, *y*-, and *z*-axes; and changing both *pitch* (i.e., the tablet's horizontal axis) and *yaw* (i.e., the vertical axis).

Key advantages of self-actuated mediator objects: autonomy, hands-free interaction, and precision.

With its self-actuated nature, the *Hover Pad* setup offers three advantages over tablet displays which serve as mediator object that are positioned physically and manually by users: (1) the tablet can *move autonomously* in space without requiring a user's physical effort; (2) it allows for *hands-free interaction* as users do not have to hold the tablet in their hand continuously – thus reducing fatigue in arms and hands as well as using hands for parallel tasks; and (3), it offers more *visual stability* compared to manually holding it still in a certain position and orientation (i.e., natural hand tremor).

In the following, this section investigates designing interactions with such displays based on this prototype. In particular, the focus is put on how their movement can be controlled either autonomously through the system or by users. This section presents techniques that, will benefit from *autonomous and self-actuated* displays. In summary, this work offers three contributions:

1. A set of *interaction techniques* that allow for controlling the display position – either in a *semi-autonomous* fashion, where the display moves and orients itself on its own following a user's request, or in a *manual* fashion, where users explicitly control the display's motion.

2. A *prototyping toolkit* (*Hover Pad*) that allows for rapid prototyping of such displays – including a detailed description of how such

displays can be constructed. This toolkit enables developers to make use of the presented control mechanisms in a simplified way.

3. A set of *example applications* that were built using our setup and toolkit. These applications make use of the presented interaction techniques to demonstrate their utility in real-world scenarios.

The main contribution lies in the engineering domain to enable the exploration of *autonomous and self-actuated* displays.

5.2.1 *Background on Spatially Aware Displays*

Our work builds on (1) *spatial exploration of information spaces* with handheld devices, and (2) on *self-actuated objects* both on tabletops and in mid-air.

SPATIAL EXPLORATION OF INFORMATION WITH HANDHELD DEVICES *Hover Pad* combines a tablet and an interactive surface where the spatial relationship between these devices is important. *Chameleon* and *Boom Chameleon* investigated manually controlled exploration of virtual reality in three-dimensional space [89, 264]. More recently, the combination of mobile devices and large displays has been explored. Schmidt et al.'s *PhoneTouch* locates where a mobile device (and which one) touched a surface [16]. Others explored tracking mobile devices in three dimensions in front of a display [39, 47].

Mobile devices have been used to explore three-dimensional information spaces. When the mobile device is used without another, larger display, these spaces are anchored around the device. In Yee's *Peephole Displays* users move the handheld display in mid-air to reveal content that is virtually located around the device [306]. With *Boom Chameleon*, users can navigate around an object in 3D space by manually moving a display in space which is attached to a boom [89]. Chen et al. constructed the information space around the user's body where the handheld display reveals different information based on its location relative to the user's body [64].

In many existing systems, the information space is anchored to a larger display in the environment where that display provides an overview (e.g., a bird's eye view) of the space which is inspected in detail using a handheld display [250, 252]). Marquardt et al. demonstrate the use of a tablet computer to physically navigate through a pile of photographs [159]. Besides volumetric data, the interaction above or in front of a large display may also extend 2D visualizations. Izadi et al.'s *SecondLight* [125], for example, takes *Magic Lenses* [43] into the third dimension.

All these approaches require to constantly hold the display. Thus, it impossible to explore the space out of reach and it becomes difficult to hold the device still at a certain position. Furthermore, to explore fine details within that space, users have to move the device in small steps, potentially slowing down the interaction [251] and fatigue increasing tremor makes it difficult to examine fine grained structures. Our design intends to overcome these limitations through self-actuated movement that allows precise positioning, hands-free interaction as well as reaching space out of the user's reach (e.g., exploring volumes reaching beyond the user).

SELF-ACTUATED OBJECTS ON INTERACTIVE SURFACES Self-actuated objects on interactive surfaces that allow for instance, to animate physically application state changes (e.g., a slider value or position), have been studied previously. Most prominently, magnets embedded underneath the surface are used to move magnetic objects on top [90]. The *Actuated Workbench* provides feedback by moving tracked objects on an interactive surface [198]. *Pico* works similarly, but adds physical constraints to movable objects [201]. Weiss et al.'s *Madgets* further enable tangibles that can move vertically in a limited range [288]. In addition, they are able to simulate physical properties, such as friction, while people move those tangibles [287].

Others experimented with alternative approaches to self-actuate objects. Rosenfeld et al.'s *Planar Manipulator Display* [219] and Pedersen et al.'s *Tangible Bots* [203] create movable objects by attaching wheels to them. Ultra-sonic air waves [160] or vibration as in *Touchbugs* [190] are also explored to control autonomous movement of objects. However, both approaches are constraint in either the objects that are able to move (i.e., lightweight objects through sound) or the level of movement (i.e., one direction with vibration). Also, they can only move in one plane (directly on the top of the surface). Nevertheless, the aspect of physical feedback present in each of these systems also inspired our approach.

MOVABLE OBJECTS AND DISPLAYS IN MID-AIR More recent work focused on moving objects and displays in three-dimensional space. Alrøe et al.'s *Aerial Tunes* [24] lets multiple balls hover over boxes using a controlled air stream in order to visualize an artistic sound installation. Lee et al.'s *ZeroN* [143] use electromagnets to position a magnetic sphere in mid-air. When projected upon, this sphere is turned into a display. *ZeroN* also allows for force feedback by changing the magnetic field. In both systems, users are able to reposition objects as form of input. Hörtner et al.'s *Spaxels* create a large scale volumetric display using small quadrocopters, each representing one pixel in space [119].

Besides objects, displays can also be moved in space (without requiring a user's physical effort). Wilson et al.'s *Beamatron* combines a steerable projector with a depth camera to empower users to move digital content in an environment through gestures [301]. In contrast to a projected display, Sinclair et al. mounted a touch-display onto a crane so that it can move forward and backward along one dimension when a user touches the display [247]. This motion allows for exploring physical attributes of virtual objects (e.g., weight). The work on *Hover Pad* allows for investigating (semi-)autonomous display motion control and interaction in a *three-dimensional* space.

5.2.2 *Movement of Self-Actuated Displays*

The tablet in the *Hover Pad* setup can move fully *autonomously*. That is, it can follow predefined paths without requiring any user interaction. However, the setup also allows for two additional types of movement, each of which is triggered by user interaction: (1) the tablet can move *semi-autonomously* (e.g., in response to an alert or due to artificial intelligence in a game); and (2), its position and orientation can be controlled *manually* by the user. In the following, first the physical motion attributes are illustrated as well as the operational and information space. Further, these two movement types are described in more detail.

PHYSICAL MOTION ATTRIBUTES The motion of self-actuated displays in mid-air can have several characteristics. We define those attributes as follows:

- *Degrees of Freedom*: The motion capabilities of objects in three-dimensional space are described through the DoF. They define which motions are possible. Three degrees of freedom describe *translation* (along the x-, y-, and z-axes) while the remaining three describe the *rotation* around these axes (*pitch*, *yaw*, and *roll*).
- *Accuracy*: The display's motion accuracy describes the granularity (i.e., the stepping) with which the display can move for each of the supported DoFs.
- *Speed*. The display can move along/around each axis with a given speed. Both the lowest and fastest possible speed parameters may constrain certain interactions.
- *Operational Range*: This parameter describes the operational values for each of the supported DoF's. In all existing systems, this parameter is limited for *translation* (as it is for *Hover Pad* as well).

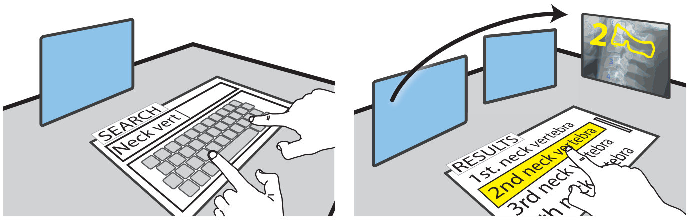
OPERATIONAL AND INFORMATION SPACE An self-actuated display can operate in information spaces with different points of origin. Here, it is important to note where the information is logically anchored to as it may change the spatial relationship between the information space and the display. In general, the following three categories exist:

- *World-centric*: The information is anchored to the surrounding environment. That is, each position in the environment corresponds to a unique location in the virtual space – similar to outdoor augmented reality [169].
- *Object-centric*: The information can also be anchored to an object. In many cases this object can be another display (e.g., a tabletop) which provides *one* view into that space (e.g., [125, 251]). If the object moves to another location, the information will move with it.
- *Body-centric*: The information can also be anchored to a person (e.g., [64]). That is, it surrounds that person and follows with him or her (i.e., the person *carries* the information). Thus, it frequently changes its location.

5.2.2.1 *Semi-Autonomous Movement*

With *semi-autonomous movements* the display can move to a location based on the user's request. However, it still moves to that location on its own without requiring the user to hold it in hand at any time. For example, the surface could show a top-down view of a human body and the tablet shows the corresponding slice of a computer tomography scan. The user could now request a specific location (say: a slice of the brain) by tapping on the location on the tabletop. This then triggers the display to move to that location in space. In contrast to existing systems, users do not have to physically search for a given area of interest in the information space. In particular, this enables two interaction techniques: *search & inspect* and *bookmark & recall*.

Semi-autonomous movement techniques allow interaction on a concept level: the system can show an item.

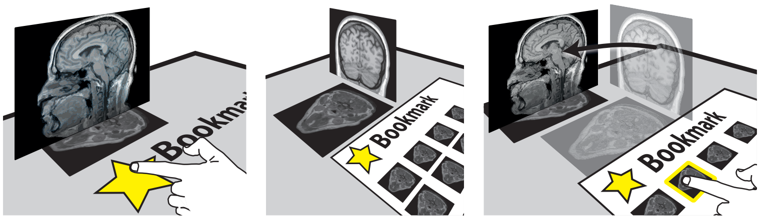


(a) (b)

Figure 64: *Search & Inspect* for searching and selecting an item (a). The display then moves autonomously to that item in space (b).

SEARCH & INSPECT Volumetric data sets are often structured and have specific, well-defined areas of interest (i.e., in a CT scan a specific density in a tissue area indicating a tumor) the system is aware of these areas and knows their location). This allows users to *search* for specific locations and subsequently *inspect* data located there. Figure 64 shows the stages of this interaction technique in more detail: (a) users perform a search (i.e., by entering the name of the area of interest); (b) within the resulting list (neck vertebrae), users can now select the item of interest from the result list; upon selection, the display transitions to that location in the volumetric data set for further inspection by the user.

BOOKMARK & RECALL Similar to *Search & Inspect*, users can set *bookmarks* of a location within the volumetric data set – for example, when they come across a detail that they wish to inspect further at a later point. Figure 65 demonstrates the use of this interaction technique: (a) the user presses a button to bookmark a location. The display then stores the location (i.e., its position and orientation); (b) at a later point in time, the user can select a bookmark from a list of bookmarks. This triggers the display to return to the position associated with the bookmark (c).

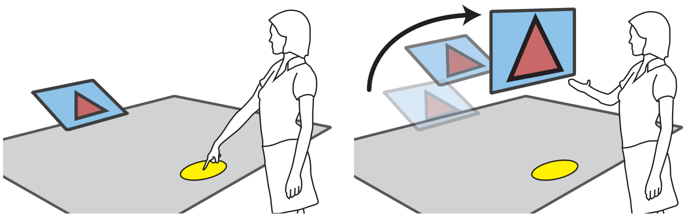


(a) (b) (c)

Figure 65: *Bookmark & Recall* allows users to create bookmarks of views (a). Later on, users can select one of these bookmarks from a list (b). This causes the mobile display to return to that bookmark's corresponding position and orientation (c).

FREEZE & INSPECT As the display positions itself absolutely within the information space, it might – from time to time – be too far away from the user. Although users could naturally move closer to the display, it might be a problem if the display is used in combination with a tabletop (which provides information context and overview). In this case, seeing small details on the display is practically impossible. At the same time, moving it closer to the user would change the visualization on the display.

To bypass this, users can *freeze* the display's current view to inspect it more closely. Figure 66 illustrates this in more detail: (a) the user issues a *freeze* command (here: on a tabletop). Note that other input modalities (e.g., mid-air gestures) could be used as well; (b) the display then freezes its current view (visual content) and moves closer to the user for inspection. Once the user is done inspecting the view, triggering the *freeze* function again moves the display back to the original position. While its view is *frozen*, the display's content is disconnected from the physical position in space and thus not changing when it is moved.



(a) (b)

Figure 66: *Freeze & Inspect* allows to *freezing* (a) a view and temporarily detach the displays from its spatial context in order to take a closer look at the frozen view (b).

5.2.2.2 *Manually Controlling the Display's Motion*

When a volumetric data set is more suited for users exploring data, the display's position has to be controlled manually. That is, users should be able to tell the display where to move to. We envision four basic types of interactions.

Manual or explicit position control techniques enable direct display movement.

PHYSICALLY MOVING THE DISPLAY The most obvious way of controlling the display's position and orientation is by moving it manually in space. That is, users can grab it and/or push and pull it to the desired location (see Figure 5.67(a)). Once the display has been brought to the intended position, the user can let go of the display and it remains in that position which frees the user's hands (e.g., for secondary tasks such as taking notes).

WIDGET-BASED MOTION CONTROL Widgets represent another opportunity to control a self-actuated display's position and orientation. These widgets can be displayed either on the display itself (see Figure 5.67(b)) or on another screen (e.g., the interactive surface). One approach is to provide buttons that correspond with movement of each supported DoF. That is, for each possible motion attribute, the use has two directions: '*increase*' and '*decrease*'. A mapping function then determines the granularity of movement – either fine-grained for *slow* or coarse for *fast*

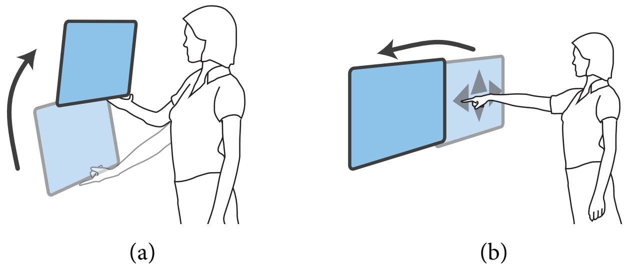


Figure 67: Physically moving the display allows users to directly grab and move the display to change its position and orientation (a). Widget-based interaction on the display's surface enables more fine-grained movements of the same parameters (b).

movements. The widget is used continuously until the display reached the user's intended location.

CONTROLLING MOTION THROUGH GESTURES Another way to control a self-actuated display in space is the use of gestures. We envision that users can apply gestures either (1) in mid-air or (2) on the connected interactive surface. Mid-air gestures allow for controlling the display position while the display is out of reach. Figure 68 shows one possible gesture: (a) the user applies a *picking* gesture to activate motion control; (b) the hand's motion is then mapped either with a *zero order mapping* (i.e., the hand's motion controls the display's position) or with a *first order mapping* (i.e., the hand's motion controls the display's speed).

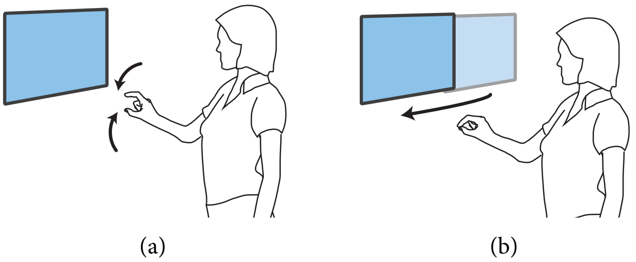


Figure 68: With gesture control, the user first performs a *pinch* gesture (a) to bind the hand's movement to the display's motion. This then allows for continuously controlling the display's position and orientation (b).

On the context providing interactive surface, users can perform multi-touch gestures on that device to control the display's motion. For instance, *pinch* gestures for controlling the height, and *swipe* gestures for controlling the x- and y-position of the tablet. Figure 69 illustrates one possible configuration: (a) *pinch in* and *pinch out* controls the display's vertical motion; (b) a *dragging* gesture changes the display's horizontal position.

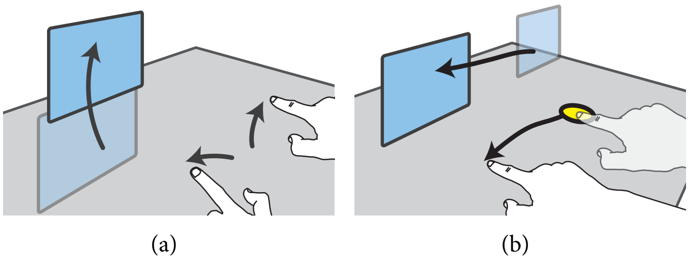

(a) (b)

Figure 69: Touch gesture motion control: controlling the vertical translation using a *pinch* gesture (a). For controlling the horizontal translation, users perform a *long touch* with subsequent dragging (b).

MOTION BY DEMONSTRATION Similar to gestures, users can *demonstrate* the motion the display should follow. In contrast to gestures, however, the display does not immediately follow that gesture. Instead, users have to initiate the motion after demonstrating it. One such approach is shown in Figure 70: (a) a user first draws a path on an interactive surface. Once drawn, the path can be revised, discarded or redrawn. Furthermore, users can refine the temporal aspects (i.e., how fast the display should follow that path); (b) Upon activation, the display now follows that path. This type of interaction would also work for mid-air gestures. However, refining and adjusting the path has to be done differently (e.g., through bi-manual input).

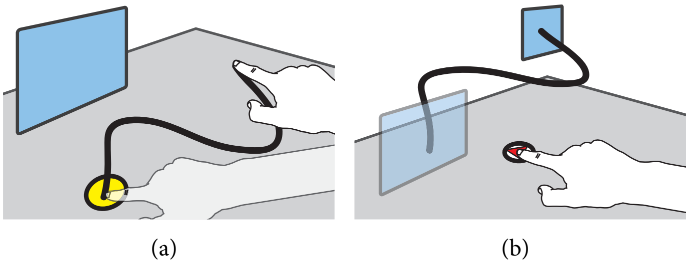

(a) (b)

Figure 70: Demonstrated movements enable users to specify (complex) paths (a) which are subsequently replicated by the display later (b).

5.2.3 *Hover Pad Prototype Implementation*

To explore the aforementioned interaction techniques and options in more detail, *Hover Pad* was designed and implemented – a prototype that resembles a *self-actuated and autonomous* display. Further, a software toolkit was designed that implements all the aforementioned motion controls. In the following, both hardware and software of the *Hover Pad* prototype are detailed.

5.2.3.1 *Hardware Setup*

Note: the hardware design and construction plans are available as open source material to ideally allow other researchers to built on this work. See `https://www.uni-ulm.de/?hover-pad`.

The prototype uses a Nexus 10 tablet as *self-actuated display* as well as a Microsoft Surface 2 (Samsung SUR40) located underneath acting as secondary display in the environment. Figure 5.71(a) shows the overall setup. To allow for self-actuated movement of a display in three-dimensional space, we designed and built a custom overhead gantry crane[1]. One sliding carriage moves the tablet along the x-axis. This carriage holds a second sliding carriage that moves the display along the y-axis (see Figure 5.71(b)). Sliding carriages are moved by separate step motors (1.8° step angle; 0.5 Nm holding torque; 12V operating voltage) connected to drive belts. The motors driving the carriages as well as the motor controlling vertical movement are connected to a controller unit. This unit provides command messages and power for these motors.

Two parallel telescope bars are connected to the carriage responsible for movement along the z-axis (see Figure 5.71(c)). Each of these custom engineered telescope bars consists of six elements (made of aluminum; supported through integrated brass rings as gliding means) with one element being 22 cm long.

Attached to them is a mount holding a tablet (see Figure 5.71(d)). This mount enables self-actuated rotation along two axes: *pitch* and *yaw*. Accordingly, two motors are integrated in the mount. The motors are controlled via an Ioio OTG board which is connected through Bluetooth with the tablet computer. The frame includes further a battery for powering the motors and the Ioio OTG board. The frame is equipped with 16 capacitive buttons located on the frame rim front, side, and back. These buttons can be mapped freely (through registering event listeners) to user-defined actions or steering commands in order to *directly* move the tablet device. For instance, a button on the right-hand side of the frame could be used to trigger movement to the left, once the user touches this button. What exact mapping is suitable in a particular application context is to decide by the interaction designers.

The overall setup allows for an operational range of 90 × 50 × 107 cm (*width* / x × *length* / y × *height* / z). The base of the operational range is aligned with the interactive surface. To limit the movement of the carriages so that they cannot run out of bounds, five limit switches are installed (two on the x- and y-axes; one on the z-axis). With our current settings on

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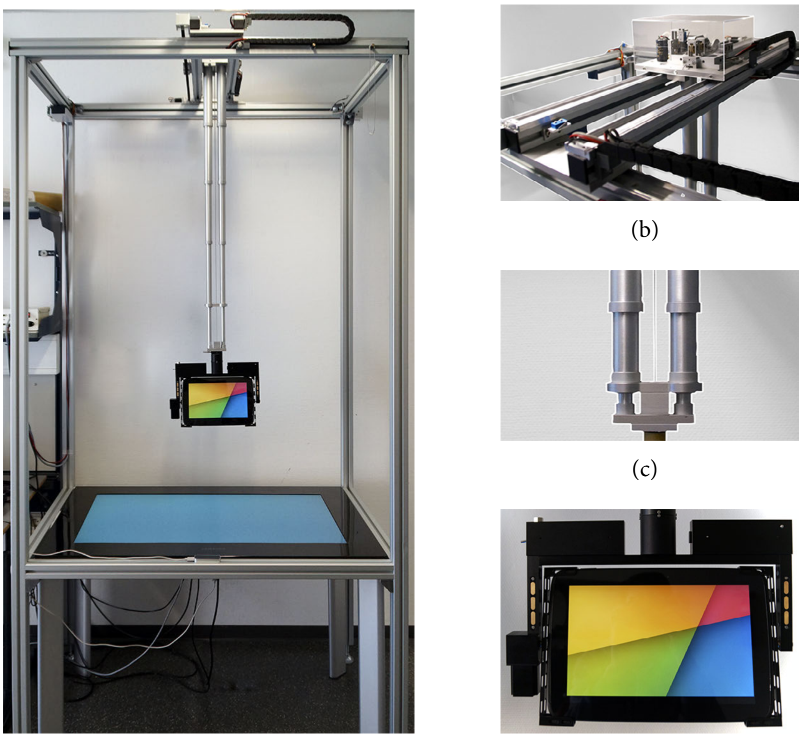
[1] The hardware implementation was substantially supported by the mechanical workshop of Ulm University as well as the electronics workshop of Ulm University.



(b)

(c)

(a)

(d)

Figure 71: Overview and details of the *Hover Pad* hardware setup (a) with details regarding the sliding carriages for x,y-motion (b), the telescope bars for vertical motion (c), and the display's frame for rotation (d).

the motor controller unit, the display needs about one second per 10 cm moving distance. Along the z and y-axis, the smallest possible movement step is about 0.05 mm. The display mount allows for continuous rotation around the z-axis (yaw) with a speed of 2.0 seconds per rotation (360°). Due to the mechanical construction, which includes a motor with a very little holding torque, the angle can be determined only with a tolerance of ±10°.

