Interacting with Large High-Resolution Display Workplaces

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INTERACTING WITH LARGE HIGH-RESOLUTION DISPLAY WORKPLACES

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ABSTRACT

Large visual spaces provide a unique opportunity to communicate large and complex pieces of information; hence, they have been used for hundreds of years for varied content including maps, public notifications and artwork. Understanding and evaluating complex information will become a fundamental part of any office work. Large high-resolution displays (LHRDs) have the potential to further enhance the traditional advantages of large visual spaces and combine them with modern computing technology, thus becoming an essential tool for understanding and communicating data in future office environments. For successful deployment of LHRDs in office environments, well-suited interaction concepts are required.

In this thesis, we build an understanding of how concepts for interaction with LHRDs in office environments could be designed. From the human-computer interaction (HCI) perspective three aspects are fundamental: (1) The way humans perceive and react to large visual spaces is essential for interaction with content displayed on LHRDs. (2) LHRDs require adequate input techniques. (3) The actual content requires well-designed graphical user interfaces (GUIs) and suitable input techniques. Perceptions influence how users can perform input on LHRD setups, which sets boundaries for the design of GUIs for LHRDs. Furthermore, the input technique has to be reflected in the design of the GUI.

To understand how humans perceive and react to large visual information on LHRDs, we have focused on the influence of visual resolution and physical space. We show that increased visual resolution has an effect on the perceived media quality and the perceived effort and that humans can overview large visual spaces without being overwhelmed. When the display is wider than 2 m users perceive higher physical effort. When multiple users share an LHRD, they change their movement behavior depending whether a task is collaborative or competitive. For building LHRDs consideration must be given to the increased complexity of higher resolutions and physically large displays. Lower screen resolutions provide enough display quality to work efficiently, while larger physical spaces enable users to overview more content without being overwhelmed.

To enhance user input on LHRDs in order to interact with large information pieces, we built working prototypes and analyzed their performance in controlled lab studies. We showed that eye-tracking based manual and gaze input cascaded (MAGIC) pointing can enhance target pointing to distant targets. MAGIC pointing is particularly beneficial when the interaction involves visual searches between pointing to targets. We contributed two gesture sets for mid-air interaction with window managers on LHRDs and found that gesture elicitation for an

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LHRD was not affected by legacy bias. We compared shared user input on an LHRD with personal tablets, which also functioned as a private working space, to collaborative data exploration using one input device together for interacting with an LHRD. The results showed that input with personal tablets lowered the perceived workload. Finally, we showed that variable movement resistance feedback enhanced one-dimensional data input when no visual input feedback was provided. We concluded that context-aware input techniques enhance the interaction with content displayed on an LHRD so it is essential to provide focus for the visual content and guidance for the user while performing input.

To understand user expectations of working with LHRDs we prototyped with potential users how an LHRD work environment could be designed focusing on the physical screen alignment and the placement of content on the display. Based on previous work, we implemented novel alignment techniques for window management on LHRDs and compared them in a user study. The results show that users prefer techniques, that enhance the interaction without breaking well-known desktop GUI concepts. Finally, we provided the example of how an application for browsing scientific publications can benefit from extended display space. Overall, we show that GUIs for LHRDs should support the user more strongly than GUIs for smaller displays to arrange content meaningful or manage and understand large data sets, without breaking well-known GUI-metaphors.

In conclusion, this thesis adopts a holistic approach to interaction with LHRDs in office environments. Based on enhanced knowledge about user perception of large visual spaces, we discuss novel input techniques for advanced user input on LHRDs. Furthermore, we present guidelines for designing future GUIs for LHRDs. Our work creates the design space of LHRD workplaces and identifies challenges and opportunities for the development of future office environments.

ZUSAMMENFASSUNG

Große Bildflächen bieten eine einzigartige Möglichkeit, komplexe Informationen visuell aufzubereiten und zu kommunizieren. Deshalb werden solche Flächen schon seit Jahrhunderten für vielfältige Inhalte, wie beispielsweise Karten, öffentliche Bekanntmachungen oder künstlerische Darstellungen genutzt. Das Verstehen und Bewerten von komplexen Informationen wird für die Büroarbeit der Zukunft essenziell sein. Große hochauflösende Bildschirme bieten das Potenzial, die Möglichkeiten von Bildflächen mit moderner Computertechnik zu verbinden. Somit können große hochauflösende Bildschirme zu einem wesentlichen Werkzeug für zukünftige Büroarbeit werden. Für die erfolgreiche Verbreitung von großen hochauflösenden Bildschirmen in Büroumgebungen werden wohlgestaltete Interaktionskonzepte benötigt.

In dieser Dissertation wird ein Verständnis dafür erarbeitet, wie Interaktionskonzepte für große hochauflösende Bildschirme in Büroumgebungen gestaltet werden können. Aus Sicht der Mensch-Computer-Interaktion sind drei Aspekte fundamental: Erstens ist die Art und Weise, wie Menschen Inhalte auf großen Bildflächen wahrnehmen und auf diese reagieren, wesentlich für Interaktionskonzepte für große hochauflösende Bildschirme. Zweitens: Große hochauflösende Bildschirme benötigen adäquate Eingabetechniken. Und drittens muss der eigentliche Inhalt mithilfe entsprechend gestalteter graphischer Benutzeroberflächen verwaltet werden können.

Um zu verstehen, wie Menschen große Informationsmengen visuell wahrnehmen und auf diese reagieren, liegt der Fokus dieser Arbeit auf dem Einfluss der visuellen Auflösung und der physikalischen Bildschirmgröße. Die Ergebnisse zeigen, dass die visuelle Auflösung einen Einfluss auf die wahrgenommene Medienqualität und auf den empfundenen Interaktionsaufwand hat. Des Weiteren zeigen die Ergebnisse, dass Menschen sich auf großen visuellen Flächen leicht einen Überblick verschaffen können, ohne überfordert zu sein. Ist der Bildschirm breiter als zwei Meter, steigt der wahrgenommene körperliche Aufwand bei der Interaktion. Teilen sich mehrere Nutzer einen großen hochauflösenden Bildschirm, passen diese ihr Bewegungsverhalten entsprechend einer kollaborativen oder kompetitiven Aufgabe an. Beim Bau von großen hochauflösenden Bildschirmen sollte berücksichtigt werden, dass höhere Auflösungen und physikalisch größere Bildschirme die Systemkomplexität erhöhen. Geringere Auflösungen bieten ausreichend Bildqualität, um ein effektives Arbeiten zu erlauben, gleichzeitig unterstützen größere Bildflächen den Nutzer dabei, Informationen zu erfassen.

Um die Eingabetechniken für große hochauflösende Bildschirme zu verbessern und ein effizientes Interagieren mit großen Informationsmengen zu ermöglichen, werden mittels funktionsfähiger Prototypen neue Konzepte in Benutzerstudien analysiert. So wird deutlich, dass durch gezielte Mauszeigersprünge auf die Blickposition des Benutzers (MAGIC pointing) weit entfernte Ziele schneller selektiert werden können. Es werden zwei Raumgestensets zur Interaktion mit Fenstermanagern auf großen hochauflösenden Bildschirmen präsentiert. Für die kollaborative Datenuntersuchung können sich sowohl gemeinsam als auch separat genutzte Eingabegeräte eignen. Hierzu werden in einer Studie Nutzereingaben mittels persönlicher Tablets mit gemeinsamer Eingabe mithilfe eines einzigen Eingabegerätes verglichen. Die Ergebnisse zeigen, dass bei der Eingabe mittels Tablets die Interaktion als weniger aufwendig empfunden wird.

Müssen Parameter durch den Nutzer angepasst werden, ohne dass eine direkte visuelle Rückmeldung möglich ist, kann dies durch den variablen Bewegungswiderstand eines Schiebereglers erleichtert werden. Es wird deutlich, dass kontextabhängige Eingabetechniken die Interaktion verbessern können. Dabei ist es essenziell, dass der Nutzer sich auf den visuellen Inhalt fokussieren kann und bei Eingaben entsprechend geleitet wird.

Um die Erwartungen der Anwender an das Arbeiten mit großen hochauflösenden Bildschirmen zu verstehen, wurden zusammen mit potenziellen Nutzern mögliche Arbeitsplätze gestaltet. Dabei bekam die Anordnung der physikalischen Bildschirme und die Platzierung des Inhalts besondere Aufmerksamkeit. Bekannte Darstellungstechniken für Desktopumgebungen wurden auf die Anforderungen von großen hochauflösenden Bildschirmen angepasst und in einer Nutzerstudie verglichen. Die Ergebnisse zeigen, dass Nutzer Techniken bevorzugen, die nicht mit bekannten Konzepten im Konflikt stehen. Das Beispiel einer Anwendung zur Darstellung von wissenschaftlichen Veröffentlichungen verdeutlicht, wie Anwendungen von erweitertem Bildschirmplatz profitieren können. Insgesamt ist es wesentlich, dass graphische Benutzerschnittstellen für große hochauflösende Bildschirme den Benutzer stärker bei der bedeutungsvollen Anordnung von Inhalten unterstützen als dies bei kleineren Bildschirmen notwendig ist. Somit erlauben diese dem Nutzer, komplexe Inhalte effizienter zu verstehen.

Auf der Grundlage der erweiterten Erkenntnisse über die Wahrnehmung von großen Bildflächen werden neue Eingabetechniken diskutiert und Richtlinien für die Gestaltung von graphischen Benutzerschnittstellen präsentiert. In dieser Arbeit wird der Gestaltungsraum für große hochauflösende Bildschirmarbeitsplätze beschrieben und es werden Herausforderungen und Chancen für die Entwicklung von Büroumgebungen der Zukunft identifiziert.

PREFACE

This thesis presents research I conducted between 2014 and 2018 at the Group for Human-Computer Interaction at the University of Stuttgart. The research ideas and decisions are strongly influenced by valuable discussions and various projects with my colleagues. Furthermore, I supervised undergraduate student projects as well as Bachelor and Master theses with a focus on my research interest, which further supported me to answer particular research questions. In collaboration with colleagues and students, we published results of these discussions and projects. Parts of this thesis are based on these publications. I refer to these publications at the beginning of the related section or chapter. To keep this thesis consistent, I have decided to use the scientific plural throughout this thesis.

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LIST OF UNITS OF MEASUREMENT

Symbol	Name	Unit of
°	Degree	Angle
EUR	Euro	Currency
Hz	Hertz	Frequency
fps	Frames per second	Image refresh frequency
bit	Binary digit	Information
in	Inch	Length
m	Meter	Length
cm	Centimeter	Length
mm	Millimeter	Length
pixel	Pixel	Point in a raster image
h	Hour	Time
min	Minute	Time
s	Second	Time
ms	Millisecond	Time
PPI	Pixel per inch	Visual display resolutions
DPI	Dots per inch	Visual resolution of printed media

LIST OF ACRONYMS

4K	ultra-high-definition
8K	8K ultra-high-definition
ACM	Association for Computing Machinery
AI	artificial intelligence
ANSI	American National Standards Institute
AR	augmented reality
BD	backtracking distance
BYOD	bring your own device
CHI	Conference on Human Factors in Computing Systems
CIMPLEX	Bringing CItizens, Models and Data together in Partici-patory, Interactive SociaL EXploratories
CRT	cathode ray tube
DaaS	Display as a Service
DFKI	German Research Center for Artificial Intelligence
epub	electronic publication
ER	error rate
FHD	full high definition
GEQ	Game Experience Questionnaire
GUI	graphical user interface
HAPTIC	HAPTICFEEDBACK
HCI	human-computer interaction
html	Hypertext Markup Language
ISO	International Organization for Standardization
IUI	intelligent user interfaces
LCD	liquid-crystal display
LHRD	large high-resolution display
MAGIC	manual and gaze input cascaded

PDF	Portable Document Format
PE	perceived mental effort
PMQ	perceived media quality
PP	priming and production
RM-ANOVA	repeated measures analysis of variance
`tang`	`tangible sliding`
SIGCHI	Special Interest Group on Computer-Human Interaction
SMEQ	Subjective Mental Effort Question
SPGQ	Social Presence Gaming Questionnaire
SUS	System Usability Scale
`touch`	`touch sliding`
TCT	task completion time
NASA-TLX	NASA-Task Load Index
TUI	tangible user interface
UI	user interface
USB	Universal Serial Bus
UX	User Experience
VISUAL	VISUALFEEDBACK
VISUS	Visualisation Research Centre at the University of Stuttgart
`VMR`	`variable movement resistance sliding`
VMRS	variable movement resistance slider
VR	virtual reality
WQXGA	Wide Quad Extended Graphics Array

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Introduction and Background

Chapter 1

Introduction

For centuries, humans have presented art and information using large spaces. Large-scale panoramic paintings were particularly prevalent in the 19th century; popularly showing landscapes or military battles. These paintings aimed to get the viewer into the scenery and impress. For such $360°$-view artwork whole buildings, so-called "Cyclorama" were built. The huge effort people made to show large-scale paintings shows a strong fascination for spatially large visual content. Besides artwork, maps are the most common visualization type presented on large surfaces. Large maps are an important tool for strategic planning and science. Moreover, Kirsh [122] argues that such spatial arrangement of physical objects and visual information plays a fundamental role in the way humans perceive and understand their environment. This importance of spatial relations is also relevant for office work today. Malone [164] analyzed how office workers organized their desks and highlighted the importance of using the physical spaces to remind the user about particular documents. With increased display work, spatial relationships are becoming increasingly important for displayed content. LHRDs allow showing these spatial relationships for larger datasets.

Computational power revolutionized most business processes in the 20th century. This computational support has reduced the mental effort required to complete tasks thus allowing more complex tasks to be completed. Since the development of the Xerox Alto, GUIs are one of the most important human-computer interfaces. Thereby, the graphical display has become a fundamental role for interaction. Due to technical limitations, the available display space is limited, and interaction design still requires effort to overcome the challenge of displaying visual content

with spatial relationships even on small screens, such as in smartphones or smartwatches (e.g. [25, 36, 69, 216]). Nevertheless, research identified the potential of large display spaces early. Almost since the invention of the concept of GUIs, researchers have explored the advantages of larger visual display spaces. In the late 1970s and early 1980s, Bolt and Donelson explored spatial data representation and navigation in a multimedia room containing a large back projection screen as main display and two additional smaller displays [35, 54]. Furthermore, Bolt explored multimodal interaction with this setup [34], and showed that large interactive surfaces and LHRDs are fundamental to human-computer interaction (HCI).

In parallel, technical advances over the last decades have allowed us to constantly increase the size of desktop screens. While the display of the first computer with GUI, the Xerox Alto, had a size of 8.5×11 in [238], Grudin [87] showed in 2001 that office workers perform better using two 17 in screens instead of one. Czerwinski et al. [45] compared, in a lab study, office work performed on a regular desktop setup with a 15 in display performing the same work on a back-projection screen with 42 in. The results show that the larger display lowered the mental demand and supported participants performing the task time-efficiently. Ball et al. [21] analyzed the navigation and visual search tasks on various display sizes. In this study, the largest display had a size of 2.7×1 m. The results showed that this larger display space enabled participants to perform the tasks faster. The authors argued that in particular physical navigation improved the exploration process. In line with Ball et al.'s [21] results, Liu et al. [153] compared a desktop setup to an LHRD for a visual classification task and showed that participants were able to perform classifications faster on larger display spaces. Andrews et al. [12] analyzed sensemaking on LHRDs and showed that the ability to arrange facts spatially supports the sensemaking process. Thereby the results are in line with theoretical work by Kirsh [122]. Paine and Lee [194] observed cosmology scientists discussing a large number of printed plots on a conference table during regular meetings. The authors observed that the plots were widely distributed to enhance theoverview and discussion. This is one example of a scenario where LHRDs would have the potential to enhance the data exploration. Instead of printing, the plots could be displayed on an LHRD. This would have the advantage that the arrangement could be stored and resumed later. Furthermore, remote collaboration would be also possible. Here, Avellino et al. [16] analyzed how GUIs for remote collaboration on LHRDs could look like. In contrast, Westendorf et al. [267] focused on on-side collaboration. The authors identified interaction patterns for collaborative decision-making using LHRDs.

While Mark Weiser's [265] "tabs" and "pads" have become ubiquitous as smartphones and tablets, the "boards" are still mostly neglected in present visions. At the beginning of the 1990s, Sun Microsystems envisioned a novel office working desk including an LHRD [241][1]. Also, Raskar et al.'s [203] vision of the office of the future included LHRDs. The authors assumed that office workers would use a combination of common desktop displays combined with large projected display spaces for displaying spatial data immersively. Streitz et al. [231] envisioned a working environment for collaboration and creativity. Thereby the key element is the multidisplay environment with mobile touch-sensitive devices and LHRDs.

LHRDs also play an important role in commercial visions. Microsoft's Office Labs Future Vision 2019[2] shows large interactive surfaces for work tasks, creativity, and communication in offices and at private homes. Roll-Royce Future shore control center vision[3] focuses on monitoring autonomous vessels on LHRDs. Also, fiction makes use of such displays. The most prominent example might be the film "Minority Report" [229], where the main actor interacts with an LHRD through mid-air gestures. While these visions have shown for more than three decades the widespread fascination with large interactive displays and research has shown their advantages in laboratory experiments, surprisingly they have not reached market readiness.

Despite technical advances, it is still challenging to deploy LHRDs. All current setups are built out of multiple screens or back projection projectors. The Visualisation Research Centre at the University of Stuttgart (VISUS) Powerwall[4] consists of 10 ultra-high-definition (4K) projectors and a number of rendering nodes. Also, Jakobsen and Hornbæk [116] used a setup with 12 back protectors. In contrast, Liu et al. [152, 153] used a grid of liquid-crystal display (LCD) displays. Multitaction[5] offers with iWall LHRDs based on 55 in touch-screens. For all setups, it is challenging to provide content on all single screens or projectors synchronously with a high refresh-rate and high resolution. Most setups are driven by multiple computers which require distributed and synchronized software solutions. In 2006, Ni et al. [187] provided a detailed overview of LHRD technology. With the release of the AMD FirePro W9100, it became possible to

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[1] A video of the envisioned interface is available at `https://asktog.com/starfire/index.html`.

[2] A video of the Microsoft's Office Labs Future Vision is available at
   `https://www.youtube.com/watch?v=8Ff7SzP4gfg`.

[3] A video of the Roll-Royce Future shore control center vision is available at
   `https://www.youtube.com/watch?v=vg0A9Ve7SxE`.

[4] `https://www.visus.uni-stuttgart.de/institut/visualisierungslabor/technischer-aufbau.en.html`

[5] `https://www.multitaction.com/hardware`

drive three displays with 4K resolution and 60 Hz refresh-rate with one graphic card. Additionally, it became possible to combine up to four of these graphic cards. This allowed driving an LHRD with one computer without distributed software solutions. Alternatively, multiple screens can be driven by advanced network services. Commercially available systems allow streaming of content to remote displays over wireless networks [141]. Display as a Service (DaaS) allows streaming and distributing content over several screens over the network. Thereby, DaaS uses a virtualization approach [155]. These networked approaches to display content on LHRDs might also enable ubicomp concepts, which envisioned that users would use their personal data on displays in the environment [263], allowing them to explore their data on various devices in an ad-hoc manner.

Overall, we see that advances in technology lowered the effort to build LHRDs over the last decades. However, various interaction concepts have been explored. When analyzing the technological trends of LHRDs with the Gartner's hype cycle [138], we see early research by Bolt and Donelson [35, 54] as innovation trigger. The first commercial products (e.g. Multitaction's iWall) for data exploration on LHRDs are available and research has identified benefits of such displays, e.g. [21, 45, 153]. Now, smaller second-generation products, e.g. Google's Jamboard[6] or Microsoft's Surface Hub[7] and workstation graphic cards able to drive an LHRD are reaching the market. Nevertheless, these products are expensive and require lots of customization. Hence, we are currently in the third phase of the Gartner's hype cycle; the "trough of disillusionment".

The main reason for the limited market success of LHRDs is the absence of well-suited for concepts user interfaces. Neither desktop interfaces nor interfaces for mobile devices can be easily up-scaled to LHRDs. Breaking well-known user interface concepts creates legacy issues for users familiar with traditional concepts. Prominent examples are Microsoft's attempt to replace the Windows start menu in Windows 8 and the introduction of ribbons in Microsoft Office 2007. To utilize the advantages of LHRDs, user interface concepts would have to be redefined more fundamentally than those changes, so we can also assume even move legacy issues. In consequence, existing user interface concepts have to be reviewed carefully, and novel concepts designed with legacy issues in mind.

The second challenge for LHRD setups is their potential to change work flows and the surrounding architectural environment. The design of today's workplaces has mostly been inspired by typewriters and the early desktop computers. In contrast, LHRDs would allow working in other and multiple body postures.

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[6] `https://gsuite.google.com/products/jamboard/`

[7] `https://www.microsoft.com/en-us/surface/devices/surface-hub`

On the other hand, such setups question basic assumptions about workplace privacy and office communication. Hence, we have to rethink the design of office environments. LHRDs could enable users to work in various body postures. In common office environments, office workers sit for the most of the time. While physiologists in 1969 recommended performing more work sitting to lower the physical effort [82], more recent research has identified health risks of physical inactivity [248]. Sjøl et al. [226] showed a relationship between increased risk of myocardial infarction and physical inactivity, and Gilson et al. [80] showed a relation between occupational sitting and musculoskeletal issues and stress. These authors argued for more moving while performing work. Here, LHRDs could enable the users to stand and walk in front of the display.

LHRD setups can be a powerful tool to explore and understand large, complex data sets. Furthermore, they have the potential to support creative processes to find optimal solutions and professional designs. However, such setups can unfold their potential only with well-suited user interfaces.

1.1 Research Questions

We know from cognitive science that humans need a spatial connection to work with tools as well as when working with visual or textual information [122]. Research in HCI has also already identified benefits in terms of user performance of LHRDs (e.g. [21, 153]). The challenging task is now to design well-suited LHRD ecosystems and user interfaces. Hence our general research explores how to utilize the advantages of LHRDs for knowledge work.

The Association for Computing Machinery (ACM) Special Interest Group on Computer-Human Interaction (SIGCHI) Curricula for Human-Computer Interaction [101], describes the human with ergonomics and the computer with Input and Output (Devices) as core aspects of the field. This is surrounded by the use and context of the interaction. For this thesis, we focus on office and knowledge exploration environments as context of use. The core aspects are surrounded by the development, design and evaluation aspect. We apply in well-established design and evaluation methods. Based on our general research question (RQ) and the Curricula for HCI [101], we identify four secondary research questions: First, we consider how LHRDs are designed and used today (RQ1), and based on RQ1 we envision how LHRD might be used in future work environments. Second, we focus on the user and ask how humans perceive and react to LHRDs (RQ2). Based on RQ1 and RQ2, we formulate RQ3: How are well-suited input techniques for

LHRDs designed? While we had with RQ2 a focus on perception and behavior, we explore in RQ3 design opportunities for GUIs for LHRDs. Finally, we ask how well-suited GUIs for LHRDs are designed (RQ4). Table 1.1 presents these research questions, and corresponds to the structure of the thesis.

Table 1.1: Overview of the research questions addressed in this thesis.

	Research Question	Part	Chapter
RQ	How to utilize the advantage of LHRDs for knowledge work?		
RQ1	How are LHRDs designed and used today?	I	2.3, 2.2
RQ2	How does humans perceive and react to LHRDs?	II	
RQ2.1	How does the visual resolution influence the user while interacting?	II	3
RQ2.2	How does the size of the display space influence the user while interacting?	II	4
RQ2.3	How utilize multiple user physical large display spaces?	II	5
RQ3	How are well-suited input techniques designed?	III	
RQ3.1	Can eye-tracking based interaction techniques enhance pointing on LHRDs?	III	6
RQ3.2	How are mid-air gesture sets for window manipulation designed?	III	7
RQ3.3	Can LHRD-tablet combinations enhance multiuser data exploration?	III	8
RQ3.4	Can haptic feedback on the input device enhance input, when the user cannot visually focus on the input device?	III	9
RQ4	How are well-suited GUIs for LHRDs designed?	IV	
RQ4.1	How should LHRD workplaces physically be designed?	IV	10
RQ4.2	How should an LHRD window manager be designed?	IV	10, 11
RQ4.2	How should applications for LHRD be designed?	IV	12

1.2 Methodology and Evaluation

To answer the research questions in this thesis (see Section 1.1), we applied common qualitative and quantitative methods in HCI. To understand how users currently work with LHRDs (see Section 2.3), we used contextual inquiry [32]. To build an understanding of how humans perceive large high-resolution content (see Part II) and to analyze novel user interfaces (UIs) (see Part III and IV), we built working prototypes and conducted a series of lab studies [77, 210]. In most studies, we gathered quantitative measurements and qualitative data through semi-structured interviews. To compare quantitative measurements we used common statistical approaches and tools [62] with significance level of $p < .05$. For designing input techniques (see Chapter 7) and GUIs for LHRDs we used participatory design methods [222, Chapter 4] and focus groups [134]. To highlight the context of the presented work, we discuss relevant related work at the beginning of each Chapter or Section.

1.2.1 Ethics

The research studies presented in this thesis were conducted within the EU project Bringing CItizens, Models and Data together in Participatory, Interactive SociaL EXploratories (CIMPLEX). For all conducted studies, we used an ethics process derived from the pd-net project [136]. Furthermore, all study designs were in line with the Declaration of Helsinki [15].

1.3 Research Contribution

This thesis contributes mainly to the knowledge of how LHRDs can be used with the following aspects: (1) We showed the influence of visual display resolution and physical display space on text and multimedia-based tasks. (2) We propose a set of novel input techniques, that enhance user input on LHRDs in various usage scenarios. (3) We explore novel GUIs designs for LHRDs and provide guidelines for future LHRD systems.

1.3.1   Research Context

The research presented in this thesis and beyond was conducted between spring 2014 and spring 2018, mainly at the group for Human-Computer Interaction at the University of Stuttgart. Collaborations within research projects and with other researchers influenced the work presented in this thesis.

CIMPLEX

The main research of this thesis was conducted within the EU project CIMPLEX[8] within the European Commission's H2020 Programme. This project investigated advanced modeling of contagion phenomena in complex social systems and how all stakeholders, from interested non-experts to modeling experts and decision makers can be included in the process of modeling and decision making. In collaboration with Marco Hirsch and Paul Lukowicz from the Embedded Intelligence group at German Research Center for Artificial Intelligence (DFKI), we explored how everyday smartphone users can be motivated to contribute personal health data as a basis for flu disease spreading models [240]. Together with Jürgen Grüninger and Philipp Slusallek from the research lab Agents and Simulated Reality at DFKI we discussed how LHRDs and multidisplay environments can be used for advanced data exploration [142].

Collaboration with Chalmers University of Technology

Together with Paweł W. Woźniak and Morten Fjeld we explored how smartphone-tablet combinations [273, 275] and tablet-tablet combinations [274] can be used for mobile data exploration and sensemaking. Additionally, Zlatko Franjcic, Asım Evren Yantaç (Koç University, Turkey) and Shengdong Zhao (National University of Singapore) contributed to the work on multidevice interaction. Furthermore, early work of Morten Fjeld [220] inspired us for the collaboration on variable movement resistance feedback [151] (see Chapter 9).

Collaboration with University of Helsinki

Together with Khalil Klouche and Giulio Jacucci, we discussed novel interaction techniques for data exploration on LHRDs [142]. Furthermore, Giulio Jacucci was involved in work about multiuser interaction in front of LHRDs leading to

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[8] `https://www.cimplex-project.eu`

the publication PacMany [173] (see Chapter 5). Jens Emil Grønbæk (Aarhus University, Denmark) and Zhanna Sarsenbayeva (University of Melbourne, Australia) were also involved in the work leading to this publication.

Collaboration with University of Konstanz

Within the Collaborative Research Center SFB-TRR 161 Quantitative Methods for Visual Computing[9] we analyzed, in collaboration with Svenja Leifert and Harald Reiterer the influence of display space on visual search performance [150] (see Chapter 4). Furthermore, we worked together on building an understanding of how potential users of LHRDs would design their work environment [146] (see Chapter 10).

Collaboration with Uppsala University

Form a long-term perspective, books have been one of the most important tools to communicate knowledge. To explore how books can be enhanced with interactive technology, we co-organized a workshop with Mohammad Obaid [190]. As result of the workshop, we co-edited a special issue on interactive books [191]. Ilgım Veryeri Alaca (Koç University, Turkey), and Mark Billinghurst (University of South Australia) were also involved in this project.

Collaboration with Cornell Tech

Within the CIMPLEX research context we explored with Chloe Eghtebas, Brendan Ritter, and Alap Parikh, how color-coded information on maps is perceived [56]. Furthermore, Nitesh Goyal contributed high expertise in sensemaking, in particular, to work about mobile data exploration [274].

University of Stuttgart

Besides the work presented in this thesis, we carried out various projects at the University of Stuttgart. This, work focused on displaying projected information in various settings [71–73, 141, 145] and using interactive technology in social or collaborative contexts [105, 123, 169, 171, 211, 271]. We conducted most of this research work in collaboration with Sven Mayer, Paweł W. Woźniak, Niels Henze, Albrecht Schmidt and student assistants Andreas Preikschat and Robin Schweigert. Work presented here is further, based on collaboration with

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[9] https://www.trr161.de

undergraduate students whom we supervised in their projects, Bachelors and Masters theses [9, 17, 26, 68, 100, 103, 125].

1.3.2   Thesis Outline

This thesis consists of five parts, with 14 chapters that follow the structure of the research questions (RQs).

Part I: Introduction and Background

Chapter 1 - Introduction.   In the first chapter, the topic of interacting with large high-resolution display workplaces is presented and our motivation, the research methodology and the context of this thesis are described.

Chapter 2 - Vision and Requirements.   In this chapter, we present our vision of how office environments will change in the next decades and how LHRDs will be part of these environments. We explore how control room staff utilize LHRDs today. We also discuss with practitioners current approaches and challenges for designing LHRD applications, highlighting potentials and future challenges for research and development. We conclude by outlining requirements for LHRDs in office environments.

Part II: Understanding Humans Interacting with Large High-Resolution Displays

Chapter 3 - Influence of Screen Resolution.   Over the last decades display and computing technology have developed quickly. Thereby also the understanding of "high resolution" has changed. However, the influence of the resolution on the interaction is not fully described yet, hence we analyze the influence of the visual screen resolutions available today on mobile devices and likely to be soon on larger displays. The results show that high visual resolution is perceivable and rated as higher quality. Furthermore, higher visual resolutions lower the perceived effort for text-based tasks. However, there was no measurable influence of the resolution on the task performance.

Chapter 4 - Influence of Physical Display Space.   Besides the visual resolution, the physical size of an LHRD influences the user behavior and performance. Here, we analyze visual search performance for text-based documents displayed on variously sized LHRDs. The results show that users are not visually overwhelmed by physically large display spaces.

Chapter 5 - Influence of Physical Display Space. LHRDs offer a unique potential for multiuser interaction. Through an LHRD game, we analyzed in a lab study how pairs of users behave when they either collaborate or compete against each other on a task. The results show that users utilize the full physical display equally when they collaborate, but position themselves close to their competitor in competitive situations.

Part III: User Input Techniques

Chapter 6 - Eye-Tracking Based Input. Among the challenges when working with current LHRD setups is the loss of the cursor, long distances between the cursor and pointing target, and the mismatch between visual focus and input focus. We explore how eye tracking with MAGIC pointing can enhance the interaction with LHRD setups, and show that MAGIC has the potential to decrease pointing time. Furthermore, we identify challenges for future deployment and development.

Chapter 7 - Mid-Air Gestures. In this chapter, we explore how mid-air gestures could enhance interaction with LHRDs. Through user-defined gesture studies, we designed two gesture sets for window manipulation. These gesture sets are designed as additional input modality to mouse and keyboard input. The concept envisions high precision input with mouse and keyboard and input involving large spaces with mid-air gestures. Furthermore, performing gestures could be possible in various body postures and support more user movement in front of the display. Additionally, we explore the influence of legacy bias on the gesture design. The results show that users are not influenced by their knowledge about other interactive systems.

Chapter 8 - Second Device Input. When users collaborate on an LHRD, they need shared input techniques. Utilizing mobile devices such as smartphones and tablets as input devices offers high flexibility for input and can be used as private interaction space. We explore how the combination of an LHRD and two tablets can be used for exploring geospatial social media data. The results show that users prefer having two individual input devices over one shared interface.

Chapter 9 - Tangible Force Resistant Feedback Slider. When users focus visually on content displayed on an LHRD, their visual attention should not be distracted in order to utilize the LHRD optimally. Hence, we explore how variable movement resistance of a slider could enhance discrete value editing on LHRDs. The results of the user study we conducted show that variable movement resistance enhances input efficiency when the user is not able to look on the input device and cannot directly see the value input.

Part IV: Designing Content for Large High-Resolution Displays

Chapter 10 - Screen Layout.   In this chapter, we explore how potential users of extended physical display space would design their physical workspace and arrange content on visual display space. Users prefer symmetrical display setups. Furthermore, we were able to identify distinct areas for specific content.

Chapter 11 - Transforming Desktops.   Based on findings of previous research, we implemented adjustments for the desktop environment KDE to enhance the interaction with LHRDs. The results of the lab study show that participants prefer novel alignment techniques that do not break well-established GUI patterns.

Chapter 12 - Reading Application.   Below the design of window managers, the design of specific software applications can also benefit from extended display space. We explore how applications for reading scientific publications could be designed to best utilize the large physical display spaces. Results of a preliminary lab study show that redesigned applications have the potential to enhance sensemaking.

Part V: Conclusion and Future Work

Chapter 13 - Conclusion.   In the conclusion, we summarize the work presented in this thesis and reflect on the research questions presented in Section 1.1; highlighting the key findings for each chapter.

Chapter 14 - Future Work.   Based on the results of the work presented in this thesis, we derive challenges and research questions for future work. The key challenges are prototyping and evaluation methods for LHRD applications; furthermore, advances in sensing and display technology are required for the commercial success of LHRD.

Chapter 2

Vision and Requirements

LHRDs have the potential to change office work practice and environment. In this chapter, we discuss the evolution of office environments form typewriter working desks to future data exploration workstations evolving LHRDs. To understand current benefits and challenges of LHRD workplaces, we take a look at current work practice. We report on an interview series with LHRD application designers and information visualization experts. Furthermore, we describe LHRD usage at a control room to understand how LHRDs are used today. Based on these findings we present requirements to build LHRD workplaces.

2.1   Vision of Office Environments

In this section, we present our vision of how LHRDs will be used in the future. We envision that LHRDs will have a transformative role in future office environments. We assume that LHRDs will become commonplace and will influence how office work is performed. However, to utilize the potential of these displays, novel UIs are required. In the future, we will see LHRDs not only in work environments, but their potential to support future work challenges creates a unique opportunity to change work practice and environments.

2.1.1   From the Typewriter to Desktop Computer

Current office workplace design is strongly inspired by the requirements of working on a typewriter. This workplace has space to store documents, the typewriter is positioned in the center, and the officer sits on a chair in front of the desk. Thomas Malone [164] analyzed these desk structures from an information science perspective and highlighted the importance of document piles for organizing work. Yet, even when computer technology was in its nascent stage, visionaries wondered about offices beyond typewriters. Vannevar Bush [38] inspired the development of computers after 1945 with his vision of the memex. He described the memex as a hypothetical information processing machine for indexing and retrieving documents quickly. Thereby, he envisioned that all documents would be stored on microfilms and referenced between each other. The invention of the computer mouse by Douglas Engelbart [58] and a team at Telefunken [46, 246] in parallel and Ivan Sutherland's contribution to GUIs [232] were leading for the success of the personal computer. With the Xerox Star, the IBM PC and Apple Lisa the first desktop computers with GUI were launched. These computers equipped with monitors, keyboards, and mice finally removed typewriters from offices. However, the typewriter still inspired how people designed interfaces [39]: A display covering only a small area in the field of view, keyboard, and mouse forces the user to be seated in front of the display. Futhermore, since the middle of the 20th century, Human Factors and Ergonomics have recommended a seated position for performing office work. Grandejean [82] argues that in the seated position the human body needs less energy and the cardiovascular circulation is less demanding. However, now with increasing computing power and advances in algorithmics, we will see a radical change and sustained, static and monotonouse tasks will disappear. In contrast, monitoring automated processes, proving results of decisions taken by algorithms and creative tasks will be more important. This change in work tasks affects all HCI-related research fields and calls for changing the work environment.