5.2.3.2 *Software Toolkit*

To enable rapid prototyping of applications that make use of *Hover Pad*'s capabilities, a software toolkit was designed and implemented. This toolkit consists of four main components: the mobile client, the surface server, the crane motion, as well as the control component (see Figure 72).

The mobile client is implemented as an Android service running on a tablet and is responsible for managing communication with the surface server hosted on the interactive surface (which runs on the SUR40 surface). The mobile client and the surface server constantly exchange the

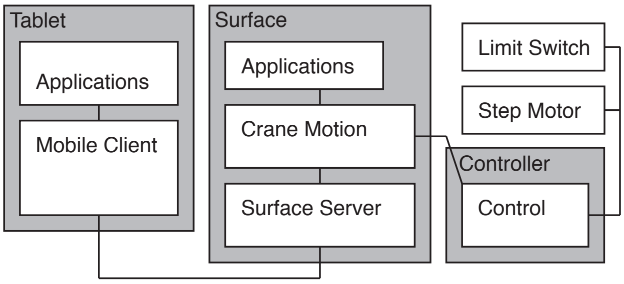


Figure 72: Overview of the *Hover Pad* software toolkit components.

tablet's position data via *JSON* objects (through HTTP via WLAN). The user's manual rotation of the tablet is sensed by an X-IMU sensor-box that is mounted on the display's back and connected via Bluetooth to the tablet. Also, when the crane motion component is called (i.e., by an application or a user's interaction) the updated position data is sent to the mobile client.

The crane motion component provides an API that provides simplified methods allowing applications to request position changes of the tablet. Application developers can do so by either providing absolute positions (which requires an initial calibration of the system) or relative position changes. In both cases, it is sufficient to provide a vector with x, y, and z values (all in mm). The crane motion component then determines the number of steps each step motor has to perform in order to reach the requested position. The control component runs on an Arduino board (here: Mega 2560) integrated into the controller unit. It receives calls from the crane motion component (via USB) and sends these commands to the step motors. In case a hardware limit switch is triggered when one carriage reaches the crane border, an exception is returned to the crane motion component which delegates this information to the calling application. Subsequently the system automatically corrects the affected axis, so that the limit switch is released and the tablet is back in the operating space.

In the following, the section briefly illustrates how the *Hover Pad* toolkit supports rapid prototyping of applications. In particular, basic motion control options are highlighted. Applications for *Hover Pad* are in general distributed, including one part running on the surface side and another part running on the tablet side. On both sides, the same control options exist (except minor syntax differences). Hence, in order to avoid redundancy this discussion is limited to the surface side.

MOTION CONTROL OPTIONS After setting up the connection to the framework, motion control calls can be performed by placing a request to move the tablet to an absolute or relative coordinate (see Listing 1). First, a coordinate is defined (through defining millimeter values, which correspond to exact physical distance). When requesting an absolute position, the tablet moves to this position in relation to the *world coordinate* system. In case of relative movement, the given coordinate is used for movement in relation to the current position.

Listing 1: Starting shortest path motion to an absolute or relative position.

```
coordinate = new Point3D(23, 42, 5); //in cm
_mController.sendAbsolutePoint3D(coordinate);
// alternative relative movement
_mController.sendRelativePoint3D(coordinate);
```

In order to rotate the tablet in a specific orientation, the movement can be controlled through activating the rotation motors for a desired period of time (e.g., 50 ms). For convenience, a target angle can be set (see Listing 2): First, the auto rotation is activated and a tolerance value is defined. Finally, the angle is defined which triggers the movement instantly.

Listing 2: Automatic rotation management of the tablet.

```
_mController.activateAutomaticOrientation();
_mController.setDeltaAngel(10); //degree
_mController.setYaw2be(90); // degree
```

CONNECTING INTERACTION TECHNIQUES. On an application level, toolkit users can connect controls that enable interaction options, by simply adding a motion request call to the corresponding callback function. For instance, a Leap Motion controller was used to track mid-air gestures in front of the *Hover Pad* setup in order to implement mid-air gestures. These gestures can be mapped easily to *Hover Pad* movement, as shown in Listing 3.

Listing 3: Mapping a gesture tracker *Hover Pad* movment.

```
_gestureTracker.gestureChange += new EventHandler<
    GestureEventArgs>(gestureDetected);
...
void gestureDetected(object sender, GestureEventArgs e) {
// distinguish gesture and trigger movement
}
```

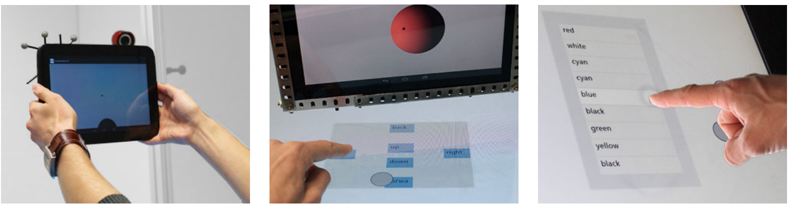
Overall, the *Hover Pad* toolkit aims for supporting developers by providing abstractions regarding the motion control options, the sensing, and the component communication. Therefore, developers can focus implementing and investigating

5.2.4 *Evaluating Effects of Automation*

In order to gain initial insights on how users perceive *autonomous* movement of *Hover Pad*, a user study was designed an conducted. The main focus of this initial evaluation was to investigate how different levels of automation of controlling the tablet display's motion would compare and how participants would perceive each of them.

INTERFACE OPTIONS. In this experiment, three interface conditions were examined, each of which allows for controlling the handheld's position in three-dimensional space above the tabletop:

1. In the **manual** condition (used as baseline condition in order to compare against existing previous work), participants had to hold it in their hands at all times. To navigate, participants had to move the tablet in the space above the surface (see Figure 5.73(a)).
2. In the **widget** condition, the tablet supports self-actuation and can thus move in space on its own. Yet, participants control the movement (x-, y-, z-direction) manually through a control widget on the tabletop (see Figure 5.73(b)). Accordingly, this condition can be classified as *explicit motion control*. In addition, participants have to manually adjust the angle of the handheld (*pitch* and *yaw*).
3. In the **list** condition (see *Semi-Autonomous Motion Control*), participants select the target they want the tablet to move to through a *target list* (see Figure 5.73(c)). Once participants selected a target, the tablet autonomously moved to this target. As well, participants can manually adjust the tablet's *pitch* and *yaw* to better focus on items.

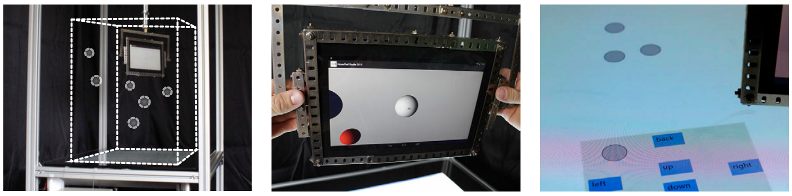


(a) (b) (c)

Figure 73: Interfaces: participants controlled the tablet's motion either *manually* (a), through a *widget* (b), or by selecting a target from a *list* (c).

PRACTICAL TASKS. Participants were given the task to explore a volumetric data set (Dimensions: 88.5 cm ×49.5 cm×80 cm) and find abstract geometric items that were hidden in the data set (see Figure 5.74(a)). In particular, participants had to find a number of colored spheres in a given sequence. To finish the task, a participant had to focus on each sphere by positioning the tablet so that a fixed cross hair is placed on that sphere (see Figure 5.74(b)). In addition, the tablet had to be within a given distance (here: 30 cm or less) and remain in this position for at least two seconds. Once a sphere was selected successfully, the next one was indicated to the participant. To avoid participants getting lost and taking too much time for the searching, the tabletop hinted on the sphere to be selected through shadows (see Figure 5.74(c)). This reduced the search to the vertical axis only.

Participants performed two selection sequences with each condition: in the first sequence they had to find 5 spheres in a set of 12 spheres (*simple task*). In the subsequent, sequence they had to select smaller spheres (10 out of a set of 20) which required more precise positioning of the tablet (*complex task*). A sequence ended once all spheres had been selected. During the experiment the time from the beginning of a sequence until all spheres have been selected was measured. Further, the number of incorrectly selected spheres (i.e., out-of-sequence selections) as well as all position and orientation data of the tablet were logged.



(a) (b) (c)

Figure 74: The study task: (a) the virtual data set; (b) positioning the cross hair on a ball; and (c) shadows of spheres as position indicators.

STUDY PROCEDURE & DESIGN. Each study session was structured as follows:

1. Participants were introduced to the study and were asked them to sign a consent form.
2. The investigator demonstrated the use of each technique to solve the task.
3. Participants performed the tasks with each condition.
4. After completing both sequences (simple and complex) for one condition, participants had to fill out a questionnaire regarding this condition.

5. After completing the entire experiment, participants filled out a final questionnaire regarding demographic data.

The experiment used a within-subject design: 3 *Technique* × 2 *Complexity* . While the order of *Complexity* was fixed in that participants started – for each condition – with the simple sequence, the order of *Technique* was counterbalanced using a Latin square. It is noteworthy that the study had three different sets for each *Complexity* so that participants would never face the same sequence. In total, evaluation sessions lasted up to 35 minutes.

APPARATUS. For the *list* and *widget* conditions, the *Hover Pad* prototype was used as described above. For the *manual* condition, the tablet from the crane was removed to enable *handheld* manual position control. An OptiTrack (6 cameras) system was used to capture the tablet's position and orientation above the surface. Accordingly, lightweight markers were attached to the tablet to enable motion and position tracking through OptiTrack (see Figure 5.73(a)).

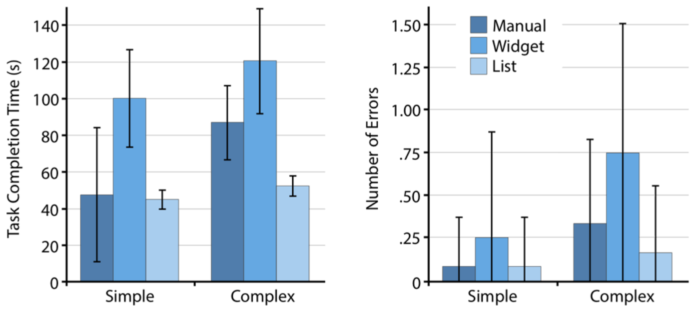
PARTICIPANTS. 12 participants (three female) were recruited ranging in age from 22 to 34 years (M=26). All were students from our university with technical background (e.g., computer science, bio-chemistry). Participants received 10 EUR as compensation for their time.

5.2.5 *Evaluation Results*

Task completion time and errors were compared using separate one way repeated measures ANOVA tests with Greenhouse-Geisser correction when sphericity was violated. For task completion time, first a 3 × 2 (Technique × Complexity) within-subjects ANOVA was performed and found a significant main effect for *Technique* ($F_{1.377,15.148} = 10.230$, $p < 0.003$) but no significant effects for *Complexity* and no interactions. For errors, the same ANOVA revealed a significant main effect for *Complexity* ($F_{1,11} = 7.857$, $p < 0.017$). Thus, for subsequent analyses, each level of *Complexity* was analyzed separately. To retain comparisons against $\alpha = 0.05$, Bonferroni-corrected confidence intervals were used for post hoc comparisons. All unstated p-values are $p > 0.05$.

The list *condition was fastest as expected.*

TASK COMPLETION TIME. For the simple task, a one-way ANOVA was performed and did not find any effect for *Technique* on task time. Post hoc multiple means comparisons, however, indicated a significant difference between *list* and *widget* ($p < 0.13$). Figure 5.75(a) shows the results for task completion times. Overall, for simple tasks, *list* was the



(a) (b)

Figure 75: Task completion times (a) and errors for each technique (b) clustered by task complexity. Error bars denote the standard deviation.

fastest (*M* = 44.8*s*; *SD* = 10.4*s*), followed by *manual* (*M* = 47.6*s*; *SD* = 73.6*s*) and *widget* (*M* = 100.2*s*; *SD* = 53.3*s*).

When analyzing task completion times for the complex task, a one-way ANOVA revealed a significant main effect for *Technique* ($F_{2,22}$ = 12.062, p < 0.001). Here, post hoc multiple means comparisons showed that *list* is significantly different (and faster) from the other two techniques (all p < 0.022). However, there is no significant difference between *manual* and *widget*. These results can also be found in Figure 5.75(a). Overall, *list* was the fastest technique (M = 52.2s; SD=11.4s), followed by *manual* (M = 86.7s; SD = 40.5s) and *widget* (M = 120.3s; SD = 57.3s).

INTERACTION ERRORS. Figure 5.75(b) shows the errors (i.e., out-of-sequence selections) during each of the tasks. As mentioned before, there was a significant main effect on *Complexity*. Naturally, the *complex* task had more errors than the *simple* one. Generally, however, the error rate was low across all tasks with a total of 20 errors out of 540 selections (3.7%). Most errors were made during the *complex* task when participants used *widget* (M = 0.75; SD = 0.75). This more than twice as much when compared to *manual* (M = 0.33; SD = 0.49) and *list* (M = 0.17; SD = 0.39). For the *simple* task, the results draw a similar picture: *widget* caused the most errors (M = 0.25; SD = 0.62) followed by *manual* (M = 0.08; SD = 0.29) and *list* (M = 0.08; SD = 0.29).

The semi-autonomous list *condition performed best and* widget *worst regarding interaction errors.*

PERCEIVED PERFORMANCE. Participants were asked to rate their perceived performance for each *Technique* with a series of statements (see Figure 76). To test for significant differences between *Techniques* Friedman's ANOVA tests were used (reported where *p* < 0.05).

Somewhat surprising, the agreement regarding the statement "*I could quickly explore the volumetric data*" did not differ significantly. While *manual* and *list* received the highest rating (both Mode = 5; Mdn = 4), *widget* (which also allows for free exploration) had the lowest rating (Mode = 2; Mdn = 3). Regarding perceived interaction speed, participants rated *list* highest (Mode = 5; Mdn = 4), which does not only concur with the measured task completion times, but is also unsurprising given its targeted approach. Likewise, the perceived precision for positioning the tablet was rated highest for *list* (Mode = 5; Mdn = 5). However, the little differing rating of *widget* (Mode = 4; Mdn = 4) and *manual* (Mode = 1; Mdn = 3) is surprising as we expected that self-actuated motion would provide more stability than physical positioning. It is noteworthy that we did not find any statistical significance regarding these ratings. Thus, our results only show some tendencies.

Participants perceived differences when holding the tablet still in a given position. Here, a significant effect for *Technique* was found ($\chi^2(2) = 10.957$; $p < .05$). Using Wilcoxon's signed rank test for post-hoc comparison confirms that the *manual* interface was rated lower than *list* ($Z = -2.827$; $p < .05$) and *widget* ($Z = -2.467$; $p < .05$). Also for fatigue a significant effect for *Technique* was found ($\chi^2(2) = 14.0$; $p < .05$). With post-hoc pairwise comparisons, it was found that participants rated fatigue higher for the *manual* interface (Mdn = 4) compared to *list* (Mdn = 2) and *widget* (Mdn = 2) with all $p < .05$.

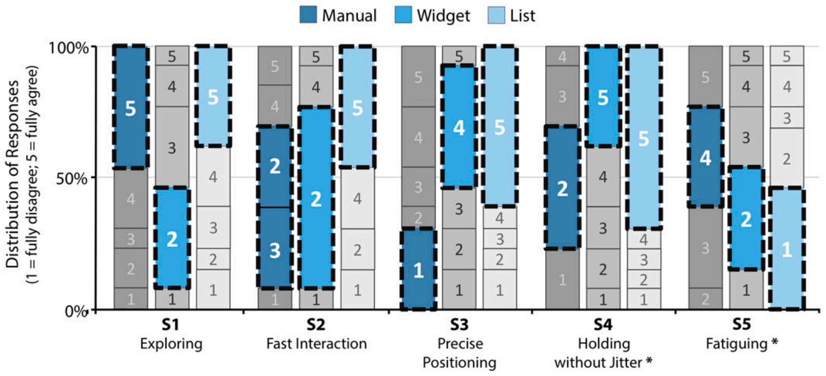


Figure 76: Mode of rating agreement with selected statements (* denotes statements with significant differences).

QUALITATIVE FEEDBACK. With regards to the participants' feedback the following aspects were found to be of particular interest: Four participants expressed that they appreciated the fast movement of the *manual* condition. Further, the flexibility to freely move the tablet was emphasized to be an *"intuitive interaction"*. One participant stated that it is *"natural as the body movement directly moves the tablet"*. However, two aspects of the *manual* condition were criticized: (1) the physical fatigue for moving (e.g., *"searching the space in higher areas quickly became very* *exhausting for the arms*") and holding the tablet in one position. And (2), participants expressed that searching items was laborious – especially given the fact that the system knew the locations.

Likewise, five participants pointed out that searching was taking an extensive amount of time using the *widget*. In particular, they stated that the tablet's rather slow self-actuated motion made search tasks more cumbersome compared to the *manual* condition (which allowed for faster movements). On the other hand, three participants reported that the widget technique allows for *"very precisely"* controlling the tablet's position. One participant expressed that the *"motor speed is fast enough to be efficient and slow enough to be precise"*.

Unsurprisingly, participants favored the *semi-autonomous* condition for selecting items (if possible). One participant stated that *"the system shows me objects and I only have to adjust the tablet"*. Two participants reported that the automated movement allowed them to anticipate where the object would be located so they could turn the handheld facing the object before it actually arrived there. Another two participants praised that they were not required to memorize the position of objects while searching for other items. Finally, participants positively underlined that the *semi-autonomous* condition – similar to *widget* – supports precise positioning of the tablet display. Similar to the *widget*, however, participants negatively mentioned the slow speed of the tablet.

5.2.6 *Discussion*

Given our task, the *list*'s difference in task completion time to other techniques increases with a task's complexity. This is because task completion time only slightly increased as the task got more complex (searching was not required for *list*), whereas the other two techniques did show a more dramatic increase (searching was required). It is likely due to a learning effect as participants always started with the simpler task with each condition – yet, no learning was required for the *list* technique as the handheld moved on its own.

Subjective preferences further indicate that the perceived interaction speed was low for both *manual* and *widget* (Mdn of 2). Although the *manual* interface was actually noticeably faster than *widget*, the low rating may be explained through the high fatigue rating: participants had to search for the item, thus experienced increased fatigue (and higher positioning jitter) and ultimately thought that they needed relatively long to complete the task. Considering the motion speed of the tablet, the low rating of *widget* is not surprising: we observed that none of the participants controlled all three axes simultaneously, which increased the overall task completion time.

Figure 76 reveals another surprising finding in that participants felt that they *explore* (*S1*) the data set using the *list* technique. The rating for *manual* was high and was the preferred technique (statements included 'natural interaction' and 'flexible'). It is one option for interpretation that participants' perceived satisfaction for *list* regarding exploration stems from the system knowing important areas (which will not be the case for unstructured data). Although designed for exploration, *widget* does not appear suitable for such tasks.

5.2.6.1 *Implications for Self-Actuated Displays*

This study reveals some relevant findings, which may be applicable for the vision of *hovering* displays. In our experiment, we chose to compare different control mechanisms which were affected by physical attributes:

Interaction Speed and Accuracy. There is an apparent trade-off between *speed* and *accuracy*. Especially when the handheld is controlled explicitly by users, it should allow for a large range of possible speeds. In this experiment, this was not the case (slow, but accurate positioning) which explains the low ratings regarding interaction speed.

Control Mechanism. While *list* was naturally appreciated for its simplicity, it will likely not work in many scenarios (e.g., those of pure exploratorive nature). For this reason, explicit controls still have to be provided. The study revealed that – in the way they were tested – there is great room for improvement. For example, combining the rapid motion of *manual* with fine-grained positioning of *widget*.

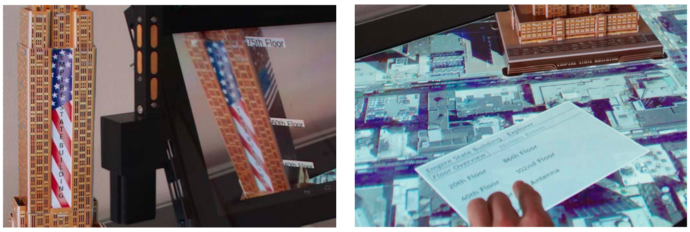
It is important to note that the results of our study are limited: the prototype hardware used for the experiment did not allow for 6 DoF and required users to manually adjust the rotation. Likely, the results will differ once a handheld could actually move in space autonomously (or with more sophisticated prototypes that mimic flying handhelds more closely than our prototype). Nevertheless, the insights gained in this first experiment already inform future research: participants greatly appreciated the self-actuated movement and could anticipate where the target is located in space.

5.3 SELF-ACTUATED DISPLAY APPLICATIONS CASE STUDIES

The vision of *Hover Pad* foresees the usage of self-actuated and autonomous displays in various contexts that involve spatial relations and volumetric data such as educational institutions (e.g., schools, museums), medical application, engineering and mining, surveillance of buildings, or product lines. In order to explore the possibilities and to investigate applicability, five applications were designed and developed. Each of these, described in the following, focus on different aspects that demonstrate how users can benefit from *Hover Pad* such as hands-free interaction to explore volumetric data in spatial context.

5.3.1 *Physical Object Augmentation and Exploration*

The first application allows users to explore a physical object (i.e., a model of the Empire State Building) that is placed on the interactive surface through the mobile display that augments said object with virtual annotations (see Figure 5.77(a)). On the surface, the user can select points of interest from a list (e.g., a *bookmark* pointing to the 102nd floor), which triggers the tablet to move and show this point (see Figure 5.77(b)).



(a) (b)

Figure 77: Augmenting physical objects with spatially registered annotations (a) allows users to select and explore diverse points of interest (b) that are than presented through the tablet.

With *Hover Pad* moving autonomously to selected targets, the interaction is predominantly hands-free. That is, users do not have to hold the tablet to maintain in one distinct position. Further, this allows users to interact with the augmented physical objects (e.g., rotate them while the augmentation follows). Physical objects of arbitrary complexity can be augmented through *Hover Pad* with labels, explanations, or hints such as alerts. For instance, a novel workpiece could be explored by workers where *Hover Pad* would provide a list of changes that could be visited and examined one by one.

As users can freely move physical objects in relation to the *Hover Pad* setup, this example application required the usage of camera based object tracking (based on Vuforia [207]) in addition to the *Hover Pad* framework. This allowed precise spatial correlation between the physical object and the rendered view on the tablet computer.

Abstractions provided by the *Hover Pad* toolkit facilitated the implementation in particular by providing a high-level interface to the motion control component. It allows during application development to define fixed positions in space that are associated with the bookmarks the user can select from the list on the surface.

5.3.2 *Map Explorer*

The map explorer application allows users to view a focused 3D visualization of buildings on the tablet (see Figure 5.78(a)). The interactive surface below provides context by displaying the surrounding environment and allows users to control the tablet position through translation and rotation widgets. The tablet acts as a *magic lens* and allows to switch between different views such as map or satellite view (see Figure 5.78(b)).