2.1.2   The Future of Office Work

Through advances in technology, more and more processes will be automated. Robots will take over most tasks in manufacturing. A similar trend is happening in transportation and logistics. Autonomous ships, trucks, plans, and cars are under development. These vehicles will not require on-board personnel for steering or maintenance. However, unexpected events will require decision making. Computer systems will be able to handle most events autonomously; nevertheless,

there will be cases where the system will not be able to decide for technical or legal reasons, or will not detect an issue. In these cases, a human still has to discover the issue and make decisions. Because these cases are infrequent, one human will be able to monitor a large number of processes at once. However, the human controller would have to keep the overview over all processes at any time to be able to detect issues. In a critical situation, the controller would also have to be able to process a large amount of data to get an overview of the situation to make the best decisions. Hence, the computer systems have to support visually scanning large pieces of information and guiding the attention of the user in required situations.

There are monitoring tasks where it cannot formally be specified what to search for, e.g. airport security searches for potentially hazardous objects [48]. It is not possible to automate this visual search task in a time efficient way because the optical variety of potentially hazardous objects is too large to be specified for an algorithm. Hence, for specific tasks, humans have to perform visual search tasks with limited support from a computer system.

In all areas of life, we rely on decisions taken by algorithms. The order of results of a web search or information presented in a news feed is created by algorithms, whereby they create a picture of how we see specific events and the world in general. To control this huge influence of such algorithms, techniques are required to verify and understand them. An integral part of proving those algorithms requires comparing data manually. Therefore, the user has to be able to see large data sets at once, and only then be able to relate different pieces of information and evaluate the value of a certain information. Overall, we require UIs that enable the user to relate and group information spatially and to view various large, complex results of algorithms. With the improvements in artificial intelligence (AI), the dependency on algorithms will increase over the next years. From a research perspective, the intelligent user interfaces (IUI) community is building an important bridge between HCI and AI [86].

For creative tasks, inspiration from existing artefacts is fundamental. The increasing amount of digitally available data requires efficient ways to explore large data sets without being able to formulate a well-defined search query. Many disciplines use spatial and visual representations of processes and relations. Goldstine and von Neuman [81] proposed using flowcharts (also called flow diagrams) to visualize the flow of algorithms. Today, these flowcharts are state-of-the-art and specified in standards [1]. Furthermore, flowcharts are used, inter alia, in systems dynamics, economics and operation science (e.g. [10]). The visual representation of events following each other allows understanding complex processes easier

than in a non-visual representation. Affinity diagrams are a common tool to structure a large number of aspects of a design problem [129]. To create an affinity diagram, all related terms should be written on cards and afterwards grouped into thematic clusters according to their relationship. This enables identifying important aspects of the design problem, and makes use of the physical space to highlight key requirements. Desktop displays do not allow generating this clustered overview. Hence, Geyer et al. [78, 79] propose a multidisplay environment for creating affinity diagrams. Furthermore, complex design processes require the knowledge of numerous stakeholders. Hence, Arias et al. [14] argue for interactive multidisplay environments supporting collaborative design.

2.1.3   Large High-Resolution Display Environments

Creative and challenging tasks can benefit from other body postures than sitting. Fortunately, advances in computing power and display technology allow re-thinking interaction techniques. As a consequence, these novel interaction techniques also enable us to re-design the workplace environment. **Displays used in workplaces will easily exceed the field of view of the user in the near future.** At the same time, the display resolution will exceed the capabilities of the human vision at any possible viewing distance.

The new dimensions of LHRDs will also require additional input techniques. To perform input on LHRDs, **computer systems will assist by knowing on which area of the display the user is looking.** Then, mouse or keyboard input can be directed to this area. The awareness of the visually observed area also allows the system to guide the user to regions of interest, e.g., notifications out of the field of view. Additionally, **we will see a number of mobile displays** either attached to the user, for example as arm wrist, or as tablet computers or smartphones. Mobile displays will allow remote input to the LHRDs installed at the workplace and enable users to perform additional touch or speech input. Furthermore, content from mobile devices will be ubiquitously transferred to the LHRD and back to allow users to take documents with them.

In future offices, we will find different types of working areas and different form factors of displays. First, people will have areas for individual work. In these areas will be a desktop to place input devices, documents and personal belongings. **The whole desk will be surrounded by an LHRD.** The abundant display will space require changes in the design of GUIs. We will keep the concept of applications grouping a number of functions to allow the users to perform certain tasks. However, the concept of application windows and window management will

change fundamentally. While commonly sized displays determine the position of controls, GUIs for LHRDs require more flexibility. For example, on an LHRD the taskbar is not in easy reach from every position. The same issue exists for function bars in applications. Hence, we need dynamic access to these functions close to the position where the user is interacting. Furthermore, stacking information in windows and tabs will become less relevant than on traditional desktop setups. In contrast, **grouping several related windows and moving them together in and out of focus will become important**. This enables users to compare visual information easily and efficiently. Furthermore, the concept of notifications and upcoming dialogue boxes will change. Applications that trigger notifications on current systems will not be hidden on LHRDs; instead they will be moved out of the focus area. This will enable the user to check their state when required without rearranging the content in the focus area. Nevertheless, there will still be situations where the system will have to move the attention of the user to a specific important event. Current approaches, e.g. of pop-ups in a corner of the display or blinking icons in the task bar, are not efficient on LHRDs, because all these positions might not be in the field of view of the user. Hence, the system will have to present these notifications dynamically on positions where the user can recognize them without changing the field of view.

In an optimal case, the desk and the display are height-adjustable independently. Mouse and keyboard will stay as main input devices. These input devices can be extended by eye-gaze-assisted input, direct touch, and speech input. Furthermore, smartphones, and tablets will be used for seamless data transfer. **This will allow users to work in different postures.** Changing the posture from time to time can have a positive influence on creativity, attention, health and well-being [80].

In corridors, in coffee and sheared areas, we will see room-high LHRDs for communicating information to people in this environment. Furthermore, and even more importantly, these displays will be used for exploring and discussing data. The use of these displays will be more spontaneous and casual than in all other areas. Comparable to GUIs in workplaces, GUIs for such semi-public LHRDs will differ from interfaces for other form factors and scenarios. Again, function access on fixed positions is unsuitable, because they might be out of reach for the user. Instead, users need dynamic function access on the area they are interacting with. This is particularly important for multiuser scenarios. Multiuser scenarios can be distinguished accorinding to whether they are collaborative scenarios or individual (parallel) scenarios. In collaborative scenarios, pairs or groups of users work together to solve a common task, thereby focusing on the same displayed content. When multiple users work individually in parallel on the LHRD, the shared resource has to be divided into individual areas, and the needs of different

users can vary. While some users need to see large data sets on an LHRD, others might be just interested in reading general information displayed in this location.

For interacting with information not accessed from personal devices, users will mostly use direct touch and mid-air gestures (see [174, 254]), because this allows interacting with the content without any preparation or to approach additional input devices. To display their own data, users will connect their mobile devices to an LHRDs, thereby **ubiquitously connecting the mobile devices to other devices such as displays in the environment.** When mobile devices stream data to LHRDs, the GUI of the streamed application has to scale from a small mobile display to an LHRD. Thereby, the mobile device can be used as input device and present tailor-made controls for the particular application.

In meeting rooms, we will see LHRDs spanning across all walls, thereby turning every surface of the wall into a display. Fender et al. [61] built a prototype of such a future meeting room. The usage of these displays will highly depend on the meeting content. During a traditional meeting mostly one large part will be used to support the structure of the meeting and underline presented information. **Other display parts might be used to mirror the presentation, show additional information, or even previously presented content.** In these scenarios mostly one person will control the displayed content; all others might view additional information on mobile devices and use them for annotating the presented content. In specific cases, these annotations might influence the content shown. Chattopadhyay et al. [41] presented a system to access presentation slides during a talk and thereby enabling the audience to engage deeper with the presentation and start collaboration including the presenter and the audience.

When using a meeting room to view and discuss complex and large data sets, the pair or group will also stand in front of the displays over longer time. **All of them will have the possibility to interact with the displayed content to a certain degree.** Hence, one user might moderate the discussion or exploration process and will control the possibilities of changing the content. For such data explorations, users follow the "bring your own device" (BYOD) [22] approach and will bring data "on" using mobile devices. This data will not necessarily be stored physically nor rendered on the device, but the device will provide access to the data, stored on remote, networked storage. These mobile devices will also be used to interact with the content on the LHRD. Furthermore, direct touch will play a major role as input technique and thereby replace the mouse and keyboard as the physical objects are not always within reach.

Work environments will benefit from LHRDs the most, as they are places where data exploration is performed as professional and economical success is depending

on it. As understanding large, complex systems and data sets is also fundamental for self-development and forming of opinions on a society level, we will see LHRDs in semi- and public space and later also in private homes.

In public spaces, we already see a high number of displays; informing about public transport and local attractions or displaying advertisements. Furthermore, they are used in museums to enhance the exploration of digital content. There, visitors will be able to interact creatively with digital copies of exhibits and will thereby explore cultural heritage in a fundamentally new way. Users will interact mostly through direct touch gestures or using the BYOD approach. At information kiosks, it will be important that the display communicates an overview about the content on the first glimpse. However, detailed information can be spread out and not available from every position. This will allow distributing users in space for parallel interaction. In contrast to displays in office environments, the aspect of privacy limits the use of public display for private content.

In private homes, LHRDs will become part of the furniture. They will be used for consuming media, playful interaction, ambient information and data exploration. Here, users will mostly interact with the display by using speech, mobile devices like smartphones and tablets, and direct touch gestures. Most of the time, applications will utilize the whole display space for ambient information and decorative purposes. When more complex information is presented, information pieces will be grouped by topic or relevance.

In summary, we observe a trend of work tasks moving from recurring and well-specified tasks towards knowledge- and data-driven decision making tasks. Desktop computers opened a window into a digital world supporting writing, calculations and communication. LHRDs offer the opportunity to change how users understand data by enabling them to explore complex and highly connected digital worlds.

2.2 Practitioners' Point of View on Designing for LHRDs

While the HCI research community has discussed ways to make efficient use of abundant display space for decades, this challenge is quite new to practitioners. Thus, we wonder how interaction design practice can borrow from research findings. Further, as practitioners begin designing applications for LHRDs, they

are bound to face a new set of challenges that may, in turn, yield new relevant research questions. We report on our inquiry where we engaged with practitioners working in four different locations who had preliminary experiences of designing for very large displays to understand their attitudes, the design challenges they face and possible opportunities for building practice-inspired research questions.

This chapter is based on the planned publication: L. Lischke, A. Beham, L. Janietz, H. Bohnacker, U. Schendzielorz, A. Schmidt and P. W. Woźniak. The Practical Challenges in Designing Interfaces for Large Displays.

2.2.1   Method

We conducted four interviews with interaction designers designing large display applications and communicating information visually. All designers worked for industry projects, but also had relations to academia. In the interviews, we focused on their understanding of large displays and their experiences of turning early designs into working applications on large display setups. All interviews were audio recorded. In total, we recorded 4:30 h of interviews.

Participants

In the four interviews, we had five interview partners, as one interview was with two employees of a design studio in Germany focusing on media installations (in the following I1 and I2). Both of these interviewees also lecture at a school for applied sciences. We also talked with a leading User Experience (UX) designer at a soft- and hardware company based in the USA (I3). Furthermore, we interviewed an information visualization expert (I4), who worked for a data analytics company and is now working at a university in Sweden. Finally, we conducted an interview with a founder of an interaction design company focusing on exploring data visually (I5). Additionally, I5 is an active researcher at a university in Finland. Due to their background and daily work, with the first three interviewees we focused on designing for LHRDs. In the last two interviews, we changed the perspective to how information visualization designers see and use LHRDs. While we used interview scripts, the script of each semi-structured interview was adjusted to the specifics of the work of the interviewees.

Analysis

As the content of the interviews was varied, and we did not use a uniform script for practical reasons, we decided that a full formal analysis of the interviews was impossible. Instead, two researchers listened to the recordings and made structured notes of remarks relevant to LHRDs. Next, in a series of interactive discussions that used affinity diagramming, the notes were grouped into themes.

2.2.2 Findings

Based on the interviews we determined eight themes to understand interaction design for LHRD in practice. We present the themes here and contrast our practice-based findings with the current state of the art in academic research.

Size and Resolution

Three interviewees had a similar understanding of what "large" meant. I3 remarked:

> "I think about it [a large display] as anything that is bigger than you would normally have on a desktop. In my opinion, that is about 42 in."

I1 and I2 explained that they had started to work with a large display when they used screens with a diagonal of 46 in. Today, they normally use screens with a diagonal of 55 in. However, this seemed to have been due to the availability of display hardware. For most customer projects, I1 and I2 used multiple 55 in screens aligned in portrait mode next to each other. According to I1, this size was optimal for installations, where the users were directly touching the displayed content. I2 argued that, for the design process, it was more important to know whether the customer had requested an application with multi-user capabilities or not. In contrast, I3 reported on projects where the customer at the beginning defined only the requirement of a "big screen". This could have been between 42 and 72 in diagonal.

Regarding digital size, I2 explained that he started to work with a resolution of 768×1344 pixel on display with a 46 in diagonal. Today, I1 and I2 work mostly with a resolution of 1920×1080 pixel (full high definition) per 55 in screen. Thereby, images, particularly text elements, are clear. Even if an increase of

resolution would also mean an increase in design complexity, they expressed their willingness to use screens with a resolution of 3840 × 2160 pixel (4K).

This vague definition reflects the "frivolous" use of terms for large displays in academia. With the advances in display technology, available displays get larger and the understanding of what large means is changing. Because of this Andrews et al. [13] propose to define large high-resolution display (LHRD) as a display that "closely matches the sphere of perception". This definition shows clear differences between the understanding in academia and industry.

Multiuser vs. Single-User

I2 argued that whether an application had multiuser capabilities or not was more important for the design process than the display size. For him, single-user applications were mostly information kiosks, providing particular information to one guest, customer or visitor. These applications use mostly one screen up to 55 in diagonal. However, multiuser applications normally do not include any interaction between the users in front of the display. As an example, he presented an interactive multimedia exploration exhibit at a museum. In such multi-user scenarios, the most challenging design part seemed to be the separation of the users and guaranteeing that their interaction zones did not overlap.

Work conducted by Peltonen et al. [197] reflects on these phenomena for public displays. However, the majority of work in HCI focuses either on multiuser interaction, which includes the users interacting with each other (e.g., [40, 117, 260], and Chapter 8) or on single user scenarios (e.g. [11, 202]). This highlights a clear contrast between how future visions of LHRD interaction in HCI fail to address the practicalities of using a large display today. In Chapter 5 we address the question of how pairs of users move in front of an LHRD when they are not collaborating. Future work should explore parallel work on LHRDs more deeply.

Input Techniques

I1, I2, and I3 agreed that direct touch was the most important input technique for large displays. I3 explained that the company she was working for only built large display installations with direct touch input. She argued that mouse and keyboard do not work with a large display in public:

> "If you have a kiosk in a store or a public place [...], nobody wants to have a keyboard or a mouse there. Touch is just convenient. And

> then, it's really fun to touch a big screen. I think there's just like the emotional part of it."

I1 supported I3's argument but raised the general question of text input on large displays.

> "Entering longer text on a large display is almost impossible. Also, an on-screen keyboard creates a wall, which prevents interaction."

I3 built prototypes allowing the user to interact through mid-air gestures, In contrast, I2 implemented projects for customers which allowed interaction through mid-air gestures, using a Microsoft Kinect. He could also think of tailored control panels. However, from his point of view, both interaction techniques were only well-suited for scenarios when the user was too far away to perform direct touch input. All gestures had to be very simple because the large display setup was used by non-experts for a short period of time. I1 assumed that speech detection would be one of the most important input techniques in future.

Other input techniques explored by academia were not known to designers. A body of work explored combinations of large displays and private devices following a BYOD approach (e.g., [40, 231], and Chapter 8). While these interaction patterns are now implementable in production environments, designers did not consider interacting with a large display using, e.g., a smartphone.

Interaction Duration

All three interaction designers (I1, I2, I3) implemented projects for show rooms, museums, and information desks. I2 explained:

> "They are short-term usage applications, for users passing by or looking for short information. Here we have a dwell time of 10 to 15 minutes."

I1 and I2 would have liked to implement applications for longer interaction durations, however, there seemed to be no market for it. A common question I1 received during industry fairs when presenting large display prototypes was:

> "How do I use my Excel on this touch display?"

This shows the interest of the industry to move tasks performed today on desktop setups to novel user interfaces built on LHRDs. However, a smaller interaction design company is not able to build such products. Concurrently, little to no academic research has addressed how LHRDs can transform office environments.

Content

On a general level, I3 saw the advantage of LHRDs compared to a whiteboard:

> "A big screen has the same advantages as a whiteboard or a big canvas if you are an artist. You're able to utilize the space and see things laid out and show a lot of complexity."

Due to the short interaction dwell time, three interviewees argued that images and graphically represented information worked were always well supported by large screens. Additionally, I1 appreciated video content. He remarked, however, the challenge of presenting the audio accompanying the video effectively. He argued that it was possible to use directed speakers. To use directed speakers, the system needed to know the position of the user, which, in turn, called for extensive extra infrastructure. I1 argued that large displays were well-suited for presentations. She saw a benefit in having a person explain when others could listen and explore content on their own:

> "The person does their presentation, and while he or she is doing it, the others are touching the screen, walking around."

This was perceived to be in line with the visual appearance of large displays. I2 explained that large displays were attractive to many consumers. I3 described large displays as "dramatic".

For accessing information, I1 explained that they observed a shift from making all information accessible everywhere on a screen to make the user move to specific positions. Thereby, the menu depth could be reduced, and more information could be on display all the time. This allowed for offering the user a better starting experience and possibly a stronger interaction trigger.

I3 wondered why employees in her team thought more about a desktop application when designing for large displays, instead of smartphones. I3 argued that the interaction concept for LHRDs were closer to smartphones than to desktop applications. Buttons and other visual elements have to be large enough to be easily touched. However, I3 argued that everything that is possible on a desktop is possible on a large display, and vice versa.

Prototyping and Testing

As I2 explained, it was not always possible to have a full-screen setup for designing and testing. Hence, I1 and I2 simulated the resolution by adjusting the resolution of parts of the interface in Photoshop. To get a feeling for the size they had a physical yardstick on the desk. When possible, a sketch of the whole interface on a wall was used. I3 saw the biggest challenge in designing interfaces which were appealing from both far away and when the user was close to the screen. I3 explained that the designs were heavily inspired by digital signage.

I1 and I2 were also engaged in usability testing for web pages to increase the viability of the customer. However, they did not establish a standardized process for large display installations. They performed only short informal testing with colleagues, customers, and passers by. They argued that customers would not order standardized usability testing for LHRD. They stipulated that the reason might have been that most customers perceived a large display as highly visible and appealing in any case. Finally, standardized usability testing particular to large displays is simply unavailable.

Technical Challenges

When implementing large display installations, designers and developers faced a number of technical challenges. First, the availability of different sizes and resolutions is limited. Hence, I1 and I2 used mostly bezel-free 55 in screens. Large displays with a higher resolution are not easily available on the market. Additionally, I2 explained that the selection of the glass to be mounted in front of the display and to be touched by users was not straightforward. It had to feel soft when the user touched it or the touch experience would be negatively influenced. Furthermore, I1 and I2 reported that multiscreen installations required the graphical power of several computers. This created the issue of transferring visual content from one computer to another. With an increase of the screen resolution, this becomes more challenging.

Visual Information Seeking

When talking to information visualization experts, we recognized that I4 saw large displays as a promising additional tool to communicate data. However, I4 argued that Schneiderman's visual information seeking Mantra [221] solved the challenge of limited visual space already for desktop setups well. Thereby, I4 warned about overestimating the effect of being able to see details and get an

overview at once. Nevertheless, I4 still saw defining the right amount of data visualized at once on a large display as a key challenge.

2.2.3   Research Challenges

Based on the eight themes we identified in the interviews, we synthesized three challenges for HCI research to impact the design of future LHRD applications outside academia.

Designing, Prototyping, and Evaluation Methods

Prototyping LHRD applications differs fundamentally from designing for desktop applications or mobile applications. Due to the physically large size of the application, it is often not possible to prototype in the original size. Furthermore, evaluation methods have to be adjusted to all application domains. Alt et al. [8] present a starting point of this for public displays. Yasuto Nakanishi [184] proposed a combination of building miniaturized models and virtual prototyping for large interactive spaces. Well-defined prototyping methods will support practitioners to communicate concepts at an early stage to customers. Simultaneously, standardized evaluation methods will help practitioners to show the benefit of well-designed LHRD applications. As the HCI field has a proven track record in establishing reliable methods, the HCI community should strive to develop methods for LHRDs before they are easily available on the consumer market.

Moving on from Demos to Work Tasks

Currently, most large display applications are designed to impress customers and partners during industry fairs and in showrooms. Furthermore, large displays are used on information desks and in museums for short interaction periods. As research discusses performing complex tasks on LHRDs intensively (e.g., [16, 114, 115, 152]), interaction designers and their customers seem to be interested in utilizing the advantages of LHRDs for tasks requiring a longer period of interaction. However, the industry seems to avoid the high costs of designing such applications. Hence, research can lower the risk by defining guidelines and providing a detailed understanding how to utilize the advantages of LHRDs in complex task. Little research work has addressed how LHRDs can transform office work or perform in big data analytics for businesses. It appears that it is a challenge for the research community to investigate the affordances of large

screens in their areas. This also presents an opportunity for HCI research to drive a possible new generation of office environments.

Input Techniques in the Wild

Past research discussed many approaches to interact with content displayed on LHRDs. This ranged from touch (e.g. [124]) through mid-air gestures (e.g. [268]), multimodal input (e.g. [51]) and eye tracking (e.g. Chapter 6) to multidevice interaction (e.g. [40]). However, nearly all commercial applications use only direct touch for data input. While this can be partly explained by the aforementioned focus on short interaction periods, an open question is why designers do not even consider alternative input modalities. It remains a challenge for the research community to make a substantial argument for alternative input modalities, which have been proposed in past publications. Through research prototypes and rigorous evaluation, the HCI community has an opportunity to participate in creating widely used viable input alternatives for LHRDs.

2.2.4   Limitations

While we did try to provide an unbiased account of the practitioners' work with LHRDs, our work is prone to two limitations. We conducted interviews with practitioners who were willing to contribute to our study and within our larger professional network. We focused on those working with more explorative, atypical projects as we believed these designers would have more experience with large screens. A question that remains, however, is how the accounts presented here differ from those that could be gathered when working with designers from leading large companies in the industry.

Furthermore, we wonder how many of the issues discussed above can be explained by legacy bias, which is present both in users and designers. As past work has shown that LHRDs often require radically new approaches, it is possible that applying well-rehearsed design processes and assuming past user requirements may a be a root cause of at least some of the issues discussed in this work.

2.2.5   Conclusion

We reported on our interviews with practitioners who design applications for large displays. We identified eight themes that characterize current interaction design

for large screens: size and resolution, multiuser VS. single-user, input techniques, interaction duration, content, prototyping and testing, technical challenges and visual information seeking. Further, we presented three practice challenges for the HCI community that emerge from the themes: *Designing, Prototyping and Evaluation Methods*, *Moving on from Demos to Work Tasks* and *Input Techniques in the Wild*.We hope that our work will help bridge some of the gaps between the academic and practitioner communities focusing on LHRDs and help interaction design prepare for even more LHRDs in everyday environments.

2.3   Contextual Inquiry into Todays LHRD Workplaces

For the last four decades, research has explored the design space and the advantages of LHRDs and multidisplay environments. However, the usage of LHRDs is still not commonplace and is limited to specific areas. Today, we see LHRDs as public displays, mostly displaying non-interactive advertisements or guiding information (e.g. [183]). Slowly, LHRDs becoming popular as interactive information screen in museums (e.g. [198]) and showrooms. Furthermore, we see LHRDs used in research labs (e.g. [34, 202]). In contrast, we observe only slowly increasing screen sizes for regular working environments. Control rooms are one exception, where LHRD workplaces are commonplace. Thus, control rooms provide the unique opportunity to understand how LHRD workplaces are used outside of academia today. Thereby, we can identify challenges and design implications for LHRD workplaces. Here, we present the results of our contextual inquiry of a public transport control room in a major south German city. The observed control room has been recently modernized and described as state-of-the-art.

2.3.1   Related Work

Contextual inquiries are a widely used method to understand workflows [32]. Different aspects of the work performed in control rooms have been studied in detail. Heath and Luff [95] highlight the combination of collaborative work and use of multimedia technology. They present a detailed and well-structured description of work processes and tools used with a focus on collaboration in underground control rooms in London. Christer Garbis [76] extended the work on ethnographical observations of work performed in control rooms with a focus on shared cognition. In particular, he highlighted the importance of shared displays for control room staff members. Wendy MacKay [159] analyzed the importance of paper flight strips in air traffic control through observations. Thereby, she highlighted the challenge to improve safety critical systems and argues for augmenting tangible paper strips, instead of replacing them in with a fully digital solution.

Müller et al. [182] observed a trend from tangible controls to digital and only visual controls. Hence, the authors recommend to use a combination of tangible controls flexible placed on touch displays. Domova et al. [53] argue to provide haptic feedback though input devices such as the mouse or slider knobs. In contrast, Heimonen et al. [96] proposed to improve human-computer interaction in control rooms through gestures and speech control. Prouzeau et al. [199] presented a system to visually compare life road traffic data with simulation data on a touch-enabled LHRD. The presented prototype changes the work environment from a desk environment to interaction while walking in front of the display. This allows the users to observe and understand the displayed content in a new way and enables users to perform more body movement while working.

2.3.2   Contextual Inquiry

To build an understanding of how work in a modern public transportation control room is performed and how interactive technology is used, we conducted 18 hours of observation. Furthermore, we interviewed staff working in the control room with a focus on workflow and used tools. To avoid influencing the staff during their work and due to regulations, we did not audio or video record our observation sessions. Instead, two researchers observed all actions during the sessions and took notes and sketches. We conducted the observation during three sessions. One session was on a Wednesday morning from 6:00 to 12:00, including the morning rush hour. The second session was during regular daytime

on a Friday between 10:00 and 16:00. The last session was during a night shift from Saturday 21:00 to Sunday 3:00. During this shift, the staff members also monitored maintenance work in the field.

2.3.3   Findings

We grouped our findings based on the observations in the categories physical arrangement of the work environment, content alignment on displays, and input techniques used to interact with digital content in the control room.

Physical Arrangement

The analyzed control room had eight working desks. Two tables were for the tram signal tower. At one desk, one assistant scheduled the tram traffic; at another desk, one assistant scheduled the bus traffic. At another desk an assistant coordinated all information channels for passengers in vehicles, on stations and using online information systems. Two additional desks were for major events and training sessions. The last desk was for the general coordinator, managing all staff in the control room. All desks were oriented towards a large projection screen. This screen is used to display live-views of surveillance cameras or urgent information to all staff members.

Every workstation desk was curved to provide easy access to all areas of its surface. Each desk was automatically height adjustable to allow staff members to adjust the table height to their preferences; thus the desk height and the height of the displays could be adjusted separately. This allowed staff members to stand and sit during their work. The possibility to work in various body postures was used by most staff members regularly, with the preferred posture depending on ongoing actions. In emergency cases the demand for coordination between staff members increased. Then, all staff members worked in a seated position because this allowed everyone to look above the displays and have face-to-face interaction.

Every working desk was equipped with six regular office screens. Each screen had a diagonal of 24 in and FHD resolution. All six screens were in landscape mode and horizontally aligned. In a regular working position, it was not possible to focus on the whole display space at once; to change the focused area, staff members had to rotate their head or body. Furthermore, every desk was equipped with a phone and a microphone for radio communication with drivers. The two tram signal tower desks were equipped with six additional screens for train protection. These screens were also oriented in landscape mode but aligned in

a 3 × 2 grid. The software and screens used had to fulfill high safety standards regarding reliability; furthermore, the train protection system had to be isolated from all other systems due to security reasons.

View Arrangement

Normally one view was displayed in one application window in full-screen mode on one screen. We did not observe application windows spread out over multiple screens or the entire display space. The single screens were used as containers to order different views; furthermore staff members could switch the displayed views between several predefined scenarios. By default, a set of scenarios is provided. They could also define personal scenarios to fit their workflow better. Besides the large visual output space, audio notifications were used for events triggered by applications that were not on display. When staff members opened new views, we observed that the views sometimes appeared in arbitrary positions. This created additional demand to search for the view and move it to the desired position. In interviews, staff members stated that they would prefer having even more display space. This would allow more views on display at the same time without switching single views or full scenarios.

Input Techniques

To perform input, staff members used one computer mouse and a regular keyboard. The working desks for the tram signal tower had an additional mouse and keyboard for the train protection system. Every workplace was equipped with an additional keypad to switch between the different scenarios. This keypad allowed warping the cursor to one of the six screens directly. However, it was not obvious to the staff members where on a particular display the cursor would appear, so this function was rarely used. Instead, the staff members usually moved while clutching the mouse until the cursor was at the desired position. The high number of independent software systems often created situations in which staff members had to interact with multiple application windows at once. In interviews, the staff members explained that they would like to have separate input focus for mouse and keyboard, because after clicking in one application they forget to reset the input focus before performing keyboard input for another application window.

Additionally to a high number of automatically logged events we observed other events, which were reported or noted on paper. This had the advantage that the reporting could performed without requiring screen space or input focus. The paper-based notes could be handed over quickly to another staff member.

2.3.4   Discussion

Our observations indicate challenges for the general design of LHRD workplaces and GUIs for LHRDs. We classify these challenges into the following categories: input techniques, physical display space, and content management.

Input Techniques

Our observations show the challenges to perform input on larger display spaces. The large display space creates a high physical demand to move the mouse cursor across the display space. Over one decade ago Robertson et al. [208] described the challenge of long cursor distances and cursor lost when using LHRDs. The additional keypad to warp the cursor to a specific display does not solve this challenge, in particular because the exact warp position is not obvious to the user. Visually searching the cursor even on a smaller area such as a regular office screen creates a highly distracting demand. One solution to replace the cursor would be enabling direct touch. In particular in this scenario, where all the display space is in arm's range, touch input could improve the interaction. More generally, we discuss in Chapter 6 utilizing eye tracking to support pointing tasks on LHRDs. When using eye tracking, the advantage is that the distance between user and the display can be arbitrary. In the next step it is important to refine research prototypes to techniques used in practice.

The possibility to have a large number of application windows on display at the same time creates the need to separate the input focus of the different input devices. For staff members at the control room would it make sense, to be able to lock the keyboard focus to one application, while working in other application windows with the mouse.

Display Space

In comparison to previous work by Christer Garbis [76], Heath and Luff [95], the personal display space per control desk has increased dramatically over the last three decades. Today, the standard working desk at the control room today is equipped with a large display space. Furthermore, the commonly used shared diagram displays have been replaced with fully flexible large projection screens. Also, other out channels such as audio notifications are used. Nevertheless, staff members stated that they would prefer to have even more display space for each working desk. This would allow seeing more "scenarios" without manually switching them. Hence, the staff members perceive physical navigation to be

less demanding than virtual navigation. This is in line with results of a lab study presented by Ball et al. [21]. Ball et al.'s results showed that participants were able to extract information faster and with less effort when navigating physically instead of virtually changing the viewpoint. Furthermore, the request for more display space indicates that humans can interact with very large visual spaces without being overwhelmed. This we will discuss later in detail in Chapter 4.

Managing Content

In the control room, we saw that one application window was displayed on one single screen. This shows that staff members make use of the physical display design to organize their screen space. Wallace et al. [262] showed that participants could extract information faster when utilizing screen bezels to divide the display space. The design of GUI for LHRDs should take physical bezels into account. For setups with a display without bezels in between, the GUI design should provide visual support to divide the display space.

When working with LHRDs, the visual position of an event becomes essential. Staff members in the control room reported that some application windows do not appear at the expected position, so when a manually opened application window or dialogue box appears out side the focus area the user has to search the GUI element visually. However, this could have safety consequences if the user dismisses an important notification triggered by the system. Hence, carefully designed notification and event systems have to be developed and to do this it is important to understand how users interact with the visual space provided by the LHRD. A detailed understanding of human visual perception on large visual areas is required, and LHRD systems should make use of the user's head and gaze position to detect their visual focused area. As a first approximation the input focus could also be used as a position for notifications and displaying new dialogues and application windows.

2.3.5 Conclusion

In control rooms, complex processes are monitored and managed so, staff members have to take system relevant and often safety-critical decisions. Staff members are supported by a large amount of information displayed on LHRDs. The usage of large display spaces enabled us to observe common work practice and identify challenges for interacting with LHRDs. The findings of our observation show that adequate input techniques for LHRD have to be developed and moved

from research prototypes to practice. Furthermore, GUIs have to present relevant information on the best spatial position to be recognized by the user.

2.4 Requirements

This section summarizes the findings of the comprehensive qualitative investigation into a set of requirements. The rationale for the selection was to cover relevant aspects identified in the investigations. To make the requirements usable for practical implementations, we present them as a small set of parameters.

Display size

To classify a display as large, we follow the definition for LHRDs by Andrews et al. [13], i.e. that the display size must match closely with the human perception and has to cover at least the field of view of the user. Also, displays larger than the field of view can be beneficial. Then, the user must to perform head and body movement to see all content. From a practical point of view, this highly depends on the distance between the user and the display. For most applications, we focus on arm reach distances to the display or in seated scenarios, we use distances between 80 cm and 120 cm.

Display resolution

The display resolution determines how much visual data can be displayed at once at the display. For the user experience and user perception the relative pixel resolution, measured in PPI, is decisive. Comparably to display size, the perception of the pixel density depends on the viewing distance. Under no circumstances should the user be able to distinguish single pixels. In Chapter 3, we will see that users perform efficiently even using low resolutions; however they value higher resolutions. Higher pixel densities on large display spaces significantly increase the technical complexity. Hence, it is a trade off between display size and display resolution and technical feasibility. In the scenarios on which we focus we use a pixel density of 88 PPI.

Display refresh rate

For moving content, and particularly when the movement is created through interaction, the display refresh rate is critical for the user experience. The refresh rate should be above the rate that the human eye can register it. For example, PAL television used a refresh rate of 25 Hz. Modern transmission standards and computer displays work with 50 Hz or 60 Hz [195]. To avoid a negative influence on the user experience or performance, we always use 60 Hz.

Preventing visual overload

When users are confronted with a large amount of visual data, they can be easily overwhelmed and lose focus. LHRDs systems must support users to focus on particular information. Furthermore, GUIs must manage the cognitive load of the user to provide optimal working conditions.

Guiding user attention

When working with LHRDs, not all the visual information displayed is in the field of the user at once. However, regions of interest, e.g. notifications, have to be discoverable by the user without extra effort. Furthermore, content changes which are not immediately necessary for the user should be displayed without user noticing.

Fast and easy access to documents and functions

With the increase of display space, the amount of displayed content also increases. The variety of content and the long distances make selecting the desired content challenging. Hence, appropriate input techniques are required. On the one hand, input techniques need to respect human physiology. On the other, these techniques have to enable the user to select desired functions and content quickly without great effort.

II

UNDERSTANDING PEOPLE INTERACTING WITH LARGE HIGH-RESOLUTION DISPLAYS

OUTLINE

To be able to design well-suited interaction concepts for LHRDs, it is essential to understand the human behavior and physiology employed during such interactions. We start in Chapter 3 with analyzing the influence of screen resolution on user performance, perception, and behavior. We conducted a lab study comparing four relative resolutions, presenting image, text and video content to participants on a tablet. The results in consideration with previous work in this area show that user performance only increases up to 90 PPI. However, higher relative resolutions affect the perceived effort and the perceived media quality.

In Chapter 4, we analyze how users explore text-based documents on various screen sizes. The results show that users are able to get an overview of large display spaces efficiently without being overwhelmed. When the display is wider than 2 m users start to walk in front of the display, which increases the perceived physical effort.

LHRDs enable multiple users to interact with visual content in parallel. This can be done either in a collaborative, individual or even competitive way. In Chapter 5, we explore movement and behavior patterns in collaborative and competitive scenarios. To explore these patterns, we designed and developed an LHRD multiplayer game for a lab study. The results show that the users distribute themselves in front of the display in collaborative scenarios, while they stand close to each other in competitive scenarios.

Chapter 3

The Influence of Screen Resolution

For decades now the physical size and the absolute visual resolution of desktop displays have been increasing. Both measures influence how much information can be displayed at the same time; thereby, also influencing the interface design and the interaction. Modern desktop displays have a FHD[10] or 4K[11] resolution with a size of 24 to 30 in resulting in an approximate relative resolution of between 90 and 180 PPI. Also, the first 27 in 5K displays with a resolution of 5120 × 2880 pixel are now available on the market. In addition the first 8K ultra-high-definition (8K) screens with a size of than 32 in are available on the market soon, although due to their physical size, the is 275 PPI lower than on current smartphones and comparable to today's desktop environments. All existing LHRDs are built out of multiple single screens or projectors, each working with one of the described absolute resolutions. For example, the VISUS-Powerwall is

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[10] Full high definition (FHD) describes the resolution of 1920 × 1080 pixel. The term 1080p is synonymy to FHD.

[11] Ultra-high-definition (4K) describes the resolution of 3840 × 2160 pixel. The term 2160p is synonymy to 4K.

driven by ten 4K projectors[12], and the iWall developed by Multitaction consists out of multiple 55 in FHD screens[13].

Knowledge about the influence of the resolution on user performance and perception is required to build LHRDs and design interfaces for such displays. A higher resolution causes higher costs for screens and requires more computing power to display content. On the other hand, a high resolution might enhance working with visual content. Same absolute resolutions, in particular FHD, are used for mobile devices, such as smartphones and tablets. Due to the smaller physical size, the relative resolution is higher with the same absolute resolution. Hence, mobile devices are optimally suited for analyzing the influence of the relative resolution on user performance and perception. In chapter 3 we present a comparison of four different screen resolutions simulated on one tablet display for common tasks performed on tablets.

This chapter is based on L. Lischke, S. Mayer, K. Wolf, A. Sahami Shirazi, and N. Henze. "Subjective and Objective Effects of Tablet's Pixel Density". In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2769–2772. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702390[a]

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[a] A video of this study is available at YouTube: www.youtube.com/watch?v=VNfwBHzxu5g

3.1   Related Work

The influence of the visual resolution of visual content on user performance and perception is within the interest scope of human factors, ergonomics, and HCI. Often the research questions focus not only on the visual resolution, but also on the comparison of different media.

The advances in display technology, over the last decades, also improved the user performance. In 1992 Andrew Dillon [50] surveyed research comparing reading on paper to reading on electronic devices. At this time, reading on paper was more efficient than reading on screen. Researchers even argued that reading on

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[12] https://www.visus.uni-stuttgart.de/en/institute/visualisation-laboratory/technical-details.html

[13] https://www.multitaction.com/hardware

paper would never be replaced by on-screen reading. In 2011, in contrast, Ball and Hourcade [20] showed that comprehension and reading speed is similar for paper and computer displays. The authors explain this contradiction fin findings with participants' increased familiarity and the improvement of technology. This suggests that the characteristics of the computer screen affect real-world tasks. Menozzi et al. [176] compared different display technologies using a visual search task. While the results show that improved output devices can increase users' performance, they also suggest that even clear differences do not necessarily result in a measurable effect.

Ziefle [283] examined the effect of cathode ray tube (CRT) screens' pixel density (60 PPI and 120 PPI) in comparison to text printed with 255 DPI. For a proof-reading task, she found that paper significantly outperformed the other conditions but observed no significant difference between the two screen conditions. In a complementing study, however, Ziefle compared three pixel densities (62 PPI, 69 PPI, and 89 PPI) and found a difference between the two lower densities and the higher one in terms of subjective feedback and objective performance when searching for characters. When LCDs replaced CRTs, studying the effect of pixel density became challenging as one LCD cannot display different densities. Therefore, studies that aimed to compare different densities have been conducted using different displays (e.g., [107, 276]) or with one display by changing the size of the visual output [42]. In both cases, one cannot differentiate between the effect of the display or its size and the effect of the pixel density.

Overall, previous work showed that an increase of pixel density from 69 to 89 PPI could improve participants' subjective ratings and objective performance for one specific task [283]. The pixel density of current devices is, however, much higher than what could be considered by Ziefle [283] at that time. Today's smartphones and tablets commonly have a pixel density of several hundred PPI and with 4K displays, also the resolution of desktop screens is rising to several hundred PPI. However, it remains unclear if further increasing the pixel density from 89 PPI will sustain the positive effect. Furthermore, previous work focused only on reading and text-based tasks, while all common displays today are also used for other media types. Ziefle's work [283] indicated that the effect of pixel density is task dependent. Today's increased relative visual resolution and the change in displayed media raises the research question about their perception and influence on performance. This is in particular important for LHRD setups, because higher relative visual resolutions massively increase the computational effort on larger displays.
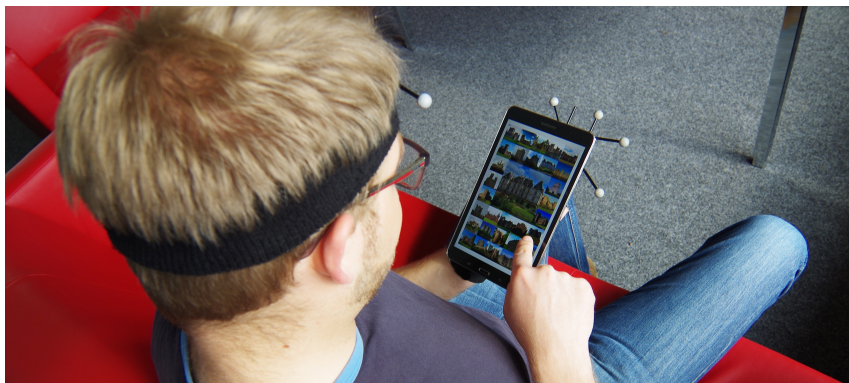
Figure 3.1: Exemplary study setup with the image task in which the participants compared various images.

3.2   Experiment

To analyze the influence of the relative screen resolution on user performance, behavior and perception, we designed a repeated measures lab study. In this study we used three tasks to assess the effect of pixel density on tablets. We used a tablet device with a resolution of 2560×1600 pixel and a density of 359 PPI. We combined groups of 4, 9, and 16 pixel resulting in additional pixel densities of 179.5, 119.7, and 89.8 PPI. In the following, we use 180, 120, and 90 PPI to describe the densities we used. These three lower pixel densities and the native pixel density result in four conditions. Using a repeated measures design, every participant performed all three tasks with all four conditions. The order of the conditions was balanced using Latin square.

We recruited 16 participants (11 male and 5 female) aged between 21 and 43 ($M = 26.7$, $SD = 5.2$) through our university's mailing list. All of them had normal or corrected to normal vision.

3.2.1   Tasks

We designed three tasks which represent actions commonly performed on tablets: messaging, information look-up and browsing social media [181]. On a more

abstract level looking at and comparing images, reading texts, and watching videos are sub-tasks of these activities.

In the image comparison task (image task), we presented five sets of 32 images. Every image set contained images of persons or objects. All images were collected by searching for keywords on Flickr. As categories, we used portraits of women and men, landscape photos of castles, cars, and coins. All images in one set were comparable in terms of color and perspective to minimize color based search strategies. The images were arranged in a grid with five columns and eight rows. All images had a size of 21.2×21.2 mm (300×300 pixel on the highest density). In the upper center, we placed one image which was three times larger (63.8×63.8 mm). One of the smaller images showed the same person or object as the larger one but from a different perspective. The participants' task was to compare the small images to the larger image and to select the matching image as fast as possible. Figure 3.1 shows the task with a participant searching the correct image. Every participant performed the task using each of the five categories and each of the four pixel densities. We ensured that every image was only shown once to an individual participant. Furthermore, the positions of the small images were randomized. We will call this "image task".

In the word count task (text task), the participant had to count how often a specific word appeared in a given text. Before one text was shown to the user, we displayed a message that specified the word that should be counted. To support the participant the target word was displayed in the upper left corner while the text was shown. We selected 12 text sequences with a length of 300 words from different fairy tales in the English language. All words which should be counted were common English words, like "she", "with", or "into" with a length of three or four characters. The target word was included in the text between one and eight times. As the font, we used a regular font (Sans) without serif with a font size of 45 pixel at full resolution. This equals a height of 3.2 mm. The font style and size is comparable to the standard font on the used tablet. We placed the text in the center of the screen. On the bottom of the screen, we placed ten buttons to enter how often the target word was counted in the text. For every condition, we repeated this task three times. In the following, we call this task "text task".

In the video analysis task (video task), the participant watched three videos of 10 s that showed five people standing in a circle and passing three balls around. The position of the camera was fixed and showed the whole group all the time. The task for the participants was to count the total number of throws in the video. We decided to use videos in which people were passing balls around because the action happening in all videos was comparable. Each video was played once with

a frame rate of 20 fps. Participants could not pause or replay the video. After watching a video, participants were asked to enter the number of throws. We call this "video task".

3.2.2 Measures

To analyze the influence of the relative screen resolution on performance, behavior and perception, we measured the following dependent variables during the study:

Distance between participant's head and screen *[mm]*. To measure the distance between the tablet and the eyes of the participants while performing the task, we used a motion capture system. Therefore, we mounted optical markers on the tablet and asked the participants to wear a headband with optical markers.

Perceived mental effort (PE). To rate the PE, we asked every participant after each task to rate the perceived mental effort on the SMEQ scale [285]. This scale goes from 0 (no effort) to 150 (high effort) and is known to be very sensitive to small sample sizes [215].

Perceived media quality (PMQ). To rate perceived media quality (PMQ) we used the ITU-T P.910 questionnaire, which goes from 0 (bad) to 10 (excellent) [204]. We asked the participants to rate the media quality after every task.

Task completion time (TCT) [s]. The study apparatus software on the tablet automatically logged the time between the appearance of the task and the completion of the task.

Error rate (ER) [%]. The study apparatus software on the tablet automatically logged the number of right and wrong answers.

3.2.3 Procedure

After welcoming every participant, we asked him or her to read the consent form and agree to the terms and provide demographic information. To track the distance between head and tablet we equipped the participant with optical markers. While the participants were performing the tasks they sat on a chair without using a table, thereby, being forced to hold the tablet to allow varying the distance. Every participant performed 33 trails from four pixel densities times the five sets of images, the three sets of texts and the three sets of videos. After

performing one task on one density, we asked the participant to rate the PE and the PMQ.

3.2.4   Apparatus

Differing characteristics of even similar displays such as contrast, brightness or response time might influence the results of the study. Therefore, we decided to use only one device to minimize the number of uncontrolled variables. In the study we used an Android tablet; namely a Samsung Galaxy Tab Pro 8.4. The tablet has an 8.4 in display with Wide Quad Extended Graphics Array (WQXGA) (2560×1600 pixel) screen resolution. To lower the perceived pixel density we scaled down the material used in the study to the respective density. We scaled the content up again using nearest-neighbor interpolation. Thereby, groups of pixels were combined without any smoothing. With the use of a motion capture system and the attached markers, we measured the distance between the eyes of the participant and the tablet while performing the tasks.

3.3   Results

For each task, we compared PE, PMQ, TCT, and ER between the four different pixel densities by conducting one-way repeated measures analysis of variances (RM-ANOVAs). Degrees of freedom have been corrected using Greenhouse-Geisser estimation of sphericity if necessary.

As post-hoc tests, we conducted t-tests with Bonferroni correction. Table 3.1 shows the resulting values for PE per pixel density and task; Table 3.2 shows the resulting values for PMQ per pixel density and task. Overall, we found no significant effects on the distance between tablet and head and on error rate.

3.3.1   Image Task

We could not show a significant effect of pixel density on PE ($F_{1.63,24.39} = 3.35$, $p = .061$, $\eta^2 = .182$). However, the analysis revealed a significant effect of pixel density on PMQ ($F_{3,45} = 12.6$, $p < .001$, $\eta^2 = .456$). Post-hoc tests revealed that PMQ for 359 PPI was significantly higher than for 120 PPI ($p < .001$) as well as than for 90 PPI ($p < .001$). Furthermore, we found a significant difference

Table 3.1: Perceived mental effort (PE) to perform the task per screen resolution. * denotes significant effects at the .05 level.

		90 PPI		120 PPI		180 PPI		359 PPI	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Task	Image	37.38	21.69	55.94	27.98	42.25	35.82	39.50	27.91
	Text*	52.50	30.69	43.06	22.79	30.31	20.88	32.13	25.32
	Video	41.88	31.02	35.56	23.41	31.81	24.71	28.13	22.01

Table 3.2: Perceived media quality (PMQ) per screen resolution. * denotes significant effects at the .05 level.

		90 PPI		120 PPI		180 PPI		359 PPI	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Task	Image*	4.01	2.40	4.78	2.39	6.71	1.97	7.36	1.44
	Text*	2.15	1.58	3.95	1.71	6.03	2.00	8.05	1.40
	Video*	3.72	1.86	5.16	1.56	6.59	1.57	6.14	1.80

on PMQ between 180 PPI and 90 PPI ($p < .015$). Post-hoc tests revealed no significant difference for all other pairwise comparisons. The analysis revealed significant differences for TCT ($F_{3,36} = 6.625$, $p < .003$, $\eta^2 = .356$). Post-hoc testing revealed significant effects for TCT while performing the task with the highest pixel density (359 PPI) vs. 120 PPI ($p < .045$). Furthermore, the differences between 120 PPI and 90 PPI were significant ($p < .005$). However, the analysis could not reveal significant differences between the other pixel densities.

3.3.2   Text Task

Significant effects for PE were found ($F_{3,45} = 13.13$, $p < .001$, $\eta^2 = .467$). Post-hoc testing showed that PE for performing the task at 359 PPI was significantly lower than at 90 PPI ($p < .009$). Furthermore, the analysis reveals significant differences between 180 PPI and 120 PPI ($p < .018$) and between 180 PPI and

90 PPI ($p < .002$). However the analysis revealed no significant effect between all other resolutions. The analysis revealed significant differences on PMQ ($F_{3,45} = 48.52$, $p < .001$, $\eta^2 = .764$). Post-hoc tests showed that all used pixel densities were perceived significantly different (359 PPI vs. 180 PPI: $p < .027$; 180 PPI vs. 120 PPI: $p < .003$, and all other pairs: $p < .001$. The analysis of TCT revealed no significant differences ($F_{3,36} = 1.728$, $p = .179$, $\eta^2 = .126$).

3.3.3   Video Task

The analysis revealed no significant effects on PE ($F_{3,45} = 3.82$, $p = .16$, $\eta^2 = .203$). However, the analysis revealed significant differences for PMQ ($F_{3,45} = 18.38$, $p < .001$, $\eta^2 = .551$). Post-hoc tests showed that PMQ differs significantly between the highest (359 PPI) and the lowest (90 PPI) pixel density ($p < .003$). Furthermore, the three lower pixel densities were perceived significantly different (180 PPI vs. 120 PPI: $p < .009$; 180 PPI vs. 90 PPI: $p < .001$; 120 PPI vs. 90 PPI: $p < .008$). The analysis of TCT revealed no significant differences ($F_{3,36} = 1.012$, $p = .399$, $\eta^2 = .078$).

3.4   Discussion

The results of our study show that the influence of pixel density depends on the performed task. Perceived media quality differs for all three tasks. The results suggest that pixel density is particularly important for text related tasks. Only for the text task, participants rated the media quality between all four presented pixel densities significantly different. In addition, perceived mental effort while performing the text related task differs significantly between the different pixel densities. This indicates that a higher pixel density and thereby a clearer font makes reading easier. In contrast, not all densities in the image task were rated significantly different. We found no differences between 359 PPI and 180 PPI, 180 PPI and 120 PPI, and between 120 PPI and 90 PPI. This indicates that the perceived differences of the visual quality for images did not vary as much as for text. Perceived video quality differs between pixel densities of 180 PPI, 120 PPI, and 90 PPI. However, perceived quality of the highest pixel density is only different compared to the lowest quality. This indicates that for video watching a higher quality might not be necessary. Overall, we could not show that a higher pixel density is beneficial in terms of task completion time or error

rate. Also, the results demonstrate that the distance between a user's head and the device does not change depending on the pixel density of the screen.

In contrast to Ziefle's [283] work on lower pixel densities, our results do not show a continuously increasing positive effect of the display's pixel density on TCT and ER. However, our results show that the pixel density influences the perceived workload and the perceived media quality. Thereby, our findings are in line with results presented by Mayr et al. [175]. In two experiments the authors compared reading performance on a display with 132 PPI to performing the same tasks on a display with 264 PPI. While the TCT and comprehension were not affected by the resolution, participants rated the tasks performed on the display with 132 PPI as physically more demanding.

3.5 Conclusion

Our results show that relative visual resolutions above 90 PPI do not lead to an increase in task performance. However, high pixel densities reduce the perceived physical effort to perform visual tasks. Thus, displays should have at least a pixel density of 90 PPI. Higher pixel densities are beneficial to allow users to perform their work more comfortably. Due to technical limitations, we are not able to identify a relative resolution, that does not lower the perceived effort any further. Furthermore, it is an open research question whether the perceived physical demand leads to increased performance when working over a longer period. In the experiment presented in this chapter as well as in related work [175], participants performed the tasks for one hour to 90 min. However, in office environment users work with displayed content for several hours or the full day.

High relative resolutions are particularly important when the user is close to the display. This is always the case whenever the user interacts through direct touch with the content on display. Also, when the user stands directly in front of an LHRD he or she is able to see small details on the display, hence here is a high relative resolution important. Users benefit from higher relative resolutions, but the work performance is not affected when the display has a resolution over 90 PPI. Hence, when designing interactive displays, there is a trade-off been increasing the system complexity through higher resolution and user satisfaction. To achieve a high relative resolution on an LHRD the absolute resolution has to be very high. This increases the requirement for computational power and thereby the system complexity and cost.

Chapter 4

The Influence of Physical Display Space

LHRDs are defined by their large physical size and high visual resolution [13]. However, it is not completely understood how both attributes affect user's perception and behavior. In Chapter 3, we showed that users need minimal 90 PPI relative resolution to perform well, but higher resolutions lower the perceived demand. In this Chapter, we focus on the influence of the available physical screen space.

We investigate how the perceived effort, as well as the visual search time for title and image searches in large text documents depends on the size of large displays. In a controlled experiment, we vary the display size by using one to six 50 in screens with 4K resolution aligned in portrait mode (see Figure 4.1) . We measured participant TCT as well as their perceived task load. Thereby, we complement previous work through an analysis of objective performance and subjective perception while searching in large textual data sets using differently sized large screens.

4.1   Related Work

Previous work investigated the advantages of LHRDs in a variety of scenarios. Ball et al. [21] compared different display sizes for a map-based visual search task in a lab study. The results showed that users were able to find relevant insights faster on larger displays. Hence, the authors argued that users benefit from the physical navigation on large displays. In contrast, Jakobsen and Hornbæk [115] argued that physical navigation does not outperform virtual navigation. Liu et al. [153] showed that users are able to classify visual objects faster on LHRD than on desktop setups. Cockburn et al. [43] showed displaying a large number of pages in parallel enhance the interaction with page-based documents.

Andrews et al. [12] analyzed how LHRDs could be used for sensemaking. The authors argued that participants in a lab study utilized the physically large display space to distribute information visually. On a theoretical level, Kirsh [122] argues that humans make use of physical arrangements of tools and information to enhance their use. Bi and Balakrishnan [28] invited participants to work over one week on an LHRD instead of a regular desktop setup. At the end of this time all the participants preferred working on the LHRD. In line with this Rajabiyazdi et al. [202] showed that researchers were able to get more meaningful insights into complex data sets on an LHRD.

Designing successful interfaces for LHRDs requires an understanding of how users explore large surfaces visually. In contrast to previous work, we investigate the effect of display size on search performance when searching in large text documents. Interaction with text documents is a very frequent task in office environments. Therefore, how to support office workers by displaying all pages of a large document at once is an important question.

Figure 4.1: Setup of the six 50 in screens used during the study. Only four screens are used in the shown condition.

4.2 Experiment

To explore the effect of display size on users' visual search performance and perceived effort, we conducted an experiment with a repeated measures design. Our only independent variable was the display width. We used an LHRD consisting out of six single screens. This allowed us to vary the display width by switching off single monitors. The six screens were mounted next to each other in portrait orientation (see Figure 4.1). Every screen was 67.3 cm wide and 113.1 cm high, resulting in one 4.04×1.13 m display for the condition where we used all six monitors. Each individual screen had a resolution of 2160×3840 pixel resulting in a pixel density of 88 PPI.

Our dependent variables were users' item search time or TCT and perceived task load recorded with the raw NASA-TLX [93, 94]. The search task concerned title and image search within text documents. Thus, we presented research papers from the Conference on Human Factors in Computing Systems (CHI) 2013 and CHI 2014 proceedings on the display asking participants to retrieve the position of titles and images in the documents by mid-air pointing at the search items.

To present text documents on the screen, we implemented a custom Portable Document Format (PDF) viewer that shows an adjustable number of pages on the display. During the study, we showed 12 pages on each of the used monitors. In

each condition, 150 US letter format[14] PDF pages (comprising 15 full CHI papers) were presented in total, while the number of immediately visible documents varied per condition according to the number of monitors used. For example, during the condition when all six screens were used, 72 US letter format PDF pages were displayed at the same time (see Figure 4.1). The pages were ordered from left to right across the monitors over the whole display.

Participants could navigate back and forth through all documents (to scroll to those that were not visible on the display) using the arrow keys on a regular wireless keyboard.

We recruited 12 participants (6 male and 6 female) through the university's mailing lists. Their effort was compensated with 10 EUR. The participants were aged between 18 and 27 years ($M = 21.17$, $SD = 2.67$). All participants spoke English fluently.

After welcoming a participant, we introduced the research context and asked the participant to fill in a demographic form. Afterwards, we asked our participants to solve two tasks. In the first task, they had to search for a specific paper title. The instructor read the title out loud and showed the them the title printed without any formatting. In the second task, we asked participants to search for an image. The instructor showed the image without caption as a printout.

For every new task, a new set of 15 CHI full papers was presented. Hence, no participant saw a paper more than once. We repeated each task three times per condition. Thus, in total, the participants performed 36 tasks (6 conditions × 2 task × 3 repeats). After performing six tasks of one condition, we asked the participants to fill in a raw NASA-TLX. We counterbalance the order of the conditions. We also counterbalanced the position of the search targets. One-third of the targets were placed in the first third of the 150 pages, one third in the second third and one third in the last third of the pages. After all tasks had been completed, we asked the participants how many monitors they would like to use if they could freely choose.

4.3   Results

During the experiment, we recorded the perceived task load for each condition and the search time (TCT) for each item that had to be searched. We used the

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[14] US letter format (American National Standards Institute (ANSI), paper size A) has a size of 21.59 × 27.94 cm.

(a) TCT results for the title search.

(b) TCT results for the image search.
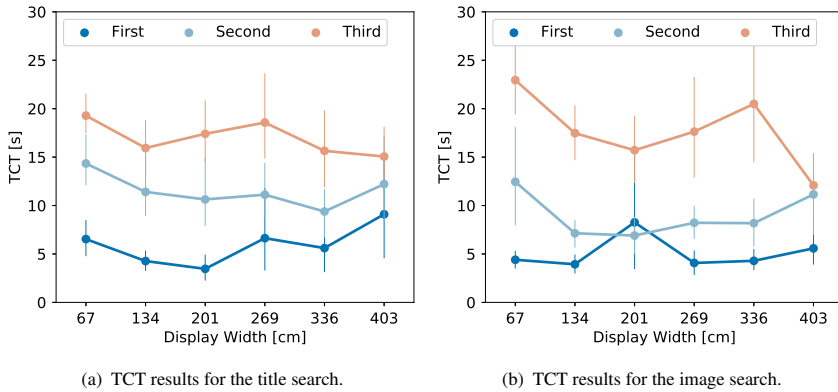
Figure 4.2: task completion time results for the title and image search. Results are seperated for different target locations: (First) The item is in the first third of the document, (Second) the item is in the second third of the document, and (Third) the item is in the last third of the document.

item's position in the overall document as an additional factor when analyzing search time assuming that the item position had a substantial effect on required search time.

For the image as well as for the title search, the descriptive statistics (see Table 4.1) led us to suggest that the number of monitors affects TCT and raw NASA-TLX to a certain extent.

Title search. While the average TCT for finding a title in the first third decreases from using one up to three monitors, increasing from three up to six monitors results in an increase of TCT (see Figure 4.2(a), line First). TCT for finding a title within the second third of the document slightly decreases with more display space. However, again the participants were slightly slower with six monitors in comparison to using only five (see Figure 4.2(a), line Second). Only when the item was placed in the last third of the document, TCT was smallest for the condition with six monitors (see Figure 4.2(a), line Third).

Image search. The TCT for searching an image shows a similar trend. If searching for an item in the first third of the document, there is no positive effect of having more than one or two monitors (see Figure 4.2(b), line First). For searching items in the middle of the document, three screens seem to be most suitable (see
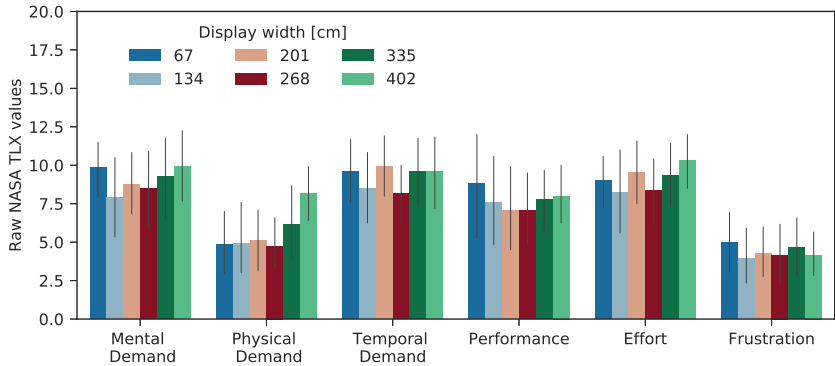
Figure 4.3: Raw NASA-TLX results for both search tasks per display widths.

Figure 4.2(b), line Scond). The largest decrease of TCT occurred if the search item was in the last third of the document.

The results of the raw NASA-TLX do not vary overall conditions (see Figure 4.3). Only the physical demand increases for the conditions with five and six screens. The question of how many screens are desirable indicated that nobody was interested in using more than four screens for daily work. Five (out of 12) participants would like to use three monitors at most.

Table 4.1: The overall raw NASA-TLX and TCT for both tasks.

Number of screens	Display width [cm]	Raw NASA-TLX		TCT title search		TCT image search	
		M	*SD*	*M* [s]	*SD*	*M* [s]	*SD*
1	67.3	39.24	11.09	13.46	6.91	11.79	8.51
2	134.6	34.24	17.97	11.40	7.74	9.29	6.62
3	201.9	37.15	13.40	10.30	7.61	9.54	6.92
4	269.2	34.17	14.47	11.77	8.60	9.97	8.06
5	336.5	38.96	14.80	10.99	8.94	8.85	6.14
6	403.8	41.81	12.38	12.04	8.01	9.53	6.48

4.4   Discussion

We conducted a study to investigate the effect of display size on item search performance and perceived task load. As search context, we used papers from the CHI 2013 and CHI 2014 proceedings displayed on an LHRD. We asked the participants to search for titles and images in the documents. For both search tasks, we found only a small effect of the screen size on TCT and perceived task load. Our results show that screen sizes up to four monitors (269.2×113.1 cm) are beneficial. We found that larger screens can support the work with very large data sets if the search item is at the end of the document.

Accordingly, our results show that TCT only decreases with an increase of display size when the search item is not at the beginning of the document. This might have different reasons. All participants started their visual searches at the beginning of the document and continued towards the end, which corresponds to searching from left to right. Thus, for items in the first one-third, only four screen were needed to display the item without a need to scroll within the content. With a high probability then the item was already displayed on one of the first three screens.

If the target is at the beginning of the document more screen space has a negative effect on TCT. The reason might be that the user is overwhelmed by the closeness of large visible content. We know from searching on maps [21] that taking a step backwards helps to cognitively capture much more information visible at the same time.

According to the participants' physical scores demand and their subjective feedback, three screens, with a size of 269.2×113.1 cm were optimal when searching for titles and images in text documents, which has also been confirmed by subjective comments. With more display space the user has to move physically in front of the LHRD. While previous work showed that physical movements could be beneficial [21], our participants perceived walking around as additional workload that was perceived to be annoying. Hence, the design of the LHRD influences how much the user moves in front of the display. On one hand, LHRD setup designers could use this intentionally, to give the user a reason to move. On the other hand, this might cause fatigue and influence the interaction negatively.

4.5   Conclusion

In this chapter, we showed that users are able to work with large visual data sets, without being overwhelmed. In general, the feedback from our participants indicates that the use of LHRDs is more beneficial to discover similarities and trends in large data sets than for browsing through large documents to search for a title or an image. Thus, in future work, we aim to shift our focus towards an analysis of the effect of screen size on tasks that involve comparing and classifying large data sets. Furthermore, users' visual search strategy might influence the search performance on LHRDs. Hence, future work should explore visual search strategies on large surfaces and explore how the knowledge about the search strategies could enhance GUIs for LHRDs.

To conclude, this work shows first results about how much display space is useful for browsing through large amounts of traditionally structured text documents. The results showed, that users perceived an increase in the physical effort when the display is wider than 269.2 cm. This should be considered when designing LHRD setups to motivate users to move. However, this creates risk of fatigue. Furthermore, we learned that there is a need for a deeper understanding of the influence of users' position, body posture, and movement to guide the design of LHRDs for future workplaces. Moreover, we suggest exploring alternative ways of content structuring when using large-sized displays.

Chapter 5

User Movement Patterns in Collaborative Settings

The large physical space of LHRDs is not only beneficial for distributing visual information for enhanced exploration, but also for multiuser interaction. Multiple users can comfortably stand in front of the display and look at the same or different content. This enables users to get more engaged in collaborative tasks, since all users observe the same perspective on the task and are able to discuss different views without the overhead of communicating new view points. Yet, as many tasks require users to switch between individual and group work, LHRDs must support these transitions for effective management of space, for example, when users observe or explore different subsets of a data set and discuss the connections between these subsets together. As games for LHRDs have recently been developed, understanding spatial dynamics in front of the screen emerges as a key consideration for building immersive game experiences. When working or playing on one LHRD, users have to negotiate for display space, while in collaborative periods they might share areas. Hence, UIs for LHRDs should support both individual and collaborative working periods. So far analysis of multiuser behavior around LHRDs has been limited, therefore, we see a need for a fundamental understanding of user behavior in both periods.

To that end, we analyze behavior, movement and proxemics of pairs using an LHRD in *collaborative* and *competitive* conditions. Because of the high engage-

ment in games, we designed Pac-Many, a multiplayer LHRD computer game, inspired by Pac-Man®. We used this game on a 4.02×1.13 m LHRD. We asked 24 participants (12 pairs) to play in collaborative and competitive game conditions. The results showed different behavior and proximity patterns for the two conditions as pairs, spread in front of the screen in collaborative games, and focused on the center of the screen in competitive games.

5.1   Related Work

In this section, we present previous work, which inspired the presented work in this chapter, focusing on collaboration around large displays, games for LHRDs, proximity and games as research apparatus.

5.1.1   Collaborative Interaction with LHRDs and Public Displays

Research has built an understanding of pair and group behavior around public displays [18, 197, 261]. Azad et al. [18] explored group behavior and formation in front of public displays. The authors analyzed group behavior in the wild as well as in the lab. Azad et al. [18] identified individual and public territories on displays. Further, Peltonen et al. [197] showed that public displays can foster social interaction between people. Wallace et al. [261] investigated collaborative touch screen interaction on an LHRD in a lab study in which pairs had to solve a jigsaw puzzle. Lastly Jacucci et al. [113] found that functionality is discovered gradually through collaborative learning in a public display scenario and further found that often the first contact with the LHRD is challenging for users. While
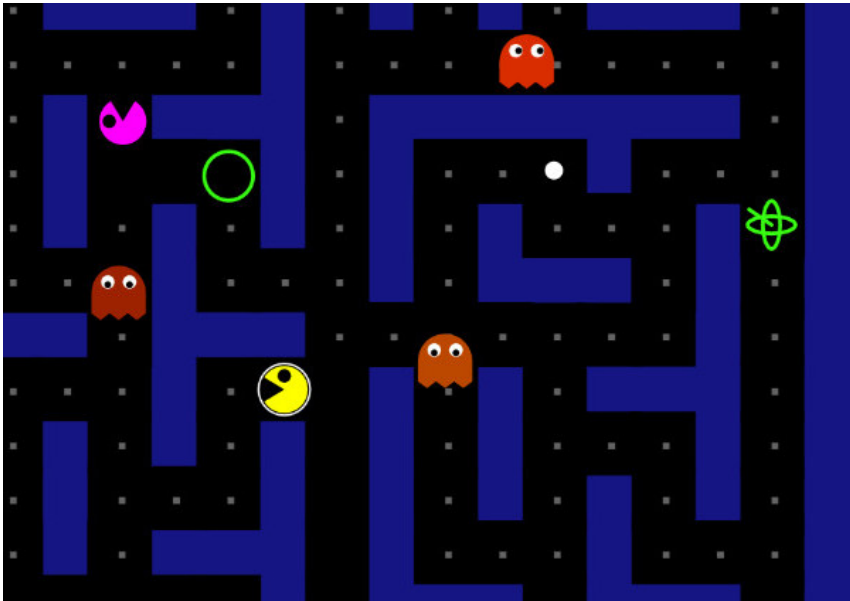
Figure 5.1: A visualization of all game elements in Pac-Many: the maze walls in a dark blue, the Pac-Men for the two players in magenta and yellow (the white circle around the yellow player indicates an active *Power Pellet*), three *ghosts* in shades of red, a blinking *Power Pellet*, an active *Pac-Portal* with the direction indicator, and a timed out *Pac-Portal* indicated by an empty green circle.

these works explored different collaborative tasks, HCI is yet to address how to build engaging playful experiences with LHRDs and leverage effective proximity based interactions analogously to tabletop interfaces, e.g. [274].

Group interaction around tabletops has been explored in detail [126, 168, 218]. Scott et al. [218] identified personal territories for individual work, shared areas for collaboration and space for storing content when groups work on a tabletop. Marshall et al. [168] designed a tabletop for a tourist office and observed users in the wild. This in the wild study showed that interacting in another user's territory often leads to unsolvable conflicts. Klinkhammer et al. [126] indicated the personal territory needed to avoid conflicts. Tang et al. [235] analyzed group dynamics while interacting with an interactive tabletop. The results show that pairs stand closer together when cooperating. More recently, the focus has been

shifting to pair and group behavior around vertical LHRDs in non-public settings [4, 117, 154]. Birnholtz et al. [30] showed that the input technique influences the collaboration. Based on an abstract classification task Liu et al. [154] analyzed five collaboration strategies with pairs of users. In a study participants used a motion-tracked controller to control the cursor. In contrast, Jakobsen and Hornbæk [117] used a data exploration task, involving different document types on a multitouch wall to analyze pair collaboration. The examples cited above all explored work-related tasks. This paper extends related work by developing a multiuser game. It focuses on uncovering differences in competitive versus collaborative situations that can inform both work and learning settings.

5.1.2 LHRD Games

Besides collaboration, games for LHRDs are moving to the focus of research. Machaj et al. [162] presented PyBomber: a multiplayer game for LHRDs inspired by Bomberman. The game was designed for a 96-megapixel display and is controlled with Nintendo Wii controllers. In a lab study, the authors investigated the effect of team size. The results of the study indicate less social interaction per person when playing with more players. Von Zadow et al. [259] proposed a multiplayer game for touch display walls. Toprak et al. [242] designed a game for wall-sized displays to motivate players to engage physically. Furthermore, previous research has explored games on public displays. O'Hara et al. [188] analyzed player behavior playing games on a public display. Grubert et al. [85] used the bring your own device approach in a public game to understand how people use magic lenses with public displays. These works show that large displays can offer a playful experience yet they do not address the question of how to instrument interfaces for an optimal screen sharing experience.