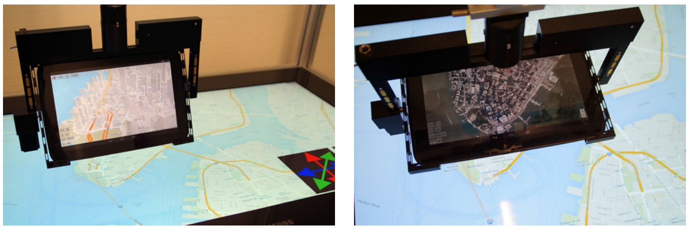
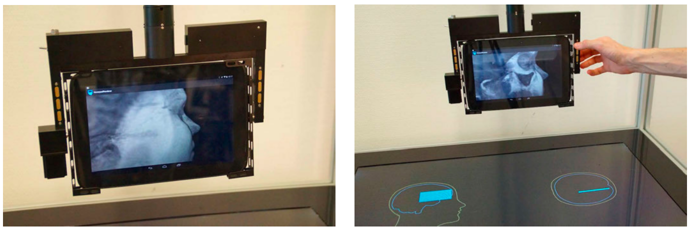

(a) (b)

Figure 78: *Hover Pad* supports exploring maps by providing context on the surface and different spatially registered views such as a 3D view (a) or an alternative satellite view (b).

The spatially registered displays (tablet and surface) allow users to simultaneously observe a focused view and context without any required transitions. Further, the motorized motion control allows logging and saving coordinates that can be revisited automatically when desired. Also, the view provided by the tablet enables autonomously controlled tracking shots that could, for instance, visualize flight route of a plane.

5.3.3 *Medical Volumetric Data Explorer*

A volumetric data viewer allows user to explore volumes such as computer tomography data sets. On the tablet a slice cut of the volume is displayed (see Figure 5.79(a)). On the surface, spatially detached from the tablet view, the slice position is visualized on a schematic outline in order to support orientation (see Figure 5.79(b)).



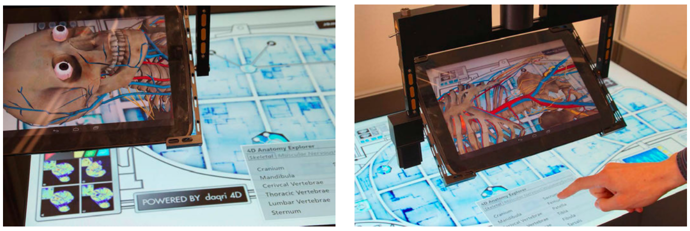
(a) (b)

Figure 79: The CT explorer allows users to explore a volumetric body scan such as a CT data set (a). Using touch buttons on the tablet rim, the user can navigate the tablet through the volume (b).

Users can control the position of the tablet in a direct and explicit way by using the touch buttons on the rim of the tablet frame. This creates a experience similar to holding the tablet in hand. However, the user does not carry the weight of the tablet which prevents fatigue. Also, the user can release the tablet which remains in its current position in order to have time to study and discuss e.g., a complex structure.

5.3.4 *Educational Anatomy Explorer*

An anatomy explorer application allows users to view and research a virtual skeleton through the tablet computer (see Figure 5.80(a)). On the surface, the user can select, for instance, bookmarked bones that are revealed by the tablet upon selecting a target from a list (see Figure 5.80(b)).



(a) (b)

Figure 80: The anatomy explorer allows users to explore, for instance, the human skeleton (a) by selecting bookmarked bones from a list (b) which triggers the tablet to move to that position.

Using the bookmarks, users can explore human anatomy as *Hover Pad* shows specific body parts in spatial relation. In particular, when a user is unfamiliar with anatomy, the application help users to find a specific body part. This application allows for instance, pupils exploring the surrounding of anatomic parts within the spatial context. That is, the main benefit of *Hover Pad* offered by this application is the ability to autonomously guide the user to unknown parts as well as the visual stability when examining the skeleton.

5.3.5 *Mixed-Reality Gaming*

A mixed-reality game for *Hover Pad* combines autonomous behavior and movement in space and interaction with tangible objects on the interactive surface. On the tablet, a virtual character is displayed that follows autonomously a virtual path. Accordingly, the tablet moves autonomously to follow the character (in order to provide a view on it) (see Figure 5.81(a)). The user it required to arrange tangible items that serve for instance, as bridges or staircases, in such way that the virtual character does not fall (see Figure 5.81(b)).

The autonomous movement that is connected to the behavior of the game character not only provides a visual level of immersion but adds through *Hover Pad* physical movement. This movement is not only controlled by the application but reacts also to the user's actions.

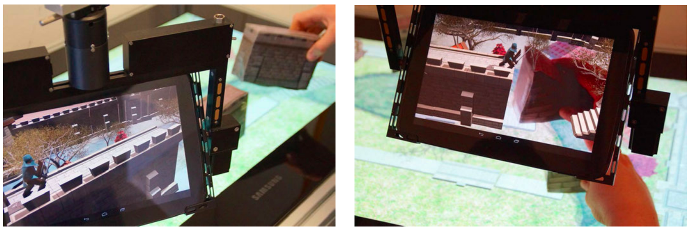

(a) (b)

Figure 81: A mixed reality game based on *Hover Pad* requires users to support an autonomously moving virtual character displayed on the tablet (a) by moving and arranging tangible items on the interactive surface (b).

The tangible objects (tracked through byte tags attached to their bottom) allow users to react quickly to *Hover Pad*'s autonomous behavior and movement in space. That is, the tangible objects can be freely moved or picked up by the user.

5.3.6 *Discussion*

The preceding example applications implemented with *Hover Pad* highlight possible scenarios in which *autonomous and self-actuated* displays provide advantages over existing, manual systems proposed in related work. *Hover Pad*'s *autonomous and semi-autonomous movement* capabilities enable search & inspect interaction, e.g., in the physical object augmentation application and the educational anatomy explorer, as well as bookmark & recall, e.g., in the medical volumetric data explorer and the map explorer. In contrast to existing systems, users can focus on the information associated with respective points of interest, instead of having to navigate the tablet to those data points manually. Furthermore, *Hover Pad* provides *hands-free interaction*. In contrast to related work, our *Hover Pad* hardware ensures that the display remains at the desired position and orientation, which enables users to study the displayed content and interact with it (e.g., on the primary display), or with augmented physical objects with both hands and without having to hold the display for prolonged periods of time. This hands-free interaction further has the advantage of providing visual stability, as *Hover Pad* fixates the display's five degrees of freedom when needed. These aspects also result in more fine-grained control of the position of the display, which is particularly important in high resolution data, such as volumetric medical data.

Self-actuated and autonomous movement of a dipslay in space enables novel interaction techniques.

The example applications presented above highlight diverse advantages that are enabled through the *Hover Pad* concept and its inherent characteristics. In the following, *Hover Pad* as well as selected systems from related work are discussed and classified (see Table 5) in consideration of their capabilities to enable interaction with volumetric and spatial data sets.

		Hover Pad	Boom Cham.	Touch Mover	Zero-N	Aerial Tunes	Paper Lens	Flex-pad	Spaxels
Physical	Degrees of Freedom	5	5	1	3	1	6	8	3
	Accuracy	Impl.	U.Def.	U.Def.	Impl.	Impl.	U.Def.	U.Def.	Impl.
	Interaction Volume	Impl.	U.Def	U.Def	Impl.	Impl.	U.Def	U.Def	Impl.
	Information Fidelity	High	High	High	Mid	Low	High	High	Low
Autonomy	Autonomous	Y	N	N	Y	Y	N	N	Y
	Semi-Autonomous	Y	N	(Y)	Y	Y	N	N	Y

U.Def.: User defined. | Impl.: Implementation defined

Table 5: Classification of spatial information systems.

While tablets that are physically moved through an information space by users could theoretically support six DoF, these 6 DoF would need to be supported by tracking methods as well. Thus, even systems that combine top-projection with paper surfaces (e.g., [254, 258]) likely only support 5.5 DoF, because projection from underneath is hard to achieve. Yet, conceptually, these systems have been shown to be sufficient for exploring the information space. Our current hardware setup provides 5 DoF (i.e., *roll* is not supported), but provides the advantages of hands-free interaction and visual stability noted before. Considering the number of available degrees of freedom of supported movement, it appears that it depends heavily on the supported application how many degrees of freedom are required. For instance, Touch Mover [247] supports movement only along one dimension, yet it allows tactile exploring of volumetric objects. Additional degrees of freedom could even be a disadvantage for some applications. *Hover Pad* however, allowing for max. five degrees of freedom provides a high level of flexibility as all five degrees of freedom can be individually utilized or not depending on the need of the application. This is not possible for approaches that require the user to manually control a handheld display.

Accordingly, accuracy of positioning a display is limited by the operating user in the case of handheld display based approaches. In contrast, systems such as *Hover Pad* that provide self-actuated position control are not limited in their positioning accuracy, as long as hardware components that provide the required movement resolution exist and can be utilized. An analog coherence exists for the operational space: handheld and user operated approaches cannot be upscaled to larger screen and projection sizes as easily as it is theoretically possible for approaches based on self-actuated movement, because movement in user-operated approaches is restricted by users' body height and arm length. Self-actuated movement also constitutes a fundamental advantage over user-operated approaches: such a system can lead users to points of interest without discarding the spatial relations. For instance, as illustrated with the *physical object augmentation and exploration* application, users can be guided through an information space, which can reduce search time and increase an understanding of spatial relations. In addition to self-actuated movement, system-driven and autonomous position control, for instance, used in games, allows users to interact with *Hover Pad* in a novel way that is a clear distinctive feature regarding user-operated approaches found in related work.

Considering the information fidelity provided, *Hover Pad* provides a high definition display as a spatial display. This level of fidelity has not been achieved by previous approaches in connection with self-actuated movement in space.

Limitations of the current Hover Pad *prototype: movment speed and operating range.*

The presented implementation of *Hover Pad* constitutes an initial step towards truly *hovering* displays that enables investigation of relevant interaction patterns, as well as prototyping of applications for such displays. The presented prototype has a number of limitations, which need to be addressed in future work. *Hover Pad* is limited in its ability to cover a range of movement speeds (i.e., dynamic range between slowest and fasted movement). Mainly, this is due to the current hardware implementation that cannot resit large inertia forces (e.g., when the telescope bar is extended to its full length, a large leverage is applied). This however, could be solved by alternative hardware implementations such as an industrial robot arm. Currently, the displays swings slightly for a short moment after reaching a desired 3D coordinate with autonomous movement, which is caused by the tension forces acting on the telescope bar. For future iterations, we plan to enhance the rigidness of the telescope bar with advanced materials (e.g., carbon composites) and reduce the weight of the display unit to address this issue. Another approach would be the utilization of a robot arm.

The current prototype, due to its static crane construction, cannot support mobility, e.g., a display device that would follow a user while walking through a museum. Recently, drone- and quadcopter-based displays have been proposed (e.g., [234]). While those approaches may facilitate mobility, they would raise other challenges, e.g., in terms of accuracy and view stability. *Hover Pad* could serve as a versatile prototyping platform for applications for such mobile displays, while associated challenges are being addressed.

The ideal Hover Pad *implementation would be an actually free floating display that can follow a user.*

This section introduced the concept of displays that can move autonomously and semi-autonomously in mid-air to navigate through three-dimensional information spaces. The potential of this new class of devices was discussed and relevant interaction patterns enabled by them were identified. The presented *Hover Pad* is a prototype system and framework allowing to explore *hovering* self-actuated and autonomous displays. This approach enables semi-autonomous control of hovering displays, including hands-free interaction and visual stability.

With *Hover Pad* system providing rich and diverse interaction and application possibilities, researching and investigating how different ways of interaction support diverse classes of tasks. For this purpose, a diverse set of example applications highlighting *Hover Pad*'s capabilities was realized. Ongoing and future research should investigate the potential and impact of *multiple* autonomous and self-actuated displays in an environment on user interaction.

6

DISTANT INTERACTION WITH PERVASIVE DISPLAYS

Large public displays and screens as well as projections have become part of our daily lives. For instance, public displays in open and shared spaces such as train stations, projected screens in class rooms, but also large displays in domestic environments such as home cinemas and entertainment systems. They all have the inherent ability to support collaboration as they allow multiple users to simultaneously access and view information. For instance, in a meeting presentation, information is shared with multiple users. However, the control of what is being displayed is usually limited to a single user (e.g., in presentation). Others cannot share, access, or manipulate virtual objects or data on the remote display.

This raises questions regarding how users can efficiently and effectively interact pervasive displays that cannot or should not be approached and operated for instance, through using touch-based interaction. Mobile mediated interaction is one option for addressing challenges regarding how the spatial gap between a user and a pervasive display can be bridged. The mobile phone can serve as a mediator device in different ways such as direct pointing or in a remote control like way. Considering the anthropomorphic spatial classification scheme used in this thesis, interaction in this context is part of the class of distant interaction which do not allow users to transition between touch-less and touch-based interaction.

In this chapter, first the aspect of direct pointing using mobile phones as mediator and pointing devices is investigated. This includes an in-depth investigation of possibilities for interaction alongside a classification schema. In order to illustrate utility example applications are discussed followed by an explorative user study that investigated how users apply interaction techniques based on direct pointing with mobile phones. Second, this chapter presents investigation of distant interaction within a specific application domain: interaction with distant pervasive displays in domestic environments with a specific dedication for television related usage.

This chapter is based on previously published work which includes the following refereed conference paper:

[3] J. Seifert, A. Bayer, and E. Rukzio. "PointerPhone: Using Mobile Phones for Direct Pointing Interactions with Remote Displays." In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 18–35

In addition, the following partially related theses were supervised by the author:

- “Interaktionskonzepte für große Displays durch Kombination von Laserpointern und Smartphones” (Interaction Concepts for Large Displays through Combining Laser Pointers and Smartphones). Marcel Imig. Master’s thesis. 2011. (*Some ideas of this thesis contributed to [3]*).
- “Pointing-Based Interaction Techniques for Mobile Phones and Shared Displays”. Andreas Bayer. Bachelor’s thesis. 2013. (*Some parts of this thesis contributed to [3]*)
- “Novel Applications for Gesture-Based Interaction with Entertainment Systems”. Katrin Osswald. Bachelor’s Thesis. 2013.
- “Leveraging Television Experience through Projected Touch Interaction”. Dennis Wolf, Bachelor’s Thesis. 2013.

6.1 DISTANT INTERACTION BASED ON DIRECT POINTING USING POINTERPHONE

This section is based on the work:

[3] J. Seifert, A. Bayer, and E. Rukzio. "PointerPhone: Using Mobile Phones for Direct Pointing Interactions with Remote Displays." In: *Human-Computer Interaction – INTERACT 2013*. Springer Berlin Heidelberg, 2013, pp. 18–35

Distant interaction and in particular direct pointing for accessing and interacting with remote displays has been investigated previously (e.g., [193]). Direct pointing interaction has been found to be a natural way for users to select and interact with objects on a remote screen (see Figure 6.82(a)) [181]. However, such settings enable only few options for interactions and are limited to basic operations such as pointing and selecting.

As mobile phones are ubiquitously available, they enable users to access remote displays in diverse ways [33]. For instance, downloading information from a remote display to the mobile phone for further inspection [46] or sharing information on a remote screen with others [25]. Pointing-based interactions offer an easy-to-use way of allowing users to interact with an object by pointing to it [222].

Hence, mobile phones with integrated pointing abilities enable diverse novel options for interaction in a natural and seamless way. Using the mobile phone as mediating pointing device and general interaction device has not been investigated previously, thus raising questions regarding how the phone's specific characteristics (e.g., options for input and output) and attributes (e.g., user data context) can be integrated into diverse interaction processes.

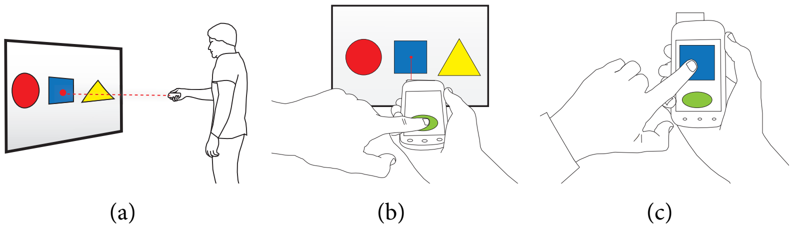

(a) (b) (c)

Figure 82: Using the mobile phone as a pointing device enables versatile interactions with remote screens: (a) Pointing to targets. (b) Performing actions on the personal phone such as selecting and downloading an item. (c) Further interaction with data on the phone.

This section contributes the detailed investigation of the novel design space of PointerPhone. PointerPhone uses mobile phones as mediator devices which in turn are used as pointing devices for new direct and natural pointing interactions with remote screens (see Figure 82). This section present a classification comprising *low-level*, *widget-level*, and *high-level* interaction techniques. Further, it shows application examples and demonstrates the integration of diverse techniques into a collaborative meeting support application which was implemented based on a prototype system that uses mobile phones augmented with laser-pointers. Furthermore, the section present observations and results of a qualitative and explorative user study and provides a catalog of design guidelines as well as lessons learned that should to be considered when designing applications based on PointerPhone interactions.

6.1.1 *Interaction Space of PointerPhone*

The underlying concept of using the mobile phone as a pointing device for direct interaction with remote displays is simple but at the same time versatile: users point towards targets on a remote screen in order to perform an action that is applied as the user triggers the action (e.g., selecting or editing an item, controlling widgets as illustrated in Figure 82). The available hardware of the mobile phone and the remote display yield a number of basic attributes and possibilities for interaction.

Basic attributes include whether the user is pointing and the location on the remote display where the user is pointing to. Further, each mobile device that is used as a pointing device can be distinguished through its ID. Accordingly, different users can be distinguished given that each user holds on to her personal mobile phone.

The diverse interaction possibilities can be classified into three levels of abstraction: low-level interaction, widget-level interactions, and high-level interaction and applications. This classification was chosen as it shows which options for interaction are available and how these can be integrated into designs on different levels.

6.1.1.1 *Low-level Interaction*

Input options based on low-level actions.

The most basic options for performing input on the mobile phone while pointing to a target on the remote display are using software buttons displayed on the phone's screen (see Figure 6.83(a)), using hardware buttons available on the phone's case (e.g., buttons commonly provided to control audio volume) (see Figure 6.83(b)), and performing gestures on the phone's touch screen (see Figure 6.83(c)). These options can be applied in flexible ways as they can be used either with one hand or with two hands.

One alternative option that avoids pressing hardware or software buttons is to trigger an action by rotating the phone along the pointing

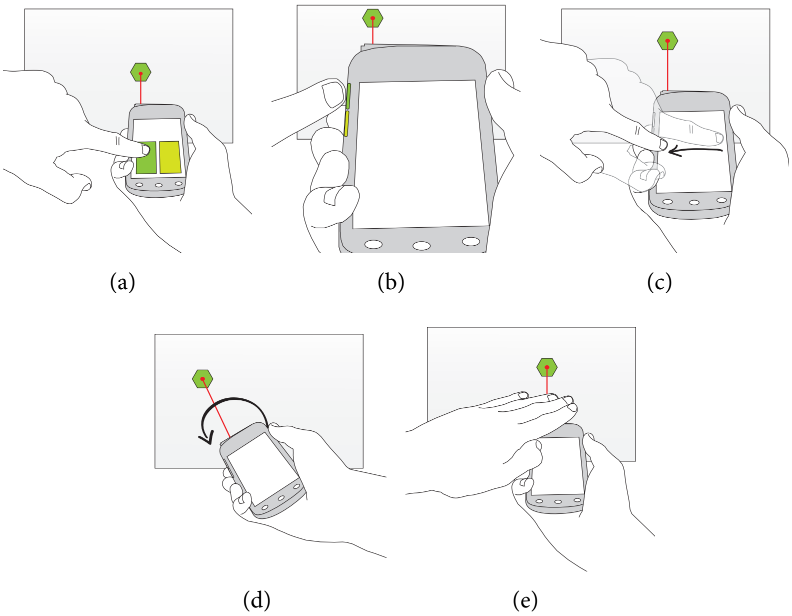


Figure 83: Basic selection and input options supported through PointerPhone: (a): software buttons; (b) hardware buttons; (c) touch-based gestures; (d) rotation-based interaction; and (e) proximity activation.

axis (see Figure 6.83(d)). Rotation in different directions (i.e., clockwise and counterclockwise) allows to encode different actions. For instance, a left and right click can be performed depending on the direction of the rotation. However, rotating the phone could also result in moving the cursor away from the target caused by unintended movement during the rotation.

As emphasized by Myers et al. (see [181]), using physical buttons causes unintended jitter effects which could lead to input actions on targets which were not meant to be selected. This is potentially also the case when interacting with software buttons or performing gestures on the mobile phone. One approach that enables users to trigger an action without touching and moving the mobile phone uses the proximity sensor, which is available in most recent mobile- and smart phones. While users point to a target, they move their hand close to the phone and trigger the action as their hand gets close enough (see Figure 6.83(e)). Similarly, users could trigger an action without moving or potentially even without touching the mobile phone through snapping with their available hand which could be sensed using the phone's microphone.

Low-level output options on a modality level.

Output options for feedback and information presentation are distributed on the users' mobile pointing device and the remote screen. The latter provides visual feedback and optionally, audio output can be provided (e.g., a television set in the user's living room remotely operated through pointing). The output options of the remote display can be targeted to one specific user only to a limited degree. If several users are using the system simultaneously, for instance, audio feedback provided by the remote screen is audible to all present persons. Hence, audio feedback is barely suitable for targeting a specific user. Visual feedback, however, can be displayed on the remote screen close to a user's pointing cursor in order to make clear at whom the feedback is targeted to.

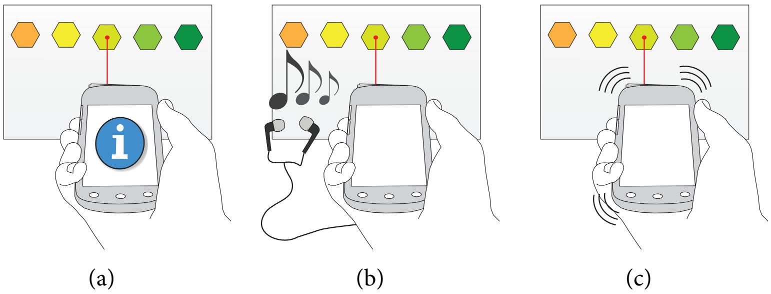

(a) (b) (c)

Figure 84: Low-level output options for PointerPhone: (a) visual feedback; (b) audio feedback; and (c) haptic feedback via vibration.

In addition, the personal mobile pointing device enables personal feedback which is not accessible to others. That is, the personal mobile devices provide visual feedback and output on their display, which is visible only to the specific user (see Figure 6.84(a)). Also, audio feedback can be provided either via speakers or headphones, which allow feedback that is not audible to others (see Figure 6.84(b)). Third, mobile devices allow for haptic feedback through vibration (see Figure 6.84(c)).