5.1.3 Territoriality and Proxemics

Hall [90] identified four distances for social interaction: intimate distance, personal distance, social distance and public distance. Further, Mueller et al. [180] extended these zones to scenarios where participants are out of sight but still in range to exchange radio signals. Research has utilized these distances for interaction with smart systems [23, 83, 167, 255]. Ballendat et al. [23] utilized them for interacting with a multimedia room. Marquardt et al. [167] implemented a toolkit enabling building proxemic interaction. Vogel and Balakrishnan [255]

designed different interaction distances for interacting with public displays. It is, however, unknown how these findings translate to LHRDs.

5.1.4   Games as Research Apparatus

Von Ahn [256, 257] proposed using games to solve real world problems by having people engage in the games. In 2004 Von Ahn and Dabbish [258] labeled images using a two player game to solve an open problem using antilogarithms. Later Law and von Ahn [137] used a similar approach to label audio files. Vepsäläinen et al. [250] investigated ways to use public displays as a gaming canvas which enables solving real world problems on the go e.g. while waiting for a bus. On the other hand, previous work also proposes using games to understand how people interact with technology [97–99]. Henze et al. [98], for example, used smartphone games to analyze touch behavior. Furthermore, games enabled a detailed understanding of typing behavior [99]. The utilization of games to explore user behavior is beneficial because participants easily engage in a game task. Consequently, our work uses a game to explore the spatial behavior when interacting with an LHRD.

5.2   Pac-Many

Inspired by the original Pac-Man game from 1980 we propose Pac-Many: a multiplayer version designed for LHRDs. Similar to the single player version, in Pac-Many players navigate their Pac-Man through a maze of *Pac-Dots*, *ghosts*, and *Power Pellets*. While the original maze is 28 tiles wide and 36 tiles tall, this is not sufficient to cover an LHRD. This needs to be adjusted to the display specifications to make use of the high resolution and the size of the display. In the following, we describe the game design and all game elements which are also shown in Figure 5.1.

To interact with the maze presented on the LHRD each player has a controller. As a controller, we propose using smartphones to facilitate the "bring your own device" approach [22]. The smartphones display a *D-pad* (short for digital pad); a four-way directional control with one button for each direction, similar to almost every game console controller, see Figure 5.2. The four buttons are then mapped to the movement directions of the Pac-Man.

Each player gets assigned a unique color. To identify which Pac-Man is mapped to which controller each Pac-Man is colored in the player's color. The buttons on the controller are also the same color, for the first identification and memorability, see Figure 5.2. All *ghosts* are colored in shades of red. Further whenever one player collects a *Power Pellet* an extra button appears on the controller which triggers the extra ability to be immune against *ghosts* for 5 s.

We invented *Pac-Portals* to overcome large distances in the maze. *Pac-Portals* teleport the player to another specific portal; a green line indicating the direction of the paired portal. *Pac-Portals* are bi-directional however after usage they are deactivated for 5 s. We placed six pairs of bi-directional portals equally distributed over the maze with the distance between paired portals at least one sixth of the screen width. All game elements are visualized in Figure 5.1.

The goal of the original Pac-Man was to collect all *Pac-Dots* with one game point each, and this can still be a game goal. However, with the large maze on LHRDs, the *Pac-Dot* count can easily be over 25,000. This can result in a very long playing time to achieve the goal. To keep the time to finish the game reasonable we propose a new game goal: to collect only a certain number of *Pac-Dots* and *Power Pellets* and use some of the *Pac-Portals*.

We further introduced two game modes to use the newly introduced multiplayer game Pac-Many: a collaborative and a competitive game mode. In the collaborative mode multiple players play as a collective to achieve the game goal. In the competitive game mode, the players compete with each other.

The Pac-Many source code is available under the MIT license[15] on GitHub[16].

5.3   Game Study

The main goal of our study was to understand the group spatial dynamics, especially movement and proxemics, in a shared LHRD scenario. Using Pac-Many, a multiplayer version of the classical computer game Pac-Man, we analyzed how *collaborative* and *competitive* game conditions would affect movement and proximity patterns of the players.

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[15] http://opensource.org/licenses/MIT

[16] https://github.com/interactionlab/pacmany

(a) Collaborative controller

(b) Competitive controller
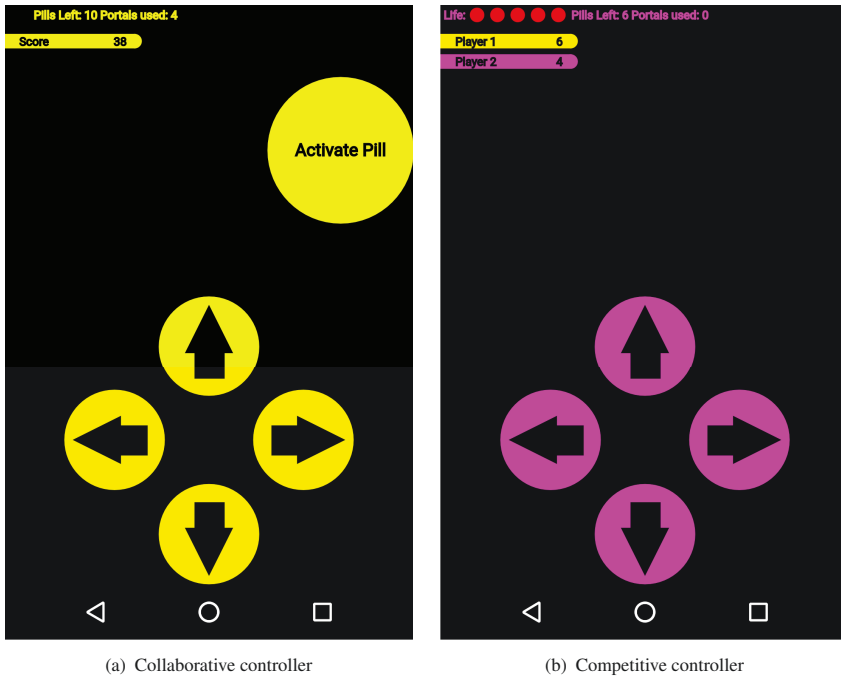
Figure 5.2: Two screenshots of the controller used for our study on a Nexus 5X. (a) shows the controller in the *collaborative* condition with a *Power Pellets*. (b) shows the controller in the *competitive* condition were each player has an overview over the independent game stats.

5.3.1   Study Design

Our study used a within-groups repeated measures design. We used CONDITION with two levels, namely *collaborative* and *competitive*, as the independent variable. During the study participants were asked to play Pac-Many. In the *collaborative* CONDITION players played together to accomplish the game goal, fight the ghosts, and thus gain one shared point count. In the *competitive* CONDITION the players played against each other with independent point counts. The order of the CONDITION was counterbalanced across all participant pairs. During the study, we constantly tracked the participant's physical positions and the screen position. After each CONDITION, we asked participants to fill out the SPGQ module [47] of the Game Experience Questionnaire (GEQ) [109]. We further
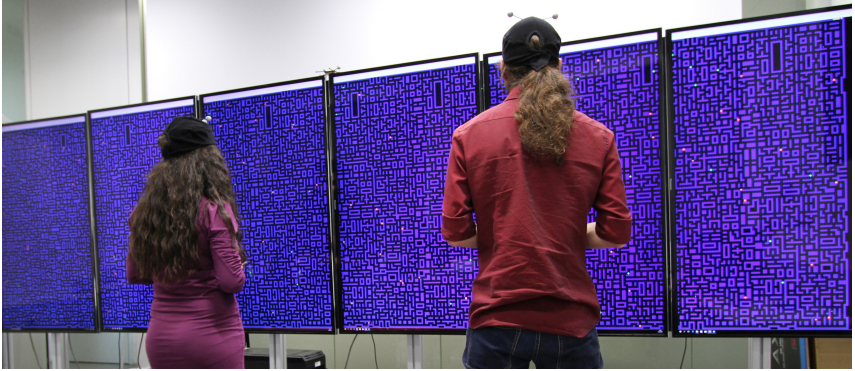
Figure 5.3: A player pair standing in front of the LHRD engaging in Pac-Many while wearing the *mocap beanie hats* for position tracking.

chose to record audio and video during the study as this could provide a more objective account of the movements than interviews, which are known to offer a subjective experience [32].

5.3.2   Apparatus

The hardware setup consisted of two smartphones, one motion tracking system, and six monitors. As smartphones, we used two Nexus 5X running Android OS (v. 7.0 Nougat). As tracking system, we used OptiTrack: a marker based motion capture system. The tracking system delivered the absolute position of the markers attached to the participant at 30 fps. We calibrated the system as suggested by the manufacturer resulting in millimeter accuracy. Each participant got a hat with markers for position and orientation tracking, see Figure 5.3.

Six screens were mounted next to each other in portrait orientation (see Figure 5.3). During the study, we used six 67.3×113.1 cm 50 in 4K Panasonic TX-50AXW804 screens, which resulted in one 4.04×1.13 m display. The display, therefore, had a resolution of $12,960 \times 3,840$ pixel.

We implemented the proposed multiplayer game Pac-Many as a Node.js application: the screen and the controllers connected to the application using socket.io for communication between the devices. The maze used in the study was 491 tiles wide and 144 tiles tall. The map size and ratio were needed to fill the full screen and to fit multiple players, resulting in a tile size of 7×7 mm. The
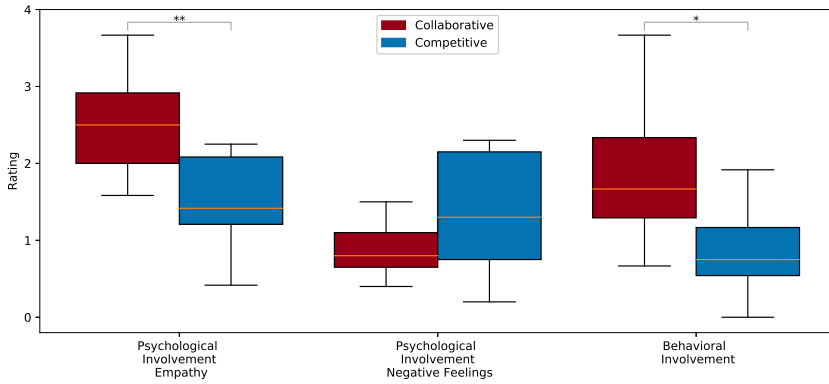
Figure 5.4: The Social Presence Gaming Questionnaire results for the *collaborative* and *competitive* condition (with ** : $p < 0.01$ and * : $p < 0.05$).

enlarged maze resulted in 36,838 *Pac-Dots*. To cover the enlarged map evenly, we decided to add more *Power Pellets* (24) and more *ghosts* (100). In our study, we used only magenta and yellow as colors for Pac-Man for the two players. To lower the influence of ghosts on the movement patterns, ghosts' movements were randomized.

In the *collaborative* game condition, the team needed to collect 400 *Pac-Dots*, all 24 *Power Pellets*, and use the *Pac-Portals* 12 times. They had 10 lives. To win the *competitive* game one player needed to accomplish half of the collaborative goal (200 *Pac-Dots*, all 12 *Power Pellets*, 6 *Pac-Portals*, and 5 lives).

5.3.3   Procedure

The participants were guided through the whole study by two researchers. When both participants arrived at our study room, we welcomed them and asked them to fill in a consent form as well as a questionnaire about their demographics. We then explained the procedure of the study. We first equipped them with *mo-cap beanie hats* which were used for the position tracking, see Figure 5.3. Afterward, we gave each participant a smartphone to interact with the game and time to get familiar with the controller and the game play. We then let participants play each condition for 20 min. After participants completed one CONDITION, we asked them to complete the questionnaires. Before the games started, the players had 15 s to locate their Pac-Man.

(a) Collaborative condition

(b) Competitive condition
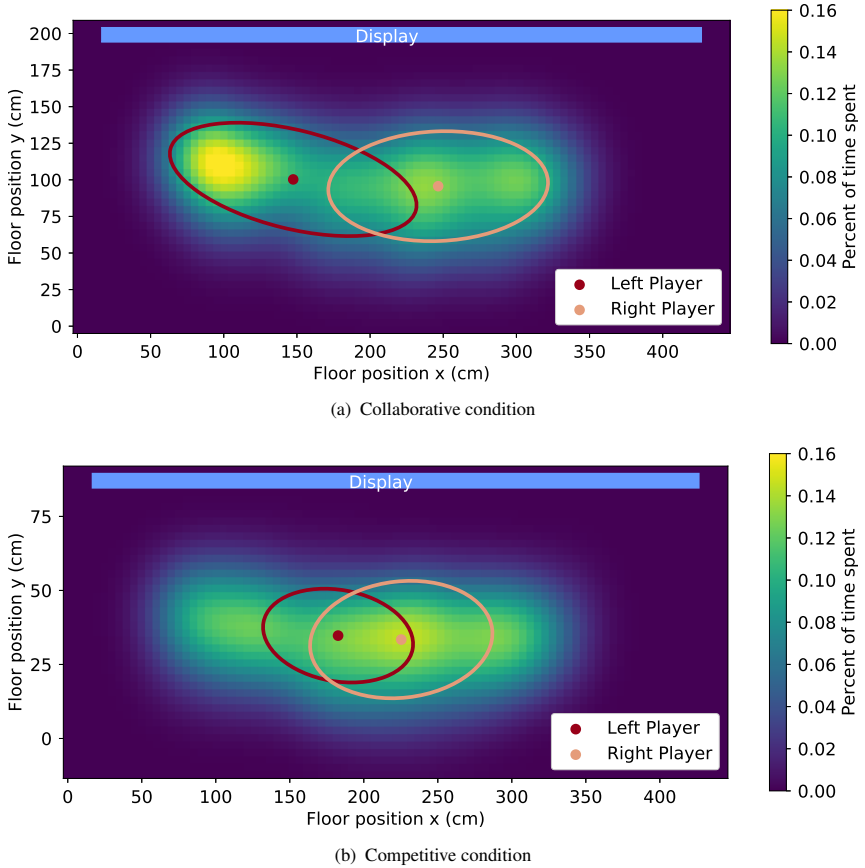
Figure 5.5: The figures show the floor visualization in the *collaborative* and *competitive* CONDITION. We classified left and right player as the players who were more than 50 % of the time on the respective side of the display; the corresponding ellipses representing four times the *SD* oriented according to the distribution.
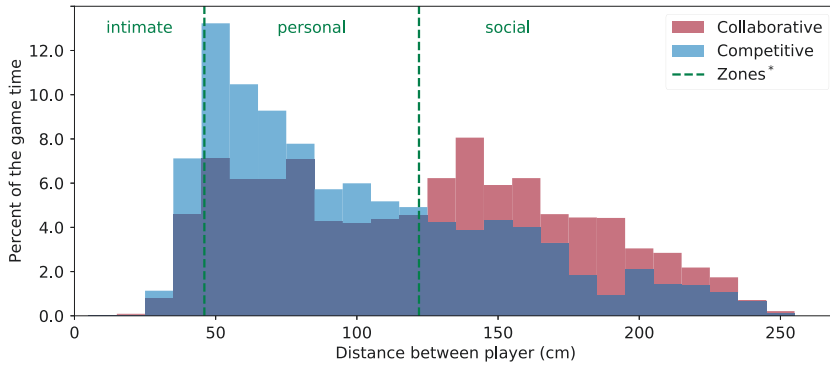
Figure 5.6: The graph shows the histogram of distance between players (player-player). * interpersonal distances of man by Hall [90].

5.3.4 Participants

We recruited 24 participants (16 male and 8 female) through our university's mailing list. The participants were aged from 20 to 36 years ($M = 24.6$, $SD = 3.88$). All of them had either no visual impairment or corrected to normal vision. Four of the pairs knew each other beforehand. We provided a remuneration of EUR 5.

5.4 Results

In total, we recorded 8 h : 05 min of game time in which participants played 65 games with an average game time of 7 min : 28 s. Each pair played on average 40 min : 26 s.

5.4.1 Engagement

We conducted a Wilcoxon signed-rank test for all three dimensions of the Social Presence Gaming Questionnaire (SPGQ) of the Game Experience Questionnaire (GEQ) to analyze the effect of CONDITION, see Figure 5.4. Our analysis revealed a significant effect of CONDITION on *Psychological Involvement Empathy*

($Z = 2.711$, $p < .007$) with *collaborative* ($M = 2.49$, $SD = 0.66$) and *competitive* ($M = 1.56$, $SD = 0.59$). Further, our analysis revealed a significant effect of CONDITION on *Behavioral Involvement* ($Z = 2.135$, $p = .0327$) with *collaborative* ($M = 1.86$, $SD = 0.88$) and *competitive* ($M = 0.89$, $SD = .55$). However, there was no significant effect of CONDITION on *Psychological Involvement Negative Feelings* ($Z = 1.683$, $p = .092$) with *collaborative* ($M = 0.89$, $SD = 0.33$) and *competitive* ($M = 1.33$, $SD = 0.77$).

5.4.2   Movements

All floor movements for both players are visualized for the *collaborative* condition in Figure 5.5(a) and the *competitive* condition in Figure 5.5(b). We classified left and right player as the players who were more than 50 % of the time on the respective side of the display, see Figure 5.5.

Player-Player Distance   As Figure 5.5 indicated a difference in distance between players (player-player distance), we conducted a paired-sample t-test to compare player-player distance in the *collaborative* condition and the *competitive* condition. There was a significant difference between the *collaborative* ($M = 128.2\,cm$, $SD = 26.5$) and the *competitive* condition ($M = 100.3\,cm$, $SD = 16.0$); $t_{11} = 4.357$, $p < .002$, see Figure 5.6 and 5.5.

We further classified the player-player distance into the four interpersonal distance zones by Hall [90]: intimate, personal, social, and public zones, see Figure5.6. We found that only 5.3 % of all movements in the *collaborative* condition fell into the intimate zones in contrast to 9.9 % in the *competitive* condition. Movements in the range between 46 to 122 cm, the personal zone, occurred 37.6 % of the time in the *collaborative* condition and 59.6 % in the *competitive* condition. Participants had a distance within the social zone for 57. % of the time in the *collaborative* condition and 30.5 % in the *competitive* condition. None of the pairs ever had a distance within the public zone.

Since we found a significant effect of CONDITION on the player-player distance, we conducted three t-tests to investigate if the three zones by Hall [90] were used differently. There was a significant difference in the time spent with one zone for all three zones: intimate ($t_{11} = -3.358$, $p < .007$), personal ($t_{11} = -4.012$, $p < .003$), and social ($t_{11} = 4.621$, $p < .001$).

Player-Display Distance   A paired-sample t-test was conducted to compare distance between the player and the display (player-display) in *collaborative*
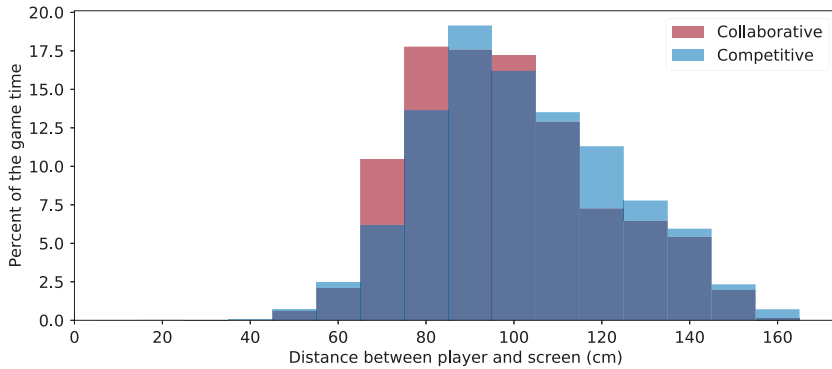
Figure 5.7: The graph shows the histogram of distance between the player and the display (player-display).

and *competitive* condition. There was no significant difference between the *collaborative* ($M = 96.1$ cm, $SD = 16.5$) and the *competitive* condition ($M = 101.4$ cm, $SD = 14.1$); $t_{11} = -1.614$, $p = .135$, see Figures 5.7 and 5.5.

Distanced Walked A paired-sample t-test was conducted to compare walked distance per player in *collaborative* and *competitive* condition. There was a significant difference between the *collaborative* ($M = 23.4$ m, $SD = 11.6$) and the *competitive* condition ($M = 33.8$ m, $SD = 9.1$); $t_{11} = -2.572$, $p < .003$.

Crossovers A paired-sample t-test was conducted to compare crossovers in front of the screen in *collaborative* and *competitive* conditions. There was a significant difference between the *collaborative* ($M = 6.9$, $SD = 5.6$) and the *competitive* condition ($M = 14.6$, $SD = 12.0$); $t_{11} = -2.454$, $p < .033$.

Head Movements We further analyzed the head movements of the players. Since our first analyses revealed that the distance between the players in the two conditions was significantly different, we further investigated if head movements to the left/right (yaw) differed between CONDITIONS. Therefore we conducted a paired-sample t-test to compare the variance of yaw head movement per player in the CONDITIONS. There was a significant difference between the *collaborative* ($M = 13.9°$, $SD = 3.4$) and the *competitive* condition ($M = 16.4°$, $SD = 5.3$); $t_{23} = -2.131$, $p < .044$.

(a) Helping
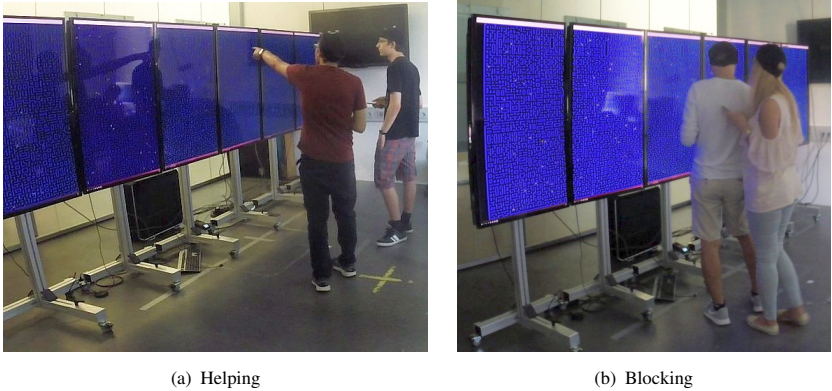
(b) Blocking

Figure 5.8: On rare location we observed helping and blocking behavior to gain benefits for the team or over the competitor.

5.5   Discussion

Our work shows that whether users compete or collaborate on an LHRD significantly affects how they move in front of the screen. When designing games for LHRDs, this may create opportunities and challenges. Game designers can use our work to exploit spatial dynamics and reward players for effective collaboration, based on how they manage screen space. On the other hand, designers should be wary of placing game content in ways that could cause occlusions and crossovers, thus possibly negatively affecting immersion. Our observations in the competitive conditions show that users are likely to invent strategies to hinder the other player's movement. This could be used as a playful game mechanic in competitive games e.g. to implement interruptible actions [31].

Perceived Engagement   Our results show clearly that the participants perceived the two conditions differently and, consequently, behaved differently during the two CONDITIONS. The results of the SPGQ show that participants felt more empathy and involvement in the *collaborative* condition. In contrast, participants reported having more negative feelings in the *competitive* condition. Overall, the results of the SPGQ revealed a deeper social engagement in the *collaborative* condition than in the *competitive* condition. This indicates that the players discovered the advantage of playing together in the *collaborative* condition, while they competed against each other in the *competitive* condition.

Player-Player Distance   An analysis of the movement patterns revealed the behavioral differences. In the *collaborative* condition players shared the space in front of the display homogeneously. Furthermore, the lower number of crossovers in the *collaborative* condition indicates that pairs separate the screen into personal areas. In combination with the shorter covered distance, we can conclude that a player focuses more on one area in the *collaborative* condition, instead of playing on the whole display. Thereby, the player avoids relocating him or herself in front of the display and reduces the physical demand. This approach of separating the screen space homogeneously is described in game theory as "Socially Optimal Solution" [193].

In the *competitive* condition, in contrast, the larger number of crossovers, the longest walked distance, and more head movement indicates that the players are trying to observe the whole display space over the whole match. Hence, this condition is physically more demanding than the *collaborative* condition. By having a shorter distance to the other player, each player tried to prevent benefits for the competitor. In game theory, this phenomenon is described as "Nash Equilibrium" [193]. Thereby, they do not use the display space as efficiently as in the *collaborative* condition.

Player-Display Distance   The distance between the players and the display (player-display distance) did not vary significantly between the two conditions. There could be a trend to stand closer to the display in the *collaborative* condition and further away in the *competitive* condition. This would allow the player to focus precisely on details in a smaller area in the *collaborative* condition. In the *competitive* condition the overview is more important, to restrict the competitor from collecting the game benefits. Hence, players tend to observe the display from a wider angle. However, the size of each game element is relatively small (approximately 7×7 mm). This small size underlines the benefit of an LHRD. On the other hand, this limits the viewing distance for a player to see all details.

Territoriality and Proximics   We further categorized the player-player distance with the four distance zones by Hall [90]. We found that the time spent within each of the areas was different for all zones between the *collaborative* condition and the *competitive* condition. The difference in personal and social zones can be explained again through game theory since in our case the distance for "Nash Equilibrium" situations is within the personal zone, and the distance falls into the "Socially Optimal Solution" situations. Therefore we consulted the video footage to understand the situations when pairs entered the intimate zone. We found crossings often shortened the distance into the intimate zone, and occurred more often in the *competitive* condition. However, we occasionally

found that players came closer to the display to block the competitor's view. In blocking situations, the blocked person came closer than 46 *cm* to see the screen (see Figure 5.7), and to get the own Pac-Man in sight again by looking around the blocking person, see Figure 5.8(b). In contrast to the blocking behavior which only occurred in the *competitive* condition we also found a helping behavior. Here one player often came close to the screen to point out locations of important game elements e.g. the location of a *Pac-Dot*, see Figure 5.8(a).

5.6   Conclusion

In this Chapter, we presented Pac-Many, a multiplayer game for LHRDs inspired by the classical computer game Pac-Man. Furthermore, we presented a lab study comparing the players' behavior in a collaborative and a competitive playing mode. The results show that the players were socially engaged in the collaborative condition and shared tasks in the game. Thereby the players minimized the physical effort and moved less in front of the display. In contrast, the competitive condition triggered physical action of the players.

We assume that the presented results are relevant for multiuser interaction also beyond gaming. The results are the first step towards understanding how multiple users behave in front of an LHRD in various situations. When the same visual content for two users is relevant or even limited, they will position themselves closely to the content (competitive scenario). When relevant content is distributed over the whole LHRD, users will make use of the full-screen space and distribute themselves in front of the display (collaborative scenario). Relevant scenarios which should be explored in future work are those in which users work separately and have to negotiate display space, and those in which only one user can change the view for all working users. From an input perspective, we will focus on this in Chapter 8.

The implementation of Pac-Many allows an arbitrary number of players to join a game. Furthermore, the game maze can be displayed on multiple distributed displays simultaneously. This allows us, in future work, to analyze the behavior of more than two players in front of one display. Furthermore, we will compare playing Mac-Many remotely to on-site playing.

III

INPUT TECHNIQUES FOR LARGE HIGH-RESOUTION DISPLAYS

OUTLINE

One critical challenge in utilizing the potential positive effects of LHRDs is to design well-suited input techniques. The size of LHRDs creates unique conditions for user input. After half a century of the evolution of the computer mouse, most people in developed countries can use the mouse efficiently for pointing tasks on desktop setups. Performing pointing tasks on LHRDs using a regular mouse in combination with a traditional cursor can be challenging. First, users describe the (re-)finding of the cursor as time consuming and challenging. Second, the distances which have to covered with the cursor are large on LHRDs. This creates the need for fast movement over long distances and precise movements for selecting small objects. These two requirements cannot be fulfilled by one pointing function. Finally, users might move physically in front of an LHRD beyond their arm range. The same issue exists for entering text, using a keyboard.

Simultaneously, input techniques well-known from mobile devices, mainly direct touch, do not necessarily support the advantages of LHRDs. While direct touch enables users to perform input on their physical body position, users might not always be able to reach the display with their arm. For example, the display might be placed behind a desk or be higher than the user's arm range. Furthermore, moving displayed content across the whole LHRD would be physically more demanding than using a mouse for drag-and-drop. On the other hand, high performance of traditional input techniques, suggests avoiding radical changes in input methods. Furthermore, familiar traditional input techniques create legacy issues in contrast to novel input techniques. Hence, we mainly aim to extend traditional user input techniques with new sensors, instead of replacing them.

In Chapter 6, we utilize eye-tracking to enhance pointing tasks. We apply the concept of MAGIC pointing to pointing on an LHRD. The ability to move the cursor to the current gaze position of the user makes the task of finding the cursor easier. Furthermore, long distances can be covered at high speed without effort.

For small and precise pointing, the user is still using the mouse, so can always decide whether or not to add the support of the MAGIC pointing technique.

As another option to extend the traditional desktop input techniques, we explore in Chapter 7 the use of mid-air gestures for large scale pointing input. When using a LHRD for office work, window management is one of the tasks involving interaction over most display space. Hence, we designed mid-air gesture sets to manage application windows and move the mouse cursor. Enhancing window management on LHRDs aims to overcome interaction challenges, while keeping the GUI familiar to the user. Even if the window management as we know it from desktop environments might change fundamentally for LHRDs (see Part IV), there will still be a need for similar actions.

When an LHRD environment allows users more freedom to move and work in different body positions, mouse and keyboard input will be difficult to perform. Furthermore, collaboration creates the need for multiuser input. In Chapter 8 we discuss using multiple tablets as input devices with private workspace for collaborative data exploration.

When exploring large visualizations displayed on a LHRD, users might spend all their visual capacity on the actual content and not be able to focus on input controls or non visual information. To support exploring multi-dimensional data sets, we present in Chapter 9 a prototype of a tangible force feedback slider. This device can present additional information about an input variable through varying the resistance to move the slider knob in a certain direction.

Chapter 6

Eye-Tracking Based Input

Pointing is one of the most performed interactions when working with visual content. On smartphones and tablets users touch the display to select particular GUI elements. On desktop setups, users use the mouse for indirectly selecting GUI elements and activating functions. When using laptops, the use of indirect touch performed on a touch pad is commonplace. Furthermore, the use of direct touch on laptops plays an increasing role. However, all these pointing techniques are challenging when interacting with content displayed on LHRDs. The physical size of LHRDs inertly limits the applicability of direct touch as an interaction technique. The display might be installed behind furniture, e.g., a table, and thereby be not in arm range of the user. Even if the user is able to touch some parts of the display easily other parts of the display might be too high or low to allow the user to perform touch input. Hence, direct touch is only appropriate as an input technique for particular LHRD setups an appropriate input technique.

Using indirect pointing, well-known from desktop environments, also creates challenges for the user. Robertson et al. [208] showed that users have to perform exhausting mouse movements to cover the long distances the cursor has to travel. In line with the results by Robertson et al. [208], we see in Section 2.3 that users lose track of the cursor position when working in multidisplay environments or with LHRDs. When the user's visual attention moves from one area of the display to another, the cursor does not automatically move to the same area. When pointing input is required, the user has to relocate or even visually search for the cursor and then move it over the full distance to the current area of interest. This causes a high mental and temporal effort. On the other hand, over more than four

decades of engineering and usage, the computer mouse has become an incredibly efficient pointing device.

To utilize the advantage of the mouse as pointing device and to overcome the particular challenges when interacting with content displayed on LHRDs, tracking a user's eye gaze carries potential. We revisit the concept of MAGIC pointing, firstly presented by Zhai et al. [278]. They showed the positive effects of MAGIC pointing on a 21 in display, reducing the required effort and target acquisition time over the increased display space.

Based on the promising characteristics of MAGIC pointing we formulate the following hypotheses:

H1: MAGIC pointing enables more time efficient pointing actions on LHRDs than mouse pointing.

H2: MAGIC pointing is less demanding than traditional pointing with a mouse on LHRDs.

To build a deep understanding of MAGIC pointing in combination with LHRDs, we conducted three user studies where we compared MAGIC pointing to standard indirect pointing with a mouse: A pointing task (see Section 6.3), with circular targets appearing on random positions on a 2.85 m wide display; a widely used one-dimensional pointing task on a curved 4 m wide display (see Section 6.4); and a map-based exploration task (see Section 6.5). The last two studies were conducted in conjunction to be able to discuss and contrast the formal pointing task and the map-based exploration with the same participants. We report the qualitative feedback for both studies in the results Section 6.5.4.

This chapter is based on:

- L. Lischke, V. Schwind, K. Friedrich, A. Schmidt, and N. Henze. "MAGIC-Pointing on Large High-Resolution Displays". In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '16. Santa Clara, California, USA: ACM, 2016, pp. 1706–1712. ISBN: 978-1-4503-4082-3. DOI: 10.1145/2851581.2892479

- The planned publication: L. Lischke, V. Schwind, P. W. Woźniak and N. Henze. Understanding Pointing for Workspace Tasks on Large High-Resolution Displays.

6.1 Related Work

For almost four decades, research has analysed the potential of eye tracking for interacting with computer systems. Bolt [33] proposed in 1982 using eye gaze for interaction. Ware and Harutune [264] argued that eye tracking enables fast target selection for large targets. Zhai el al. [278] proposed using eye gaze to move the cursor to the gaze position. The authors introduced two MAGIC pointing approaches. In one approach the authors proposed to move the cursor constantly with the gaze point. In the second approach the user was able to move the cursor to the gaze position by actuating the mouse. The authors compared both approaches with regular pointing using a computer mouse. The results indicated shorter target acquisition times when participants were able to move the mouse cursor to their gaze position on demand. Fares el al. [60] increased the target acquisition time of MAGIC pointing through warping the cursor as soon as the user started to move the mouse. To reduce the required time to trigger the demand for moving the cursor Drewes and Schmidt [55] proposed using a touch sensitive mouse for triggering cursor warps using MAGIC pointing. Zhang and MacKenzie [279] compared three eye tracking based pointing techniques and mouse pointing using a standardized pointing task. The results showed that mouse pointing had the highest throughput. However, users also appreciated the eye tracking based techniques. Vertegaal [251] compared eye gaze supported pointing techniques to mouse and stylus input using a one dimensional pointing task. In contrast to Zhang and MacKenzie's [279] results, Vertegaal showed that gaze supported input techniques allow faster target selection. Fono and Vertegaal [66] utilized the user's eye gaze to select windows and zooming selected images. Through a study the authors showed that participants were able to select windows significantly faster using eye gaze than with regular manual pointing. Fortmann et al. [67] proposed supporting the cursor rediscover process by using eye gaze. Dickie et al. [49] showed that users can switch tasks faster in a multidisplay environment when the system moves the input focus to the screen where the user is looking at. Furthermore, utilizing user's gaze for interaction has the advantage of no input device having to be operated. Due to this advantage Zhang et al. [280] proposed using gaze interaction as exclusive input technique for public displays.

Stellmach and Dachselt [230] proposed two input techniques using the eye gaze of the user to select an area on the screen and a smartphone for precise target selection. In line with these two techniques, Turner et al. [245] proposed using eye gaze and multitouch to perform rotate, scale and translate tasks on remote displays. Voelker et al. [252] proposed combining direct touch with eye gaze interaction in multidisplay environments. Serim and Jacucci [219] argued that

touch input becomes more imprecise with increasing distance to the gaze point. Hence, they proposed using the gaze point to support more precise pointing.

Previous work points out the potential of gaze supported input in particular for LHRDs. LHRDs enable users to spread out and organize visual content on a large area. This requires the user to change the visual focus area frequently, and the input devices have to trace these changes in focused areas. Hence, detecting a user's gaze position provides an opportunity to shift the system focus implicitly.

6.2   Method

Zhai et al. [278] proposed utilizing a user's gaze position to reposition the cursor in addition to the commonplace manual method of pointing using a mouse. The authors compared two MAGIC pointing techniques to manual pointing using a mouse. The results showed that users perform best when the cursor does not constantly follow the gaze position, but moves to the gaze position when the mouse is actuated. For analysing the usage of MAGIC pointing in combination with LHRDs, we implemented this technique in a similar way to Drewes et al. [55]: The eye tracker observed the gaze position of the user constantly, however to move the cursor to the gaze position, the user presses the right button on the mouse. Thereby the user has full control on whether to use or not use MAGIC pointing for moving the cursor.