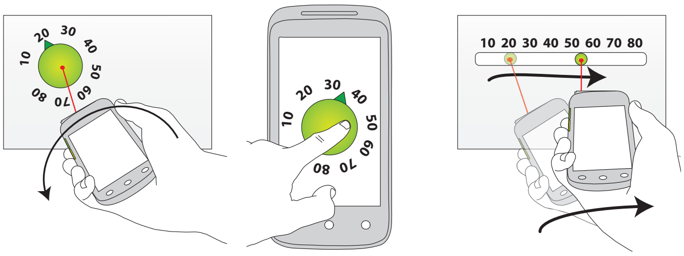
6.1.1.2 *Widget-Level Interaction*

'wid·get' - : *any small mechanical or electronic device [163]. In this context mainly* UI components *for specific applications.*

Often, interaction with diverse applications requires users to specify specific pieces of information or data (e.g., numeric values, strings) in order to control the state of an application. For instance, users control the zoom level of text or specify the volume of audio data using a slider, or select an option from a list using radio buttons. To facilitate this task, many different widgets are available, including sliders, radio buttons, and text fields, each of which supports the input of a specific data type.

When using mobile phones as pointing device, to interact with applications on a remote or shared display, users require support to interact with all kinds of standard user interface widgets. The given configuration yields up to three different options for interacting with widgets:

1. Rotation of the mobile phone (see Figure 6.85(a)).



(a) (b) (c)

Figure 85: Controlling widgets for entering data can be implemented in three ways: (a) Rotating the phone to change the value; (b) manipulating the proximal widget representation on the phone screen; (c) distal interaction with widgets on the remote screen.

2. *Proximal* interaction on the touch screen (see Figure 6.85(b)).

3. *Distal* interaction through direct pointing to the widget on the remote screen, selecting it and moving the pointing cursor to change the value of the widget (see Figure 6.85(c)).

As analyzed by Rashid et al. (see [208]), the performance of proximal and distal selection of targets (e.g., clicking a button) depends on the complexity of the tasks. For complex tasks which involve (many) small targets, proximal interaction is superior to distal interaction which was superior in simple tasks (i.e., interaction with few large targets).

Widget	Orientation	Proximal	Distal
Turning Knob	Yes	Yes	Click & Drag
Sliders	Yes	Yes	Click & Drag
Button	Yes	Yes	Click
Radio Buttons	Yes	Yes	Click
Check Boxes	No	Yes	Click
Text Field	No	Yes	No

Table 6: Overview of the widget control options.

However, not all three interaction options apply to each widget, depending on the type of data supported. Table 6 offers an overview of standard widgets and how they can be controlled through pointing with a mobile phone based on PointerPhone. Accordingly, only widgets that are designed for the input of continuous values, that is, sliders or turning knobs, could be directly controlled via rotating the phone while pointing to them in order to change their value. Yet, it is also possible to control these widgets proximally on the mobile phone's touch screen or distally on the remote screen. Standard buttons can be controlled using all three options, given that the phone rotation is mapped to a selection. Radio buttons could be selected and rotating the phone could change the selection. Check boxes are less suited for this alternative due to their size. Text fields require the user to interact with a keyboard which is most convenient for the user on the mobile phone.

6.1.1.3 *High-level Interactions and Applications*

This section discusses PointerPhone-based interaction techniques that build on the previously discussed low-level and widget-level interactions.

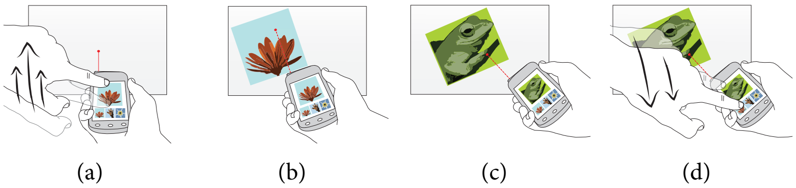

(a) (b) (c) (d)

Figure 86: Transmitting an item from the mobile phone to the remote screen ((a) and (b)) and vice versa picking up an item from the screen ((c) and (d)).

Sharing and exchanging data.

Users can share and exchange data that is stored on the mobile phone by transferring it to the remote screen. To do so, users select one or several items to share, point to any desired target position on the screen, and trigger the transfer. For instance, users could select an image, point to the desired location, and perform a swipe gesture on the phone towards the remote screen (see Figure 6.86(a)). On the remote screen the image appears at the location of the pointing cursor (see Figure 6.86(b)).

In order to receive data from the remote display, users point at the intended item (see Figure 6.86(c)) and trigger the transfer. As illustrated in Figure 6.86(c), a swipe gesture on the user's phone could be used to *pull* the item. However, any other low-level input can be applied here.

Proximal context menus.

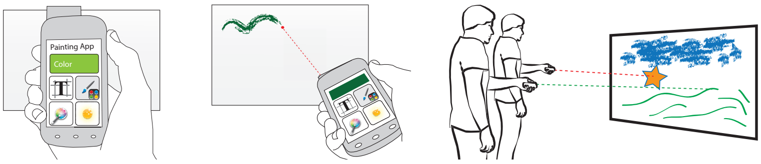
Pointing-based interaction with a remote display through a mobile phone supports the handling of meta information of items such as files which are displayed on the remote display. For instance, context menus are often used in order to change the name of a file. These provide a list of possible options that can be applied to the selected file. Using the mobile phone as pointing device, users first select a file (see Figure 6.87(a)). The corresponding context menu is then displayed on the mobile phone (see Figure 6.87(b)), thus for instance facilitating the input of a new file name (see Figure 6.87(c)). Users are not required to keep pointing at the selected file while using the context menu.

(a) (b) (c)

Figure 87: Proximal context menus: (a) A user selects a file. (b) The context menu is displayed on the phone. (c) A new file name can be typed in.

Distnat drawing and sketching as high-level interaction.

Through pointing to the remote screen, users can edit and create graphical content such as sketches or drawings. Depending on a selected tool and the corresponding parameter settings (e.g., a brush and a selected color) multiple users can create sketches simultaneously (see Figure 88). As different phones are distinguished, each user can select different tools and settings at the same time.



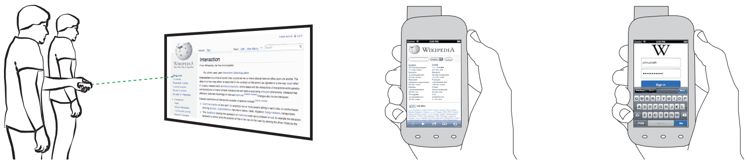
(a) (b) (c)

Figure 88: A sketching application. (a) The phone provides a palette of different tools. (b) Tools are applied through pointing. (c) Multiple users can work simultaneously.

Private input & output using the personal mobile phone.

Personal mobile phones as pointing devices allow users to receive personal output (e.g., visual or auditory) as well as to perform input on the personal device in collaborative settings. For instance, when multiple users share a view on a web page, a single user who is interested in following a specific link can point to it and open the corresponding web page on their personal device (see Figure 6.89(a) and (b)). This allows users to look up additional information without interrupting or disturbing the group activity.

Additionally, input can be performed on the personal device which, on the one hand, avoids cluttering the remote screen with a large virtual keyboard. On the other hand, input on the personal device allows users to enter sensitive information such as a password. For instance, when a user needs to login to a user account to access some information, the password can be entered on the mobile phone (see Figure 6.89(c)).



(a) (b) (c)

Figure 89: Input and output on the personal device: (a) To avoid disturbing a group activity, the user may point to a link and (b) open it on their device. (c) Entering information on the personal device.

In addition, different types of data such as files, geographical coordinates, contact cards, or appointments can be distinguished and, once selected through pointing to their representation on the remote screen, they can be handled with different applications on the mobile phone. For instance, a user could point to an address and select it, which opens the map application on the mobile phone and displays the given location.

(a) (b)

Figure 90: Using the mobile phone as a remote control for browsing web pages on a distant screen.

Remote control like interaction.

As more television sets support additional diverse applications such as web browsers, one emerging idea is to use secondary display devices to achieve remote control [61, 70, 208]. Using the personal mobile phone for this kind of interaction allows multiple users to interact simultaneously, for instance with web pages displayed on a smart TV (see Figure 90).

6.1.2 *Collaborative Meeting Scenario*

To show how different interaction options can be integrated and used as building blocks for a realistic application context, we designed and implemented a collaborative presentation system that supports users in a meeting scenario.

(a) (b) (c) (d)

Figure 91: Collaborative presentation and meeting support (a). Additional information can be accessed through specific icons ((b) and (c)). Users can share data with others on the remote screen (d).

Usage scenario for distant mobile mediated interaction in a meeting room context.

Bob is giving a presentation for some colleagues on a large projected remote screen (see Figure 6.91(a)). Each meeting participant is equipped with a mobile phone which can be used to point to the remote display and control a cursor through phone pointing interaction techniques. Each participant's pointing cursor on the remote screen is distinguished by a different color. Hence, each meeting participant has a visual representation of who and how many users are currently pointing to specific pieces of information on the remote screen. Each projected presentation slide contains diverse pieces of information. For instance, an overview plan may allow specific views on details of the plan through the selection of a corresponding icon (see Figure 6.91(b)). This allows users to individually explore and access additional information without disturbing others, as pointing to an icon on the remote screen and selecting it results in a detailed preview on their personal mobile phone. Icons next to a person's name indicate that the contact card can be downloaded to the mobile phone by pointing to it and selecting it. Additional background information can easily be accessed, for example, by pointing to an image on the remote display (see Figure 6.91(c)). In their meeting, the participants also discuss with each other about the presented topic. This discussion and brainstorming is supported through collaborative sketching on a drawing canvas on the remote screen whereto each user can contribute using their phones (see Figure 6.91(d)).

6.1.3 *Usage Assessment & Evaluation*

In order to gain an understanding on how users would use the system and how they appreciate the different interaction techniques, a qualitative evaluation was designed and conducted. The aim was to gain qualitative insights regarding direct pointing-based interaction with a mobile phone and remote display.

6.1.3.1 *Evaluation Design*

The study session consisted of two parts: After participants were introduced to the study, they performed a series of practical tasks. Tasks that involved collaboration were performed by the participant together with the investigator. After the practical tasks, they filled out a questionnaire. During the session, participants were encouraged to think aloud and continuously talk about their actions. Further, the investigator took notes and the task performance was recorded on video.

PRACTICAL TASKS. Practical tasks were selected to expose participants to a broad variety of different application contexts. Participants used the PointerPhone prototype for the tasks. The following list of tasks was performed by participants in randomized order.

1. *Browsing.* Participants had to browse through a website that was displayed on the remote screen. The PointerPhone prototype was used for controlling widgets and link selection. They followed text-based instructions, which involved selecting links, downloading images to the phone, and interacting with widgets such as radio buttons through pointing.

2. *Photo sharing.* Selecting and transferring two photos from the phone's library to the remote display and retrieving photos from the remote screen.

3. *Sketching.* Collaborative sketching of a simple building on a shared sketching canvas on the remote screen which required different brushes (selected and configured on the mobile phone). Users also performed text entry on the phone and placing the created text on the sketching canvas for labeling the sketched items.

4. *Completing a form.* Filling in a form on the remote display which included interacting with different kinds of widgets for data input via the mobile phone.

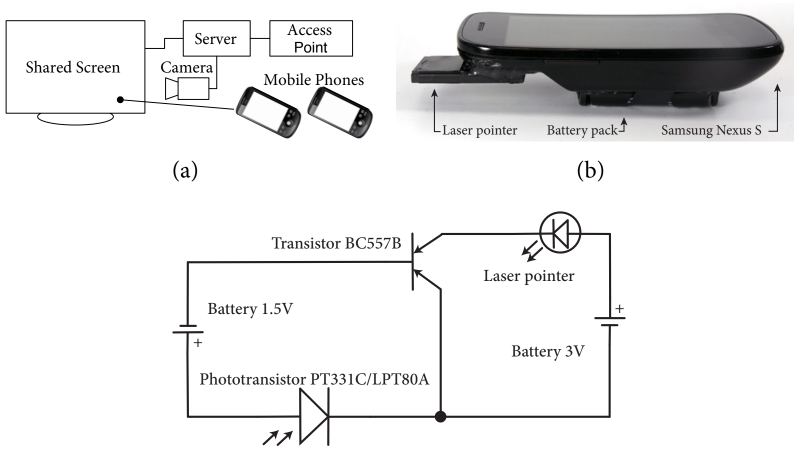
5. *Context Menu.* Renaming, copying, and deleting files displayed on the remote screen by using a proximal context menu on the mobile phone.

6. *Playing.* Playing a simple Pong-like game involving two users who would steer the position and angle of a racket by pointing to the screen to control the translation and rotating the phone to control the angle.

APPARATUS. The main components of the apparatus system are mobile phones as pointing devices and a remote display that is connected to a server computer (6.92(a)). The mobile devices are connected to the server through WLAN for the exchange of data and commands.

In order to achieve high-level pointing accuracy and low latency, the approach of using laser pointers and camera-based tracking for the pointing task was adopted (as previously demonstrated by [181, 193]). That is, a camera is used to capture the remote display. If a user points to the remote screen, the laser pointer creates a bright point on the image which can be extracted through simple image processing. The location of the laser pointer is used to control the user's pointing cursor that is displayed on the remote screen. For distinguishing different laser pointers (and thus different users), a color filter is applied during the image processing step. This tracking approach requires only one calibration sequence before using the system until the camera or display setup is changed (i.e., if they are moved).

A standard mobile phone (a Samsung Nexus S, running Android 2.3) was augmented with a laser-pointing module which can be controlled via the mobile phone's software stack (see Figure 6.92(b)). The laser pointer is turned on and off via a simple circuit with a photodiode that is placed right in front of the flash light LED of the mobile phone (see Figure 6.92(c)). On the Android platform [98], this component can be controlled via a given interface provided through the SDK.



(a) (b)

(c)

Figure 92: (a): System components schema. (b): Mobile phone prototype with attached laser pointer. (c) The circuit used for controlling the laster pointer via the built-in photo flash diode.

Based on the system prototype, a number of mobile applications for the mobile phone and a corresponding application for the remote screen were developed which implemented all functionalities that were required for the evaluation tasks. To allow participants to experience several possibilities of the PointerPhone interaction, the applications provide different options to perform any single action. For instance, users can make selections distally on the remote display, as well as proximally on the phone display. For the sake of consistency, the activation of the pointing (turning on the laser pointer) is the same in all applications. Short tapping on the hardware button on the bottom right activates permanent pointing. Holding the button activates the pointing until its release.

PARTICIPANTS. 14 participants (7 female) were recruited aged between 20 and 31 (M = 26). Of these, 10 were students (diverse backgrounds) and 4 were employees. After the study, they were rewarded for their effort with 10 EUR.

6.1.4 *Observations and Design Implications*

In the following, the section discusses the results of the feedback sessions and, where possible, findings are summarized as a set of design implications that support application designers when considering pointing interactions for their work.

1. *One- and two-handed interaction.* During the usage of the apparatus with the different applications it was observed that participants switched between using one or two hands to hold the mobile phone depending on the task. For instance, during the sketching task, 7 of the 14 participants held the phone with two hands. An additional 4 participants held the phone in their right hand and supported it with the left. Only 3 participants used one hand to hold the phone and point during the sketching task. In contrast, during the data sharing task, 13 participants used a single hand to hold the phone, of whom 5 used the thumb of the same hand and 8 used the index finger of their other hand to interact with the phone interface. Accordingly, the manner in which users choose to hold the phone depends on the given task. For tasks that require precise pointing input (e.g., sketching), users tend to use two hands. Tasks that require less precise pointing, however, lead users to prefer one-handed operation. Hence, interfaces for the hand-held pointing device should encourage two-handed interaction when designed for tasks that require precise pointing. Inversely, interfaces for simple tasks should be adapted to one-handed usage.

2. *Selecting targets.* During the browsing task, participants could select targets such as links either distally on the remote screen or proximally on the phone's display. It was observed that participants preferred to select large targets distally while small targets (e.g., text links) led to a preference to select proximally. This concurs with the findings of Rashid et al. who investigated distal and proximal target selection [208]. Further, it was observed that distal selection forced users to switch their focus from the remote display to the phone to ensure hitting the correct button. Accordingly, user interfaces for proximal interaction should be designed to allow users to keep their focus on the remote display — for instance, through the use of hardware buttons on the phone if available or a single large software button, so that the user does not have to look at the pointing device.

3. *Navigating.* When users selected an area of the remote screen that should be displayed proximal on the phone, several participants tried to interact with the proximal representation like they were used to interact with smartphone web browsers that allow navigation through dragging and zooming in and out. However, this applies only to small adjustments. Participants expressed that they can select easily an area through pointing to it which is more comfortable than navigating on the phone screen.

4. *Providing output and feedback.* Several times users would focus on the remote display while they select a target there, yet they were not aware of the resulting change on the mobile phone. Inversely, this phenomenon was also observed when a user focused on the phone and performed an action which resulted in an event on the remote display. Hence, it is essential to provide cues (e.g., audio feedback or vibration) which notify users regarding resulting actions.

   Several participants raised the general point that the remote display should not be used to display user-specific information that is not intended for all users. For instance, when interacting with a web page, users could display tool tip information through pointing at an item for a few seconds. These should be displayed on the personal device.

5. *Controlling pointing actions.* Participants had to manually enable or disable the pointing mode through toggling a button (i.e., turning on and off the attached laser pointer). However, when a participant was engaged with performing a task, they forgot to turn the pointer on which resulted in confusion. Hence, if application work-flows allow to anticipate when pointing is required, the system should automatically do so. For instance, when pointing to a web page on the remote display in order to transfer a clipping to the phone for

further inspection, the pointing should be disabled automatically to prevent unintended updates.

All users indicated that they liked that they could see a cursor where they were pointing at. This indicated that alternative implementations (e.g., inertial sensing [196]) should provide a visual cursor throughout the interaction.

6.1.5 *Discussion of Pointing-Based Interaction*

This work investigated options for mediated interaction when using a mobile phone as a pointing device for interaction with a remote display. Related work on pointing interaction, the use of mobile phones for controlling content on public and shared remote displays, as well as collaboration provides a large body of research on interaction techniques for specific contexts. Using the mobile phone as a personal pointing device provides not only powerful computing and sensing technologies but also the user's personal data context such as photos, calendars, and messages. These rich options for interaction are likely to attract the design of applications in the future. Hence, application designers considering PointerPhone applications should be supported through a design space and corresponding guidelines for using aspects from the design space.

Key challenge for pointing interaction with mobile phones: technology and infrastructure.

Different options exist regarding possible implementations for the application of phone pointing-based interaction outside the laboratory setting. Using inertial sensing to determine the phone's pointing direction is a promising approach, as most available smart phones are equipped with the required sensors (i.e., accelerometer and gyroscope). However, each time a user intends to use such a system, the user needs to calibrate their phone to determine the pointing direction. Moreover, during the interaction the calibration may have to be repeated to maintain the pointing accuracy. Alternatively, direct pointing using a laser pointer can be easily added to standard smart phones. For instance, laser pointers can be plugged into the audio jack of the phone [262] and operated through an application. This approach would require the remote screen to be equipped with camera tracking. As an alternative, the laser pointer could be based on infrared light which can be sensed by specific screens (e.g., Microsoft PixelSense [166])

The presented design space provides building blocks for the design of PointerPhone like applications.

The investigation of the design space provides the list of basic attributes and characteristics. Furthermore, we provide a classification of low-level interaction options regarding input and output options, widget-level interaction techniques, and high-level interaction techniques and applications. This classification into three levels of abstraction is not fixed and can be extended as it includes only selected examples for applications, and technological features for input are likely to be extended. These techniques can be used as building blocks for complex applications.

Finally, this work showed how several interaction techniques can be integrated into a presentation application for a collaborative meeting context. A prototype implementation of the system based on mobile phones combined with laser pointers was used to realize a number of applications that were used for a qualitative study. Results from the study support a collection of five design recommendations that should be considered for the design of pointing-based applications.

6.2 INTERACTION IN A CONTINUOUS DISPLAY SPACE

Parts of this section (early versions of the implementation and study execution) draw on results of theses supervised by the author:

- "Novel Applications for Gesture-Based Interaction with Entertainment Systems". Katrin Osswald. Bachelor's Thesis. 2013.
- "Leveraging Television Experience through Projected Touch Interaction". Dennis Wolf, Bachelor's Thesis. 2013.

Ever since television became the main source for entertainment and media in domestic environments the static setup based on one fixed screen required all other things (including interiors and people) to be arranged around it [170, 249]. More recently, this traditional setup is increasingly often supplemented by users taking advantage of *second screens* (e.g., [60, 274]). For instance, smartphones or tablet devices allow users to perform secondary tasks while the shared content on the main screen remains available for all users. For users, these second screens yield a number of advantages including social connectivity and sharing the experience with remote friends as well as quick access to additional background information supplementing the primary screen content [68, 104]. In particular *smart TVs* promise users to benefit from interconnected personal second screens and a shared primary screen which aims to support sharing content from the personal device with other users (e.g., [223]). For instance, through transferring photos from a smartphone to the primary screen.

Use of second screens potentially isolates *users, contradicting the goal of* pervasive interaction spaces.

This section investigates if and how users can take advantage of second screens combined with smart TVs in their domestic environments. Observations and design considerations indicate that this setting of using personal devices as the only second screens has two inherent major disadvantages.

- First, while focusing on their second screen device, users bear the risk to be isolated from co-located friends and the events and content of the primary screen.
- Second, it is apparently cumbersome to transfer data from a second screen device to the shared primary screen. As an effect, users rather pass around the mobile devices. This however, increases challenges raised through the limited display space available.

Based on these considerations, requirements and user needs were derived which are used to inform the design and implementation of a *continuous projected display space* system, called *smarTVision*. It enables users to create any number of second screens and placing them in their environment in addition to their existing devices (see Figure 93). *smarTVision* provides a flexible input and output space that enables diverse forms of

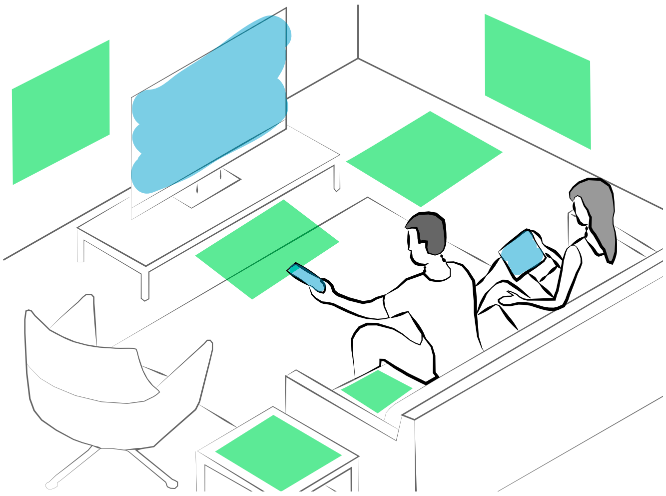


Figure 93: The continuous projected display space augments the existing devices with second screens that can be placed anywhere in the users' environment.

interactions. In particular, interaction over a physical distance is explored regarding different spatial settings including mediated contact-based interaction using touch, as well as contactless interaction based on mid-air gestures and remote control devices.