6.3   Target Pointing Study

We conducted a controlled laboratory experiment to build an understanding of the advantages of using MAGIC pointing when interacting with content displayed on an LHRD, focusing on our two research questions. In this study, participants had to select circular targets on a 2.85×1.13 m large screen. The targets appeared in random order in 72 defined areas. For detecting the user's gaze point we used a monocular, head mounted eye tracker.
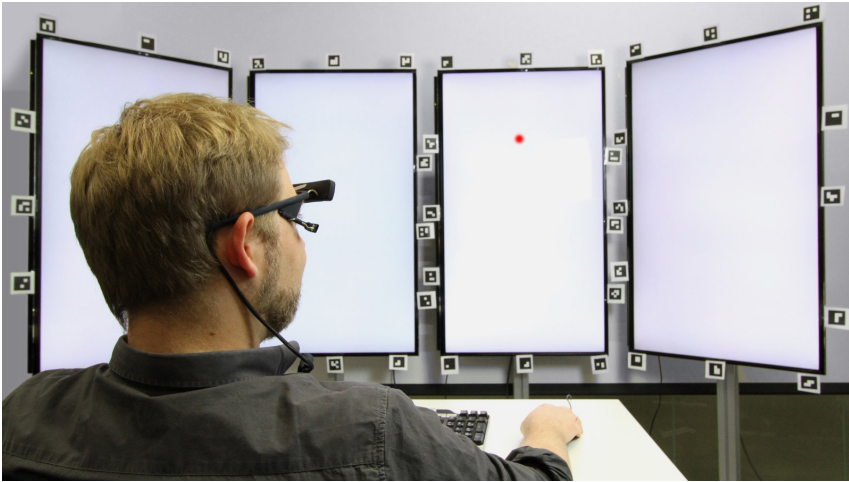
Figure 6.1: Pupil Pro eye tracker and LHRD experimental setup.

6.3.1   Study Design

The study used a within-subjects design with two conditions: *MAGIC pointing* and *mouse only*. In the *mouse only* condition, participants had to select the targets as fast as possible by moving the mouse cursor to the target position. In the *MAGIC pointing* condition, the participant was able to jump the cursor position directly to his or her gaze position on the screen by pressing the right button of the mouse. While performing this condition the participant was still able to move the cursor using the mouse.

Apparatus

Display Setup: To evaluate MAGIC pointing on LHRDs we built an experimental setup consisting of four Panasonic TX-50AXW804 50 in screens with a resolution of 3840×21604 pixel in portrait mode. Total display resolution was 8640×3840 pixel (88 PPI). Figure 6.1 shows all screens in portrait mode facing the participant's position. The two screens on the left and right were tilted to the central screens to have the same distance between the participants' position and all screens. The whole display had a size of 2.85×1.13 m. To provide an optimal view on the display all screens were mounted 0.75 m above the floor.

Each of the four screens was tiled into a 3×6 grid, which leads to 72 possible target locations on the whole LHRD. Each target appeared twice in each condition, which results in 144 targets per condition. The order of the targets was randomized. We ensured that two targets did not appear at the same position directly after each other. We decided to place the starting point in the center of the second left screen. We used this position because the setup of four screens does not allow using the center of the LHRD as starting position.

Participants were seated 1.5 m from the display resulting in an angular size of the display of 79.1° (H), 40.3° (V). Size and color of the cursor were set to the default settings of Windows 8.1. The background color was white. The target was a red filled circle with 216 pixel in diameter (5.8 cm), which corresponds to a visual angle size of 2.26°.

Eye Tracking: We used the Pupil Pro [120] and the Pupil Capture software. The eye tracker is a head-mounted monocular eye tracker for eye tracking. We used a head-mounted eye tracker, because this allows participants to move the head while using the eye tracker. To the best of our knowledge no commercial stationary eye trackers can track the eye while rotating the head by 90°, which is necessary to see the whole display. To determine where the participants looked on the display we attached 12 markers on the bezels of each screen. We used the markers provided by Pupil Labs with a size of 4.5×4.5 cm.

The computer running the LHRD used Microsoft Windows 8.1. All screens of the LHRD were registered and mapped by the Pupil Capturing software according to the virtual desktops of the computer. By using *MAGIC pointing* the mouse cursor could be placed to the computed gaze point on the LHRD.

Procedure

We conducted the study with 12 participants (9 male, 3 female) aged between 20 and 39 ($M = 26.1$, $SD = 4.8$). The data from three additional participants could not be considered because the eye tracker could not track the pupil while the participant wore glasses or because the eye lashes occluded the pupil.

The participants were seated at a table in front of the LHRD. After explaining the task the eye tracker was set up for the participant. Following the default calibration routine of Pupil Capture software, a test run of the experiment was started and the participants were asked to familiarize themselves with the task for both conditions.

Upon pressing the space key on the keyboard, the next target appeared, and the mouse cursor was reset to the start position on the second left screen. A target

selection ended when the left mouse button was clicked on the target position. Therefore, we did not count errors. After completing each condition we asked every participant to fill out a raw NASA-TLX questionnaire [93, 94] to rate the task load. Afterwards, we conducted semi-structured interviews.

6.3.2 Results

To compare the two input techniques, we compared the TCT and the perceived workload, using the raw NASA-TLX questionnaire.

Task Completion Time (TCT)

The TCTs were not normally distributed. Therefore, we performed a Wilcoxon signed-rank test. The test revealed a statistically significant effect of the input method on the TCT ($N = 864$, $Z = 1.984$, $p < .0474$). Participants were signifi-

faster TCT for mouse only   neutral   *faster TCT for gaze warp*
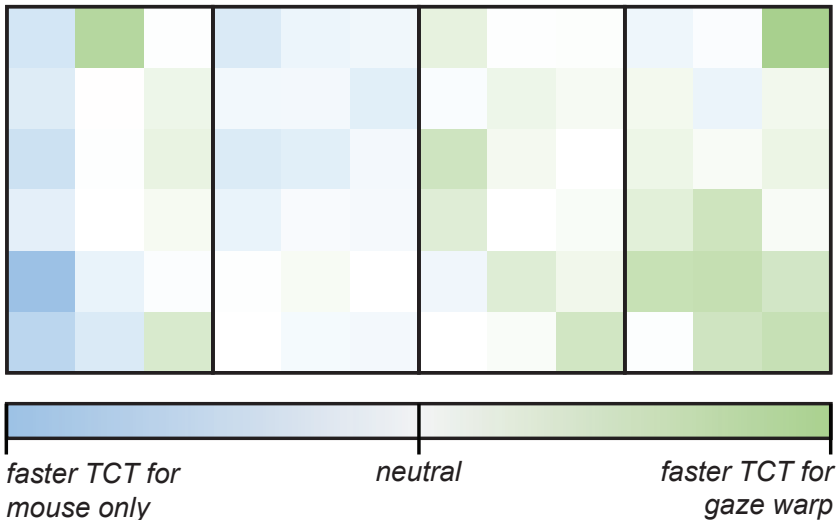
Figure 6.2: TCT distribution: blue indicates faster target hits for *mouse only*, green indicates faster hits using *MAGIC pointing*. White implies neither condition had an advantage.

cantly faster using MAGIC pointing ($Mdn = 1.675$ s, $M = 1.804$ s) than using mouse only ($Mdn = 1.677$ s, $M = 1.936$ s).

To understand how the TCT differs across the screens, we analyzed the TCT for each target position. As Figure 6.2 shows, TCT is heterogeneously distributed. There is a tendency at the left-hand side of the LHRD for shorter TCTs of the *mouse only* condition and at the right-hand side for shorter TCTs of the *MAGIC pointing* condition. The comparison of the average TCT per target shows that the mouse only condition was maximally 1.763 s faster than MAGIC pointing. For the *MAGIC pointing* condition the TCT average per target was maximally 1.541 s better than the *mouse only* condition.

To get deeper insights into why the TCT is heterogeneously distributed, we analyzed the angle between the position on which the cursor was warped, and the target position. On average the deviation between cursor position after gaze warp and target was 3.56° ($SD = 3.55$) (which is equivalent to $M = 352$ pixel, $SD = 352$). Figure 6.3 shows the deviations for each target location. The angle with lowest average from cursor position after warping to the target location is 1.79°, the highest angle between both is 6.26°.

lower distance from
gaze target to target point

higher distance from
gaze target to target point
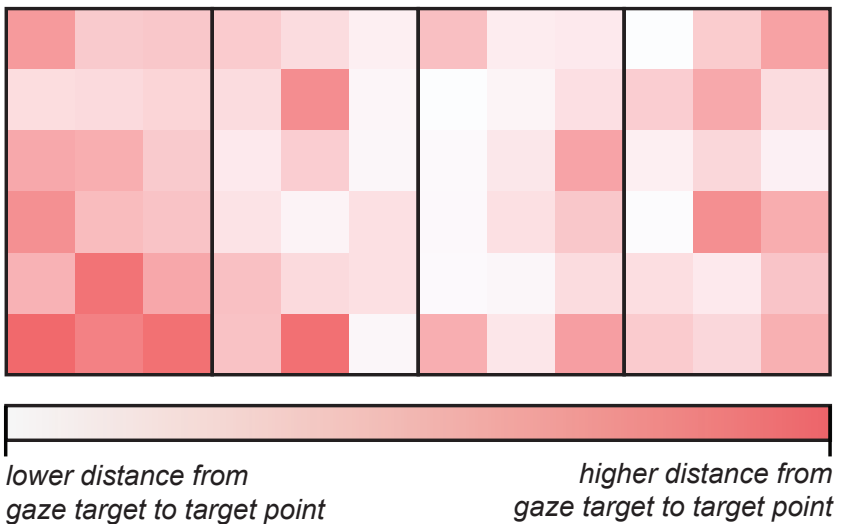
Figure 6.3: Distance between cursor position after gaze warp and target position. High distances indicate calibration issues.

Furthermore, we compared how many gaze warps the participants performed to acquire targets. On average, participants used 0.97 ($SD = 0.36$) gaze warps per target acquisition. Figure 6.4 shows the frequency of gaze warps per target acquisition. The target with the fewest average number of gaze warps was focused 0.542 times per target acquisition. The target with the highest average number of gaze warps was focused 1.208 times per target acquisition.

Subjective Feedback

We analyzed the perceived work load measured through the NASA-TLX questionnaire (see Figure 6.5). A paired sample t-test of the normally distributed scores revealed a significantly lower work load using gaze warp ($M = 36.91$, $SD = 23.43$) than using mouse only ($M = 61.75$, $SD = 20.75$).

The results from the raw NASA-TLX support the qualitative feedback from the participants. All but one participant appreciated gaze warping on LHRDs as valuable and pleasant to use. An important aspect reported by one participant was that using the mouse for large distances requires a large area on the desk. Another noteworthy observation is that positive subjective ratings of the MAGIC pointing condition does not necessarily correlate with the task completion times

few gaze warps   frequent gaze warps
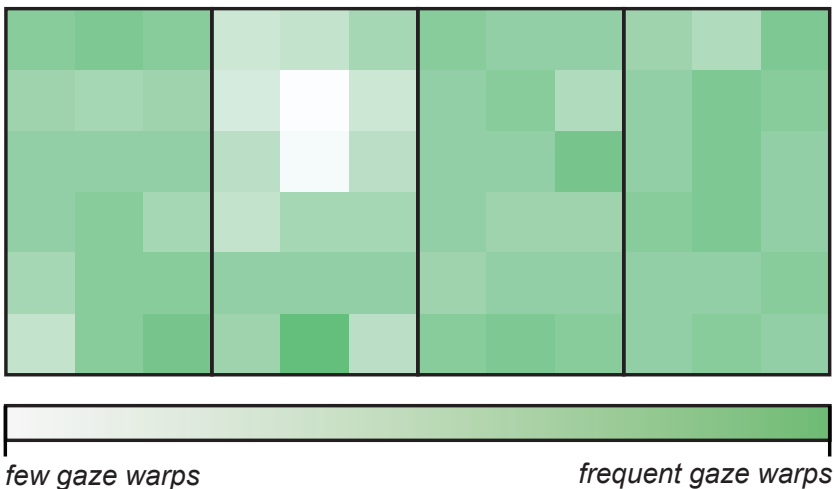
Figure 6.4: Frequency of gaze warps. Green color indicates more overall use of gaze warps on a target location.

of the users. Participants with similar completion times after performing both conditions still favoured using MAGIC pointing instead of mouse only.

6.3.3   Discussion

Overall the results of this study show a positive effect of MAGIC pointing, both in terms of TCT and task load.

The results revealed a significantly shorter TCT when using MAGIC pointing on LHRD. Hence, the hypothesis **H1**, that MAGIC pointing increases the time efficiency of pointing tasks is true. However, a more detailed analysis indicated heterogeneously distributed TCTs over the display space. The analysis of TCTs per target shows a difference between the left side of the LHRD for improved task performance of the *mouse only* condition and to the right for the *MAGIC pointing* condition (see Figure 6.2).

The analysis of distances between target position and cursor position, after gaze warp, also shows heterogeneously results. Gazes to the left displays of the LHRD are detected to be less precise. In the areas, where the *mouse only* condition revealed shorter TCTs, the distances between cursor position after gaze warp were larger than in areas where the *MAGIC pointing* condition revealed shorter TCTs (compare Figure 6.2 and Figure 6.3). The grater distances between the target position and cursor position after the gaze warp could be caused by participants not looking directly at the targets in this area. However, more probably, the
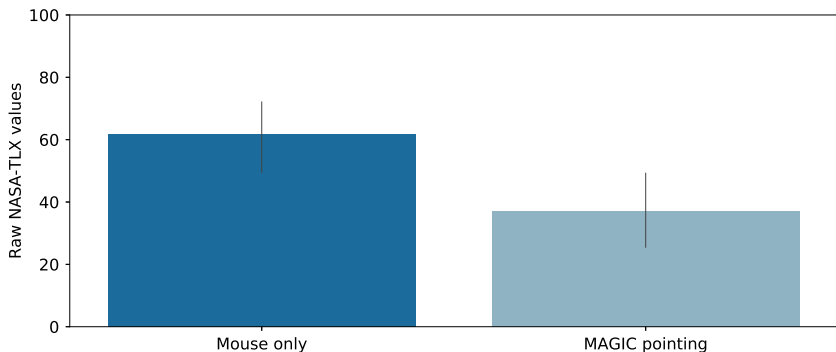
Figure 6.5: Average raw NASA-TLX-score of MAGIC pointing and mouse only.

quality of the gaze data is heterogeneous over the display space. This could be caused by the monocular Pupil Pro eye tracker which detects eye movements of the right eye from the right side. We would have assumed more homogeneous results when repeating the experiment with a binocular eye tracker, instead of a monocular one.

In contrast to TCT, frequency of performed gaze warps was homogeneous over the whole display space (see Figure 6.4). The optimum would be one gaze warp per target acquisition, in which participants would be expected to be faster using MAGIC pointing. If more than one gaze warp was performed, the cursor was not moved to the target position in the first trial. Participants used the gaze warps on all areas of the LHRD. Only on the screen where the cursor was placed at the beginning of each trial did the participants use fewer gaze warps.

Participant's task load decreased significantly with MAGIC pointing. Hence, the hypothesis **H2** the MAGIC pointing lowers the perceived workload, is correct. The significant lower task load indicates that they could attend much less the current cursor position and focus more closely on their main task. Additionally we assume that, with training TCT will further decrease.

The results indicate that MAGIC pointing would support pointing tasks, even better if the eye tracking provided more accurate gaze tracking. Thereby, the improvement in TCT could be homogeneous over the whole display space. As suggested by the results (see Figure 6.2), we assume an increasing benefit with longer amplitudes between cursor position and target position.

6.4 One-Dimensional Pointing

The results of the pointing study presented in Section 6.3 show that users are able to perform pointing tasks faster using MAGIC pointing. However, the results also indicate accuracy issues of the eye tracker due to the monocular eye observation. Furthermore, we assume that the positive effect of MAGIC pointing increases with the distance between the cursor and the target. Hence, we refined the apparatus of the study. We increased the display width by 1.34 m to 4.02 × 1.13 m, and changed to a binocular eye tracker. Additionally, we used a more formal standardized pointing task. This one-dimensional pointing task emulates the original Fitts' original experiment [63], which is commonly used to evaluate pointing performance (e.g., [59, 161, 279]). Again, we used a within-subjects design study design. Hence, all participants performed all conditions. To balance learning effects, we altered the starting condition.

6.4.1 One-Dimensional Pointing Task

To analyze the pointing performance, we used a one-dimensional pointing task, described by Sasangohar et al. [214] and ISO/TS 9241-411 [59]. We chose this, because of the aspect ratio of the visual field of view and the aspect ratio (13:4) of the LHRD setup. During the pointing task, the study software showed two rectangular targets, which the participants were asked to select alternately. To indicate which target had to be selected, it was highlighted in red. As soon as the participant selected one target, the other one was highlighted. If the participant missed the target, the screen flashed red. Similarly to Sasangohar et al. [214], we used the target amplitude (A) as independent variable with four levels: 690, 1380, 2760, and 5520 pixel. We also used the target width (W) as independent variable with four levels: 84, 169, 338, and 675 pixel (1.12° (H), 2.32° (H), 4.64° (H), 9.20° (H)). Thereby, the index difficulty [160]

$$ID = log_2(\frac{A}{W} + 1)$$

for the easiest task was $ID = 1.02$ and for the hardest task $ID = 6.06$. This is in line with the recommendations of ISO/TS 9241-411 [59], which recommend index difficulties between 1 and 6. Using two independent variables, each with four levels, and independent variable with two levels resulted in $4 \times 4 \times 2 = 32$ conditions. In every condition, participants performed 20 trials. The study instructor asked every participant to focus on accuracy, but also to perform the trails as fast as possible. Figure 6.6 shows a participant performing this task.

6.4.2 Measures

We measured the following depended variables during every study session:

Task completion time (TCT) [ms]. During the one-dimensional pointing task, we measured the time between the selection of the first target and the selection of the next target as TCT.

Error Rate [%]. A missed target in the pointing task was counted as an error. The error rate is the ratio between the error count and the total number of trials.

Use of Eye Gaze warps [number of warps]. As an indicator of how often the participants used MAGIC Pointing, we counted how often participants performed gaze warps in conditions with MAGIC pointing.

Figure 6.6: A user is performing the one-dimensional pointing task.

Perceived Task load [raw NASA TLX score]. To assess the perceived effort for each task and condition, participants rated the effort on the raw NASA-TLX questionnaire [93, 94].

6.4.3 Apparatus

To conduct the study we used six Panasonic TX-50AXW804 50 in screens with a resolution of 3840×2160 pixel aligned in portrait mode. This resulted in a 4.02×1.13 m display space, with a total resolution of $12,960 \times 3840$ pixel. To provide an equal viewing distance to the screens we aligned the screens in a semi-circle with a distance of 1.2 m to the participant. Thereby the display had a viewing angle of approximately $180°$ (H) and $42°$ (H).

To realize MAGIC pointing we used a Pupil Labs headset [120] with a high-resolution (FHD) world camera and binocular eye-cameras running a 120 Hz capture frequency. For calculating the gaze position we used the Pupil Labs software, version 0.9.3 together with marker-based surface detection. We displayed the markers on the LHRD. This lowered the space between the single screens and enabled a more continuous image on the LHRD. We placed six markers per display for registering the 3D translation of the eye tracker.

One Microsoft Windows 10 workstation, with two Nvidia TITAN Pascal graphic cards drove the six 4K 50 in displays and the Pupil Labs eye tracker. The same

machine ran the custom-made study software. We used only one workstation to minimize time legacy issues and guarantee perfect timing.

In the middle of the display, at 1.2 m distance from the screen, we placed a chair for the participant. We placed a table with a standard office computer mouse and a keyboard in front of the chair.

6.4.4   Participants

We recruited 35 participants (16 female, 21 male) aged between 19 and 31 ($M = 23.7$; $SD = 2.9$) by invitations over university mailing lists. Every participant received 10 EUR as compensation for taking part in this study. Because of technical challenges with the eye tracker with participants wearing glasses, participants were required to use contact lenses, if needed.

6.4.5   Procedure

After welcoming every participant, we asked them to read and sign the consent form. Afterwards, we invited them to take a seat in front of the LHRD and to fill in the demographics sheet. We explained the general purpose of the study
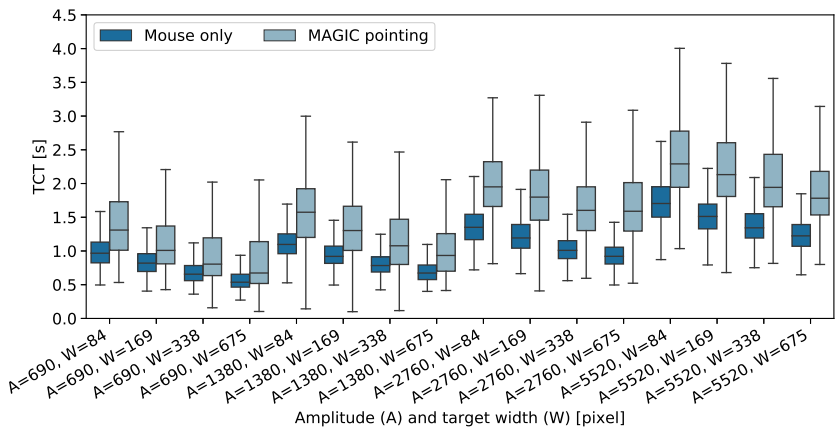
Figure 6.7: The Task completion time (TCT) of the one-dimensional pointing task per condition.

and asked the participant to put on the eye tracker headset. When this was mounted we calibrated the eye tracker using the Pupil Labs calibration routine and when completed the participant was given time to become familiar with the one-dimensional pointing task and the input technique. When the participant was ready, we started the trials with logging, alternating the order of the input technique used and randomizing the level of the other two independent variables. After performing the 640 target selections, we asked the participant to answer the questions of the raw NASA-TLX and changed the level of the input technique to complete the abstract pointing task.

6.4.6 Results

During the study the apparatus logged mouse clicks, cursor warps, when using MAGIC pointing and TCT. The perceived task load was measured using pen and paper. Based on this data, we conducted the following analyses.

Task completion time (TCT)

To analyse the TCT-values for the one-dimensional pointing task, we used the TCT values logged by the apparatus. We removed trials with a TCT larger than 7.5 s, as outliers. We conducted a one-way RM-ANOVA to analyse the effect
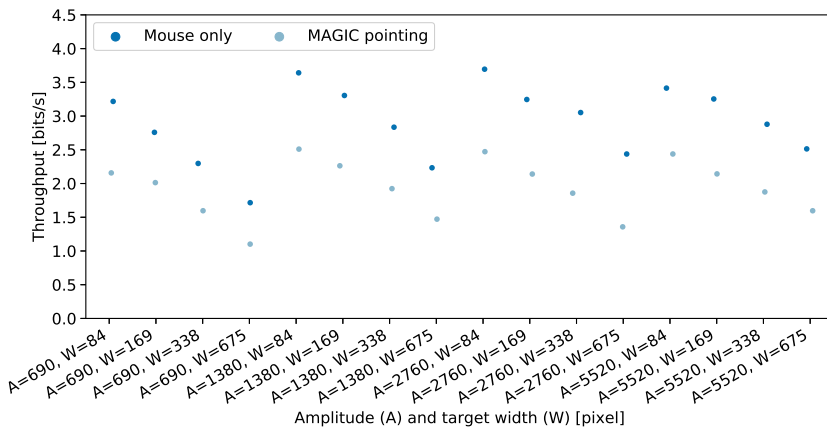
Figure 6.8: Throughput per target width (W), amplitude (A) and input technique.

of the independent variables on the TCT. Figure 6.7 shows the TCT values per condition. The analysis revealed a statistically significant effect of input technique on TCT ($F_{1,23092} = 5754.656$, $p < .05$). Furthermore, analysis revealed a statistically significant effect of target width (W) ($F_{1,23092} = 1949.100$, $p < .05$) and amplitude (A) ($F_{3,23092} = 3032.387$, $p < .05$). Moreover, there were statistically significant interaction effects of target width (W) × Amplitude (A) ($F_{3,23092} = 5.263$, $p < .05$), target width (W) × input technique ($F_{1,23092} = 4.823$, $p < .05$), Amplitude (A) × input technique ($F_{3,23092} = 168.503$, $p < .05$) and target width (W) × Amplitude (A) × input technique ($F_{3,23092} = 7.381$, $p < .05$).

Throughput

Based on the TCT of the one dimensional pointing task, we calculated the throughput ($TP = \frac{ID}{MT}$ [bit/s]) [59]. Figure 6.8 shows TP per target width (W), amplitude (A) and input technique. The MAGIC pointing had an overall mean TP of 1.93 bit/ Input using only the mouse had an overall mean TP of 2.90 bit/s.

Error rate

In the one-dimensional pointing task participants made on average $M = 0.028$ ($SD = 0.164$) errors when using MAGIC pointing. When participants used only the mouse, they made on average $M = 0.016$ ($SD = 0.126$) errors. For
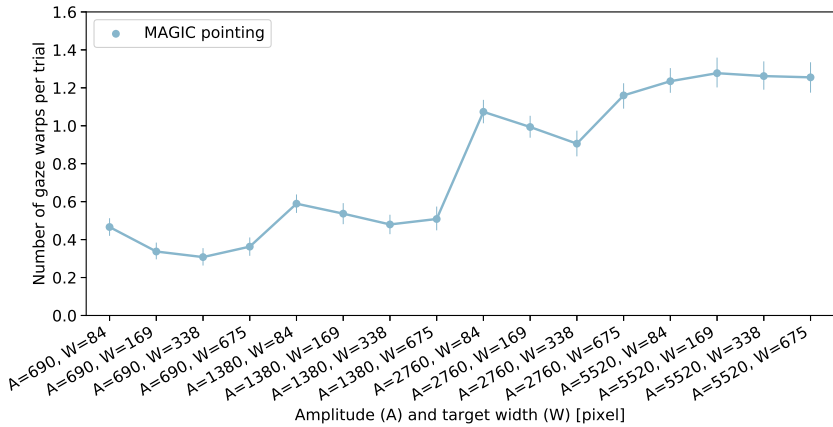
Figure 6.9: Number of gaze warps per condition in the one-dimensional pointing task.

this task, we conducted a three-way RM-ANOVA to analyse the effect of the conditions on error rate. Input technique ($F_{1,23076} = 36.22$, $p < .01$), target width ($F_{3,23076} = 26.83$, $p < .01$) and amplitude ($F_{3,23076} = 4.90$, $p < .01$) had a significant effect on error rate. Additionally, all two-way interaction effects and the three-way interaction effect were significant (all with $p < .01$).

Use of Eye Gaze warps

We also invested how target width and amplitude affected the use of eye gaze warps by the users (see Figure 6.9). We found a significant combined effect of target width × distance ($F_{9,11663} = 4.13$, $p < .01$). Significant main effects were observed for target width ($F_{3,11663} = 10.19$, $p < .01$) and amplitude ($F_{3,11663} = 792.68$, $p < .01$).

Perceived Task Load

For the one-dimensional pointing task, a one-way RM-ANOVA for the combined scores of the raw NASA-TLX revealed no statistically significant difference between the two input techniques ($F_{1,34} = 0.096$, $p = .758$). Furthermore, we compared the responses for every item of the raw NASA-TLX (see Table 6.1). Figure 6.10 shows raw NASA-TLX-scores per item.

Table 6.1: Statistical comparison of the raw NASA-TLX results of the one-dimensional pointing study per item.

raw NASA-TLX items	$F_{1,34} =$	$p =$
mental effort	2.982	0.118
physical demand	2.984	0.093
temporal demand	2.566	0.118
effort	3.659	0.064
frustration	0.273	0.605
performance	6.215	0.017

6.4.7 Discussion

In all conditions, participants performed slower when using MAGIC pointing. This is in contrast to the results of previous work [251, 264, 278]. On the other hand, the results of this study are in line with the results presented by Zhang and MacKenzie [279]. They used the two dimensional pointing task, specified in ISO/TS 9241-411 [59]. This task is comparable to the one dimensional pointing task we used in this study. In both tasks, participants repeat pointing to targets on the same position. This eliminates the visual search of the target and allows to measure only the motor movement time of the cursor. In contrast, Zhai et al. [278] used a random order of targets. This requires locating the target visually, before moving the cursor to the target. Hence, the results of the one dimensional pointing tasks, show no benefit in terms of time performance, when the position of the target is known by the user. We did not observe a difference in terms of target acquisition time in the map based search task. The descriptive statistics indicate shorter TCT when using MAGIC pointing. In line with the resulting TCT values, the throughput, calculated for the one-dimensional pointing task, is lower in all conditions, where participants used MAGIC pointing.

Interestingly, users still used MAGIC pointing throughout the study, despite the fact that they perceived it as performing significantly worse. This indicated that there is a certain appeal to techniques based on eye tracking. As users were eager to use MAGIC pointing as the distance between targets increased, we hypothesize that gaze warps were perceived as desirable when the distance to be travelled by the cursor was above a certain threshold. In practical tasks, this threshold may
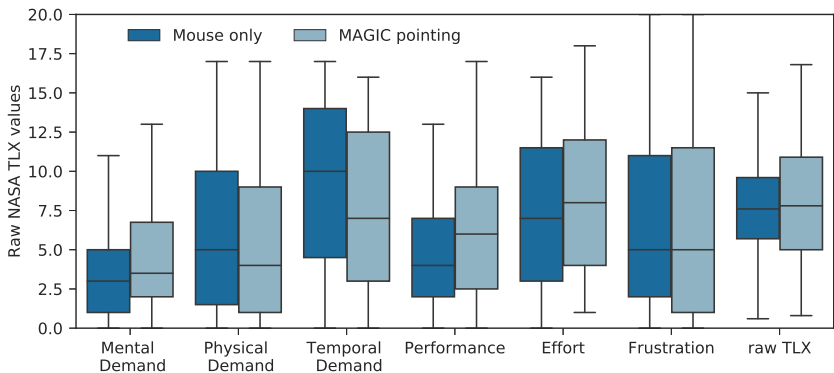
Figure 6.10: Raw NASA-TLX values comparing both input techniques.

be determined by the maximum mousing distance that can be performed without clutching or a distance that does not require head rotations. In this context, we can attribute the inferior performance in the one-dimensional pointing task to the the fact that tracking head rotation precisely in a multiscreen environment may have been not accurate enough. As users were more incline to use gaze warps with pointing distances requiring excessive head rotation, they also used gaze warps in cases where the eye tracker can offer the least accuracy.

The increase of number of gaze warps with increasing distance and the increasing number of errors could also be caused by calibration issues. When the amplitude between the targets is larger than the visual field of view, the participant starts to rotate the head. Thereby, the head mounted eye tracker might start to move. This lowers the calibration quality.

6.5   Map Based Study

The pointing studies presented in Sections 6.3 and 6.4 analysed the pure input performance. In particular the one-dimensional pointing task analysed only the motor task. In contrast, in this task we focus on an exemplary task that can be performed on an LHRD. We designed a visual search task based on targets presented on a map. Comparable to the studies in Section 6.3 and Section 6.4, we used an repeated measures design to compare pointing using only the mouse to MAGIC pointing. This study was conducted in conjunction with the study described in Section 6.4, using the same apparatus (see Section 6.4.3) and the same participants (see Section 6.4.4).

6.5.1   Task

To analyze MAGIC pointing in the context of a task known to be effectively performed on an LHRD [21], we designed a visual search task inspired by Zhang et al. [281]. We presented each participant with a street map of Paris. We placed 43 map pins, indicating hotels. All hotels were located in clusters around four points of interest. The system showed the name and price of the hotel when the user clicked the pin. This information disappeared after two seconds. Each participant was asked to search for the cheapest hotel close to any of the places of interest. The task was completed after the participant entered the result into a text box and clicked on the button "done". By clustering the hotels around the
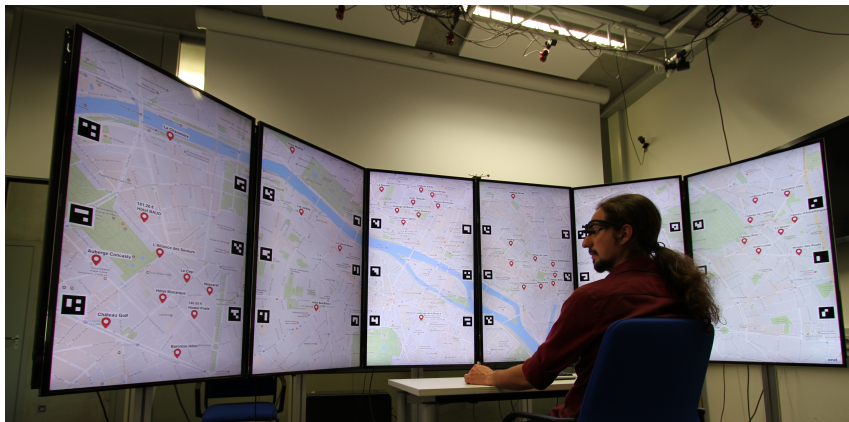
Figure 6.11: A user is performing the map based search task.

places of interest and by the requirement that the search target must be close to any point of interest, we created short and long distances between pointing targets. We asked the participants to search carefully and as fast as possible for the best option. Figure 6.11 shows the map on the setup, while a participant is analyzing hotel prices.

The one-dimensional pointing task involves motor acquisition of the target and also requires the visual process of (re-) discovering the cursor as well as locating targets on a visual rich background. These visual search processes are challenging to perform on LHRDs [208].

6.5.2   Measures

We measured the following depended variables during every study session:

Task completion time (TCT) [s]. We measured the time between the map with the pins were shown, and the participant pressed "done" to indicate the task completion as TCT.

Perceived Task load [raw NASA-TLX score]. To assess the perceived effort for each task and condition, participants rated the effort on the raw NASA-TLX questionnaire [93, 94].

6.5.3   Procedure

After completing the abstract pointing task described in Section 6.4, we continued with the map based search task. We explained the task and showed an example map. Every participant could play around with the example map to get familiar with the functionality and the input technique. As in the abstract task, we altered the order of pointing techniques. When a participant reported that she or he understood the task, the actual experimental task was started. After entering the solution and pressing the "done" button, we asked them to fill in the raw NASA-TLX questionnaire. After this, we followed the same procedure with the second input technique.

6.5.4   Results

During the study the apparatus logged mouse clicks, cursor warps, when using MAGIC pointing and TCT. The perceived task load was measured using pen and paper. Based on this data, we conducted the following analyses.

Task completion time (TCT)

We compared the TCT for the map search task (see Figure 6.12). The average TCT when participants used only the mouse as input technique was $M = 146.088$ s ($SD = 58.561$) and MAGIC pointing as input technique was $M = 143.873$ s ($SD = 75.276$). A one-way RM-ANOVA revealed no statistically significant effect of input technique on TCT ($F_{1,68} = 0.019$ $p > .05$).
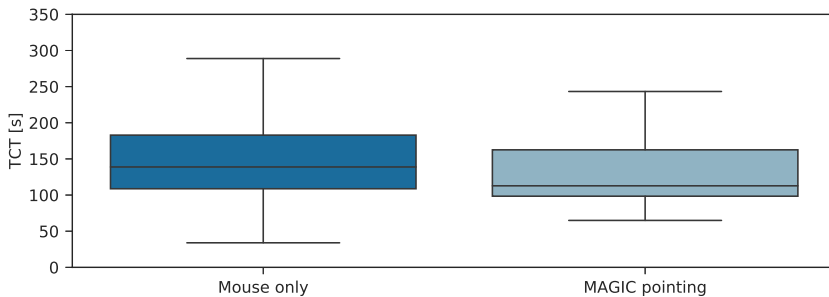
Figure 6.12: TCT for the map based task per input technique.

Perceived Task Load

For the map based search task, the comparison also revealed no statistical significant difference between the two input techniques ($F_{1,34} = 0.28$, $p = .60$). Also the comparison of the single items revealed no statistical significant difference (see Table 6.2). Figure 6.13 shows the raw NASA-TLX-scores.