6.2.1 *Background of Second Screen and Distant Interaction*

This work is influenced by a large body of previous research on second screen applications and usage, everywhere displays and interactive surfaces, interaction techniques, as well as technological foundations and frameworks.

The concept of second screen applications.

Second screens setups allow users to perform tasks parallel to other activities or other users without interfering with other users. Early work by Myers et al. present first applications for second screen setups that facilitate interaction with distant displays and collaborative activities [180, 183]. Further work investigated how personal second screens support collaborative planing task on a primary interactive surface [8, 241, 261]. Also in the context of television second screens have been used to provide additional information that supplements television content [36, 60] and supports communication with the users' social network [37]. For instance, Robertson et al. used seconds screens to control media content displayed on a shared display [218]. More recently, a considerable amount of work investigated in large field studies how multiple devices are used for media play back [69] and what usage patterns of utilizing multiple devices simultaneously emerge through second screens [68]. Tsekleves et al. showed that second screen usage is not only limited to television but applies to all kinds of device classes (i.e., PCs, game console, personal media players etc.) [267] Vanettenhoven and Geerts observed that the use of specific social media is related to whether it is related to the television content or not (e.g., use of Twitter is likely to be related, while Facebook rather not related) [274]. Further motivations (e.g., desire to feel connected to a larger community) for using social media while watching television were investigated by Schirra et al. [227].

Work considering augmented TV.

Also the surrounding and immediate environment of television setups have been investigated as options for extending the television experience. For instance, Harboe et al. added an ambient display (i.e., ambient orb) to provide remote user presence information along with light weight messaging options [106]. With IllumiRoom, Jones et al. present projections to augment the immediate surrounding of a television to create a highly immersive experience [130]. Projections have also been used to render additional user interfaces next to a television set [276], next to a laptop computer (Bonfire) [133] and next to a mobile phone [302].

The vision of everywhere displays.

The general underlying vision of *everywhere displays* has a long history comprising most diverse approaches. To name but a few, pioneering work by Wellner, the *DigitalDesk* [290, 291] uses projection to augment a desk with digital content. Underkoffler et al. present the *I/O Bulb* an early approach for input and output in a pervasive information space [273]. Several approaches actuated the projected displays using motorized projectors that allow to freely position displays in the environment using a motorized projector [58, 205, 301]. In order to provide perspectively corrected projection such as demonstrated by Bimber et al. [44], different systems incorporate depth-cameras to reconstruct environment's geometry [301]. Also the *Luminar* system incorporates physical movement of a projector-camera-system, shaped like a *Angle Poise* lamp, to place projected displays on a desktop [146]. Cotting et al. investigated how projected display can be blended in the environment in different shapes using amorph *bubbles* [67]. Further, the the whole floor of a room can be used as a display [50] which enables versatile foot-based interaction options [233].

In addition, much work has been invested in researching how everywhere displays can be provided in mobile contexts. For instance user worn systems, Mistry et al. present *Sixth Sense* which projects on objects in the user's environment e.g., a newspaper [171]. *OmniTouch* uses the user's body as projection screen [111] and *AMP-D* provides a continuous projected output space ranging from hand- to floor projections [12]. Also handheld projector devices are used to enable everywhere displays (e.g., [295]).

Essential for all approaches in this field is the ability of the user to interact with the system. Accordingly, a large body of work exists regarding interaction techniques based on different technologies. For instance, Fails and Olsen present *Light Widgets* which allow interaction in everyday environments based on optical tracking of *skin colored* objects [85]. More recently, depth-cameras have been used as touch-sensor (e.g., [298, 299]. In addition, gestural interaction with television setups were investigated [277] as well as pointing-based interactions [48, 3, 275]. Technologies and interaction techniques have been also encapsulated as toolkits such as the *Ubidisplays* toolkit by Hardy [107, 108] as well as the *Worldkit* by Xiao et al. [304]

In contrast to this previous work, the *smarTVision* approach abstracts from the traditional setup of one central and main display device. Using a single television set as primary screen is most likely a legacy originated from the limited technological hardware possibilities. *smarTVision* aims to use all kinds of surfaces in the environment to display primary and secondary screens.

6.2.2 *Concept of* smarTVision

This section details how the concept of *smarTVision* was designed that aims for supporting interaction in a pervasive interaction space with different spatial constellations between users and pervasive displays. Essentially, the concept comprises output options (for visualizing content) and input options (supporting different possibilities for interaction).

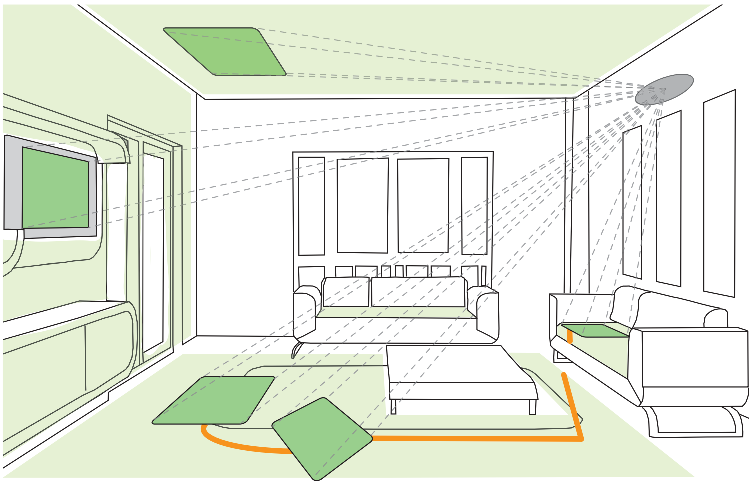


Figure 94: The continuous projected display space allows second screens that can be placed anywhere (i.e., floor, walls, and ceiling) in the users' environment. Screens can be logically *grouped* using visual links.

Visualization options: second screens, visual links, and visual indicators.

As illustrated in Figure 94, the conceptual display space of *smarTVision* spans across the ceiling, the wall, and the floor. Within this space, any number of second screens can be freely placed to provide information displays in arbitrary prominent places. That is, for instance, second screens placed on the ceiling may be suitable for content which that is only of limited interest to users.

In addition to projected second screens, *visual links* can illustrate the coherence of multiple distributed second screens (see Figure 94, orange line). Such links support users to easily understand, for instance, which social media feed is connected to which television content. This is in particular the case, when users would watch multiple channels simultaneously.

A third visualization option of *smarTVision* are *visual indicators* that render highlights on physical objects in the user's environment. For instance, in a quiz game played by several users, results of the users' guesses could be visualized by projecting such *indicators* onto the players.

Interaction Options: direct touch, mid-air gestures, and remote control.

With *smarTVision* allowing users to place second screens at any position in their environment, several spatial constellations arise between user and interface, the user wishes to interact with. Due to this flexibility, interaction options need to support to access and interact with interfaces and displays across different distances. These spatial constellations can be categorized in two main categories: *within reach* and *out of reach*. This reflects again the anthropomorphic classification model used in this thesis.

(I) INTERFACE WITHIN REACH. In case the second screen that displays the interface the user is intending to interact with, is in the user's immediate vicinity (e.g., on the couch table) direct touch-based interaction is an option provided in the *smarTVision* concept.

(II) INTERFACE OUT OF REACH. In case the second screen is placed at a remote position relative to the user, distant interaction techniques are required. Hence, the *smarTVision* concept includes three interaction options: using *remote control*, a *proxy interface*, and *hand gestures* in mid-air.

The first option of using (mediated) interaction trough a remote control device (e.g., smartphone) allows users to remotely control content on a distant second screen. A second option is to use *proxy interfaces* (projected second screens) which are places in the immediate vicinity of the user, which offer similar interaction options as a remote control device. However, no additional hardware is required and touch-based interaction offers differentiated control options (e.g., touch, long touch, swipe etc.). A third option supported in the *smarTVision* concept is using mid-air gestures in order to interact with second screens in the user's environment. For instance, in case a photo album is displayed at a remote second screen.

6.2.3 *Prototype Implementation*

In order to investigate the *smarTVision* concept more in depth, a prototype system was designed and implemented. In the following, the hardware setup and the software architecture are illustrated.

6.2.3.1 *Hardware Setup*

The hardware of the prototype setup comprises a stage lighting rig that is mounted on two tripods (see Figure 6.95(a)). This rig spans across a couch and a couch table (which are typical pieces of furniture in most living rooms). In order to render projected second screens, three BenQ W1080ST full HD projectors are mounted to the rig (see Figure 6.95(b)). Two of them are facing the floor and one projector is responsible for projecting on the wall, which is facing the user sitting on the couch. A fourth projector is placed in front of the couch table facing the ceiling in order to provide the ceiling display.


(a) (b)

Figure 95: The prototype hardware setup: (a) a traverse mounted on two tripods spans across the room, holding a depth camera and projectors. (b) Three projectors are attached: two illuminating the floor and one for the wall display.

These projectors yield a display space which allows to render any visual content (i.e., TV content or interfaces) that comprises the couch, the couch table, the floor around and in front of the table, the wall, and the ceiling (see Figure 96).

In addition to the projectors, a Microsoft Kinect depth camera is attached to a pole that is mounted on the rig (see Figure 6.95(a)). The depth camera is facing the floor and in particular the area of the couch and couch table in order to support touch-based interaction on these. Finally, a Leap Motion sensor is attached to the border of the couch table, which is used to support mid-air hand-gestures.

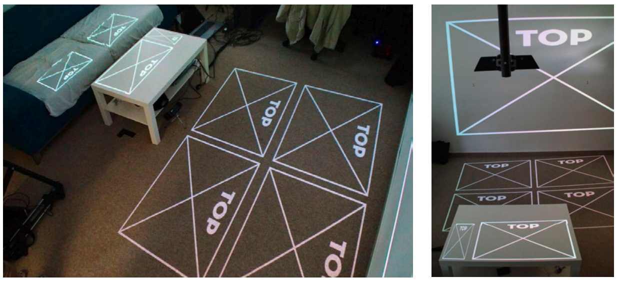

(a) (b)

Figure 96: The projected display space of the prototype implementation.

6.2.3.2 *Software Architecture*

The software implementation is based on the UbiDisplays *framework [107].*

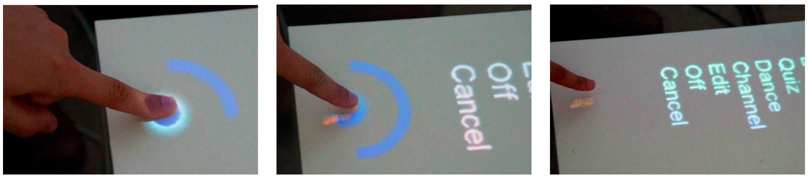
The software architecture draws on the *UbiDisplays* framework by Hardy [107] and includes custom modifications to support the distribution of multiple second screen applications. This framework offers, after an initial calibration step, the possibility to define dedicated areas for placing *surfaces* at any position. Such surfaces allow to display HTML and Java script based content. The framework also provides out of the box touch-detection (based on a depth-camera) and delegation of touch events to the surfaces where the events are injected for interaction purposes.

In order to manage complex applications, the *smarTVision* implementation includes also a central server for coordinating the internal application logic and corresponding states (in particular important if several surfaces access a shared data model or timing critical content). The server written in Node.js [132].

6.2.4 *Example Applications*

In order to explore and to illustrate the benefits of the *smarTVision* concepts, several demo applications that draw on this conceptual basis were designed and implemented. This offered examples include on the one hand basic applications, such as *main menu* and *second screen placement widget*. On the other hand, three highly content specific applications are detailed that illustrate how users can benefit from the *smarTVision* concepts.

MAIN MENU CONTROL In order to provide one central entry point for allowing users to initiate interaction (e.g., starting an application, selecting television channel), a main menu control was designed. *smarTVision* constantly displays a mundane slightly gleaming button on the couch table. The location is fix and chosen to allow direct access of the user while remaining seated on the couch.

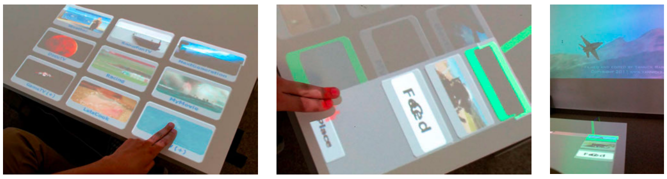


(a) (b) (c)

Figure 97: The user performs a long touch on a permanently present button (a); the count down is visualized (b) before the menu is finally opened (c).

In order to activate the main menu, the user performs a long touch on the corresponding button (see Figure 6.97(a)). The time progress is illustrated by an animation indicating how much longer the user has to keep the finger on the button (see figure 6.97(b)). This design prevents accidental opening of the main menu. Finally, the menu is set up and offers the user to select (via touch) from a list of options and applications.

SECOND SCREEN MANAGER With *smarTVision* extending and augmenting the traditional television setup, the way how users can coordinate second screens that provide different television content is an essential aspect; as it is likely to be used often (e.g., for selecting a television channel) and has a major impact on whether users are adopting to use second screens as supported through *smarTVision*.



(a) (b) (c)

Figure 98: The second screen manger interface.

By selecting the corresponding option from the main menu, the user opens the screen manager. Initially, a subset of available television channels is presented as a tile overview (see Figure 6.98(a)). By selecting one channel, this channel is assigned to the main screen (by default centered on the wall facing the users). The corresponding preview on the couch table is highlighted with a green frame to indicate which view is being displayed on the main screen. Further, a *visual link* (i.e., a straight line) connects the preview and the main screen (see Figure 6.98(b) and 6.98(c)).

In case, the television content is provided in several perspectives from different cameras, a sub menu opens when selecting a channel from the main overview. For instance, sports events such as car racing are already broadcast in such a way that users can select their favorite camera view. In the case of *smarTVision*, the user can select any number of interesting camera views from a list (see Figure 6.98(b)). Not only different camera views may be offered in this overview list, but also related content such as social media feeds (e.g., Twitter).

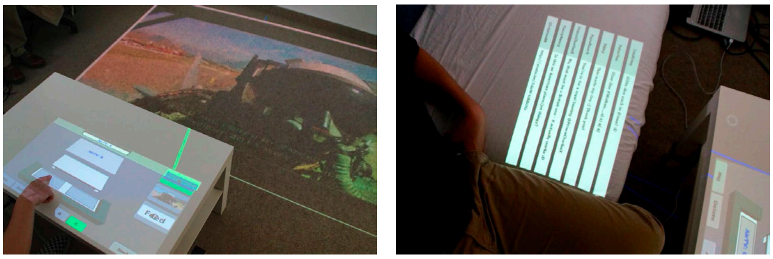

(a) (b)

Figure 99: The manager allows placing second screen e.g., on the floor (a secondary camera perspective) (a) or on the couch (a social media message feed) (b) next to the user.

Users require effective means for managing where such different camera views and other contents are displayed. Therefore, the second screen manager provides a straightforward interface which allows users to place, move, or delete second screens (see Figure 6.99(a)). This interface provides a schematic representation of the environment and offers predefined places where second screens should be placed (e.g., a social media message feed next to the user on the couch; see Figure 6.99(b)). This interface, displayed directly in front of the user allows to interact with remote second screens by mediating the interaction.

AMBIENT FLOOR DISPLAY Since the *smarTVision* design includes the whole floor, wall, and ceiling as potential display space, a relatively large space can be turned into an information display. However, from the user's point of view only selected areas make sense to be turned into second screens. Otherwise using all space for displaying specific information bears the risk of *information overload* leading potentially to confusion and stress. Nevertheless, the large display space can be used for displaying subtle and ambient content as first demonstrated by Jones et al. [130].

smarTVision allows to use the whole display space as ambient display which supports to create a highly immersive experience. For instance, television content presented on the main screen can be augmented by displaying extending content throughout the room. Figure 6.100(a) shows a star field displayed on the floor and around the main screen which aims for creating an illusion of moving through space along a space craft shown on the main screen. Figure 6.100(b) displays the surface of an ocean while a ship is displayed on the main screen.

While the concept of extending the television content around the main screen has been investigated previously, *smarTVision* is the first approach that allows to include the whole (living) room around the user as display space, which is likely to create a deeper immersion than previous approaches.

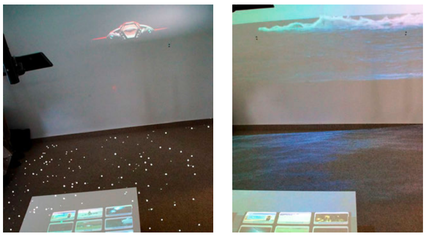
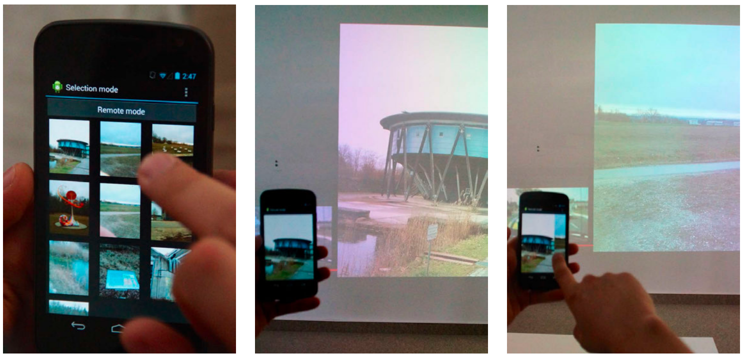

(a) (b)

Figure 100: Using the whole floor as ambient display.

SHARING MOBILE PHONE CONTENT One key criterion while designing *smarTVision* was that this concept should blend into the existing device infrastructure. That is, already present devices should rather be included than replaced. Therefore, *smarTVision* was designed to include and connect also personal devices such as smartphones and tablet computers which are often used as second screen devices.



(a) (b) (c)

Figure 101: Using the phone as remote control.

Such personal devices are used to store large amounts of different kinds of data (e.g., images, videos, URL bookmarks etc.). In order to share such content with other users within the context of the *smarTVision* setup, users connect their mobile phone, which runs a *smarTVision* client app. Once connected, users can for instance, select a photograph and display it on a large shared second screen (see Figure 6.101(a) and (b)). The location where the content is going to be displayed can be predefined through a settings menu on the mobile client app. Further, users can browse through whole collections of files such as photo albums by performing swipe gestures on the phone to flip through the data (see Figure 6.101(c)).

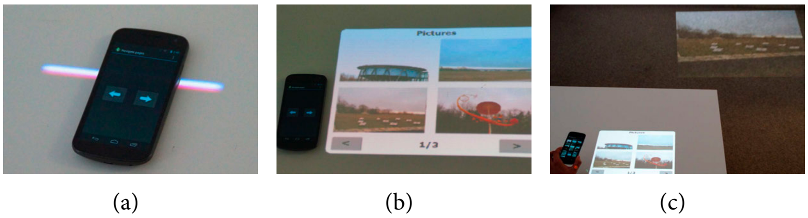
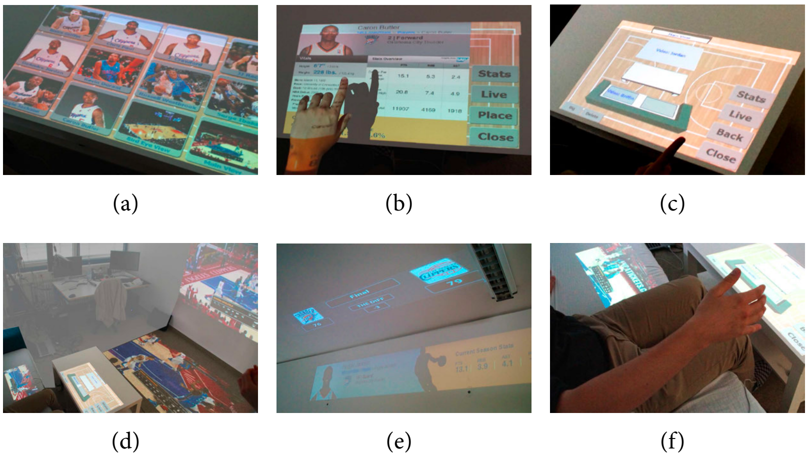

(a) (b) (c)

Figure 102: Using the phone as remote control with external display.

In addition, users can place their mobile device on the couch table, where it gets first detected (see Figure 6.102(a)), which initiates an external interface (c.f., [4]); the photo album tile view is displayed on the couch table (see Figure 6.102(b)). By selecting an image tile in the external interface, the image is displayed on a predefined screen (see Figure 6.102(c)).

SPORTS PLAY APPLICATION The first content specific example application supports following a basketball game broadcast. This application aims for providing most different perspectives and views (on different players), as well as different content types (e.g., game statistics, social media etc.) in order to allow users to follow all kinds of aspects that matter during such complex game play.

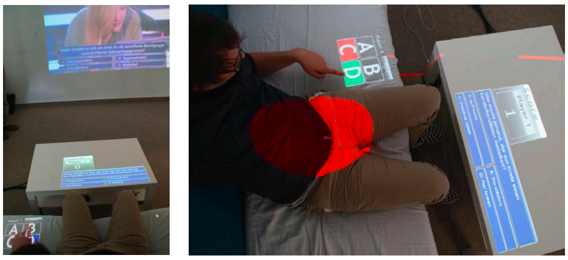

(a) (b) (c)

(d) (e) (f)

Figure 103: Second screen application supporting the experience of sports games (here basketball)

A central menu serves as a player overview that is displayed on the couch table (see Figure 6.103(a)). By selecting a player via touch, a detailed player view is opened (see (b)). Here, users can select to open and place (see (c)) the player specific camera view (which constantly follows this particular player) using the screen manager. This allows users to arrange any number of different views in their environment such as camera views of specific players, an overview camera (see (d)), and game statistics for instance at the ceiling (see (e)). Users can easily browse through different statistics by using hand gestures to *swipe* to the next page (see (f)).

QUIZ APPLICATION Another example application supports users to play along while watching a quiz show. This application can be played either by one or two players in the current implementation. Users are provided with a second screen that contains the answer options (see Figure 6.104(a)). Next to the user on the couch, a small selection interface is projected which allows users to make a selection which answer option they think is correct. By the time, the answer is revealed in the quiz show, corresponding feedback is provided through a visual indicator, which illuminates the user with either red (wrong answer) or green light (correct answer) (see Figure 6.104(b)).



(a) (b)

Figure 104: The quiz game application.

DOCUMENTARY APPLICATION The last example application focusing on documentary content seeks to illustrate the potential of *smarTVision* to support interactive television. This documentary application allows users to watch a documentary as with a conventional television setup. However, at times, the system provides visual queues (i.e., an *info* icon) that additional content is available that the user could explore. Whenever such an icon appears on the main screen, a play button is displayed right next to the user (see Figure 6.105(a)). If the user presses this button, the additional content is started to be played on a second screen (e.g., the couch table), as illustrated in Figure 6.105(b). While the additional content is played, the content on the main screen is paused in order to prevent confusion. Through this option of providing logical links to additional information, *smarTVision* supports exploring topics according to the users' level of interest.

(a) (b)

Figure 105: An interactive documentary application.

6.2.5 *Initial Evaluation & User Feedback*

In order to gather first insights regarding how users appreciate such a system, an initial users study was performed that followed an exploratory approach. Due to the absence of comparable systems and approaches no direct comparison could be performed. Therefore, the goal of the this study was to collect qualitative feedback from users how they subjectively assess the concept and in particular the prototype implementation of the *smarTVision* system. In addition, the goal of this initial user study was to measure the robustness of the prototype implementation which potentially can lead to specific aspects that require special attention in future development cycles. Regarding the robustness, in particular the ratio of correctly detected touch-input events is to consider.

METHODOLOGY FOR EXPLORATORY EVALUATION. The methodology that was adopted for this study was to confront participants with the *smarTVision* system, which they used to test several example applications. During the interaction with the given applications, participants were video recorded and these logs were annotated and analyzed afterwards. Further, questionnaires regarding the subjective assessment were to fill in by the participants.

PRACTICAL TASKS. Participants were given practical tasks based on two applications: the *quiz* and the *interactive documentary* application. Using the quiz application, participants were asked to (1) initially place the single player interface so that is was comfortably to use. Then, (2) participants were asked to answer three quiz questions which required selecting an answer option each time. Finally, (3) they were asked to place *display interface* on the floor in front of themselves.

Using the *documentary application*, participants were required to answer three questions regarding the documentary content (in that case, a documentary about astronomy), which required them to follow several *links* to additional content.

PARTICIPANTS In total, we recruited 12 participants (five female), aged between 22 and 34 years (M=26). 10 participants were students, one graduate student, and one employee. 10 of the participants had a television set at home. The others used a computer for watching television content.

Regarding their television consume, 7 participants reported to watch on average about two hours per day. Two participants stated to watch three or more hours every day, and the others stated that they do not watch regular television at all but rather consume selected movies and shows for instance, via DVD.

RESULTS & OBSERVATIONS In terms of touch accuracy, three different states can be distinguished:

- *Input detected correctly.* 73%. A touch input event was detected correctly and resulted in the intended action.
- *Input not recognized.* 12%. A touch input event was not detected at all.
- *Input misinterpreted.* 15%. A touch input event was detected but resulted in the wrong action, such as selecting wrong button next to the intended one.

Accuracy of touch-detection requires improvement (only 72 % correctly detected events). Alternative technologies (i.e., touch sensitive surfaces) should be further explored.

This relatively low touch accuracy indicates a large impact of the subjective user satisfaction and assessment of such an interactive system. Nevertheless, the question appears why this low detection performance occurred. Looking at different targets (i.e., different buttons such as *Main Menu*, or *Back*) it shows that depending on the position in space, relative to the Kinect depth camera, which is used to implement the touch detection, the sensing accuracy varies. That is, touch targets that are close to the optical center of the Kinect camera, yield a much larger accuracy than targets in the periphery. One reason for this effect is the larger spatial distance between depth-camera and target. Another reason is that the user's hand posture differs greatly depending on the location of the touch target. In summary one can say that a depth camera-based approach for detecting touch does not yield an acceptable detection accuracy. One approach for improving this aspect of the *smarTVision* implementation would be using touch sensors that are integrated into the surfaces in the *smarTVision* environment.

Qualitative feedback. By means of a post-hoc questionnaire, which was completed after the hands-on experience with the *smarTVision* prototype, a subjective assessment regarding several aspects was collected. Due to the exploratory character of this initial evaluation, only the most relevant results are reported.

Regarding the interface clarity and overview, participants rated the *smarTVision* system mildly positive (see Figure 106). For instance, 10 participants rated it regarding the statement *"I always had a good overview over the distributed second screens"* with full or large agreement. Regarding the aspects *readability* and *antithetical appeal* the ratings were more heterogeneous. Regarding the last two statements (*"Second screens blend well into the environment"* and *"I think projected second screens are convenient"*) illustrated in Figure 106, the rating is again tending towards a mildly positive rating, indicating that projected second screens are an acceptable augmentation of the environment, which yield some convenience to the user.

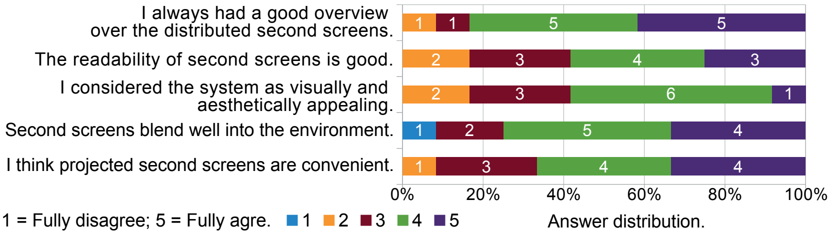


Figure 106: Subjective rating results of interface aspects.

Regarding the interaction with the system, participants reported that *placing second screens* was straightforward (11 participants selected *fully agree* or *agree*). Also regarding the *usefulness*, a majority tended towards a positive rating. Similar, *color-based feedback* was mostly appreciated by user which is reflected in a mainly positive rating. The rating of the statement that *"Touch-input works reliable"*, the ratings were slightly less positive (including only one rating of the negative spectrum of the rating scale, i.e., one '2'). More interestingly, the shadow casted by the user's own hand and fingers was rated mostly heterogeneous, indicating that this aspect is mostly effected by personal preference. Overall however, the majority (10 participants) rated the *smarTVision* prototype as *"easy to use"*, which points to a general low complexity of interaction required in the given tasks during the study.

6.2.6 *Discussion of Interaction in a Continuous Display Space.*

Departing from the observation that users often use so called second screens (e.g., smartphones, tablet, or laptop computers) while following (with differing levels of involvement) television content, the concept of *smarTVision* was developed. The design is mainly informed by the assumption that users are willing to use second screens that are not only

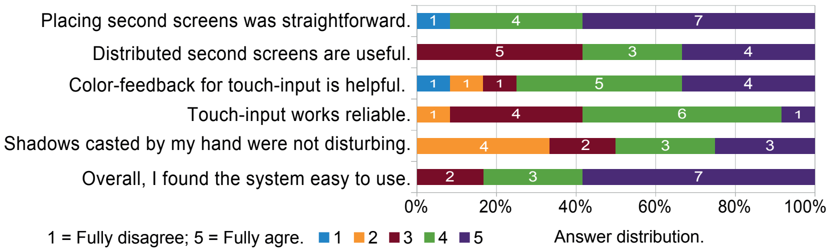


Figure 107: Subjective rating results of interaction provided by *smarTVision*.

handheld and thus, rather private displays. For instance, for sharing content with others, users can benefit from second screen that are placed in such a way that it can be viewed by multiple users. Further, the design was influenced by the hypothesis that users would like to use several second screens along the content shown on a primary screen.

Based on these considerations, a conceptual design for *smarTVision* was created. It includes *input* or *interaction* options and *output* or *visualization* options. Due to the heterogeneous spatial arrangements that are possible when using multiple distributed projected second screens, a relatively large range of spatial constellations needs to be covered. That is, contact-based interaction (i.e., touch) in the immediate vicinity of the user is considered but also mediated interaction for controlling second screens that are out of reach of the user. Here, in the context of *smarTVision*, two different forms of mediated interaction were considered: (1) mediated interaction through a personal mobile device and (2) mediated interaction based on a projected interface. The latter allows to change its size, the spatial appearance, and depending on the particular application context can be a *shared* or a personal / individual interface for mediated interaction. On the output and visualization side *smarTVision* offers a high level of flexibility allowing to render any visual content on the room's floor, wall, and ceiling. In particular, projected second screens can be freely placed. Visual links can be used to illustrate logically connected second screens in order to group them. And finally, visual indicators allow to highlight physical objects in the environment.

smarTVision *demonstrates that mediated interaction can be used in variety of different forms integrated into one interaction space.*

The presented example applications demonstrate on the one hand that *smarTVision* offers diverse opportunities to design applications that are uniquely possible based on the *smarTVision* concept. For instance, placing several camera views related to one sports event is not possible with previously existing approaches for second screen applications. However, this depends also heavily on the spatial parameters given in each context. That is, in the case of the presented prototype system a living room was partially mimicked by placing a couch and a table in the laboratory. In realistic environments it is likely that more pieces of furniture are available raising the question how much space would be available for projected second screens in realistic settings. While this remains an open question, one can argue that even in crowded places such a concept as *smarTVision* can be applied since projection also on larger pieces of furniture is possible (as demonstrated e.g., with the *quiz application* that provides an interface on the couch next to the user).

The initial user study revealed in particular that the technical implementation of *smarTVision* leaves room for improvements. One aspect several participants pointed out during the study is the *readability* for instance, of text displayed in projected second screens. The readability is mainly influenced by the limited resolution of the projectors that were used for the prototype. These feature a full high definition resolution (i.e., 1920 × 1080 px) which however, yields a relatively low *dots per inch* ratio considering the space covered by the projection. Further, the color of the background is not compensated which results in color aberrations. One possible solution for this issue was presented by Bimber et al. with the SmartProjector system that enables real-time radiometric compensation of projection screen particularities [44]. Also, the geometrical particularities are not properly dealt with. That is, the *smarTVision* system assumes that all surfaces are flat and perfectly horizontal that are used for projection from above. This is, however, not the case as for example the surface of the couch is quickly changing depending on how many users are sitting on it. On possibility to solve this issue is to use Kinect Fusion approach [126, 167] for reconstructing the geometry of physical objects in the environment which would allow to pre-warp images so that they appear correctly in the projection.

Another aspect that was revealed by the user study the level of touch-event detection accuracy. Even though the measured performance of 74% correctly identified touch-events is relatively low, participants were not as negative when rating subjectively the accuracy. One aspect that could explain this mild judgment is that the overall amount of time spend with performing touch-input was relatively short compared with the complete study session. Thus, negative impact on this judgment is low as only a comparably low number of touch inputs had to be performed. Hence, users might be less critical if they had to repeat a touch-input event once or twice. Nevertheless, it would be interesting to explore alternative implementations for instance, based on several depth-cameras that can compensate perspective and occlusions.

Future directions for further investigating these novel interaction possibilities that were presented in this section, should aim for long-term evaluation and observation of prototypes deployed in real domestic environments in order to gather more insights on user needs and requirements.

Part

FINDINGS & CONCLUSIONS

7

DESIGN PATTERNS & RECOMMENDATIONS FOR APPLICATIONS BASED ON MOBILE MEDIATED INTERACTION

The goal of this chapter is to provide a set of design patterns which are based on the insights and observations that were collected within the scope of the research presented in the previous chapters. The primary motivation is to provide a generalized understanding of the research together with its overall value so that an audience which extends beyond the field of HCI can derive benefit from it. Particular insights which are presented as common in the research community and field of HCI may be of limited value, for instance, for application or interaction designers as these do not suggest specific actions or solutions for problems beyond a given scope. For their work, more practical and less detail-oriented summarizations are more beneficial. This means that a higher level of abstraction increases the number of cases in which such an insight can be used to inform design decisions thus increasing the general applicability. For instance, there are several examples for *design guidelines* or *style guides* that aim to provide help in solving common design or interaction challenges (e.g., see [30, 99]).

In addition to design guidelines, there are different approaches for formalizing generalized insights. For instance, *rules* and *principles* are rather general while on the other end of the spectrum *standards* provide a highly detailed form of documenting best practices and general solutions to given design or interaction problems. In order to support easy access to such generalized and abstracted summarizations, a clear and well defined structure is required. Interaction and design *patterns* offer a formalized high-level format which allows the summarization of research observations and insights in a general way, for instance, for supporting the design process.

This chapter first provides an overview of different formalization approaches and details, in particular *design and interaction patterns*. This approach of formalization has been chosen to provide compact summaries of the insights collected in the research conducted within this thesis. Again, the anthropomorphic classification framework is used to structure these patterns. Finally, the chapter offers a discussion of the patterns presented.

7.1 FORMALIZATIONS TOWARDS REUSABLE PROBLEM SOLUTIONS

This section provides an overview and classification of approaches which aim to formalize and generalize detailed insights towards a more general and *reusable* form of documentation. The basic motivation is to provide knowledge regarding previously successful problem solutions in such a way that supports the work of designers (e.g., application or interaction designers). The notion of *problem* in this context is equivalent to *challenge* as it refers to decision-making situations such as to design a service or an interaction that works well. Existing knowledge and the experience of experts such as practitioners in a specific field can form the basis for such a solution. Beneficiaries of such problem solutions are in particularly novices in a specific field who can apply such *design rules*.

7.1.1 *Formalization Approaches*

In order to be useful to others, the experience needs to be formalized and documented so that it is accessible for others. Several forms of formalization or documentation of *design rules* have emerged which can be classified and characterized based on their level abstraction ranging from low to high generality. In the following, an overview is provided and cases are discussed in detail.

Design principles as most general design rules.

Design principles are general design rules that can be applied to inform the design of any kind of interactive system [81]. According to Dix et al. such principles can be classified into three main categories: *learnability*, *flexibility*, and *robustness*. Each of these categories is subdivided into even finer grained principles. For instance, the category *learnability*, which refers to the *"ease with which new users can begin effective interaction and achieve maximal performance"* [81, p. 260], comprises the subcategories *predictability*, *familiarity*, *consistency*, amongst others.

These principles are derived from designs of existing interactive systems. These are, effective and successful human-computer-interfaces that are considered to provide a high level of *usability* are analyzed and particular helpful aspects are isolated. Principles such as predictability should be considered during the design process. However, they do not inherently provide specific actions that need to be considered in order to implement the respecting principle as they are very general.

Golden rules provide high-level design goals.

A second approach for formalizing design rules are so called *golden rules* and *heuristics*. Their utility during the design-process is limited to be check-lists of aspects that designers should be aware of and should consider when making design relevant decisions. Examples of such collections are Nielsen's *10 Heuristics* [187], Shneiderman's *8 Golden Rules* [243], and Norman's *7 Principles* [188]. Principles included in Norman's set of rules are for instance, *"Make things visible"* which refers to providing users with an overview of what actions can be done (i.e., considering affordances); another example is *"Design for error"* which refers to anticipating possible accidental actions by users and providing corresponding means for recovery (e.g., asking for approval before deleting a file).

Such collections of golden rules and heuristics are compiled by experts which draw from a wide range of experiences. As a result, the sets target the same domain but differ in the number of rules and partially in the particularity of their focus. Furthermore, their rather general nature highlights what designers should be aiming for. However, no specific guidance is provided as to how these goals should be implemented.

Guidelines for design can be very detailed and suggestive.

Guidelines — also referred to as *style guides* – are more suggestive than principles. Their aim is to achieve a consistent wording, interaction paradigms, and action sequences within a given domain. Accordingly, there are several examples for *style guides* which are concerned with a specific platform such as the *OS X human interface guidelines* [30] or the *Android design* guide [99].

The generality of guidelines is rather low as they define certain aspects such as font sizes, colors that should be used in specific application contexts and interaction concepts that should be preferred in specific cases. The goal of such a guideline is to provide a level of consistency across several applications provided by different manufacturers. Guidelines are compiled by designers or design teams and are (most often) based on design principles and rules. Style guides may also comprise *design patterns* (e.g., in the Android design guidelines [99]) which are detailed in the following.

Design patterns.

Design and interaction patterns are even more focused and targeted on specific design challenges than guidelines. Since design is focused on finding suitable and successful solutions for certain aspects of interactive systems, it is important to understand how similar challenges were solved previously. It is difficult to reuse knowledge regarding prior design solutions if there is no information available regarding to how other applied this presumably working solution and why they did it in a specific way [141]. Design patterns are seek to fill this gap as they are neither too general nor to specific. That is, they convey designers how a design challenge can be solved in a rather detailed way, yet they are not so specific that they can hardly be applied to a specific problem. Design patterns offer an effective way for communicating design solutions as they follow a well defined structure, which makes them easy to access.

Design patterns were first applied by C. Alexander within the context of architecture [23]. He proposed a set of formal patterns (including 253 cases) to support communication between stakeholders in a given project. The concept of formalizing working and approved problem solutions as design patterns has been adopted in other fields such as software development [93], for ubiquitous computing applications [141], and for media spaces [45] to name but a few. Examples for design pattern collection in the domain of application and interaction design are the Yahoo design pattern library [305] and the Android design patterns [99].

Standards provide the highest authority.

In contrast to the previously discussed formalizations of design rules, *standards* are set by legal national or international institutions. In order to ensure compliance with a maximum size community of designers, they require sound underlying theories. Due to their highly specific level of detail, standards are for instance, suitable for specifying aspects of contracts or for project advertisements as they are highly detailed, which enables them to be used in legal contexts.

One example that is particularly relevant in the context of HCI is the ISO standard *ISO 9241* [123], which includes several parts that are directly related to the design process for interactive systems. For instance, part 110 is focused on *Dialogue principles*, part 151 on *Guidance on World Wide Web user interfaces*, and part 210 is focused on *Human-centred design for interactive systems*.

Standards mainly differ from the previously discussed formalization approaches in the sense that they offer the highest level of *authority*. This means, standards are set by a strictly formalized process which ensures a high level of agreement. Furthermore, the level of *generality* is lower compared to the previous approaches, i.e., the applicability of standards is more specific to an application and problem domain than for instance, *golden rules*. Considering these two dimensions (authority and generality), the previously discussed design rule formalizations can be arranged according to Dix et al. [81], which provides a rough overview of how these design rules are related to each other (see Figure 108). Considering this overview, the standards clearly offer the highest degree of authority and detail level. Yet it is almost impossible for individuals to make direct propositions or to contribute to the process of setting standards. Principles and golden rules, however, are extremely broad and draw on experiences of several decades. Hence they are not suitable formalization approaches for generalizing observations and findings of HCI research. Guidelines however, are more targeted to ensure a uniform experience within one platform (e.g., Android), which includes all kinds of specifications including colors and font sizes, which is a level of detail that is difficult to reach based on research efforts. This leaves pattern as the most suitable approach for formalizing observations and findings from research efforts focusing on interaction techniques. As

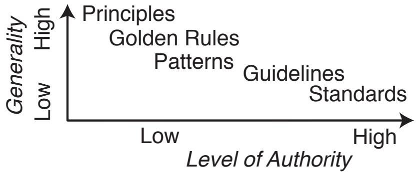


Figure 108: Overview of design rule formalizations [81].

patterns have a narrow focus on a given design problem, specific observations that provide sufficient evidence for generality, can be formalized through them. Hence, this yields the opportunity to generalize interaction research findings and makes them accessible and *usable* for interaction and application designers.

7.1.2 *Interaction Patterns Structure*

A main characteristic of interaction patterns is that they follow a strict structure which supports several aspects: accessibility and readability, comprehension, and utility. As a result of the clear structure, potential users can quickly get an overview of what the pattern is concerned with.

In general, patterns include the following points:

NAME. The name should be easy to remember and aim to outline the core challenge which is addressed by this pattern. This supports for instance, finding the pattern and communication between stakeholders.

PROBLEM. A short problem statement expands the name of the pattern with a focus on what challenge is being solved by this pattern.

CONTEXT. A context description outlines situations (application and interaction context) in which this problem occurs.

PRINCIPLE. To further outline the pattern, principles should be listed, which are usually basis of the pattern.

SOLUTION. The solution itself to the addressed problem.

WHY. Furthermore, an explanation of how the solution works and reasons that provide evidence for the validity of the proposed solution. This includes an analysis of possible side effects on usability.

EXAMPLES. Finally, existing examples where the pattern has been successfully applied help to convey its application.

7.2 DESIGN PATTERNS FOR MOBILE MEDIATED INTERACTION

This section presents a set of design patterns for mobile mediated interaction and applications. This collection draws on observations and results of the research presented in the preceding chapters. Accordingly, this set does not claim to be a complete set but constitutes rather a first step towards a library of design patterns for mobile mediated interaction patterns. Presented patterns cover four fields: *input*, *output*, *data transfer*, and *social interaction* between multiple users. Patterns are organized into four groups: general cross-device interaction which includes all kinds of spatial constellations as well contact-based and contactless interaction.

7.2.1 *Cross-Device Interaction Patterns*

This first set of interaction design patterns applies to all three spatial constellations that were investigated within this thesis.

7.2.1.1 *Personalized Interaction*

PROBLEM. Mobile mediated interaction with pervasive displays provokes situations in which distributed applications are not customized and thus do not meet the user's preferences (e.g., in terms of preferred languages, font sizes).

CONTEXT. In general, mobile mediated interactions are intended for applications and interfaces running on distributed setups that include personal (mobile) and shared (public) pervasive displays. In particular, *spontaneous* interaction (i.e., a low threshold allowing immediate interaction without almost no initial configurations) and '*walk up and use*' scenarios are aimed to be supported by mobile mediated interaction. In such usage contexts, users may often face situations in which they are interacting for the first time with a pervasive display (e.g., in a public setting such as in a hotel lobby). These pervasive displays and corresponding applications cannot be targeted to a public audience and cannot respect individual users' preferences. This however, requires users to accept a default setting or to deal with (potentially time consuming) configurations.

PRINCIPLES. Affecting principles include *learnability* (*familiarity* and *consistency*) and *flexibility* (*customizability*).

SOLUTION: The mediator device – for instance, the mobile phone – transfers a structure list of preferences to the pervasive display server application upon initializing a connection between mobile phone and server.

WHY. A structured list of preferences (e.g., in an Extensible Markup Language (XML) format) can be transferred in the background and processed by the receiving entity by investing very low effort. That is, all kinds of preferences (e.g., font sized, interface languages) can be adapted very quickly, which would take a user substantial time to conduct (i.e., finding a corresponding menu for each parameter and adjusting it). This configuration has to be performed only once using the user's mobile phone client application. These configurations are stored on the mobile phone and can be applied at a later time.

EXAMPLES. The contact-based approach of MobIeS allows users to temporarily connect their mobile phone to an external pervasive display in order to enlarge the available display space (see Figure 109, confer Section 3.2).


(a) (b) (c)

Figure 109: Personalized interaction example 1: the MobIeS allows users to extend the mobile interface temporarily with an external screen in order to use more display space.

After establishing physical contact between the mobile phone (a) and external display, a connection to the pervasive display server is established and preferences regarding font size (b) and grid size (c) are transferred and adjustments are conducted.

Another example for dynamically customized interfaces is the *IdLenses* approach by Schmidt et al. [232, 16]. Here the user creates an *IdLense* by bringing her mobile phone into physical contact with an interactive surface (see Figure 7.110(a)). After a connection has been established, a lens is rendered around the corner of the mobile phone. All labels and text-based content displayed within the lens is translated into the user's preferred language (see Figure 7.110(b)).


(a) (b)

Figure 110: Personalized interaction example 2: *IdLenses* allow users to view content on an interactive surface through a customized view [16].

7.2.1.2 *Private Input*

PROBLEM. Typing in passwords or other sensitive and private data on an interactive surface puts the user at the risk of unwillingly disclosing this information to others in the immediate vicinity.