Qualitative Feedback

At the end of every study session, we conducted short semi-structured interviews with every participant. Overall we recorded 92 min of interviews. The interviews underlined the quantitative results of the studies. Twelve participants mentioned they assumed they would have performed better with more precise gaze tracking. Also, six participants mentioned that they forgot to use MAGIC pointing because they were so familiar with using the mouse as a pointing device. However, twelve participants reported that they were able to perform the task faster with MAGIC pointing than with using the mouse only. Six mentioned that MAGIC pointing was, in particular, helpful for moving across long distances with the cursor. We concluded that overall, participants appreciated MAGIC pointing for the one dimensional pointing task. For the map based task, the participants had various opinions of the value of MAGIC pointing. While some claimed that the distances between the targets were too short for using MAGIC pointing, others argued that MAGIC pointing allowed them to focus more on the task. Instead of caring about the cursor position, the participants felt able to concentrate on the map and request the cursor to move to the visual focus area on demand. In line with this,

Table 6.2: Statistical comparison of the raw NASA-TLX values per item of the map based task.

raw NASA-TLX items	$F_{1,34} =$	$p =$
mental effort	0.073	0.788
physical demand	1.434	0.239
temporal demand	1.609	0.213
effort	0.335	0.566
frustration	0.263	0.611
performance	0.275	0.603
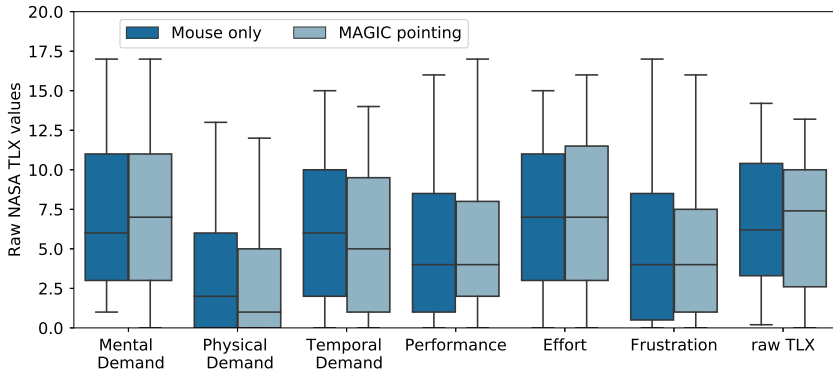
Figure 6.13: Raw NASA-TLX values for the map based search task.

seven participants explicitly mentioned this as an advantage and would also like to use their gaze point in other applications to reposition the system focus and the cursor position to the focused visual field.

6.5.5   Discussion

For the map search task, the results of the quantitative measurements revealed no statistically significant differences. Nevertheless, participants reported that they were able to focus more on the actual content when using MAGIC pointing without caring about the cursor position. However, some participants stated that they were not used to MAGIC pointing and forgot about using it. This indicates, that a longer training period before the study would be required. Furthermore, the task design generates only a small number of data points per participant. We measured only the TCT for the full task, which was performed once per condition. However, solving the task involves several visual searches and comparisons.

6.6   Implications for MAGIC pointing

In line with the related work, these three studies on utilizing MAGIC pointing for LHRDs show the complexity of studying pointing task on an abstract level. Our one-dimentional pointing study (see Section 6.4) is in line with the results

of the work conducted by Zhang and MacKenzie [279]. While Zhang and MacKenzie used regular office displays and a two-dimensional pointing task, we used a one-dimensional pointing task due to the aspect ratio of the LHRD. However, in both tasks the participant is aware of the position of the cursor, the current and the next target. This leads to the comparable result that users perform pointing tasks faster using only the mouse for pointing. In contrast, Vertegaal [251], Sibert and Robert [224] showed that gaze supported pointing can also outperform mouse pointing when performing abstract pointing tasks. However, both studies [224, 251] utilized the dwell time for selection, instead of pressing a button on the mouse. However, it is questionable how usable dwell time based selection techniques are for a real world application, because of the midas touch problem [111]: Users might select objects unintentionally by looking for a certain time frame on one position.

In contrast to the one-dimensional pointing study (see Section 6.4), the target pointing study (see Section 6.3) showed that participants are able to select targets faster with MAGIC pointing than with only using the mouse for pointing. Equally to Zhai et al.'s study [278], participants in our second study were not aware of the target position before the target appeared. Often when users are working they are not aware of the cursor position or the GUI element to select for triggering a specific function. Thereby we can conclude that the process of target selection using indirect pointing techniques often consists of several steps: First the user must visually search for the target and the cursor. Afterwards the user moves the cursor to the target to select it. With increasing display space the first step becomes more demanding. Hence, we conclude that MAGIC pointing is beneficial in particular for interacting with content displayed on LHRDs.

To implement MAGIC pointing as an additional input technique for LHRD setups, our results show that there is the requirement to increase the reliability of the precise eye tracking. When the setup requires that the user rotates the head, or even allow full-body movement, the quality of the calibration has to be high over the whole interaction period. Besides MAGIC pointing, eye tracking could support the attention management on LHRDs. When working with displays larger than the visual field of view of the user, users might not recognize relevant information or notification. The knowledge of the user's gaze position would allow managing the position of notifications in relation to their relevance and the user's gaze position.

6.7 Conclusion

We have shown that eye tracking can be utilized for interacting with LHRDs. MAGIC pointing can increase the pointing performance for pointing on targets with a large amplitude. Furthermore, MAGIC pointing enables users to rediscover the cursor quickly and effortlessly. As shown in Section 2.3, rediscovering the cursor and changing the input focus quickly is an everyday challenge when working with multidisplay systems. To deploy eye-tracking based interaction techniques in working environments, the accuracy of the eye tracking method has to increase. We experienced that the calibration quality decreases over time when the user moves the head frequently.

In future work, it should be explored how eye tracking can be utilized for interacting with LHRDs beyond MAGIC pointing. The knowledge of where the user looks allows judging of what content on display has been recognized. This would allow moving users' attention to important information not looked at. Furthermore, the system could summarize the seen content.

Chapter 7

Mid-Air Gestures

In Part IV, we show that users of LHRDs work and interact focused on a small subarea of the display. The surrounding area is used for displaying additional information. Only in the focused area is high-precision user input required. In the peripheral areas quick access is needed, but the precision is less important. However, the physical position of the focused area might change over time. Hence, both quick access and high-precision input have to be available on the whole display. Mid-air gestures could be a well-suited input technique for less accurate, but large scale input. For high precision input on small areas the mouse or keyboard input is sufficient. In this chapter, we focus on mid-air gestures which can be detected by sensors placed in the room or on desk. This gives an advantage over solutions to enhance interaction with content on LHRDs utilizing gaze, as discussed in Chapter 6. Also, when using a mobile second device, as discussed in Chapter 8, the user has to carry additional technology around. In contrast, when using mid-air gestures, the user can move freely in the tracking space. This could enable users to switch between different body postures while working and might support users to stay active while interacting with content on the LHRD. While the user is focusing on detailed information, he or she might prefer working in a seated position using mostly mouse and keyboard, but when building relations between some information piece or discussing data with a second person, the user might want to stand and walk in front of the display. In these situations, mid-air gestures might be well-suited for interacting. Additionally, when the user is relating visual information and reorganizing the working space mid-air gestures might also be carried out in a seated position.

As discussed in Part IV, application windows are common visual content containers, and it is unlikely that this concept will disappear in LHRD interfaces. Hence, in this Chapter we focus on designing mid-air gestures to interact with window managers on LHRDs. In the first user-defined gesture study, we explore full-arm gestures that can be recognized by a Microsoft Kinect. In the second study, we focus on less tiring gestures performed with one hand. These gestures can be detected by a Leap Motion. Furthermore, we analyze the influence of legacy bias and the possibility to reduce this bias though applying priming and production.

This chapter is based on:

- L. Lischke, P. Knierim, and H. Klinke. "Mid-Air Gestures for Window Management on Large Displays". In: *Mensch und Computer 2015 - Tagungsband.* Berlin, Boston: De Gruyter Oldenbourg, 2015. ISBN: 978-3-11-044392-9. DOI: 10.1515/9783110443929-072

- The planned publication: L. Lischke, P. Knieriem, H. Klinke, P. W. Woźniak and N. Henze. Mid-Air Gestures for Supporting Office Work on large high-resolution displays.

- The planned publication: L. Lischke, M. Altmann, P. Knieriem, P. W. Woźniak and A. Schmidt. Gestural Input for Large High-Resolution Workplaces: An Elicitation Study.

7.1 Related Work

In this section, we will discuss previous work focusing on mid-air gestures for data input on LHRDs. Furthermore, we present work on the methodical approach of gesture elicitation studies. Based on this we will highlight the relevance of exploring mid-air gestures for interacting with LHRDs in office environments.

7.1.1 Mid-Air Gesture Input for LHRDs

Over recent decades, mid-air gestures have been explored for interaction with visual content. Richard Bolt [34] proposed using mid-air gestures to interact

with multimedia content on wall-sized displays. Nancel et al. [186] presented a design space for pan-and-zoom gestures on LHRDs. The authors proposed to use additional input devices for 1D and 2D gestures and mid-air gestures in 3D. While Nancel et al. [186] focused on visual data exploration, Markussen et al. [165] proposed complex mid-air gestures for text input on remote displays. Vogel and Balakrishnan [254] explored mid-air gestures for pointing and clicking on distant LHRDs and compared three gesture sets. While Vogel and Balakrishnan [254] used optical gesture recognition, Haque et al. [92] proposed using forearm mounted electromyography. Dingler et al. [51] combined different optical tracking technology to enable various grained gesture input in dependency to the distance between user and display. To enable precise mid-air pointing detection, Mayer et al. [172] modeled the human pointing behavior.

The presented previous work explored mid-air gesture input for a variety of applications on LHRDs. However, gesture input has not been explored for window and content management in an office scenario.

7.1.2   Gesture Elicitation

Gesture elicitation studies are a common participatory design technique to design input gestures for interactive systems [179]. Gesture elicitation studies include the user in an early state in the design process, by asking the user about a gesture (*sign*) for a given action result (*referent*) [269]. Gesture elicitation studies have the potential to reveal a gesture set which is more preferred by users than those designed by experts only [178].

Gesture elicitation studies are applied to reveal gesture sets for a large variety of interactive systems. Ruiz et al. [212] conduted a gesture elicitation study to design smartphone motion gestures. Comparably, Kray et al. [130] designed multiuser gestures using two smartphones. Alexander et al. [6] explored foot-based interaction through a gesture elicitation study. In particular, touch gestures are well explored through gesture elicitation studies. Frisch et al. [70] presented gestures for multitouch and pen gestures for information editing. Wobbrock et al. [269] asked study participants to perform touch gestures for interacting with an interactive tabletop. Based on these performed gestures, the authors calculated the agreement score ($A_r(r)$) as follows [269]:

$$A_r(r) = \sum_{P_i \subseteq P_r} \left(\frac{|P_i|}{|P_r|} \right)^2$$

In 2015, Vatavu and Wobbrock [249] redefined the agreement calculation and proposed using the agreement rate:

$$\mathcal{AR}(r) = \frac{\sum_{P_i \subseteq P_r} \frac{1}{2}|P_i|(|P_i|-1)}{\frac{1}{2}|P_r|(|P_r|-1)}$$

Whereby P_r is the set of all gestures for referent r and P_i is the subset of identical gestures. To provide comparability to previous work (e.g. [268]) we will report the agreement scores ($A_r(r)$).

Meredith Morris [177] designed multimodal input using mid-air gestures and speech for web browsing on remote displays through a gesture elicitation study. Wittorf and Jakobsen [268] conducted a gesture elicitation study, to identify 25 gestures for object selection and manipulation. In contrast to previous work, we focus on gesture elicitation for interacting with window managers for office work.

Morris et al. [179] argued that one issue of gesture elicitation studies is that participants are influenced by their prior knowledge and perform gestures based on state-of-the-art interaction techniques. To minimize this legacy bias, the authors [179] proposed priming study participants beforehand and to request them to perform multiple gestures for the same referent (production). However, the influence of legacy bias and the reduction techniques are still questioned. Hoff et al. [102] conducted a gesture elicitation study with 30 participants to design gestures for interacting with a multimedia player. Thereby the authors used a between-subject design and used priming and production in one condition. Their results indicated only a small effect of using priming and production in a gesture elicitation study [102].

Overall, we see that gesture elicitation studies are a valid and widely used method to design interactive systems. Furthermore, this method has also been applied to LHRD input. Hence, this method is well-suited to identify mid-air gestures for LHRD workplaces. Additionally, we will analyze the influence of priming and production on the resulting gesture set.

7.2   Full-Arm Mid-Air Gestures

In a first iteration, we focused on gestures performed with one or two arms. This has the advantage that the gestures can be easily detected, e.g., by a Microsoft Kinect. Full-arm gestures enable the user to point comfortably to every point on the large visual space. Furthermore, full-arm gestures perform more body

movement while interacting. We propose to extend the interaction space by allowing window management with mid-air full-arm gestures. This enables using familiar pointing techniques with mouse or touchpad for tasks where fine-grained input is required, while interactions including the full interaction space can be performed through mid-air gestures.

Today, all common desktop environments support window management tasks though shortcuts. This allows users to quickly and easily switch between applications and different views. As a starting point for our study, we analyzed default shortcuts for window management on Microsoft Windows 8.1. However, shortcuts are limited in the number of different arrangements to which they provide access. This becomes critical when interacting with LHRDs.

We derived 12 commands from existing shortcuts on Microsoft Windows and previous work as referents. Table 7.1 describes the functionality of all referents.

7.2.1 Study

In order to design a full-arm gesture set for window management on LHRDs, we conducted a gesture elicitation study with 12 participants (10 male and 2 female) aged between 20 and 28 years ($M = 25$; $SD = 2.5$). Participants were recruited through our University's mailing lists. All participants had an academic background. The study took approximately 60 min per participant. During every session, we provided refreshments and snacks as compensation.

Apparatus

To enable all participants to experience working on an LHRD, we used six 50 in 4K displays aligned in portrait mode. The resulting display had a native resolution of $12,960 \times 3,840$ pixel powered by a single workstation running Microsoft Windows 8.1. With respect to Endert et al. [57]'s guidelines, we arranged the displays in a curved configuration allowing the participants to see all areas of the display easily (Figure 7.1). A standard office chair was placed the center of the LHRD ensuring equidistance to all parts of the display. Further, a camcorder was placed on top of the LHRD to record gestures as well as the comments the participants gave.

Table 7.1: Referents and their functionality.

Referent	Function
Put cursor there	Allows moving the cursor to the center of a specific window. Moving the cursor over longer distances and keeping track of the cursor is a well described issue when interacting with LHRDs [208]. Hence, it is required to replace and recover the cursor easily. Moving the cursor to a particular window allows switching between different tasks quickly.
Select window	Activates the chosen window. As soon as the windows is activated, keyboard events will be handled by this window. The same action is performed by pressing ALT+TAB on Microsoft Windows.
Shift window	Allows moving a selected window from one screen to another connected screen.
Move window	Enables the user to move a selected window freely to any position of the whole display.
Close window	Allows to close a selected window, comparable to pressing ALT+F4 on Microsoft Windows.
Maximize window	Enables the user to scale a selected window to the size of the whole display.
Minimize window	Hides the focused window.
Resize window	Allows to freely change the height and width of the selected window.
Show all windows	Presents a thumbnail overview of all opened windows.
Show Desktop	Hides all windows and presents the desktop. This is comparable to WINDOWS+D when working on Microsoft Windows.
Select multiple windows	Allows to select several windows to manipulate a group of windows at once.
Zoom content	Enables the user to increase or decrease the size of a window's content

Procedure

At the beginning of every study session, we asked each participant for consent to take part in the study and to record and process videos. We also asked them to fill in a short demographic questionnaire. Afterwards, the participants ranked the presented window management commands by the frequency of use and importance in everyday usage.

After this first part, we introduced our LHRD setup to the participants. Every participant was invited to familiarize themselves with the LHRD before we started the gesture elicitation session. For every referent, we showed the action in three scenarios as screenshots including a *before* and *after* state. For example, for the referent *Move window* we presented a browser window on the left side (*before*) and the same browser window on the right side (*after*) of the LHRD.

For each of the referents, we asked the participants to invent and perform a mid-air gesture or rethink the previously invented gesture. Participants were encouraged to think aloud since this session was recorded via audio and video.

7.2.2 Results

We first analysed participants' ranking of the 12 window management commands. Without any exception, all participants ranked *Put cursor there* as the most used and *Select window* second most used command for window management. These
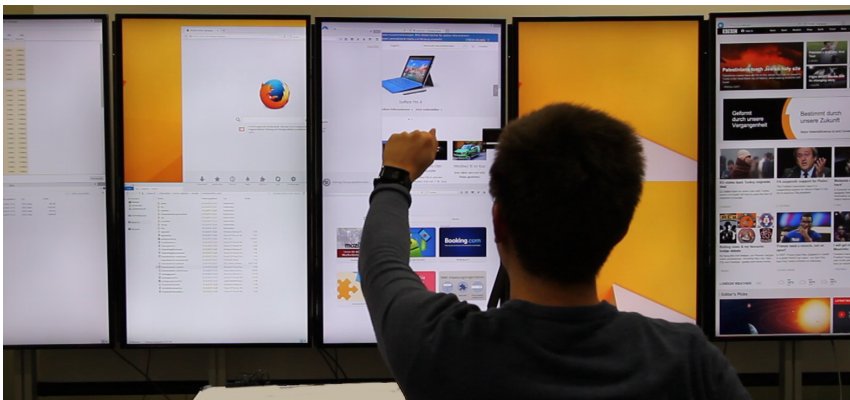
Figure 7.1: Participant performing a *Move window* gesture.

were followed by *Shift window*, *Close window*, *Move window*, *Maximize window*, *Resize window*, *Minimize window*, *Zoom content*, *Show Desktop* and *Show all windows*.

During the course of the gesture elicitation study, we recorded 3:39 h of video and audio which we transcribed and analyzed. In total, we recorded 432 (12 participants × 12 referents × 3 scenarios) gestures. Sixty-eight of these were identified and classified as unique.

The agreement score $(A_r(r))$ for each referent was calculated using the approach presented by Wobbrock et al. [269]. A single number [1..0] for each command reflects the consensus of all participants by allocating the group sizes of equally proposed gestures. The overall agreement is 0.460, the single agreement scores per referent are shown in Table 7.2.

In two cases, it was possible to use the very same gesture for more than one command. *Maximize window* and *Resize window* for example are executed with the same gesture. The final gesture set is depicted in Figure 7.2 and consists of nine unique gestures enabling all 12 window management commands. Table 7.3 describes the nine gestures of the gesture set.

| (a) *Put cursor there* | (b) *Move window* | (c) *Resize/ Maximize Window* | (d) *Minimize window* |
| (e) *Close window* | (f) *Zoom content* | (g) *Select multiple windows* | (h) *Show Desktop/All* |
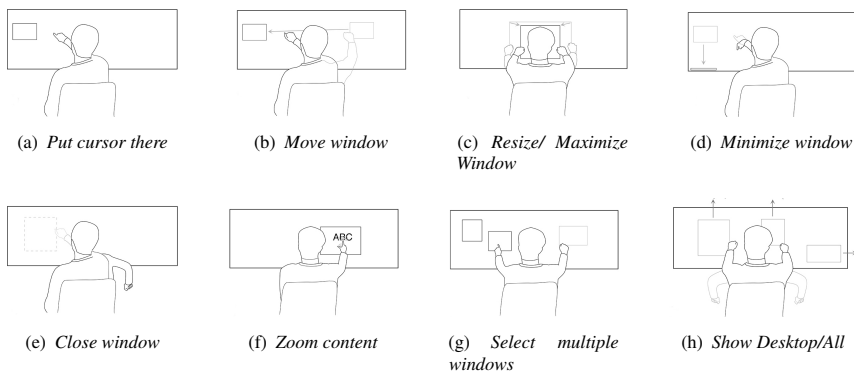
Figure 7.2: User-defined gesture set based on the results of the user study.

Table 7.2: Agreement Scores of the full-arm gesture elicitation study.

Referent	Agreement Score ($A_r(r)$)
Put cursor there	0.847
Select window	0.292
Shift window	0.375
Move window	1.000
Close window	0.240
Maximize window	0.324
Minimize window	0.264
Resize window	0.708
Show all windows	0.101
Show Desktop	0.236
Select multiple windows	0.583
Zoom content	0.408
Overall agreement	0.460

7.3   Hand Mid-Air Gestures

The results of the first study revealed a mid-air full-arm gesture set for performing window management task on LHRDs. Large full-arm gestures are prone to the challenge that users might perceive perfoming them as tiring, and also require more time to be performed than hand and finger gestures. Furthermore, participants of the study might supply gestures based on their prior knowledge. To minimize this legacy bias, Morris et al. [179] propose priming study participants beforehand and asking them to perform multiple gestures for the same referent (production). In this study, we compare gesture elicitation results between participants who were primed and produced multiple gestures, and participants who just supplied gestures.

Table 7.3: Description of the gestures of the full-arm gesture set.

Referent	Gesture
Put cursor there	The user points with his or her index finger at a window to move the cursor to it.
Select window	For activating a window for interaction, participants perform a grab gesture in the direction of the targeted window.
Move window	The participants perform a grab gesture with one hand in the direction of the window he or she would like to move. To move the window he or she moves the fist to the target position and release the window by opening the hand again. Participants did not distinguish between *Move window* and *Shift Window*, so we removed *Shift window* from the gesture set.
Close window	Participants perform a grab gesture in the direction of the window which should be closed, and moved the arm downwards.
Minimize window	The participant selects the window, to be minimized, by pointing on it with the index finger and then bending the wrist downwards.
Resize window	Participants perform a grab gesture with both hands in the direction of the window they aim to size up or down, and bring their fists closer together to downsize the window, or apart to upsize it. Hence, we remove the dedicated *Maximize window* command.
Show all windows and *Show Desktop*	To minimize all windows participants move both arms above the desk to the center of the display and down again. To open all windows participants perform the gesture from the desk up to the center of the display.
Select multiple windows	To select several windows, participants perform a grab gesture with one hand and pointed with the other hand on other windows to select.
Zoom content	To zoom content in a specific window the participants perform a pinch gesture, as on touch displays, in the direction of the window.

Study

To elicit a gesture set as an additional input mode for working with LHRDs, we focus on functions provided by window managers. We used window functions provided by Microsoft Windows 10: *Minimize window*, *Maximize window*, *Close window*, *Select window*, *Move window*, *Resize window*, Dock window (left/ right), *Scroll content* and, *Put the cursor* to a specific position.

We recruited 40 participants (33 male and 7 female) aged between between 19 and 31 years ($M = 25.43$, $SD = 2.77$) using our university mailing lists. The majority (34) of the participants were right-handed, five were left-handed and one was ambidextrous.

Apparatus

For conducting the gesture elicitation study, we used an LHRD with a size of 4.03×1.13 m, consisting of six 50 in screens aligned in portrait mode. We asked every participant to sit in front of a table at 1.5 m distance to the LHRD. We provided a mouse and a keyboard on that desk. For analyzing the performed gestures, we video recorded every session with two cameras. One camera was positioned below the display horizontal center. The second camera was placed on the table, observing the participant's hands from above.

Procedure

After welcoming every participant, we asked him or her to read the consent form and agree to the terms. After agreeing to the terms, every participant was instructed to sit at the desk in front of the LHRD. We explained the setup and invited the participants to familiarize themselves with the large display space in a sandbox interaction period. During this time, participants were free to run an arbitrary number of application windows, e.g. Microsoft Excel or Firefox. After they experienced how working with such a display looked like, we showed every participant every function by presenting its action. Afterwards, every participant rated the importance of the functions. To rate the functions, we presented all function names printed on paper cards and asked the participants to order the cards according to the importance or to remove the card if the functionality was not needed [272]. Then we showed 20 participants a 2:30 min priming video. In this video, a person is performing the interaction gestures presented by Wittorf and Jakobsen [268]. After that, we asked every participant who had seen the video to perform five different gestures for every function. The other 20 participants were invited to perform one gesture for every function and received no priming.
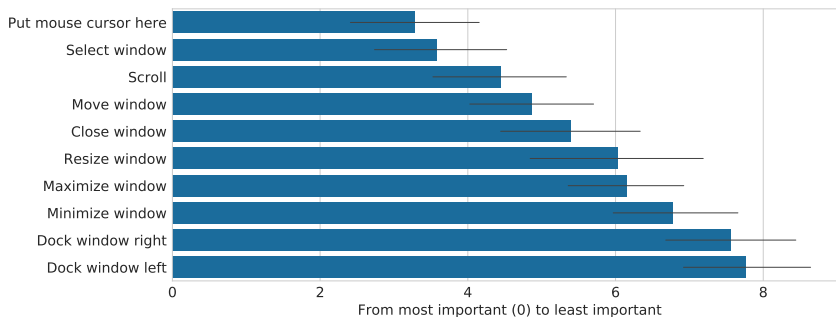
Figure 7.3: Importance of referents as rated by participants.

7.3.1   Results

The participants rated the importance of the referents in the following order (from most important to least important): *Put mouse cursor there*, *Select window*, *Scroll content*, *Move window*, *Close window*, *Resize window*, *Maximize window*, *Minimize window*, *Dock window right* and finally *Dock window left* (see Figure 7.3).

Overall, participants performed 520 gestures. To calculate the agreement score we used the approach presented by Wobbrock et al. [269]. Table 7.5 shows the agreement scores per referent and condition.

To analyze the influence of priming and production (PP) we compared the agreement scores for both gesture sets statistically. A paired t-test revealed no statistical significant difference in terms of agreement between the gesture set with PP and without ($t_{10} = -1.6482$, $p = .1303$).

Based on the agreement scores we designed gestures for all referents. Table 7.4 provides a description of all gestures of the gesture set.

7.4   Discussion

In the first study (see Section 7.2), we present a consistent set of full-arm gestures for window management while working with an LHRD in office environments. We derive nine gestures for assisting window management from a gesture elicitation study using an LHRDs. The freedom of 3D mid-air gestures allows using

Table 7.4: Referents and the desrcribtion of the gestures of hand mid-air gesture set.

Referent	Gesture
Put cursor there	The user points with the index finger to the desired position and moves the hand towards the display.
Dock window left or right	The user moves the flat hand to the right or left side.
Select window	The user spreads the index finger and the middle finger, pointing in the direction of the desired window and moving the hand towards the display.
Resize window	The user points with both index fingers towards the window and moves both hands either closer together to make the window smaller or away from each other to enlarge the window.
Scroll content	The user spreads the index finger and the middle finger, but moves the hand up- or downwards to move the content.
Move window	The user spreads index and middle finger again in the direction of the window and rotates the hand in the desired direction.
Close window	The user performs a grabbing hand movement in the direction of the window and moves the hand towards the end of the display.
Maximize window	The user points with the fist towards the focused window and opens the hand.
Minimize window	The user points with a flat hand in the direction of the focused window and moves the hand downwards.

the same gesture for related actions. Participants performed the same gesture for resizing and maximizing a window. Having the same gesture for two references reduces the complexity of the gesture set. Furthermore, it is questionable whether window maximization is still useful on LHRDs. The proposed combination of one gesture for resizing and maximizing windows, indicates that the participants perceived less importance for maximizing windows on LHRDs. In Part IV we discuss detailed requirements for GUIs for LHRDs. *Move window* and *Shift window* are also perceived as one command. The difference between moving a window to another screen or any other position is not relevant if the display space is perceived as one continuous display space. Furthermore, the commands *Show Desktop* and *Show all windows* are the inverses of each other. Hence performing the gesture in reverse is natural.

Through the presented study, we were able to derive a well-defined gesture set. While we determined a high agreement score for the most important commands, the results are still constrained by the small number of participants. Furthermore, an evaluation through a working prototype and a comparison to other interaction techniques would provide valuable knowledge. In particular, it would be valuable to understand the possible advantages or drawbacks of mid-air gestures as an additional input technique. On the one hand, the gestures of the presented gesture set could require too much movement and thereby cause fatigue. On the other hand, they could encourage more body movement in an office environment.

The agreement scores in the second study, with and without priming and production as well as overall, are low in comparison to the first study (see Section 7.2) and in comparison to previous studies [268, 269]. One reason could be that the large number of participants creates a higher diversity than in the smaller study in Section 7.2. The fact that we cannot show an influence of priming and production indicates that the participants perceived the LHRD setup as fundamentally different to known interactive systems. Due to this, they performed gestures not based on known gestures.

On the other hand, the small influence of priming and production as legacy bias reducing technique is in line with previous work. Hoff et al. [102] conducted a gesture elicitation study with 30 participants to design gestures for interacting with a multimedia player. Thereby the authors used a between-subject design and used priming and production in one condition. Their results indicated only a small effect of using priming and production in a gesture elicitation study [102].

Overall, the two studies showed that potential users of LHRD workplaces have diverse notions of gestures for interacting with window managers. Hence, the results of the two studies provide first conceptional prototypes for gesture input.

Table 7.5: Agreement Scores per referent and condition of the hand gesure elicitation study.

Referent	Overall	With PP	Without PP
Put cursor there	0.190	0.185	0.230
Dock window right	0.158	0.240	0.182
Dock window left	0.158	0.240	0.182
Select window	0.142	0.092	0.234
Resize window	0.126	0.097	0.245
Scroll content	0.126	0.147	0.154
Move window	0.085	0.086	0.135
Close window	0.038	0.063	0.065
Maximize window	0.055	0.058	0.120
Minimize window	0.070	0.102	0.100
Overall agreement	0.115	0.131	0.165

In future work, working implementations of the gesture sets should be developed. Working implementations would allow evaluation of users' performance and most importantly the usability of gesture input for interacting with window managers on LHRDs. High usability would motivate users to change input modalities frequently, and be more likely to utilize the full large display space. Furthermore, changing the input mode from mouse pointing to mid-air gesture input enables more body movement and working in different body positions.

7.5   Conclusion

Through user-defined gesture studies, we designed mid-air gesture sets for interacting with window managers on LHRDs. We designed one gesture set for full-arm mid-air gestures, requiring large body movement. We also designed another gesture set for mid-air hand gestures, which can be performed over the keyboard. During the design process of the hand mid-air gesture, we analyzed the influence of the legacy bias on the proposed gesture set. The results showed that

the legacy bias has only a small influence on the proposed gesture set supports findings of previous work [102]. Additionally, it indicates that interacting with LHRDs is perceived differently to interaction with other interactive devices.

Future work should evaluate the quality of mid-air gesture sets for interacting with content displayed on LHRDs. To analyze the quality of the gesture set it would require comparing performance regarding TCT and accuracy (ER) with state-of-the-art interaction techniques. Additionally, the memorability of every single gesture is important. Rico and Brewster [205] proposed to analyze the social acceptance of performing gestures for mobile devices in public settings. Even if LHRDs are not used in public space, they might be used in collaborative settings (see Chapter 5 and, 8). Thus, the social acceptability also plays an important role gestures designed for interacting with LHRDs. Performing mid-air gestures could increase the body movement while working with an LHRD. The effect of moving only parts of the body (e.g. the arms) while exploring data, has been under-explored so far. Additionally, more body movement while working with an LHRD could have a positive health effect.

Chapter 8

Second Device Input

Almost three decades ago, Mark Weiser [265] envisioned environments in which tabs, pads, and boards were omnipresent. Today, we see pads as tablets and tabs as smartphones. Boards are still on the horizon as LHRDs. The interplay between multiple devices with a variety of form factors can be beneficial for working with visual data. LHRDs have the advantage that users can navigate physically, instead of zooming and panning in the software view. Furthermore, these displays can show details and provide an overview at the same time. Additionally, multiple persons can stand in front of an LHRD and look at the same visual information. In contrast, mobile devices such as smartphones and tablets enable users to carry information with them around. Furthermore, they can be used as a personal workspace in combination with LHRDs. This combination of different form factors can enhance collaboration focusing on one data set. While all users see the same visualization on the LHRD, everyone can view additional visualization on their personal device.

The physical size of LHRDs enables users to distribute visual information on a large area. Thus the information can be arranged with a spatial meaning. The ability to layout information with spatial meaning supports working with information and the exploration process of this information [122]. Geolocated data has an inherent spatial meaning. In contrast to other data sets, the spatial layout is explicit, and no design process is required. We make use of this inherent spatial meaning of geolocated data to explore multidevice interaction for exploring

social events based on geolocated Twitter data. Thereby we use the application ScatterBlogs[17] and extend this application of LHRD and multidevice capabilities.

8.1   Related Work

Over the last decade, social networking services have developed to become a common and widely used communication channel. Today it is not only used to exchange messages between people who know each other but also to share opinions and information about events publicly [119]. Hence, Twitter users can be seen as "human sensors" (e.g. [282]) providing i.a. social trends that are complicated to detect with electronic sensors. Furthermore, social network services have become one of the most important information sources about emergency cases [139]. Data collected by using this approach is not only relevant for marketing strategies, but also for crisis management. As a social networking service, Twitter is, in particular, an important data source, because all Twitter messages are public and some contain information about the user location while tweeting. This enables to classify events and trends as local or global. Furthermore, if users tweet multiple times, movement patterns can be determined.

Sakaki et al. [213] use Twitter messages (tweets) to generate notification about large events such as earthquakes in real-time. However, some tweets contain incorrect or false information. Hence, analysts need tools to extract or validate important information from tweets [192]. A set of publications discusses approaches to visualize tweets for sense-making. MacEachren et al. [158] conducted an online survey asking practitioners in emergency management about their expectations and requirements for a visualization and analyzing tool using tweets

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[17] https://www.scatterblogs.com/

as the basis. As a result, they designed a web application showing aggregated geo-located information on a map in combination with the possibility to access single tweets. Hao et al. [91] proposed color coding for positive and negative statements in tweets. Aditionally, the authors present the aggregated data on a map to detect local trends. Besides analyzing the content of Twitter messages, Krüger et al. [132] presented an analytics tool to derive movement patterns from tweets. These movement data can not only be relevant for emergency management but can also be used as basic information for urban planning. All these tools analyzing social networks systems use for at least some visualizations maps.

The smartphones and tablets have the advantage of being lightweight and easy to move around. On the other hand, their physical interaction space is limited. This triggered a research area on multidevice interaction. Lucero et al. [156] explored using multiple smartphones for collocated photo sharing in groups. The presented system makes use of mutual spatial awareness of the other smartphones to display photos across the device and to enable gestures on multiple devices. Woźniak et al. [274, 275] explored using tablet smartphone and tablet combination to explore visualized information and to support sensemaking. Their results show that the combination of extended visual space and the tangibility of the devices enhances the data exploration process. While Woźniak et al. [274] used a motion capture system to provide the spatial position of the device, Rädle et al. [201] proposed a framework using a regular RGB camera mounted above the devices.

While systems utilizing only mobile devices focus on extending the interactive space in mobile settings, frameworks combining different display form factors focus on providing an additional interactive spatial dimension, enhancing collaboration and interacting with remote (large) displays. Already in 2004, Ballagas et al. [22] proposed interacting with large public displays by using the input capabilities of user's personal phones. Alt et al. [7] utilized this approach too for interacting with a public notice area system on public displays. Schmidt et al. [217] proposed a gesture set for collaborative interacting with a large horizontal display and smartphones. The gestures are based on touching the large display with the user's smartphone, thereby, directly identifing the user. In contrast, Von Zadow et al. [260] proposed mounting a small touch display on the user's wrist as a control panel for applications displayed on an LHRD with touch input capability. This system has the advantage that the user always has all controls close by, without overlaying content on the LHRD. Krone et al. [131] proposed using a tablet computer to manipulate large scientific visualizations displayed on an LHRD. Nancel et al. [185] high-lighted the unique input capabilities of tablets for interacting with LHRDs. The authors argue that a large variety of control elements can be displayed on the tablet, and furthermore the touch display

can be utilized to perform high precision pointing. Based on Nancel et al.'s [185] concept Chapuis et al. [40] developed Smarties, a multicursor input system using tablets to interact with content on LHRDs.

Previous work shows a high potential for interacting with content on LHRDs through mobile devices such as tablets. Mobile devices enable the users to move freely in front of the LHRD while interacting. Furthermore, the mobile device can be used as personal workspace. The combination of large collaborative space and a small private workspace can support collaborative data exploration.