CONTEXT. Many shared pervasive displays such as interface surfaces or kiosk allow users to perform input actions either using a virtual keyboard displayed on a touch-enabled display or through a hardware keyboard. These are also used for typing in PINs or passwords. However, when typing on an interactive surface, the input of the user can easily be observed and thus the user's privacy can be compromised.

PRINCIPLES. Main principle affecting this pattern is *flexibility* and *adaptability*.

SOLUTION. In order to enter private and sensitive data, users utilize their mobile phone which is used as mediator device for interaction with the pervasive display. To do so, the mobile phone needs to be connected with the pervasive display to allow the transference of data (e.g., password data) and second, the user requires an option to select input and text fields. Through selecting a text field, a proxy text field is opened on the mobile phone, which allows the user to enter data more privately. When the user is finished with typing, an explicit action is required (e.g., a gesture, hitting enter) to initiate the transferring of the data back to the pervasive display.

WHY. By dislocating the keyboard to the user's mobile phone, users can better shield the entering process from bystanders, which is increases the protection against shoulder surfing attacks. Firstly, the mobile keyboard is smaller and thus harder to observe. Secondly, it is difficult to predict how the user will hold the mobile device when entering the text which is a disadvantage for a potential observer.

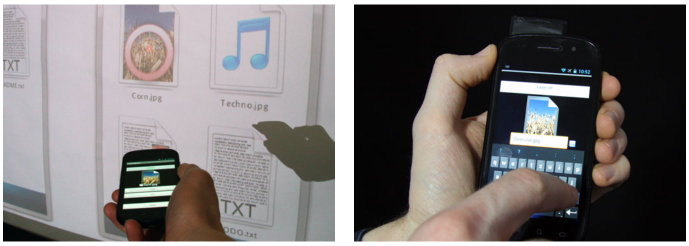
EXAMPLES. The first example which considers the application of this design pattern is the work on the *Smart ATM* (see Section 4.3.2). Here the user utilizes the mobile phone to enter the PIN and all relevant data for withdrawing money. This data is used to generate a token that is later transferred to an ATM to initiate payout (see Figure 111). First, the user enters the relevant information such as the PIN (see Figure 7.111(a)). At the terminal, the transaction is transferred and no data input is required (see Figure 7.111(b)).

The transaction has been successfully executed.

(a) (b)

Figure 111: The Smart ATM allowing private input.

Another example for the application of the private input design pattern is text input in the context of PointerPhone (see Section 6.1). Users use the PointerPhone to interact with remote displays that cannot be approached (e.g.,. due to social conventions, physical constraints). Hence, users are forced to carry out all interaction mediated by their mobile phone; including text input (see Figure 112). For instance, to rename a file, a user selects a file (see 7.112(a)) which initiates the keyboard on the mobile phone (see 7.112(b)).



(a) (b)

Figure 112: PointerPhone supports private input on the mobile phone.

7.2.1.3 *Private Output*

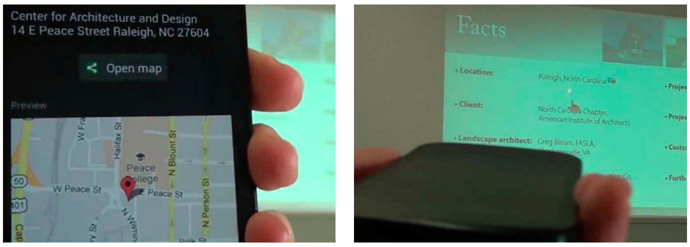
PROBLEM. Output and feedback generated on a pervasive display are not targeted to the intended recipient.

CONTEXT. Mobile mediated interaction with pervasive displays allows multiple users to interact with one pervasive display simultaneously. Feedback and output in response to the actions of one specific user may not necessarily be targeted to them. This can result in confusion or misunderstandings. Apart from providing confusing information, private information can also be disclosed as a result of this. This means that by providing feedback publicly, privacy issues could potentially arise.

PRINCIPLES. This design pattern is affected by the principle of *robustness* and *responsiveness*.

SOLUTION. In order to provide clear and targeted output and feedback that can be directly received by a user, the mobile mediator device is used. Three variants are supported by most of the currently available mobile and smart phones: *audio*-, *visual*-, and *vibrotactile* output and feedback that is intended for a specific user should be provided through these channels.

WHY. The mediator device (i.e., the mobile phone) is associated with one user. Hence, users who operate a mediator device will directly understand that this output is intended for them.



(a) (b)

Figure 113: Private targeted output through PointerPhone.

EXAMPLES. One example of how the private output design pattern can be implemented is demonstrated by the PointerPhone prototype (see Section 6.1). Here, the mobile phone is used for instance, to provide targeted visual feedback after selecting a target on a distant pervasive display (see 7.113(a)). In this example, the user selects a postal address that is displayed on this remote display. The output is displayed on the mobile phone in order to prevent other users from being disturbed (see 7.113(b)).

A second example shows how audio feedback can be delivered privately: based on the Phone Touch technique [230], the user touches a music title which triggers the playback via headphones (see 114).

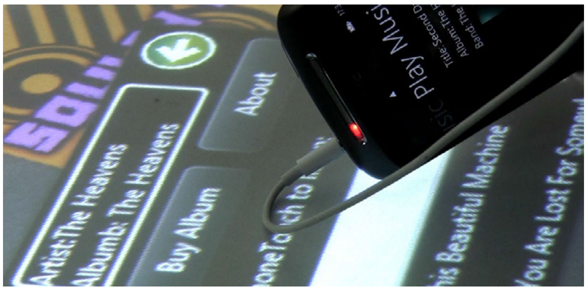


Figure 114: Targeted audio feedback supported by the phone touch technique [16].

7.2.1.4 *Showcasing Data to Other Users*

PROBLEM. Users wish to share and showcase selected files and pieces of data (e.g., photographs) that are stored on their personal mobile devices with other users. Directly showing files on the mobile device's display is limited by its size which is targeted for a single user and showing multiple files allows the display of only one item at a time.

CONTEXT. Sharing data with others, which is stored on the personal mobile phone, is a regularly recurring task. Using the mobile device on which the file is stored for displaying it, is limited as the screen size is small, multiple users cannot jointly view items, and optionally handing the mobile phone to others raises privacy related risks. Standard sharing approaches include for instance, sending data via an e-mail service to the other user's account where it can be subsequently downloaded from. By using this approach it is required the email address is known and the external mail service is available. Furthermore, it generates the complexity of fetching data from the service for the recipient. Alternatively, users can adopt more direct approaches such as sharing data via Bluetooth or Android Beam [100], which however, do not allow recipients to review data before downloading them on their device. Mobile mediated interaction allows using a shared device (e.g., an interactive surface) for sharing and exchanging files. Accordingly, a shared device should be used, on which data can be presented to others, which would be supported by mobile mediated interaction techniques.

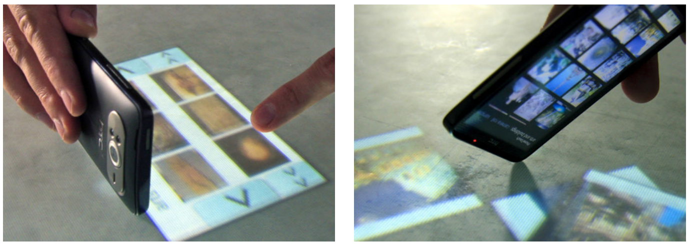
PRINCIPLES. Relevant design principles are flexibility, customizability, adaptability.

SOLUTION. Users require effective means for adjusting or selecting (1) the *target device* on which shared data is displayed. Furthermore, (2) a privacy preserving mechanism for selecting and disclosing data is required. Several options and variations exist for both aspects depending on the spatial interaction constellations.

For the first aspect for instance, the Phone Touch [230] technique can be used which is based on physical contact between mobile phone and an interactive surface. Other approaches are MobIeS (see 3.2) (i.e., pervasive display selection is based on NFC) or PointerPhone which requires the user to connect to a specific pervasive display. The second aspect – selecting files for disclosure – is responsible for allowing users to select only those files for sharing, which are actually intended to be visible by others. The shared pervasive display (e.g., an interactive surface) allows multiple users to inspect and view data jointly while the sharing user keeps their personal device under their control.

WHY. Sharing and disclosing data on third-party devices, which are not explicitly assigned to a specific user, can be regarded as neutral workspaces. Using these for data disclosure prevents uncontrolled access to the personal device of a user. Furthermore, the potentially larger screen spaces of shared pervasive displays supports jointly reviewing data.

EXAMPLES. One example of how this pattern of using an external pervasive display as a device for sharing data has been used are the interaction techniques Shield&Share and Select&Touch2Share (see Section 4.1). As illustrated in Figure 115, the personal mobile phone is brought into physical contact with the shared surface. During this physical contact, the data is transferred and subsequently displayed there.



(a) (b)

Figure 115: Sharing data using Shield&Share (a) and Select&Touch2Share (b).

Another example is PointerPhone (see Section 6.1). Here, the user first selects a file and points to the shared surface which is selected for displaying the said file. In order to trigger the transfer, the user performs a swipe gesture towards the remote display.


(a) (b) (c)

Figure 116: Sharing data using PointerPhone: (a) the user selects a file for sharing and (b) points to a pervasive display where the data should be displayed. (c) After performing swipe gesture the file is transferred and displayed on the remote display.

7.2.1.5 *Picking Up Data*

PROBLEM. When interacting with pervasive displays, users would like to save selected data at certain times for personal use later.

CONTEXT. Mobile mediated interaction also involves situations where users wish to save selected files for later use, which they interact with on a shared (not personal) device. For instance, a photo collage created on an interactive surface should be saved and stored in such a way that a user can access this work later. By *picking up* data with the mobile mediator device, users can transfer data through a simple mechanism (e.g., a gesture).

PRINCIPLES. Affected design principles include learnability, predictability, familiarity, generalizability, and consistency.

SOLUTION. Various possibilities exist to implement this design pattern, which is mainly affected by the spatial constellation in which the user is acting. However, two general aspects need to be considered: (1) a *selection* of a target that is to be picked up and (2) a *trigger* action to start the data transfer.

Options for the first aspect include physical contact using the phone (touch-based selection as for instance, the Phone Touch technique [230]), using a personalize *cursor* that is connected to the personal phone (e.g., MobiZone, see Section 5.1), or direct pointing (e.g., PointerPhone, see Section 6.1). The second aspect can be either implemented through the selection process itself (e.g., Phone Touch) or through a separated action such as a gesture (recognized at arbitrary agents, e.g., the phone or an interactive surface).

WHY. By using the mediator device for saving a copy or logically *removing* a piece of data from a shared pervasive display, the user benefits from a rather *direct manipulation* approach, which work provides a high level of transparency regarding the action and connected results. Furthermore, users are not required to conduct time consuming interactions with for instance, menu-based saving approaches which would require users to firstly authenticate themselves to access their personal storage.

EXAMPLES. Please confer section 7.2.1.4 provided examples there, however, in reverse interaction order.

7.2.1.6 *Data Object Mobility*

PROBLEM. When interacting in a pervasive interaction space, which includes several classes of different devices, users wish to start a task using one device and to continue using it, depending on the current context, on another device.

CONTEXT. When working on a task on one device within the context of a pervasive interaction space, users should be able to pause the work and continue it later for instance, on another device. This changing of devices can be motivated by context changes as for example, a task should be continued together with other users (single user ↔ multiple users), or the location setting has changing (stationary/desktop ↔ mobile). In any case, users wish to transfer the current state of their work to another device where the task should be finished. Hence, the interaction should provide some level of *data object mobility* that would allow for the transference of data related to a specific task to another device where it can be finished.

PRINCIPLES. Design principles affected by this design pattern include flexibility and adaptability.

SOLUTION. In order to implement this design pattern, the application used to work on a given task is required to create a comprehensive bundle of files and data that is related to a given task. Furthermore, the application is required to be available in a distributed way. This means that on each possible device in this pervasive interaction space, an instance of this application needs to be running and needs to provide an interface to receive and load the aforementioned tasks related bundles.

WHY. The context in which users perform tasks can dynamically change over time, either through changes regarding their location or regarding social aspects. The ability to interrupt the work on a given task using one device (e.g., a smartphone) and continuing it on another (e.g., a shared interactive surface) allows users to follow strategies and to use natural processes that they are already used to in other contexts.

EXAMPLES. The work on MobiSurf (see Section 3.1) illustrates how users can start browsing websites using their personal mobile phone. When the context of the work changes (i.e., they transition from the *individual* to the *shared work phase*), users can transfer websites from their personal to a shared device.

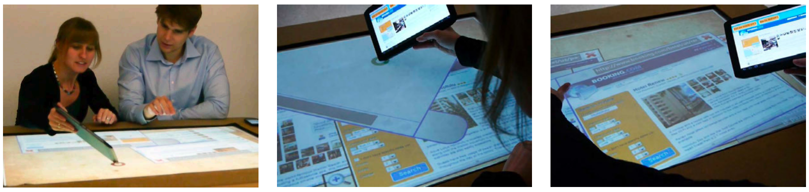

(a) (b) (c)

Figure 117: Data object mobility in the context of MobiSurf: users can easily switch between mobile and shared devices while working with websites (a). Using the PhoneTouch technique [230] the data object is transferred (b). The received web page is then immediately loaded (c).

7.2.2 *Patterns for Contact-Based Interaction*

The following patterns are focusing on recurring challenges in the context of contact-based interaction and provide solutions for these.

7.2.2.1 *Connect on Touch*

PROBLEM. In order to apply mobile mediated interaction techniques, the mediator is required to establish a data connection with the surrounding pervasive display infrastructure. Manually configuring and establishing this connection can be time consuming and tedious.

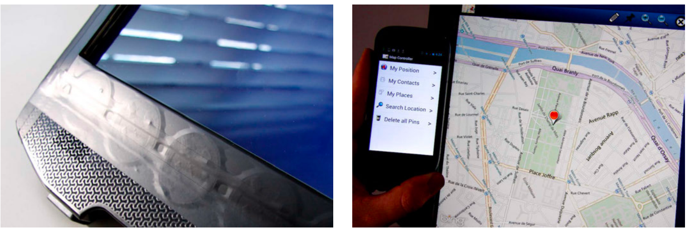
CONTEXT. Mobile mediated interaction techniques are intended to support also so-called *walk up and use* scenarios, which allow users to quickly start interacting within a pervasive interaction space. Therefore, it is essential that the costs for setting up required data connection between the personal mobile mediator device (i.e., the user's mobile phone) and the pervasive displays in the given environment is low and requires little effort. Otherwise, this effort might be perceived as too high in comparison to the potentially short interaction intended by a user.

PRINCIPLES. Relevant design principles include flexibility and task migratability.

SOLUTION. In order to enable the mobile mediator to automatically perform the configuration, an explicit action should be utilized to trigger the configuration, which ensures that the user is actively willing to engage in interaction in this context. Hence, physical contact-based interaction which requires the user to touch the pervasive display with the mobile phone, can exploit the event of touching as said explicit action. However, in order to automatically set up the connection, corresponding relevant information is required. An NFC-based approach for providing these pieces of information is particularly suitable: users hold their phone on an NFC tag which is attached either next to (e.g., [4]) or integrated into ([109, 110]) a pervasive display. The mobile phone immediately reads the tag and uses the provided information to set up the connection to the pervasive display.

WHY. This implicit or automatic approach of setting up the connection between the mobile mediator and a pervasive display reduces the overall time to setup a connection substantially as the user does not need to perform manual input (of e.g., an IP address). NFC tags can be integrated at little cost into existing infrastructures that provide contact-based interaction.

EXAMPLES. One example that demonstrates a possible implementation of this pattern is the work on MobIeS (see Figure 118, confer Section 3.2).



(a) (b)

Figure 118: Touch to connect a mediator with a pervasive display: (a) NFC tags are placed on the rim of a display. The mobile phone is used to read the stored information on the tag and (b) the connection is automatically established.

7.2.2.2 *Predictable Touch Impact*

PROBLEM. Using touch input (e.g., using the finger or a mediator device) does not allow the user predict in all cases what resulting action can be expected.

CONTEXT. Many user interfaces that incorporate interaction touch-based make it impossible for users to anticipate what result will be provoked by an input action. In the context of mouse-based interaction, *tooltips* have been widely adopted to provide information regarding what result is to be expected when performing a click at a specific target. This however, is not possible in the context of touch-based interaction as no pointer is available.

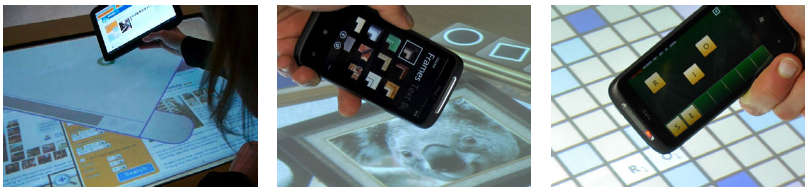
PRINCIPLES. Involved design principles include learnability and in particular predictability.

SOLUTION. The mediator device is used to preview the action that is associated in a particular situation. In order to indicate which effect an action in a particular situation has, the mediator display can be used to show for instance, an icon which expresses the potential effect. For example, when using a painting application which allows users to edit graphical content on a virtual canvas, the mediator is used as a tool which controls the brush and color parameters. These settings should be visualized on the mobile phone.

In situations when the mediator is not used as a specific tool (as the case with the painting application), a mediated touch event performed with the mediator triggers a default behavior. For instance, when touching photograph on an interactive surface, the default action could be *copy to mediator*. In that case, the user should be prompted for their approval. Furthermore, in cases where several actions are possible (e.g., copy, cut, delete), again, the user needs to be prompted for a selection.

WHY. This way, in particular actions that do not result in obvious changes and actions (e.g., *cutting* a file appears similar like deleting a file), are communicated in a transparent way to the user.

EXAMPLES. Examples of how the design pattern for predictable touch input has been implemented are (1) the MobiSurf system (see Section 3.1) where the resulting action is defined by touched targets (see Figure 7.119(a)). And (2) the work on cross-device interaction [16] based on Phone Touch [230], demonstrates how the mobile phone's display can be used to visualize explicitly what actions are assigned to touch events performed with the mobile phone. For instance, decorating frames can be added to pictures (see Figure 7.119(b)) and characters can be places in a Scrabble-like game by the mobile phone (see Figure 7.119(b)).



(a) (b) (c)

Figure 119: Providing information about potential touch results (b and c [16]).

7.2.2.3 *Drag & Share*

PROBLEM. When using mediated interaction techniques that are based on physical contact between the mediator device and a pervasive display (e.g., an interactive surface), users wish to sequentially share a number of files.

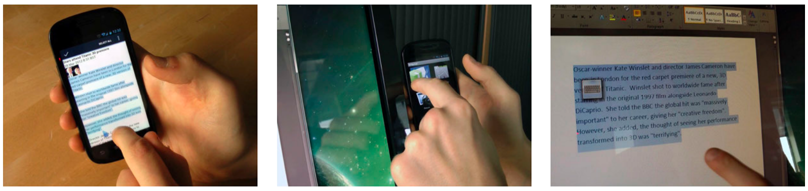
CONTEXT. When the mediator device and the pervasive display are in physical contact, the touch event itself is not an option for triggering and controlling data sharing activities (as it might have been used for the initiation of e.g., a cross-device interface). Hence, users require during the persistence of this phase a possibility to control sharing activities of data with other users by means of a shared pervasive display device.

PRINCIPLES. Affected design principles include learnability and synthesizability.

SOLUTION. The solution is to apply *bi-manual* interaction: one hand is potentially occupied with holding the mediator device. Hence, the user can use the other hand for *dragging* items from the mobile phone (either directly starting on the phone's display across the device borders or starting from an external user interface that is rendered next to the mobile phone) to the shared surface area.

WHY. The approach of dragging items from the mediator device onto a shared surface while both are in physical contact is a working solution as in most cases users have one hand free and available to perform this additional interaction.

EXAMPLES. The first example demonstrates how this design pattern has been adopted for a *cross-device* drag-and-drop approach [7]: users can select data items – here, a text selection (see Figure 7.120(a)). While the phone and the external screen are in physical contact, the user starts dragging the item across the device borders (see Figure 7.120(b)), and drops the item at the intended destination (see Figure 7.120(c)).



(a) (b) (c)

Figure 120: Dragging data across device borders [7].

A second example that is the MobIeS system (see Section 3.2, cf. [4]). Here, the user first creates an extended personal UI that spans on the external display. Now, the user can simply drag-and-drop items from their UI to another user's UI (see Figure 121).

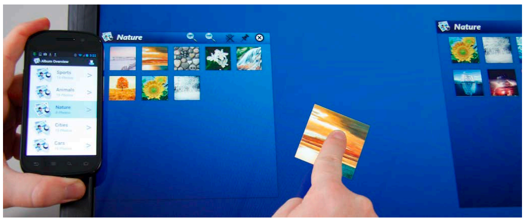


Figure 121: Dragging data from an external personal user interface onto a shared surface area.

7.2.3 *Patterns for Close-By Interaction*

The subsequent patterns are focusing on specific aspects that occurred during the design of interaction techniques that are located within the user's reach, i.e., nearby interaction.

7.2.3.1 *Fuzzy Selection*

PROBLEM. Users wish to select and manipulate multiple files simultaneously (e.g., copying several images from an interactive surface to the personal mediator device) and not one item at a time.

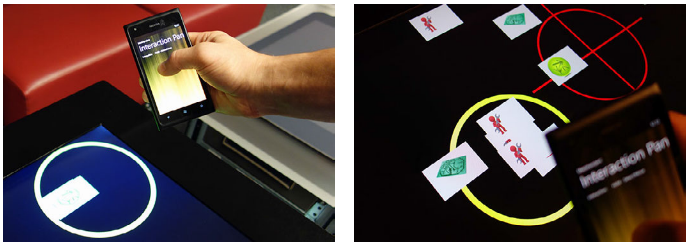
CONTEXT. When users are working on tasks that involve managing and manipulating relatively large amounts of files, direct touch-based interaction techniques tend to be limited as these do not allow selecting and manipulating multiple files at the same time. This kind of action, selecting multiple files simultaneously and subsequently applying some action, is widely available on desktop computer systems, where a user can select a range of files by defining a range using the mouse. Due to the absence of such possibilities in the context of, for instance, managing images on an interactive surface, users are forced to sequentially select all relevant files.

PRINCIPLES. Relevant design principles include flexibility and customizability.

SOLUTION. The solution to this challenge is based on using personalized proxy in the form of a cursor with arbitrary size, which is connected to the user's mobile phone. This cursor can be resized to cover all the files the user is currently interested in. Furthermore, by using the mobile phone, actions can now be applied to several items at the same time, while maintaining the advantage of identified interaction as the mobile mediator device is connected with the cursor. For controlling the position and size of the cursor several options exist: the size and location can be associated to the user's hand holding the mediator device in a defined spatial relation to the pervasive display (e.g., over an interactive surface). Alternatively, the cursor could be spatially detached from the mobile phone which requires the user to manually adjust these parameters of the cursor.

WHY. The cursor provides a simple yet effective means for selecting multiple files as the size can be changed and actions are applied to all contained files. However, files that are not intended for manipulation, but which are located within this area, are also selected.