8.2   System

Social media analysis is becoming more important for emergency management as well as in marketing [135, 225]. In particular geolocated social media data is an important data source. Displaying a map with geolocated data as an overlay on a large high-resolution display (LHRD) allows fast and efficient visual exploration. In this work we focus on the exploration of geolocated twitter messages.

Our application is based on ScatterBlogs. We adopted the ScatterBlogs' map view. ScatterBlogs analyses twitter messages and displays important terms, as text, on the geo-position of the twitter message on a map. Therefore, most common words in English, so called stop words, are filtered. As a result events are easier to detect. Thom et al. [239] describe in detail how the text is visualized.

The map view based on ScatterBlogs is a Java application displayed on a LHRD. For our study we used three 50 in 4K Panasonic TX-50AXW804 screens in portrait mode. This resulted in a display approx. 2.01×1.13 m (see Figure 8.1). All three displays were driven by one Microsoft Windows 8.1 workstation.

LHRDs have the advantage of enabling physical navigation and enhanced collaboration between multiple users. However, the used input device has to support physical navigation as well as multiuser input. Hence, the input device has to be easy to carry around and easy to operate. Furthermore, the user might use the device while standing, walking or sitting. When multiple users explore social media data collaboratively, they need private as well as shared visualisations. Tablets are comfortable to use while standing or sitting. Additionally, they provide sufficient display space for content manipulation and pre-filtering [200]. Hence, we designed and implemented an Android application as control for the map view on the LHRD. The Android application provides an additional map view. This map view (see Figure 8.2) shows detailed geo-information; however,

Figure 8.1: Users interacting with tablets in front of the LHRD.

it would also be possible to display another social media data set as an overlay on the map view.

The Android application allows users to define word-filters for filtering the twitter tags and highlight the appearance of the filtered term. The appearance of a term will be indicated through a textual overlay as well as through a heat map. To identify correlations between the appearance of different terms, users can assign colours for each filter. When multiple filters are activated, all heat maps will be displayed as overlays. Besides, filtering for particular terms, the application allows users filtering the twitter tags by time and discovering spatial and temporal spreading and trends. Furthermore, the Android application allows users to pan and zoom the map view on the LHRD.

Communication between the map view on the LHRD and all user input tablets is managed by a central server. The map view application running on the LHRD and all tablets connect to this communication server, which distributes the information over a network protocol to all requiring devices. This communication server allows the users to connect an optional number of user controls. Furthermore, it would also be possible to connect multiple map views displayed on LHRDs for remote collaboration.

Figure 8.2: Tablet application in front of the map view on the LHRD.

8.3   Evaluation

For the evaluation of our interaction technique, we recruited 12 participants (10 male and 2 female) aged between 20 and 30 ($M = 22.5$, $SD = 3.37$) through our university mailing list. We then conducted a within-groups controlled experiment.

We asked pairs of participants to explore two large events based on twitter messages collaboratively. We used recorded and pre-filtered twitter messages. One data set contained a large fair in 2012 and the other data set contained twitter messages about a flood in 2013 in Germany. This size of both data sets was limited so that the task did not require specialist data analysis knowledge. We were aware that building two data sets of equal complexity was impossible unless they were artificial. We opted for two real data sets with same size to maintain the real-life context of the task and focus on the user experiences of browsing and analysing twitter data. The task consisted of answering nine factual questions about the geographical area and time frame presented in the data set. The task was complied when the two participants answered all questions correctly.

Participants explored the two data sets using our interaction technique (with one 8.4 in Android tablet per participant) and a single laptop computer to control the screens as a baseline. We counterbalanced the data sets and interaction modalities to reduce order effects. After a greeting and a general introduction to the system, the pair of users was presented with the task and asked to provide the most

accurate answers possible. They were then given full freedom in choosing an analysis strategy and help from the experimenter was available at all times.

We measured cognitive load with the raw NASA-TLX [93, 94] and coherence in collaboration using the Networked Minds [29] questionnaire. After the study, we conducted semi-structured interviews with the participants to capture the experience of using our system. We asked about the qualitative differences between the two systems and the suitability for collaboration.

8.4   Results

Raw NASA TLX scores indicated that the tablet technique requires significantly less effort ($M = 8.63$, $SD = 2.47$) than using the laptop computer ($M = 10.47$, $SD = 2.17$) as revealed by a Wilcoxon signed-rank test ($p < .05$). Figure 8.3 presents the results. Further, the systems scored comparably in the Networked Minds Questionnaire. Multiple Wilcoxon tests revealed no significant differences.

Reflecting on the qualitative feedback from the participants, we noticed that the LHRD had a large novelty effect. All the participants described the experiences as "fun" and "intuitive". They were impressed by the viewing capabilities of the display. They found the tablet interfaces appealing and easy to use. The ability to work independently of the parter for some time was found to be useful.
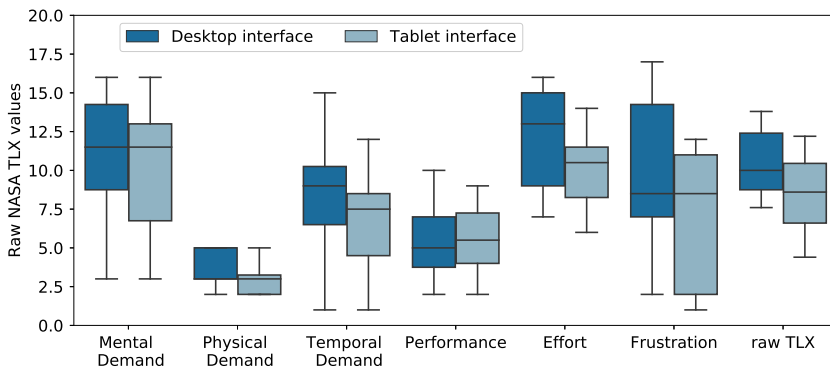
Figure 8.3: Raw NASA-TLX scores comparing the two conditions.

8.5   Discussion

We have gained insights into how multiple mobile devices can support collaboration in data analysis on LHRDs. Our results show that participants found our interaction technique to be less cognitively demanding. We believe this may be not only due to the fact that tablets provide a more intuitive interface, but also because using a personal device reduced the burden of having to negotiate control of the laptop computer with the analysis partner. Further, as tablets allowed users to move more freely around the room, our results may indicate that navigating the large screen space physically reduces workload.

We found no difference in how users perceived the collaborative aspects of both systems. We hypothesise that the possible existence of such differences may only be revealed in longer tasks or ones that require more sense making. As the networked mind questionnaire is specifically designed to measure contagion, our results may be affected by the fact that the users assessed mainly how well they perceived their partner's qualities.

The overall positive response of the participant indicates that using mobile devices for collaborative data analysis on LHRDs should be explored further. Futher studies with low- and high-fidelity prototypes will enable us to develop interaction patterns for interaction with LHRDs. Thereby an important aspect will be the collaboration between single users. In the current prototype all users have the same rights to manipulate content on the LHRD, therefore when focusing on different aspects there is the risk that they might change the view on the LHRD and hide information another user is working with. Hence, future systems should manage the need for different views. We believe that readdressing the well-known principles of interactive information visualisation in an LHRD context will produce new interaction opportunities.

8.6   Conclusion

With this work, we have shown that a combination of shared LHRD and the privately used mobile devices could support collaborative data exploration and sensemaking. In the next step, we will move from tailor-made multidevice solution to general multidevice frameworks enhancing collaborative sensemaking. Furthermore, multidevice interaction is just one possible technique to enhance the input on LHRDs so, a combination of interaction techniques discussed in this thesis should also be evaluated.

Chapter 9

Tangible Force Resistant Feedback Slider

One key advantage of LHRDs is their ability to show large and detailed data sets. LHRDs offer a surface that can go beyond the human field of view and they are also close to a user's visual resolution [13]. Thus, the user has only little capacity to focus visually on other elements or objects than shown on the display. To enhance interacting with data further, we explore how haptic feedback on the input device can support the user.

Often, data exploration processes require parameter adjustment, to see the influence of different parameter values. One commonly used GUI metaphor for value adjustment is the linear slider. GUI sliders are a common and well-explored input metaphor (e.g., [2, 3, 157]). In professional environments, not only GUI sliders, but also physical sliders are used. For example, music mixing tables use a large numbers of physical sliders. We see them also used in medical imaging tools. The wide use of sliders indicates their high potential for interactive data exploration.

In this chapter, we explore how additional haptic feedback provided as movement resistance of the physical slider knob can enhance the data exploration process. To evaluate the additional haptic feedback, we designed and deployed a physical input slider and conducted a pointing lab study. The results show that the additional haptic feedback enhances the the value adjustment if the user is not able to look at the input device. In contrast to all other input techniques discussed

in this part, the variable movement resistance slider (VMRS) is envisioned as an independent novel input technique for visual data exploration. We assume that mouse and keyboard might not be used in in combination with the VMRS. Instead we assume that the user is mostly exploring various scenarios that require parameter adjustments.

9.1 Related Work

The concept of VMRS is based on previous work about tangible interaction and slider interfaces. We readdress these findings to design a new input device for interaction in visually rich environments.

9.1.1 Tangible Input

Tangible user interfaces (TUIs) are a widely discussed concept for data exploration. Ishii [110] provides an well focused overview about general research on TUIs. Fitzmaurice and Buxton [64] compared graspable to non-graspable UIs and demonstrated that graspable UIs can increase user performance. Also, a comparison between direct touch and graspable UIs revealed that users perform better when using a graspable UI [244]. Based on these findings, there is a large body of work about touch interaction in comparison or connection to graspable controls. Weiss et al. [266] designed tangible controls, such as knobs, sliders, and keyboards, made from silicone for interaction on an interactive tabletop. In a lab study, the authors showed that the tangible controls allowed faster data input with fewer overshoots than when using the touch interfaces. Furthermore, tangible sliders required fewer eye fixations in comparison to direct touch manipulation [243]. Thus, tangible sliders appear to be suitable for single-value input.

Previous work has also shown that tangible interaction positively affects recall and TCT. Hence, Müller et al. [182] argue for using tangibles when interacting

with large and complex systems, such as in control rooms. Voelker et al. [253] compared tangible knobs to direct touch for rotary input. In the comparison, the authors distinguish between eyes-on and eyes-free interaction. The results presented by Voelker et al. [253], indicate that graspable interfaces are in particular well suited for situations where the user is not able to look at the controls.

Recent studies have shown that the motivation for eyes-free interaction on mobile devices can address environmental, social, device feature, and personal motivational factors [277]. Interaction without direct mapping to the input data and eye-free interaction in mobile and fixed settings motivates us to explore haptic feedback for slider input.

9.1.2   Remote Input

In contrast to most previous work, Jansen et al. [118] utilized the positive effects of graspable UIs for interacting with content on wall-sized displays, instead interactive tabletops. While the use of haptic display to overcome the limited size of mobile displays is well understood [36, 104], here we typically study the use of haptic for remote input on large, vertical displays. These are displays located in the same room, but often too far away to be easily reached and touched.

9.1.3   Sliders for Data Input

Sliders are widely used in software applications. Ahlberg et al. [3] showed that GUIs using sliders for database queries are more efficient than text based queries. Software sliders are also often used in online surveys as visual analog scales [74]. The visual appearance of sliders can influence the input provided by the users [170]. We assume that not only visual feedback influences user's behavior but also haptic feedback can have an impact on the input. With this chapter, we provide a starting point for comparing value selection on physical and software sliders with different feedback modalities.

Inspired by music mixing tables, various interaction concepts using motorized faders have been presented. Gabriel et al. [75] explored applications for music performance. Using the same device concept, Shahrokni et al. [220] proposed to use motorized sliders for teaching system dynamics. This scenario pointed out the potential of motorized sliders to communicate data through different modalities. This might also support interaction with complex financial data [209].

In a qualitative study, Crider et al. [44] indicated that motorized sliders could help users keep focus while exploring 3D-visualizations. However, none of these concepts provided a detailed, quantitative analysis of user performance using motorized sliders for input. Furthermore, all previous designs that used motorized sliders addressed pseudo-continuous input (i.e. users would input an analog value, and it would be later digitized). Our work is interestingly different as it addresses discrete input, which is often needed for everyday devices.

9.1.4   Haptic Feedback as Output

Visual information overload can be a threat to the interpretation of displays presenting large data sets. In such cases, haptic feedback can be a means of information transmission [236]. Marquardt et al. [166] designed a puck for exploring data haptically on tabletops. The puck provided feedback through pressure against the user's finger, and through adjusting the sliding resistance on the surface. Snibbe and MacLean [227] built a rotary knob for controlling multimedia application. To provide additional feedback, the authors explored different haptic feedback patterns.

Parkinson et al. [196] used motorized faders to provide haptic feedback to explore sound waves with an additional sense. In particular, visually impaired users get a novel representation of sound waves. Follmer et al. [65] used a combination of visual projection with a 2.5D shape-changing display. Here, we study input tasks requiring the input of discrete data, such as integer values, enumerators (e.g. day or month), or other accurate values. The haptic representation of such values is typically a detent; a Dirac-like (i.e. double cone-shaped) feedback felt by the user when passing the slider over one of the multiple equidistant positions, giving discrete input. Such detents were originally suggested to provide the user with physical feedback during media browsing. While Ullmer and Ishii [247] suggested detents to support browsing, in this work we propose detents to support accurate input when visual feedback is not available.

While mobile haptic support for input on handheld and desktop proximal displays is well understood, here we study haptic support of distal input on large vertical displays. Our work is oriented to the needs of data-intensive visualization, and it targets a research gap less charted than mobile haptics.

9.2   Design

In our search for new effective ways to provide discrete remote input, we were mainly inspired by two past designs. Firstly, we saw the effectiveness of SLAP tangible widgets [266] interacting with large screens [118]. Secondly, we noticed that professional soundboards, used in studios or during concerts are often manipulated by their operators without visual attention. Professionals focus on the task content (e.g. sound engineers while manipulating sliders) and use present that require the board to adjust slider positions with motors. Consequently, the current state of a particular setting can be perceived by simply touching to feel the position of the slider. However, that usage scenario is limited to highly trained users. Consequently, we decided to limit our inquiry to a single slider.

9.2.1   Designing for One-Dimensional Input

The next question that we faced was how to implement haptic feedback in a way that would allow even novice users to benefit from the properties of a physical slider fully. Again, we turned our attention to devices used in soundboards. While these usually employ motors to reposition the slider knob, the same motor can also be used to create resistance or decrease friction while moving the slider. After an initial prototyping phase and informal testing, we decided to explore `variable movement resistance sliding` (VMR) further.

Given that one can vary the movement resistance, the question is how and when to do that. Inspired by Matejka et al. [170], we noticed that adding visual notches to a scale affects the user input. We assumed that not only visual notches have an influence, but also haptic notches. We inquired how these notches could be manifested in haptic feedback. After several attempts, we determined that a sinusoid function with roots where the notches are located provided the most pleasant experience (as evidenced in our informal studies).

We still needed to determine how many notches our VMRS could accommodate. Here, we were constrained by the hardware — all commercially available motorised slide potentiometers have a slideway no longer than 10 cm. Hence, we had 10 cm of slideway available. We chose to include ten points on our scale. This implies that the notches are separated by 1 cm, and the immediate vicinity of the notch is 0.5 cm on each side of it. Consequently, we endeavored to design the feedback so that the user could feel they were within the input space of one of the discrete values when within 0.5 cm from the target. We deemed this value
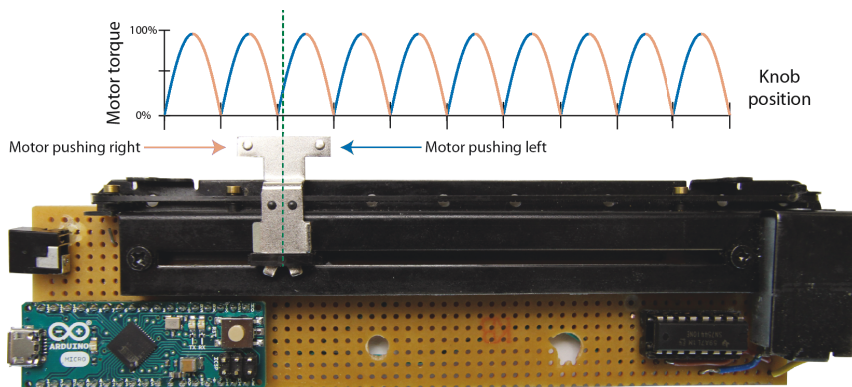
Figure 9.1: The design of the variable movement resistance in our device. The light red curve depicts the feedback when the user is sliding right; the blue one shows feedback for sliding left.

to be reasonable as the perceptual threshold for two-point active touch (i.e. the smallest distance between two points that the users can perceive, as two distinct points) can be as high as 0.34 cm [52].

9.2.2   Feedback Design

Finally, we had to design the `variable movement resistance sliding` (VMR) feedback so that it facilitated providing discrete values. Figure 9.1 depicts our design of the resistance feedback. When the user is sliding away from a discrete point, the slider is pushing the finger back to the previous point. However, once the slider notch reaches half the distance to the next point, a critical distance is reached (resistance is pushing with the maximum force), and the slider starts pushing the finger towards the next discrete point. The resistance increases and then decreases along a sinusoidal curve. The discrete values are regions where movement resistance is zero. Our aim was to create an illusion of the discrete notches being present under the user's finger while sliding.

9.2.3   Implementation

For implementing a VMRS, we used a motorized slide potentiometer, often used in professional soundboards. The slide potentiometer we used is manufactured by Bourns (PSM01-081A-103B2) and has a 10 cm travel length. We connected this to an Arduino Micro (see Figure 9.1). The Arduino positions the slider knob by actuating the motor of the slide potentiometer. The Arduino reads the resistance of the slide potentiometer and the capacity measured at the slider knob. On the 10 cm slideway, we can distinguish between 1024 slider knob positions.

The measurement of the capacity at the slider knob allows reacting on touch events triggered by the user. The program running on the Arduino can cause slider actions on its own, and can send measured slider knob positions to a connected computer. To connect the Arduino and a computer, we implemented a Universal Serial Bus (USB) and a Bluetooth interface.

The motorized slide potentiometer and the Arduino Micro can be powered either by a battery or over a wired connection. Using Bluetooth for communication and a battery for providing power enables the user to hold the device in one hand, move around freely and manipulate the input value with the other hand. For the lab study presented in this paper, we used the wired connection.

We implemented VMR by adjusting the torque and direction of the motor while the user moved the slider knob. The combination of the motorized slide potentiometer and the Arduino controller allows bidirectional feedback. The motor can push the slider knob in the direction of the knob movement, and thus the user feels that the slider has less resistance. When the motor pushes the slider knob in the opposite direction of the movement direction, the user perceives more resistance (see Figure 9.1). By using a combination of the two techniques, we create an impression of a pattern of the discrete value notches.

For interacting with the VMRS, we designed and 3D-printed a case, see Figure 9.2. This makes handling the device comfortable and safe. The dimensions of the VMRS are determined by the measures of the technical implementation. The VMRS is 19.5 cm long, 5.2 cm high and 4.0 cm wide.

9.3   User Study

With the lab study presented in this chapter, we are starting to build an understanding of how a VMRS influences user behavior and could enhance exploring
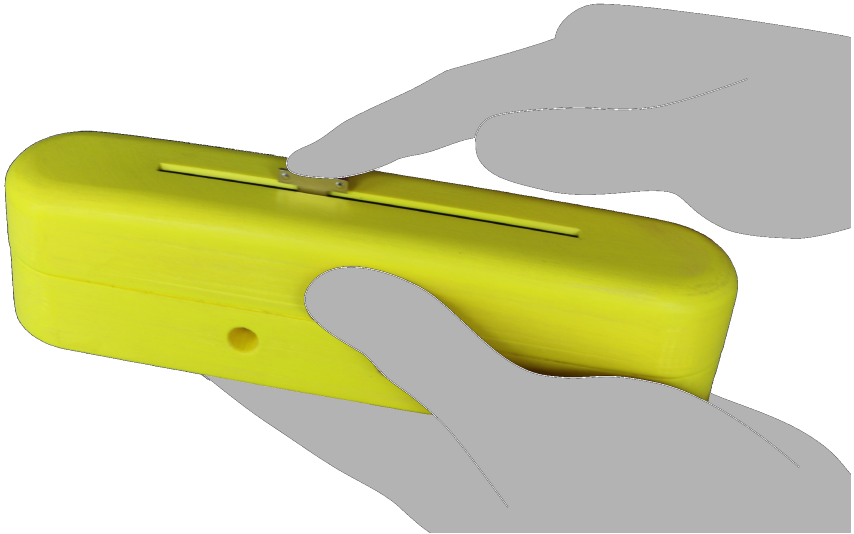
Figure 9.2: A variable movement resistance slider (VMRS) device with a
3D-printed case.

complex data set visually. This understanding is important for designing applica-
tions using motorized sliders. In this lab study, we focus on the following four
hypotheses:

H1: Employing `VMR` will not result in increased task completion time (TCT)
compared to the other input methods.

H2: Using a `VMR` will not result in inferior accuracy compared to the other input
methods when users are provided with visual feedback.

H3: A `VMR` will offer superior accuracy to the other input methods when users
are not looking at the device.

H4: A `VMR` will increase the perceived workload over other input methods when
users are able to look at the device.

Previous research [253] showed that tangible controls could lead to shorter TCTs.
However, the influence of resistance feedback on TCT and accuracy has not yet
been explored. The additional feedback might help to select the correct values.
The resistance feedback interrupts the fluent sliding on purpose and has to be
processed by the user. On the other hand, the additional resistance feedback could

(a) Selecting a target value using the VMRS with VF.

(b) Selecting a target value on the VMRS covered by a cardboard box (NVF).

(c) Selecting a target value on the tablet with VF.

Figure 9.3: A participant is performing trials under various conditions.

enable users to perform large value changes quickly, and focus only on precise value selection. Hence, we expect that the positive and negative effects on TCT balance each other (**H1**). We also assume that the influence of resistance feedback is low in contrast to visual feedback, and hypothesize that resistance feedback does not influence accuracy when users are able to observe the state of the input device (**H2**). However, if users do not focus on the visual state of the input device, resistance feedback is supportive (**H3**). When users are able to observe the state of the input device, resistance feedback is additional information that has to be processed by the user. Hence, we assume that resistance feedback increases the perceived mental effort (**H4**).

9.3.1   Study Design

To compare data input using a VMRS, with and without `variable movement resistance sliding` (VMR) as feedback and a software slider displayed on a touch display, we conducted a lab study. We recruited 17 participants (11 male and 6 female) aged between 21 and 39 ($M = 26.88$, $SD = 5.17$). For the study, we used a repeated measures design; such that every participant performed 32 trials for all five conditions.

Task

To verify our four hypotheses, we asked the participant to select particular target values indicated by a marker on the visualized slider on the remote display. On this display, we showed, in all conditions, a representation of the slider and the target position indicated by a green arrow below the slider representation. We

assumed no differences between moving the slider knob to the left or right-hand side, so every trial started with the slider at the far left position. This enabled longer sliding distances than a centered starting position. To select a value, participants had to release the slider knob. In every condition, participants were asked to enter 32 values. The target values were equally distributed on the slider scale. We excluded minimal and maximal values because past studies [170] have shown that sliders have an inherent affordance for providing input at the ends of the scale and these inputs should be excluded from the analysis. We used the same target values in all conditions to get comparable results but randomized the order of the targets for every condition to avoid learning effects.

Conditions

In the user study, we compared discrete data input on a 10-point scale in five modalities. As independent variables, we varied the VISUALFEEDBACK and HAPTICFEEDBACK.

The independent variable VISUALFEEDBACK had two levels; `visual feedback` (VF) and `no visual feedback` (NVF). The independent variable HAPTICFEED-BACK had three levels; `variable movement resistance sliding` (VMR), `tangible sliding` (tang), and `touch sliding` (touch). To provide the different levels of HAPTICFEEDBACK, we used the VMRS device and an Android tablet with touch screen. When using the VMRS, we provided either VMR or `tangible sliding` as HAPTICFEEDBACK. In the VMR or `tangible sliding` conditions, participants could touch the slider knob and the slider. Additionally, the VMR condition used resistance feedback while sliding. The HAPTICFEED-BACK on the Android tablet is called `touch sliding` as touching the screen surface was the only present haptic feedback.

In the conditions with `visual feedback` (VF), the current position of the slider knob was visible on the input device and the remote display. On the tablet, we implemented this by displaying a software slider with a knob (see Figure 9.3(c)). For the VMRS, the physical slider knob indicated the current position of the slider (see Figure 9.3(a)), and the remote display also showed the current position of the slider. In conditions with `no visual feedback` (NVF), the position of the slider knob was hidden on the control as well as on the remote display. In these conditions, we covered the VMRS with a cardboard box (see Figure 9.3(b)). The box was large enough to avoid restricting user movements.

Using two independent variables with two and three levels would result in six conditions. During pre-testing, we experimented with the `touch sliding`–`no`

visual feedback condition by displaying only a black screen on the tablet. However, it was excessively difficult to enter data without any indication of the state of the control. Selecting values without any feedback, besides touching the display surface, is not feasible. Hence, we removed the condition where the tablet would be used with no visual feedback. In total, this resulted in five conditions, see Table 9.1.

Measures

We measured the following dependent variables in our study:

Task completion time (TCT) [s]. The time between the moment the participant was presented with the target and when they stopped moving the slider. The task was considered completed once the user moved their finger away from the slider for more than one second.

Absolute error [mm]. The distance between the position of the slider provided as input and the target position. The distance was only counted as an error when it was more than 2 mm. We logged and analyzed absolute error values as they may provide insights on the limits of the granularity of discrete input possible.

Error rate (ER) [%]. The relative number of trials which resulted in an error i.e. where the provided input differed from the target position by more than 2 mm.

Backtracking distance (BD) [mm]. The total slider distance covered after the initial left-to-right slide i.e. the distance of the extra movement used for additional positioning.

Table 9.1: Conceptually possible conditions in our study. The shaded row was removed due to the physical limitations of the tablet.

Condition	Device	VISUALFEEDBACK	HAPTICFEEDBACK
1	VMRS	VF	VMR
2	VMRS	NVF	VMR
3	VMRS	VF	tang
4	VMRS	NVF	tang
5	Tablet	VF	touch
6	Tablet	NVF	touch

Subjective Mental Effort Question (SMEQ). A measure of mental effort proposed by Zijlstra [284]. While all other measures were recorded per trial, we employed the SMEQ after all trials in every condition. We decided to apply this scale as it offers a quick "snapshot" assessment of mental effort that did not interfere with the course of the study [215].

Apparatus

For conducting the user study, we asked every participant to sit in front of a table. On the table, we placed the input device according to the condition. We did not restrict the participants in picking up the device allowing the users to assume the most comfortable position as past work provides no insights on optimal ways to hold a slider. Depending on the condition either the VMRS or a Samsung Galaxy Tab S 8.4 Android tablet was used. The VMRS device was used in the `tangible sliding` and VMR conditions. The `tangible sliding` was implemented by deactivating the slider motor. At a distance of 1.5 m, we placed a 50 in remote display. This display presented all instructions and target positions. Furthermore, the current state of the slider was visualized in the `visual feedback` conditions. All content presented on the remote display was implemented as a web application, running on a Python web server. This web server also handled the communication with the input devices. The slider interface on the Android tablet was implemented as a native Android App. To generate comparable results, the slider shown on the tablet also had a slideway of 10 cm with 1024 steps like the VMRS which were set on change for comparable accuracy. For analyzing a participant's behavior, the server application continuously logged the position of the slider knob as well as start and end times of every trial. To rate the perceived mental effort, we handed out printed SMEQ scales.

Procedure

After welcoming every participant, we asked them to read the consent form and agree to the terms. Afterward, we invited them to take a seat at the apparatus and to fill in a demographics sheet. As soon as a participant was ready to begin, the first assigned condition was displayed. In the preparation phase of every condition, the participants could familiarize themselves with the input method and the provided feedback through performing uncounted test trails. They were instructed to focus on accuracy. As soon as they felt comfortable with the condition, the set of 32 trails started. After performing all trials of one condition, we asked them to rate the mental effort on SMEQ scale [284]. We alternated the order of the input devices (VMRS and Tablet) and randomized the provided HAPTICFEEDBACK

and VISUALFEEDBACK. At the end of the study, every participant received 5 EUR as compensation.

9.3.2 Results

During the study, the apparatus continuously logged the slider knob position and touch events and recorded TCT. The perceived mental effort was measured using pen and paper. Based on this data, we analyzed the measurements.

Task Completion Time (TCT)

TCTs were extracted from the logs generated by the study software. The grand mean was 2.23 s ($SD = 1.25$). Using `tangible sliding` with `visual feedback` was the fastest ($M = 1.83$ s, $SD = 0.06$) while a VMRS with NVF was the slowest ($M = 2.44$ s, $SD = 0.09$). We conducted a two-way RM-ANOVA to investigate the effect of HAPTICFEEDBACK used and the presence of VISUALFEEDBACK on TCT. The main effect of HAPTICFEEDBACK on TCT was statistically significant ($F_{2,1647} = 8.60$, $p < .001$). The presence of VISUALFEEDBACK also had a significant effect ($F_{1,1647} = 6.52$, $p < .05$). The results by HAPTICFEEDBACK $\times$ VISUALFEEDBACK are shown in Figure 9.4. There was a significant HAPTICFEEDBACK $\times$ VISUALFEEDBACK interaction effect ($F_{1,1647} = 23.44$, $p < .001$). We then conducted post-hoc analysis using Tukey's Honest Significant Differences (HSD) test. There were significant differences for the
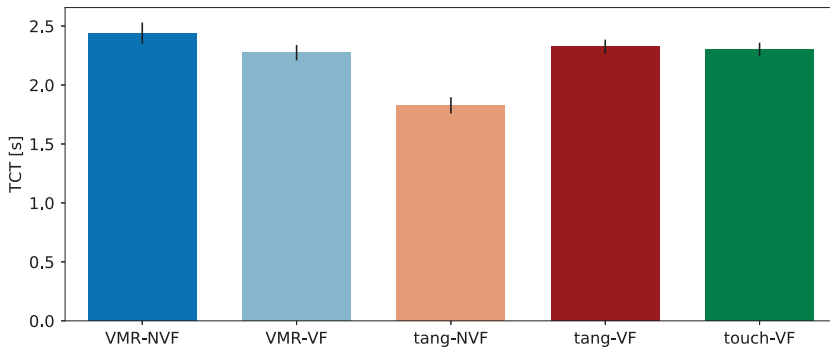
Figure 9.4: Mean task completion time (TCT) per HAPTICFEEDBACK $\times$ VISUALFEEDBACK in s. The error bars show standard error.

HAPTICFEEDBACK pairs `tangible sliding` – VMR and `tangible sliding` – `touch sliding`. The analysis revealed that using the VMR was significantly slower than `tangible sliding` in the NVF condition ($p < .001$). There was no significant effect for conditions with `visual feedback`.

Absolute Error

Absolute error distances were extracted from application logs. The grand mean of absolute error was 2.65 mm ($SD = 4.30$). The two conditions that produced the largest error were VMR with `no visual feedback` ($M = 4.95$ mm, $SD = 5.30$) and `tangible sliding` with `no visual feedback` and ($M = 7.46$ mm, $SD = 5.02$). In contrast, `tangible sliding` with `visual feedback` produced the lowest error ($M = 0.34$ mm, $SD = 0.64$), see Figure 9.5. A two-way RM-ANOVA revealed a significant effect of HAPTICFEEDBACK and the presence of VISUALFEEDBACK on absolute error. The main effects of HAPTICFEED-BACK ($F_{2,1647} = 123.66$, $p < .001$) and VISUALFEEDBACK ($F_{1,1647} = 1045.25$, $p < .001$) were statistically significant. A significant HAPTICFEEDBACK $\times$ VISUALFEEDBACK interaction effect was observed ($F_{1,1647} = 53.05$, $p < .001$). Post-hoc analysis with Tukey HSD showed significant differences for all HAP-TICFEEDBACK pairs under the `no visual feedback` condition. VMR produced significantly less error than `tangible sliding` and `touch sliding` with `no visual feedback` ($p < .001$). There were no significant differences for HAP-TICFEEDBACK with `visual feedback`.
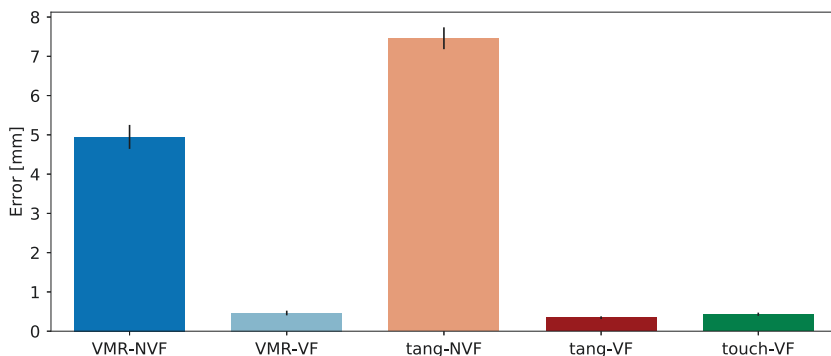
Figure 9.5: Mean absolute error per HAPTICFEEDBACK $\times$ VISUALFEED-BACK in mm. The error bars show standard error.

Error Rate (ER)

ER results were similar to absolute error. The mean ER for all conditions was 25% ($SD = 34$). Using `tangible sliding` with `no visual feedback` produced the highest number of errors ($M = 80.30\%$, $SD = 39.83$). `tangible sliding` with `visual feedback` produced the lowest ER ($M = 0.88\%$, $SD = 0.93$). After conducting a two-way ANOVA, we determined that significant effect of HAPTICFEEDBACK and VISUALFEEDBACK on error rate was present. The main effects of HAPTICFEEDBACK ($F_{2,1647} = 208.6$, $p < .001$) and HAPTICFEEDBACK ($F_{1,1647} = 1502.7$, $p < .001$) were statistically significant. A significant HAPTICFEEDBACK $\times$ VISUALFEEDBACK interaction effect was observed ($F_{1,1647} = 121.2$, $p < .001$). Tukey HSD revealed that significant pair differences were observed only for pairs in the `no visual feedback` (NVF) condition, all with $p < .001$.

Backtracking Distance (BD)

Figure 9.6 illustrates our backtracking measurements. The grand mean backtracking distance was 2.30 mm ($SD = 9.05$). `touch sliding` produced the largest backtracking distance ($M = 5.13$ mm, $SD = 13.67$) and `tangible sliding` with `visual feedback` required the least amount of backtracking distance ($M = 0.27$ mm, $SD = 3.69$). A two-way RM-ANOVA revealed a significant effect of device used ($F_{2,1647} = 21.83$, $p < .001$) and presence of feedback

(a) Input correction per HAPTICFEEDBACK.

(b) Input correction per VISUALFEEDBACK.
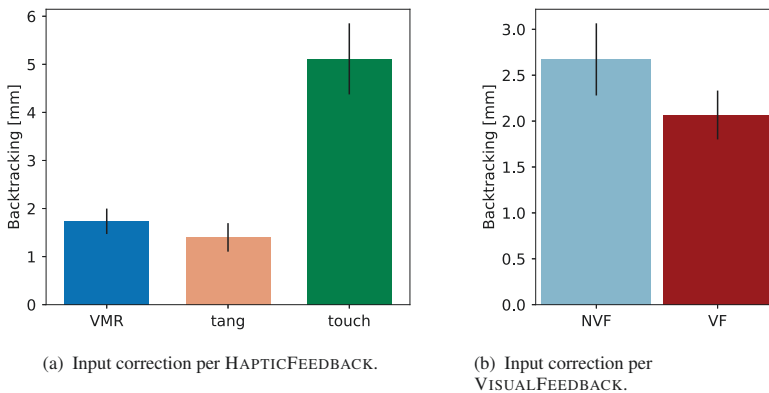
Figure 9.6: Input correction measured as mean backtracking distance (BD) in mm. Error bars show standard error.

($F_{1,1647} = 19.05$, $p < .001$). No significant effect was observed for HAPTICFEED-BACK × VISUALFEEDBACK interaction. Post-hoc analysis with Tukey HSD showed significant differences for `touch sliding` – `tangible sliding` and `touch sliding` – VMR (both with $p < .001$) which was due solely to the difference with `visual feedback`.