EXAMPLES. The FlashLight&Control technique (see Section 5.1) is one example of how this design pattern for *fuzzy selection* can be implemented. By tracking the position of the user's hand holding the mediator device over an interactive surface, the cursor that supports selecting multiple files, can be resized and relocated (see Figure 122).



(a) (b)

Figure 122: Fuzzy selection using the FlashLigh&Control technique [6].

7.2.3.2 *Bookmarking Views of Volumetric Data Sets*

PROBLEM. Using mediated interaction techniques to explore spatial volumetric data sets, the user is confronted with the problem that previously found interesting or relevant details of the data set are hard to recover or to finding them again in the volumetric space.

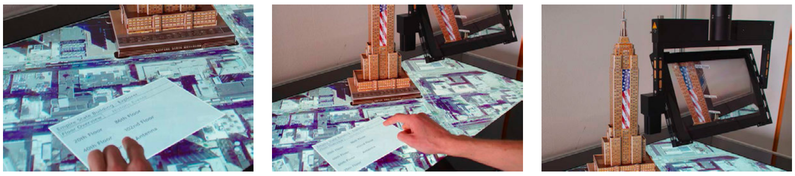
CONTEXT. Spatially aware displays enable users to explore volumetric data (e.g., CT scan data) and to inspect them in relation to their spatial dimensions. However, the spatial display can only provide one specific view into the volume. Hence, users can only see a particular subset of the data. This makes it difficult and tedious to revisit points of interest.

PRINCIPLES. Relevant design principles are robustness and recoverability. Furthermore, flexibility and task migratability are affected.

SOLUTION. Given that the mobile mediator device that provides the spatial view in the volumetric data set supports autonomous and self-actuated movement, users can bookmark points of interest. This means that, if a user would like to save a specific view for later inspection, this view is bookmarked. Later, the exact position and viewing angle of the spatial display can be recalled and the display can be returned.

WHY. Self-actuated movement of spatially aware displays allows a system to autonomously find a specific position in space. This frees the user from searching previously found locations again as the system can autonomously return to them when requested by the user.

EXAMPLES. One example that illustrates how users benefit from this design pattern is the *physical object explorer* application designed for *Hover Pad* (see Section 5.2). Here, novel users are given a list of points of interest (see Figure 7.123(a)). When the users selects one of these (see Figure 7.123(b)), the spatially aware display moves autonomously to the requested position (see Figure 7.123(c)).



(a) (b) (c)

Figure 123: Bookmarking views on spatial data.

7.2.3.3 *Adjusting Movement Accuracy*

PROBLEM. When interacting with self-actuated and motorized moving spatial displays, the movement speed needs to adapt to the current application context to prevent movement that is either too slow or too fast, resulting in a lack accuracy in movement.

CONTEXT. Using self-actuated spatially aware displays can change their movement speed within a specific range (i.e., the range from slowest to fastest movement). User need to be able to control the speed in order to control the precision the display can be positioned. The faster the spatial display is moving, the lower the resulting movement and positioning accuracy.

PRINCIPLES. Design principles involved in this pattern are mainly flexibility and customizability.

SOLUTION. In order to control the movement speed and accuracy, different options are available, depending on the given approach for controlling the movement. For instance, when using a widget (e.g, displayed on a connected interactive surface), an additional slider could be used for adjusting the movement speed.

WHY. The user can explicitly control the movement accuracy when needed. This means that for rather exploitative activities in which the user wants to get a rough overview of a complete volumetric data set, faster movement can be used and vice versa slow movement for the examination of specific details.

EXAMPLES. Widget-based movement control as introduced with *Hover Pad* (see Section 5.2) allows users to manually control the movement speed. As illustrated in Figure 7.124(a), a user can configure the speed of movement which is applied when using the widget subsequently (see Figure 7.124(b)).

7.2.4 *Patterns for Distant Interaction*

This fourth set of design patterns is focusing on aspects and issues that arise in the context of distant mobile mediated interaction. That is, the mobile mediator device and the user are too far away from external pervasive displays to apply for instance, touch-based interaction techniques.

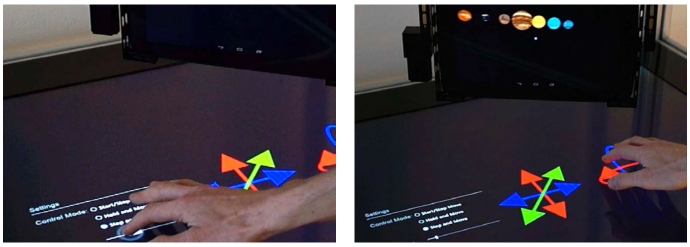

(a) (b)

Figure 124: Using a widget to control movement speed.

7.2.4.1 *Focus Shifting*

PROBLEM. When using mobile mediated direct pointing interaction with a remote display, users often have to switch their focus from the mediator to the distant display and back. While focusing on one device, important events that are displayed on the other device can easily be missed.

CONTEXT. When using a mobile phone to interact with a distant pervasive display via direct pointing interaction, the user often has to shift their focus from the mediator device display to the distant display and vice versa. For instance, when pointing to a target (e.g., an image) a user might want to select an action from a list on the mobile phone. Hence, the user first looks towards the distant display to see what she is currently pointing at and to adjust the pointing. Then the focus is shifted towards the display of the mobile phone. Now when the user selects an option (e.g., *'delete'*) the file is removed from the distant display while the user is focusing on the handheld device, this can potentially leads to irritation. For instance, on the remote display a dialog could show up which prompts the user for their confirmation.

PRINCIPLES. Design principles involved are robustness and observability as well as flexibility and dialog initiative.

SOLUTION. To solve this challenge, applications that support direct pointing based interactions should implement means for notifying users when a presumably important change has happened on the other device. This means, a visual, audio, or vibration notification provided by the mobile phone could inform the user and encourage her to look up at the remote display. For guiding the user's attention from the remote to the handheld display, the remote display can provide visual cues and the mobile mediator provides audio and haptic cues.

WHY. Users expect that their actions result in changes within such distributed applications that build on direct pointing. Only the exact timing is not obvious and thus simple multi-modal notifications can help the user to recognize changes.

EXAMPLES. Examples of how this pattern can be implemented are provided by PointerPhone (see Section 6.1). One option, as detailed before, is to use haptic feedback that is provided by the mobile phone's vibration actuator for indicating that a change has occurred on the remote screen. As illustrated in Figure 7.125(a), a user is notified via a short vibration of the phone when a new file is pointed at.

A second option is illustrated in Figure 7.125(b), where the user is notified that a proximal menu has appeared on the mobile phone, by changing the cursor's color from green to red.


(a) (b)

Figure 125: Feedback for supporting focus shifts.

7.2.4.2 *Shifting Distal and Proximal Interaction*

PROBLEM. Direct pointing interactions allow only coarse selections, i.e., of large targets due to the low input precision while pointing over a larger distance. Hence, complex tasks are tedious to perform through distal interaction.

CONTEXT. With an increasing distance to a remote screen, the input accuracy of users decreases due to the fact that smaller movements of the user result in larger location changes of the pointing cursor. Therefore, longer sequences of input actions using direct pointing in combination with distal interaction are tiring and error prone. Therefore, applications should support the shift from distal to proximal interaction.

PRINCIPLES. Design principles involved are flexibility and robustness.

SOLUTION. Applications should support the shift from distal to proximal interaction. This means that a coarse selection is performed remotely on the distant display. This triggers the transfer of a proximal representation of the target, which can be edited in the following by (relatively) precise touch-input on the mediator device's touch display.

WHY. The main advantage of providing a proximal representation is that users are not required to keep pointing at the target. Therefore, this enables users to hold the mediator in any comfortable position to perform the selection task.

EXAMPLES. One example from the context of PointerPhone (see Section 6.1), is the dynamic transfer of input widgets. For instance, as illustrated in Figure 126, the user points to a slider widget and selects it via distal selection. As a result, a representation is displayed on the user's mediator display where they can adjust the value of the slider.

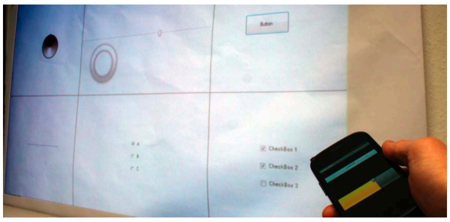


Figure 126: Shifting interaction between distal and proximal representations.

7.2.4.3 *Placing Projected Screens*

PROBLEM. Interacting with projected pervasive screens, which can be dynamically created, placing them in the user's environment is a recurring problem.

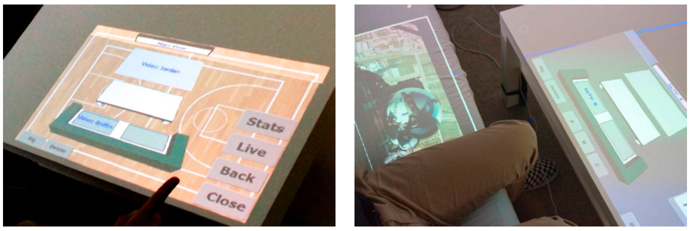
CONTEXT. Projected pervasive displays offer a high level of flexibility as they can be generated quickly and display any content in the user's environment. However, the process of placing them in the user's environment raises challenges regarding how to determine the target position and once they are positioned, how can they be removed again?

PRINCIPLES. This design pattern is affected by the design principles flexibility and customizability.

SOLUTION. Using a projected mediator interface that allows users to control the position of each generated projected pervasive screen solves this design problem. Next to the user's location in a pervasive interaction space, the placing interface is rendered. Here the user can control the location of each projected screen via touch input.

WHY. This solution demonstrates that the mediator device does not necessarily need to be a physical handheld device such as a mobile phone. The projected mediator is placed within the user's reach, hence, touch-based interaction can be applied for controlling distant items or screens.

EXAMPLES. The work on projecTVision (see Section 6.2) presented several cases where this pattern was applied. Figure 7.127(a) shows a projected interface next to a user where they can place projected screens in her environment which are related to a basketball application. It allows users to place for instance, player statistics next to a main view which shows the game itself. Figure 7.127(b) shows a projected secondary screen next to a user, who used a similar interface as in the first example to select the location for the screen.



(a) (b)

Figure 127: Placing projected secondary screens using a mediator interface.

7.2.5 *Discussion*

This section presented a set of design patterns that provide and illustrate working solutions to recurring design challenges in the context of mobile mediated interaction based applications. Design patterns have emerged as a common form for reporting experiences regarding how to solve specific design challenges (e.g., [66, 156]). Among other formalization approaches for design rules, patterns are a well accepted form for communicating prior knowledge and can be used during the design process [121] as they include clear suggestions regarding how to solve a specific problem.

The existence of various pattern collections (e.g., in the field of ubiquitous computing) raises the question of how the presented set refers to these existing ones. In general, the existence of a multitude of diverse pattern sets for specific application domains do not have to be regarded as mutually exclusive but rather as mutually complementing sets. With mobile mediated interaction being a novel approach for interactive in the pervasive interaction space, no prior set for design patterns in this context has been presented. However, related sets of patterns exist in the field of ubiquitous computing (e.g., [66]).

However, there is some debate regarding the value and usefulness of design patterns [197]. While it is a promising approach, one main point of critique is that the format of pattens is not standardized. This leads to a multitude of patterns sets that all follow a general theme and structure yet details are likely to differ. For instance, there is no standard that defines how many prior design cases must be provided to serve as solid basis from which a design pattern can be derived from. Borchers suggests the notion of "proto-patterns" for patterns that are based on only few examples [45]. Accordingly, the patterns presented in this section could be referred to as such proto-patterns as most of them are based on few examples and experience which was collected in the scope of this thesis' work. Therefore, in order to increase reliability and generalization more application specific investigations regarding the interaction techniques presented in this thesis would be required.

8

CONCLUSION

With this thesis, we set out for researching novel approaches for overcoming limitations and issues that arise within the scope of the *pervasive interaction space*. Due to its inherent characteristic of being distributed across an increasing number of classes of devices, users face challenges and issues regarding *personalized user interfaces* and missing *personal context*. Further, interaction across varying spatial configurations and logical boundaries of different devices eliminate the options for interaction. Considering these motivating challenges, *mobile mediated interaction* was identified as general approach for solving these. Following this concept, this thesis introduced a spatial anthropomorphic *classification scheme* for *interaction techniques* as well as a number of techniques that addressed the motivating challenges. Based on this research, a first collection of *interaction design patterns* for mobile mediated interaction techniques has been derived.

8.1 RESEARCH SUMMARY

Related work analysis and derived classfication model.

After the introduction, the work presented in this thesis set out by initially classifying and framing the identified research questions. Accordingly, related research fields were illustrated in detail and distinguished from the specific aims of this work. In particular, cross-device interaction, contact-based as well as distant interaction techniques were discussed. Based on this analysis, a spatial classification model has been derived which reflects the human gestalt – hence, an anthropomorphic classification model. This model has primarily been used to structure the work presented in this thesis.

Co-located collaboration.

The third chapter of this thesis focused on the aspect of co-located collaboration within the context of contact-based interaction. To enable this investigation, a system has been implemented that incorporates touch-based interaction to allow data exchange between personal and shared devices. By conducting an extensive user study, the effect of seamlessly connected personal and shared pervasive displays has been examined. This chapter further presented work on a novel technique for applying continuous physical contact between a personal and a shared device as well as an application case study, which illustrates how contact-based interaction techniques can facilitate shopping tasks by including mobile mediator devices.

Data disclosure & privacy management.

The fourth chapter presented research focusing on sharing and disclosing of personal data within a pervasive interaction space setting. This research focuses on how users can effectively control what data is shared with others given that mobile mediated interaction techniques are used. An empirical user study has been conducted to compare four different variations of techniques. In addition, this chapter details an original approach (*TreasurePhone*) for mobile mediated privacy management. Also regarding these two aspects case studies have been conducted and were presented in this chapter: first, a cross-device data sharing technique based on the drag-and-drop metaphor. Second, a *hybrid* approach for interaction with public terminals.

Contact-less close-by interaction.

The fifth chapter was the first to address contact-less interaction approaches for mobile mediated interaction. In particular, this chapter focused on *close-by* handheld interaction. Initially, manual handheld position control for controlling a fuzzy item selection approach (*MobiZone*) was investigated. Challenges and issues raised by this manual position control for a mobile mediator device motivated further research on autonomous and self-actuated position and motion control for spatially aware mediator devices (*Hover Pad*). Possibilities for applying the novel interaction techniques that are based on (semi-) autonomous movement, have been detailed by means of five example applications.

Contact-less distant interaction.

The sixth chapter addresses possibilities for interacting with a mediator device across a larger distance which cannot be compensated by a user. In this sense, pointing based interaction techniques were explored (*PointerPhone*) and identified options are ranging from *low-level* to *high-* or *application-level*. Further, this chapter illustrated an approach for interacting with multiple projected pervasive displays that are freely positioned in the user's environment (*projecTVision*).

Interaction design patterns.

Finally, the seventh chapter discussed how observations and general insights that were gained in the context of the presented research could be formalized and made accessible for application and interaction designers. Respectively, design patterns were identified as suitable formalization and 15 patterns were identified and detailed in this chapter.

In general, an explorative approach has been adopted for all research activities. That is, after the existing literature and prior art has been examined, a conceptual solution has been worked out. Based on this theoretical solutions, prototypes have been designed and developed which were used to conduct empirical evaluation studies. These have been designed following the common standards set in the field of HCI, which is reflected by the quality and number of preceding publications by the author of this thesis.

8.2 THESIS CONTRITIONS

The preceding section summarized and recapitulated what has been researched within the scope of this thesis and how these aspects were approached methodically. This section now reconsiders the core contributions of the presented research – on the one hand in regards to the research community of HCI and on the other hand contributions targeted to beneficiaries beyond the academic environment.

The contributions made within this thesis target four different levels and can be classified into the following categories:

1. *Theoretical* contributions.
2. *Technological* contributions
3. (Interaction) *design* specific contributions.
4. *Empirical* contributions.

1. A spatial anthropomorphic classification model for mediated interaction techniques.

Based on the analysis of related literature and the prior art, we developed a user-centered classification model. This model distinguishes oneself from related approaches as it is based on the human gestalt, that is, it follows an anthropomorphic approach for categorizing classes of interaction. Two major areas are distinguished by this model: contact-based and contact-less interaction, while the latter is differentiated further into interaction within reach and out of the user's reach. On the one hand, this model is a valuable contribution to the HCI research community. In an academic context, such a model can be used to identify comparable solutions or approaches to a novel approach which is helpful for instance, when searching for baseline approaches within the context of a comparative study. In addition, the classification model can be used to identify open research opportunities when combined with additional aspects such as *collaboration support*. On the other hand, this model can be useful to practitioners in the field of application and interaction design who are working on solutions suitable for the pervasive interaction spaces. In particular, this model facilitates identifying alternative approaches in a specific interaction setting.

2. Technological aspects of mediated interaction.

The second, and one of the core contributions of this thesis, is a set of multiple technological insights and advances for HCI systems, which includes both, hardware and software aspects. To illustrate this contribution exemplary, the Shield&Share interaction technique (see Section 4.1) introduces a novel approach (by advancing an existing concept) for realizing continuous physical contact-based cross-device interaction. This thesis introduces also novel ways to apply existing technologies in the context of contact-based interaction techniques. For instance, the work on MobIeS (see Section 3.2) demonstrates how NFC can be used to allow creating ad-hoc cross-device interfaces for mobile phones and pervasive displays. With the *Hover Pad* toolkit (see Section 5.2), the thesis presents a first technological approach for self-actuated and (semi-) autonomous movement and hence, position control for a spatially aware display. This toolkit (hardware construction plan and software framework) is available as open source project to allow others to start research in this domain. And finally, as a last example for the technological contributions to the field of HCI, this thesis introduced an original approach for combining laser pointers with smartphones (see *PointerPhone* in Section 6.1) which enables a rich set of interaction options for direct pointing interactions. All these technological insights and rich experience can be adapted (i.e., advantages and disadvantages of approaches are well documented) and enable future research to draw on.

3. Design aspects of mediated interaction.

The third aspect which describes a contribution of this thesis are insights regarding interaction design. On the one hand, the thesis provides multiple smaller findings in the context of each presented interaction technique. This includes also numerous best-practices as for example, in the context of PointerPhone (see Section 6.1). On the other hand, the thesis contributes an additional set of fifteen high-level interaction design patterns (covering mobile mediated interaction in general, as well as physical contact based, close-by, and distant interaction) which aim for supporting application and interaction designers.

4. Empirical evaluation of mediated interaction aspects.

Finally, this thesis contributes *empirical insights* and study results that help to develop a deeper understanding of mobile mediated interaction techniques applied in a pervasive interaction space. These empirical insights are based on multiple user studies (including quantitative and qualitative study designs), for which each technique was implemented as fully functional prototype which allowed examining the interaction technique under realistic conditions. In particular, aspects regarding the potential of mobile mediated interaction techniques to support *co-located collaboration*, *privacy management*, *data disclosure*, as well as interaction techniques including *(semi-) autonomous and self-actuated movement* were examined and evaluated by means of user studies which meet the community specific standards. These insights based on empirical observations deepen the understanding and assessment of presented designs and technologies.

8.3 OPEN ISSUES & FUTURE WORK

Within the scope of this thesis' work several new questions came up during conducted research. Also, the chosen methodical approach for conducting the research presented in this thesis raises additional questions that could not be investigated within the scope of this thesis and are thus open for future research activities.

Regarding the latter aspect – limitations of the methodological approach – in particular the inherent issue of low external validity has to be acknowledged. That is, by exclusively conducting laboratory studies, the empirical results feature a low level of external validity. Yet, conducting evaluations in a controlled laboratory environment neglects and cancels potentially strong influence factors that could be present in the context of using interaction techniques outside the laboratory environment. Hence, the external validity of the empirical evaluations is limited to that effect.

In situ investigation for external *validity.*

Accordingly, future research activities that focus on investigating mobile mediated interaction techniques in situ, have a high potential to yield interesting complementary insights. Such a research effort would also allow to target larger sample sizes of evaluating users, compared to the presented laboratory studies. In particular, this would broaden the view on the tested interaction techniques, as such samples are likely to achieve a higher level of heterogeneity of participants (i.e., age, background, interests etc.).

Long term usage.

Such investigations focusing on the usage and application of mobile mediated interaction techniques in situ would also facilitate collecting data regarding *long term usage*. As the presented results do only focus on short term usage within the context of rather short experiments, the questions arise how using such interaction techniques influences *application usage* in pervasive environments, and which *social implications* can be observed for instance, regarding co-located collaboration and data sharing behavior.

Security aspects of mediated interaction.

Further, the investigation of interaction techniques outside the laboratory environment brings up a series of challenges that need to be solved beforehand. In particular, a first challenge is regarding the required infrastructure that is necessary to enable mobile mediated interaction techniques since most of the techniques presented in this thesis require also custom hardware setups. While this aspect is rather an issue in terms of costs, an open question is regarding the (data) security of users when adopting mediated interaction techniques. In short, connecting the personal mobile phone to a pervasive infrastructure puts personal data at the risk of unauthorized access by an attacker. This aspect has not been considered in the scope of this thesis as user studies were exclusively performed in controlled environments. Similarly, another open question is regarding how a generally applicable communication protocol for applications running in a distributed setup (as applied for pervasive interaction spaces) should be designed and what the general requirements to such a protocol are.

Hover Pad *interaction and visualization.*

Within the scope of specific parts of the thesis, more targeted questions were identified and have not been investigated within the scope of this thesis. For instance, regarding the *Hover Pad* system additional work should investigate and evaluate the presented position control interaction techniques. Similarly, questions regarding the benefit provided through the secondary horizontal display should be assessed. And further, multi-user scenarios involving shared control of the *Hover Pad* position as well as remote interaction is likely to yield original insights regarding this novel technology. Another promising direction for further research work is to extend the work on continuous display spaces presented within the work on *projecTVision*. Questions that remain open consider the users' awareness of content in such a distributed and scattered display space. Further, how does such a setting impact television consumption and how would users utilize this infrastructure. And finally, what influence would this technology have on the user's data sharing and on the collaboration in general.

projecTVision *usage and application.*

8.4 CLOSING REMARKS

The *smartphone* as presented by Apple in 2007 with the *iPhone*, featuring a touch-sensitive display and being equipped with several sensors as well as a broadband data connection is relatively young. Currently, one can observe an increasing momentum regarding diversification of such smart mobile phones in terms of form factors. For instance, form factors ranging in the middle of mobile phones and tablet computers complement the palette of device sizes in addition to so called *mini* versions of mobile phones which are particularly small. At the same time, current trends indicate that *wearable* devices such as *smart watches* or head-mounted display devices will eventually penetrate the market. It is open to speculation if devices with a palm size form factor – like current mobile phones – will be displaced by said emerging devices. However, the presented principals of mediated interaction based on a mobile phone as mediator device, are likely to be helpful even for devices with other form factors which cannot be passed or borrowed on to other users (e.g., a mobile phone which is handed over in order to show a photograph to a friend). Hence, we are positive that the presented results and insights in this thesis can be valuable beyond the age of the smartphone.

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