Subjective Mental Effort Question (SMEQ)

Lastly, we look at SMEQ results. The mean score was 20.36, ($SD = 21.76$). `tangible sliding` with `no visual feedback` producing the highest reported mental effort ($M = 36.06$, $SD = 27.26$) while `tangible sliding` with `visual feedback` was perceived as least demanding ($M = 9.82$, $SD = 9.08$), see Figure 9.7. Ziljstra [284] indicated that an ANOVA may be used to analyze SMEQ results. A two-way RM-ANOVA revealed that there was a significant effect of the presence of visual feedback on the SMEQ result ($F_{1,80} = 11.41$, $p < .01$). No effect was observed for HAPTICFEEDBACK or VISUALFEEDBACK × HAPTICFEEDBACK interaction.

9.4 Discussion

The results show that the VISUALFEEDBACK has a significant effect on TCT as well as on ER and SMEQ. The condition with `visual feedback` using `tangible sliding` was statistically significantly faster than `touch sliding`.
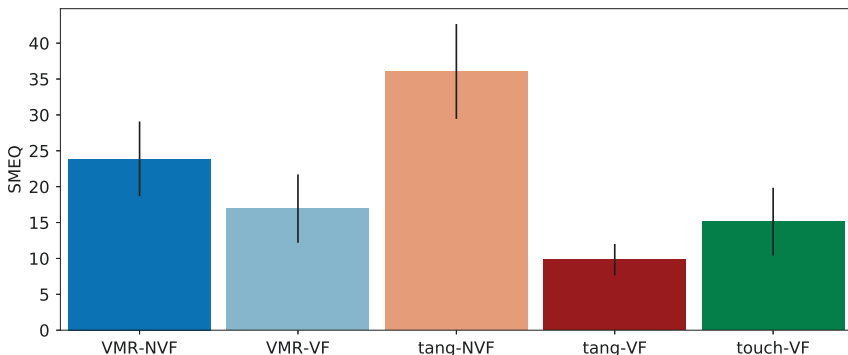
Figure 9.7: Average ratings of the perceived mental effort per VISUALFEED-BACK × HAPTICFEEDBACK. Error bars show standard error.

This is in line with the results of Jansen et al. [118] presenting a comparison between touch slider input and tangible sliders. Furthermore, Voelker et al. [253] showed comparable results for rotating tangible knobs. When `visual feedback` was provided, using VMR did not cause a longer TCT than `touch sliding`. However, in conditions without visual feedback, `tangible sliding` was significantly faster than VMR. Hence, **H1** is only supported for conditions with visual feedback. This indicates that the added sliding resistance required for implementing VMR does come at the cost of increased input time.

Regarding ER, we found no statistically significant differences when visual feedback was provided. Hence, we can conclude that using VMR has no negative influence on the accuracy when users can see the result of their input. This supports **H2**. The results also support **H3**. When no visual feedback was provided, participants exhibited significantly higher accuracy using VMR. This shows that the use of VMRS is particularly beneficial when users are not provided with direct visual feedback on their input. Combining the results for ER and TCT, we can conclude that, when no visual feedback is available, VMR offers superior accuracy at the cost of increased TCT. With VMR's accuracy being as much as 66% higher than `tangible sliding`. Therefore VMRS should be the input technique of choice for tasks where accuracy is the key measure.

As expected, participants perceived the task as more mentally demanding when `no visual feedback` was provided. HAPTICFEEDBACK, `tangible sliding` and VMR had no influence on the perceived mental effort when selecting values. This shows that our assumption that users might perceive more effort when processing multi-modal feedback was not correct and **H4** is to be rejected. As a consequence, we see that VMRSs can be deployed in lieu of existing remote discrete input methods without increasing the mental effort of the users. Overall, all resulting SMEQ scale values are relatively low. This can be explained by the atomic interaction that was required during our study. Independently of HAPTICFEEDBACK and VISUALFEEDBACK, each of the trials represented a facile input task.

Surprisingly, participants had to correct more, regarding backtracking distance, using the slider on the touch display than using a tangible slider knob (`tangible sliding` or VMR). Both the `tangible sliding` and VMRS provide a physical resistance. This might incline participants to select values carefully. Also, this resistance seems to lower the movement speed, because the longer backtracking distance distance neither influenced the TCT nor the final accuracy of the selected value. A further explanation for the effect could be the fact that users are accustomed to using a touch surface on a daily basis. As a consequence, they tend to

use rapid movements with which they are familiar and apply corrections later. We also found no significant difference between `tangible sliding` and `VMR`, which suggests that the additional resistance in the slider does not introduce an added need for corrections.

Based on the results, we can conclude that VMRSs offer superior accuracy at the cost of increased TCT when the users are provided no visual feedback. Using VMRSs does not cause added mental effort or increase the need for correcting input. The results show that `VMR` enables more accurate data input when no direct visual mapping to the input can be provided. We believe that this fact suggests that VMRSs can be useful in scenarios such as exploring large data sets in visually rich environments, e. g. in front of a wall-sized display. In such scenarios, not all variables which can be adjusted can be visually observed at once. When multiple variable input has to be performed, a set of VMRS could be used. For example, a multivariate function for more than four variables is impossible to visualize statically. We suggest that users could perceive some of the variables as slider positions and modify them through the variable resistance. This raises the question of whether data analysts can profit from such multi-VMRS and adapt the technology to their work as do sound engineers using soundboards. The presented advantages of haptic feedback on the input device for data input, should trigger an exploration of communicating possible input in a tangible way for LHRDs. The combination of large visual information spaces and haptic feedback on the input device has the potential to enhance the exploration of complex data sets.

9.4.1 The Question of Form Factor

We have established that VMRSs can provide more accurate input and multiple application domains can benefit from their use. We now wonder what questions need to be answered before VMRSs can be deployed in real-life tasks. Looking back at past work [44, 118], we can observe that slider or slider-like devices need to be mobile to be applicable to large-screen environments. Past research offers few answers concerning what such devices may look like or even how many sliders they should contain. Previous studies explored only slider devices that look like parts of a soundboard — large boxes with an array of vertical sliders or single slider. The form factor of a slider device remains an open question. Based on our experiences of designing and implementing slider prototypes, we suggest three possible form factors. To illustrate our vision, we built low-fidelity cardboard prototypes of the devices shown in Figure 9.8. We suggest three form factors that can serve as an initial step in a design inquiry.
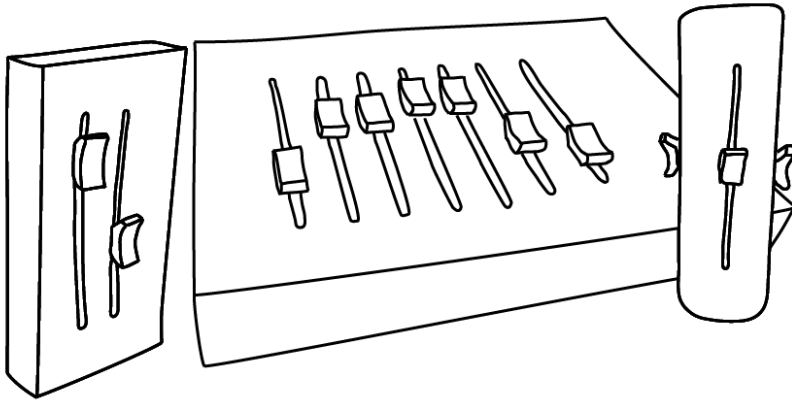
Figure 9.8: Bar, tablet and cylindrical slider devices. We propose those three form factors as starting points for designing devices that use VMRSs.

The bar device (see Figure 9.8 left) has four sliders – two in the front and two in the back. The prototype is lightweight and fits easily in a hand. The size is similar to an off-the-shelf smart phone. With this design, we show the need for exploring slider input and output on both sides of the device. An open question is how users can perceive changes in slider position while holding the device in hand.

The tablet-like device (see Figure 9.8 middle) is similar to devices investigated in previous work. This form factor has several advantages. Users may find it more familiar as it is possible that they may have previously seen similar devices (e.g. soundboards). The seven sliders arranged in parallel enable displaying complex patterns or even curves. However, the bulkiness of the device is a significant disadvantage, especially when one considers a scenario where the user is walking along a display.

The cylindrical device (see Figure 9.8 right) uses four sliders located on the sides of a cylinder. There is enough space on the cylinder that the user can easily hold the device in the hand. It also can be held a bit higher to feel the position of the sliders with the palm. The cylindrical shape permits investigating the usage of sliders together with wand-like interactions, which are known to be effective in some use cases for large screens (e.g. [254]).

9.4.2   Limitations

While we strived to create an exhaustive study, our work is prone to certain limitations. Firstly, we recognize that our design of the VMRS is just a single design instance of an artifact.Further studies can investigate whether using different hardware e.g. a longer potentiometer would result in differences in performance. Furthermore, we still do not know what the influence of the slider device form factor is.

Secondly, we used an abstract atomic task in our experiment. As no prior systematic research has been conducted on VMR input, we decided to investigate the details of the single-value input first. However, we see that a more complex task, perhaps involving multiple sliders, may have revealed different properties of the VMRS. A longer study, incorporating multiple inputs, could also investigate the effects of fatigue. Furthermore, because of the atomic task, we did not look at the influence of the HAPTICFEEDBACK feedback type on recall and distraction from the actual task, besides data input. As indicated by previous work [44, 182], these two measurements might reveal important results.

Lastly, we note that we used a single implementation of VMR. While our design process suggested that the sinusoidal curve was the best choice, we wonder if further refinements to the feedback pattern are possible. A separate study can be run to compare different feedback curves in the future. However, the feedback curve can also highly depend on the assumed scenario and the study task. Our work shows the usefulness of using VMRSs per se, but we see that the intricacies of feedback design may need further exploration.

9.5   Conclusion

This chapter introduced the notion of using VMRSs for providing discrete remote input. We described the design and implementation of a VMRS. We then evaluated the device in a controlled lab study. We showed how HAPTICFEEDBACK changed users' performance comparing VMR, `tang` and `touch`. We found that VMR had no negative influence on the ER and the perceived mental effort for value selection. However, VMR increased the accuracy of the input when no direct visual mapping to the data could be provided. Using a VMRS caused TCT to increase. In general, participants did less corrections when using `touch sliding` or VMR. The results suggest that using `variable movement resistance sliding` (VMR)

can be an effective way to provide remote discrete input in scenarios where the users' visual attention on the input device is limited.

To have a coherent and manageable study design, we decided to constrain our study within a number of factors, which can be explored in future work. In this study, we used direct mapping of the input slider to the representation on the remote display. The affordance of the VMRS device allows a user to rotate the device with all degrees of freedom. Also, the representation on the remote display could be rotated. Overall, rotating the VMRS device and the representation on the remote display would result in 16 combinations. An open question is how the orientation of the device would affect interaction and accuracy. Another direction would be to go beyond off-the-shelf devices and build sliders that not only offer VMR but also other types of haptic feedback such as vibration or pressure. In the next step, it will be important to analyze using VMRS for data input in a real-world setting. Here the task could be exploring the influence of different input parameters of a simulation.

As this chapter is the first inquiry into VMRS to our knowledge, we hope to inspire further work on how to efficiently use VMR in interactive systems. We have shown that the proposed techniques are relevant for remote displays, but we are eager to explore other scenarios, especially in tasks where the users' visual attention is limited. We believe that our insights into the applications of VMRSs will lead to deploying them in real-life tasks and enable in-the-wild evaluation.

IV

GRAPHICAL USER INTERFACES FOR LARGE HIGH-RESOUTION DISPLAYS

OUTLINE

By Andrews et al.'s [13] definition, LHRDs provide many times larger visual space than regular office displays. On the one hand, this has manifold advantages for exploring large data sets. As we discussed in Chapter 4, humans are very fast in over-viewing large visual areas. Furthermore, research has identified benefits of using physical navigation over using virtual navigation [21, 153]. Also, the human ability to make use of spatial arrangements to build relations between pieces of information can be well-supported by LHRDs. On the other hand, traditional GUI concepts for desktop interfaces might not work anymore or might not support utilizing the advantages of larger display spaces. The large display space of LHRDs has a high degree of freedom in how to arrange content. Hence, GUIs for LHRDs have to support users to utilize the space meaningfully; to not overstrain the user with arranging content. However, there are no straightforward approaches for designing GUIs for LHRDs. Designing GUIs for LHRDs is particularly challenging when focusing on tasks which are performed on desktop setups today. In these cases, users are influenced by legacy bias of familiar interface concepts. This results in a complex interplay between user needs and expectations and theoretical knowledge developed in HCI, cognitive science, and related fields.

In Chapter 10, we use a two-step user-centred approach to identify users' expectations about how a LHRD workplace should be designed. First, we focus on the physical arrangement of screens around the desk, and then we explore different areas on screens for various content. The results show that users have clear expectations about screen arrangement and content placement.

In contrast to the user centered approach in Chapter 10, Chapter 11 explores how desktop environments developed for traditional desktop setups can be adjusted for LHRD workplaces. We derived concepts from theoretical work, implementing four concepts for the desktop environment KDE and using these implementations

for lab study evaluation. The results show that participants struggled with designs where traditional GUI concepts are intentionally broken up.

In Chapter 12, we move from the design of window managers to the application level of GUI design. A large body of work has explored working on LHRDs with data that has a inherit spatial meaning such as map-based tasks (e.g., [21, 40]). When data have an inherit spatial logic, the visual arrangement of the data representation is given by the data itself. However, it is unclear how to arrange data with little or no spatial order. One common example is page-based documents. A significant amount of information is stored on page-based documents, which mostly have a linear order with numbered pages. However, there are multiple ways to convert this linear order into a display layout, futhermore, multiple documents do not have this linear relationship. When working with page-based documents users tend to rearrange pages [189], which creates an interesting and important application scenario for LHRD GUIs.

The presented work in all three chapters show that GUIs for LHRDs require easily accessible methods to arrange content with a spatial meaning. Thereby the interplay between visual focus area and preferential areas has a high relevance. Furthermore, GUIs should provide support to cluster related content visually without effort. Well-suited GUI for LHRDs could allow users to perform task switches more easily. Furthermore, they will support users to relate, cluster and understand large complex visual data sets.

Chapter 10

Screen Layout

Today's GUIs and interface guidelines focus mostly on mobile devices (e.g. smartphones or tablets) or on desktop setups. This covers GUIs for displays sized between approximately 3 and 30 in. Due to the limited space on small displays, full screen applications are commonplace. But already on tablet-sized devices with high resolution displays two applications can be displayed simultaneously. This allows the user to see additional information or compare content visually. Desktop interfaces provide more freedom to the user to arrange content. All design guidelines for common desktop environments assume that the whole display space or at least the main screen is in the visual field of view of the user all the time. Based on this assumption, central navigation menus are placed and window functions, such as maximizing are provided. However, these concepts do not optimally support users working on LHRDs. Thus, navigation menus placed on the edge of a screen, lead to long distances between cursor and target. Additionally, users need advanced support in arranging content. For LHRD interfaces, simply maximizing application windows is not supportive. In contrast, the system should support grouping and aligning content. However, changing interfaces in well-established environments, such as an office, is challenging. Users are highly trained with the interfaces they use daily. The complexity of changing well-known GUI concepts is illustrated by Microsoft's decision to replace the Windows Start Menu in Windows 8 with a full screen view and reintegrating a start menu in Windows 10. Shneiderman et al. [222, Chapter 8] describe these challenges for changing GUI concepts on a general level. This

underlines the importance of understanding user needs and expectations when changing interface concepts.

In order to understand the expectations of potential LHRD users, we conducted a user-centred design study. We invited 16 participants to explore and discuss their expectations for a physical LHRD workstation design and assumptions about content arrangement. The results of the study show that participants preferred symmetrical screen arrangement and had a common understanding about dedicated areas for particular content classes.

10.1   Related Work

In this section we discuss previous work on understanding display usage, the influence of physical display design and prototyping LHRD GUIs.

Bi and Balakrishnan [28] invited participants to perform their daily work one week long on an LHRD. The participants of this study preferred working on the LHRD over their regular setup with one or two displays. In particular, the authors highlight the potential for multiwindow and data intense tasks. Jonathan Grudin [87] conducted a field study to understand how users make use of multiple screens and how they arrange content. He observed that participants did not spread application windows over several screens. In contrast, they used the screens to separate tasks from each other. Grudin concluded that GUIs for LHRDs have to support users separating different task visually. In line with the observation that users utilize screens as containers for content, Wallace et al. [262] showed that participants of a lab study utilized the screen bezels to cluster the visual space to perform visual searches faster.

Endert et al. [57] argued that changes in physical LHRD setup have an influence on user performance and perception. Shupp et al. [223] compared flat LHRD setups to curved setups, in which the LHRD consisted of the same single screens. In user studies the authors showed that participants performed visual search tasks

faster on curved screens than on flat screens. Ten Koppel et al. [237] analysed the user behaviour in front of differently shaped public displays. The the authors concluded that flat displays created the highest honey pot effect and curved setups triggered fewer simulation interactions. Takashima et al. [234] explored which display shapes users preferred. The authors focused on a scenario where one or multiple users stand in front of the display consisting of several screens. To allow participants in the design study to arrange the displays, the authors created a mock-up based on three boards with wheels. The results showed that participants changed the layout depending on the viewing distance and the focused task. Past work shows the high influence of the physical screen layout. So far, this has not been explored for office environments.

Swaminathan and Sato [233] called for rethinking GUIs for LHRDs two decades ago. Surprisingly, little work has been conducted in order to understand GUI-requirements for LHRDs. Kuikkaniemi et al. [133] explored GUIs for collaborative information presentation on LHRDs. The focus on presenting information requires a different set of functionality than interfaces for office work require. Knudsen et al. [128] conducted design workshops from various disciplines to understand how experts would use LHRDs for their daily work. The results indicate that users perform their work in the center of the display and use the peripheral for secondary tasks, while Knudsen et al. [128] focused on data exploration scenarios in which the user is standing in front of the setup. We are exploring an office scenario where a regular working desk is part of the setup.

10.2   Design Study

We conducted a user-centred design study to gain an understanding of how users would prefer to arrange multiple large screens. Further, we explore how potential users would make use of the large display space in a variety of tasks. We used a repeated measures design presenting three different scenarios to all participants. We asked the participants to arrange screens as well as the application windows for the following three scenarios: (1) a software developing scenario ("Assume you are developing an android app"), (2) a text processing scenario ("Assume you are writing a longer report or thesis."), and (3) a visual collaboration data analysis scenario ("Assume you want to analyze and discuss a complex data set with your colleagues."). We then asked the participants for each scenario to perform two tasks; firstly to arrange four screens then secondly, to place commonly used as well as the scenario-dependent application windows on the displays.

For every participant we provided a regular office desk, a chair, and four lightweight cardboards as screen mockups. Each piece of cardboard was the size of a screen with 50 in diagonal (113.1 × 69.7 cm). We used four 50 in screen mockups, because as discussed in Chapter 4 this size enables physical navigation but does not increase the physical effort. We used lightweight cardboard so as not to restrict participants to positions where today's heavy 50 in screens would have been easy to place. Consequently, participants could design their own arrangement with low physical effort. We provided tripods and tape in case this was required for a particular setup. Then the study conductor offered physical support to arrange the screen mockups at the desired position, so height and orientation could easily be changed. The physical size of LHRDs makes prototyping LHRD environments challenging. The prototypes require large physical spaces and due to their size even lightweight mockups have to be mounted properly. Hence, Yasuto Nakanishi [184] proposed using scaled down mockups. However, prototyping LHRD environments in the original size has the advantage that participants can experience the large size of these devices. Thus, participants act more naturally with the mockups [234].

Afterwards, we asked participants to create paper prototypes for applications. Paper prototyping is a well-established technique for designing user interfaces [228]. We designed the study in line with the recommendations for prototyping multiple display environments by Bailey et al. [19]. We prepared a number of application window printouts. These printouts contained basic application windows for daily office work, including browsers, calendars, and e-mail software. Additionally, we prepared scenario-specific printouts for the three scenarios. Each application window was available on paper in two different sizes to see how dominant the participants wished each application window to be. Furthermore, we encouraged all participants to sketch other applications if they were missing in our prepared application set. For this activity, we supplied various colored pens, A4 paper[18], and scissors. In such cases, we asked the participants to describe the respective functionality.

After welcoming the participants, we explained the first scenario and any answered questions. We then asked the participants to arrange the screens using the four pieces of cardboards in one desired arrangement, and then to attach the printed application windows with pins. Afterwards we repeated this procedure with the two other scenarios.

During scenario (1), we asked the participants to design a setup for a situation focusing on software development (see Figure 10.1). In addition to basic applica-

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[18] International Organization for Standardization (ISO)216 A4 paper has a size of 21.0 × 29.7 cm

tion windows, we provided task-specific window printouts of Eclipse, a virtual Android device, and a log window. During scenario (2), we asked participants to set up the cardboards and printed application windows for an office task focusing on text writing. For this purpose and in addition to the basic applications, we provided task-specific printouts of Microsoft Word, Textmaker, larger text documents printed on A4 paper, and PDF documents presented in the Adobe Reader. Scenario (3) was a collaboration task. Here, we asked the participants to design for a situation where they had to analyze large data sets in groups of three or four people. To support this scenario, we provided printouts of different data plots; a data set in from of an Excel sheet and an SPSS output document. Additionally, participants could sketch their own ideas directly on the cardboard.

During the whole design process, participants could freely move in front of the display mockups. We also encouraged them to sit down during the design procedure as well as after they had finished a design task to experience the design from multiple perspectives.

Every participant took approximately 10 min per scenario to design a favored screen arrangement and window placement. After designing for each scenario, the attending researcher recorded the designed screen by taking photos. In addition, participants explained every design of the screen arrangement as well as the window placement in a semi-structured interview. We compensated the participants for their time and effort with 10 EUR.

We selected computer scientists and engineers as they are used to performing complex tasks involving multiple applications, windows, and screens at the same time. We recruited 16 participants (10 male and 6 female) from our university campus and via the computer science mailing list. The average age of the participants was 21.25 years ($SD = 2.36$). All had a background in engineering or computer science to ensure the participants were able to complete the first task.

10.3   Findings

In this section, we present the findings from our design study in two steps. First, we focus on the arrangement of the individual screens. Second, we analyze the placement of the content displayed on the arranged LHRD.

Figure 10.1: Cardboard and printout arrangement designed by one of the participants during the study.

10.3.1   Screen Arrangement

In the first part of the study, we collected 19 screen arrangements from 16 participants. None of the participants changed the screen arrangement between scenario (1) and (2); the programming and text processing scenarios. Three users changed the screen arrangement for scenario (3); analyzing and discussing a complex data set with colleagues. Using a bottom-up analysis, we structured the 19 screen arrangements and grouped them by similarity, resulting in four screen arrangement categories: (a) *screen band:* all screens are placed directly next to each other in the same orientation. (b) *screen block:* all four displays are placed in a grid of 2×2 in landscape orientation. (c) *cockpit arrangement:* two displays in the center above each other in landscape orientation and one screen on each side of the stacked displays either in portrait or in landscape orientation. (d) - (f) *two plus two arrangement:* two screens in the main focus area have one orientation and the two screens in the periphery the other one. We present these six screen arrangements as sketches in Figure 10.3.

The *screen band* (a) was designed by six participants, the *screen block* (b) was proposed by four persons, the *cockpit* (c) by five, and the *two plus two arrangement* by three.

Two arrangements were proposed only once. One was a variation of screens in landscape and portrait orientation. The other was an asymmetrical arrangement containing two screens in landscape orientation behind the center of the desk and

two screens in landscape orientation stacked above on the right side behind the desk. This arrangement can be seen as a hybrid between the *screen band* and the *screen block*.

The three participants who changed the screen arrangement for the collaborative scenario changed the setup to a *screen band* or even isolated one screen to be able to stand with colleagues in front of that screen.

While six screen arrangements were designed as one display plane, the majority of the arrangements (13) were arranged in a bow shape. According to post-task comments, a reason for a bow shape was that the distance between the peripheral screens and the user is smaller compared to a planar setup. Moreover, three participants mentioned that they would also like to stand in front of their display from time to time. Two of them would like to sketch ideas and take notes on the screens in the periphery. Therefore, they would like to have the peripheral screens equipped with technology that allows touch or digital pen input.

None of the participants saw a need for touch input over the whole display. This indicates the need of a screen arrangement which enables users to work in two different body postures. All participants want to be able to interact with their digital environment in a sitting posture. Additionally, participants explained that they want to stand in front of the displays and work with absolute input e.g. touch input. Therefore, the participants would use the screens that are not placed directly behind the desk. These screens are accessible, because they are placed on the left or right side of the desk.

Surprisingly, no participant placed a screen laying on the desk, as an interactive tabletop. The reason could be that users place physical objects on their desk and these would cover the virtual work space. Another reason could be caused by the tripods, which could have implied a requirement to mount the screens instead of integrating them in the desk.

10.3.2   Interaction Areas

The majority of screen arrangements (15 of 19) combined all screens to one display unit to use it as a single display area, assuming the single display would not have any or only thin bezels. Only two participants separated a screen physically to be able to stand in front of the screen and discuss the displayed content with others. However, only two participants wanted to spread windows over the boundaries of screens. None of the participants wanted to fill the whole

(a) Single user scenario   (b) Collaborative scenario
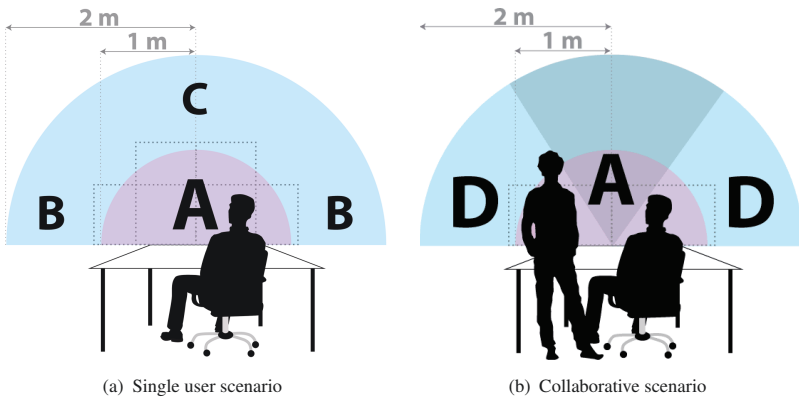
Figure 10.2: Interaction areas on an LHRD. Single user scenario: (A) main focus, input and output (B) gathering information, output, reading and browsing (C) status information, communication. Collaborative scenario: (A) desktop input (D) creative working, discussing, sketching.

display with a single window. A few participants asked for displaying content on one screen in full display mode. Mostly, the participants used multiple windows on one screen. Participants stated that they would only use half of one screen for one window. This might have different reasons. On the one hand, a 50 in cardboard could be perceivable as one unit. On the other hand, Grudin [87] sees a need to organize content on LHRDs. He argues for partitioning the screen space to keep an overview. In line with this, participants in our study stated that they would often like to compare the content of different windows. They would place two windows close to each other. The possibility to compare information from different sources without window switching is one of the main advantages the participants saw of LHRDs.

All window arrangements were independently categorized by two researchers. They concluded that the participants' arrangements of the windows indicate four areas that are used for different tasks, see Figure 10.2(a). For the programming scenario (1) as well as for the text-processing scenario (2) all participants placed the most frequently used windows in the middle of the display. Interestingly, all participants used the areas to the left hand side and right hand side of the display's center for web browsing or reading. All participants used multiple browser windows for gathering information. This led to the question of whether they would still see a need for browser tabs. However, only one participant stated

he would not use browser tabs anymore. All others would use tabs to group different topics, but they would use more browser windows and fewer tabs. The use of PDF viewers is comparable to the use of browser windows. All participants pinned at least two windows of a PDF viewer, typically on the other end of the display opposite the web browser. Therefore, they used the browsers on the left of the center and PDF viewers on the right or the other way around.

Modern screens with 50 in and 4K resolution allow displaying multiple A4 pages in original size. Even if the pages are magnified for a better readability multiple pages can comfortably be displayed. Thus, we asked participants how they would expect that a PDF viewer would display multiple pages at once. We further discuss in detail how page-based documents could be displayed on LHRDs in Chapter 12. The majority (9) would expect to see three or four pages horizontally from left to right and then again three or four pages in a next row. All others would feel overwhelmed by seeing more than three pages at once. Therefore, one participant proposed to view the previous, the current and the next page at once. Thereby, the current page should be enlarged. In particular, for the text processing scenario some participants would like to use the areas left and right of the main focus area to stand in front of the displays and sketch ideas. Surprisingly, all participants had an exact idea about applications, which they would never close. Half of the participants said that they would be distracted by their e-mail client or calendar. The other half would like to have as much status information as possible, for example, multiple clients of their e-mail program and calendar on screen. However, all of them placed these windows above the main focus area. While sitting in front of the screen, the area above the main focus area is not in the field of vision. Nobody mentioned concerns about privacy issues when using such a large screen. Nevertheless, all participants hid their mail clients for the collaborative task. For this task, the participants would use the main focus area to edit the visualizations and to manipulate the data. They would use the areas left and right for the main focus area to display the visualizations (see Figure 10.2(b)). These results show interesting similarities to how smaller groups use space on interactive tabletops. Scott et al. [218] found three areas on interactive tabletops: (1) Personal space in front of the user, where he or she works independently form others; (2) Group space used for shared activity and the overall goal of cooperation; (3) Storage space to place objects, not currently being used.

(a) *Screen band*   (b) *Screen block*   (c) *Cockpit arrangement*

(d) *Two-plus-two arrangement* (e) *Two-plus-two arrangement* (f) *Two-plus-two arrangement*
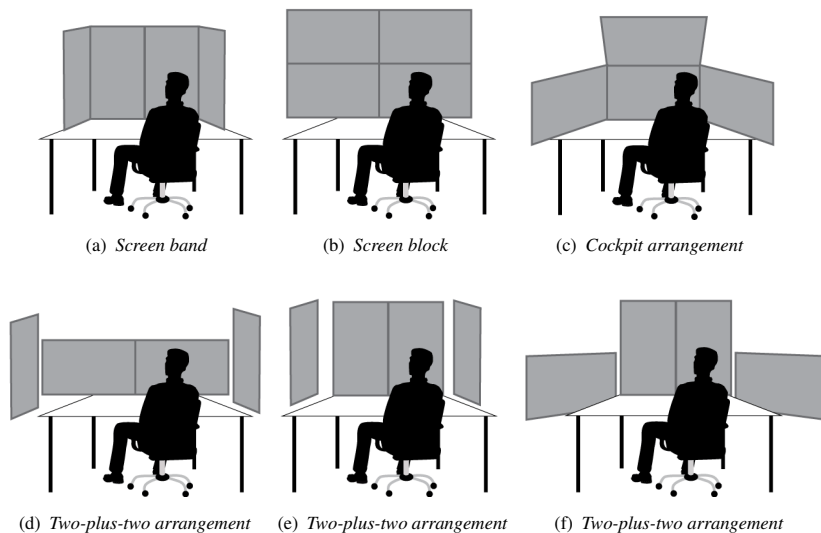
Figure 10.3: Classification of screen arrangements extracted from the study.

10.4   Guidelines

As result of the presented study, we derive guidelines for designing LHRD workplaces and UIs for such environments. The guidelines focus on a physical screen setup as well as on content arrangements.

Symmetrical Setups

When designing LHRD workplaces, the user and desk should be placed in the center of the setup. Users do not only prefer rectangular display setups; as shown in Figure 10.3, combinations of screens in landscape and portrait mode are also desired. Furthermore, all users prefer a symmetric arrangement of screens and if physical constraints allow, users appreciate curved setups. This has the advantage of equal viewing distances to all screens.

Provide Guidance

Even if the study design clearly specified that the prototypes screens have no bezels, participants were concerned about this. With a few exceptions in the center

of the setup, participants did not spread single windows over multiple screens. We conclude that providing one large display without bezels is less important for users. In contrast, also Grudin [87] argued, users make use of separated screens, to use them as "containers" to group related windows.

Enable Body Movement

It is beneficial to allow users to work in different body postures. This can help to get an overview over larger data sets [115] by physical navigation. Furthermore, when discussing display content users perceive standing in front of the display as more natural. Therefore, height adjustable display setups are beneficial to support single user as well as multi user workplaces. However, this requires advanced input techniques others than mouse and keyboard. Direct touch input would allow multiple users to manipulate data at the same time. Due to this all touch, sensitive screens have to be within arm's reach.

Support Content Spreading

LHRD space allows users to distribute content, instead of stacking it. This has several implications. Hiding content in tabs is not an appropriate content arrangement on large displays; instead, content is spread over the whole display. However, this creates the need for new methods that connect multiple windows to one group. Each group should be displayed closely together and should provide functions applying to all windows, e.g. close or hide all.

Central Focus

When displays are larger than common desktop displays, users have more options for arranging content spatially. The display space is separated in a focused area and a peripheral area in the surroundings. The focus area is always in low middle of the setup. Users place the most frequently used applications there. Such applications are used, inter alia, for text processing, programming or larger calculations. As these applications require most attention and interaction by the user, precise interaction techniques are needed in this area.

Supportive Content on the Sides

The display areas on the left and right of the focus area are used for supporting content. Users place web browers, documents or additional data here. Shifting attention from the central focus area to the left or right side requires head or

body movement; furthermore, moving the pointing device to exterior areas is laborious. However, users do not need high precise input. A comparable concept for visualization, named "focus plus context screens", provides high quality interaction in the focus and lower precision in the context area around it [24]. User interfaces should assist users to place displayed content without overlap and in a context-aware meaningful way.

In collaborative settings or for discussions, there might be an attention shift in the direction of these areas. The focus area will be still used for preparation and adjustments. However, the results will be displayed in the supportive areas. In contrast to the concept of "focus plus context screens" [24], in this case high-resolution is also needed in these areas.

Observing on the Top

Applications presenting notifications, messages and status information are placed by all users in the upper area of the display. These applications are mostly placed at the outside of the field of vision when looking on the focus area. This has the advantage that notifications and messages do not distract users. Interface design should consider how to avoid distractions, e.g. by fading out unneeded information. However, it should be possible for important events to get the user's attention. Changing color or blinking could realize this.

If an LHRD setup is designed for collaboration and discussion, privacy plays a more important role. Users need appropriate mechanisms to easily hide private information like calendars, emails or instant messages. One solution would be to extend applications with features which allow hiding or closing all of them with one action.

10.5   Conclusion

This chapter contributes a description of how users would perform office work with LHRDs in three common scenarios. We identified six screen arrangements for workplace setups, all favoring an arrangement in landscape format, even if some included portrait screen orientation. The findings suggest that users would like to work in different body postures with different input modalities. This calls for space to stand and sit in front of an LHRD. In addition, touch-sensitive input areas, where users can stand in front of the display, are needed.

This work presents insights into how users would arrange content on abundant display space. When used by a single user, the participants would employ the lower middle center for their main focus with additional information displayed on the left and right side of the central area. Status information would be shown above the center area. In collaborative situations, areas would be used comparably. Participants would edit and prepare data in the center area of the screen and employ the space on the sides for presenting and discussing visualizations. To explain circumstances, users would like to be able to apply touch input on the regions left and right of the main input area.

The presented findings and guidelines will help designing GUIs for the usage of LHRDs in office environments and will support GUI and LHRD setup designers to build well-suited concepts. Thereby they should focus on supporting the user to arrange visual content. The approach of eliciting design guidelines through a user centred design study, has the challenge that participants' ideas and expectations are inspired by commonly used designs, mostly of desktop environments. This legacy influence will help users adapting form desktop interfaces to LHRD interfaces, but could lead to GUIs which utilize the advantages of LHRD non optimally. Hence, also fundamentally new GUIs should be prototyped and evaluated in future work.

Chapter 11

Transforming Desktops

Since the innovation of the desktop metaphor as GUI element by Xerox [121], the physical display space commonly used for office work is constantly increasing. Simultaneously the screen resolution is increasing disproportionately high. While Apple built one of the first personal computers, the Apple Lisa, with a 12 in display, we see displays today with more than 30 in diagonal. Due to technological advances, this trend will continue, and LHRDs will become commonplace. Surprisingly the increases display space has not led to fundamentally new GUI concepts. In contrast, we can observe an slower evolutionary process of adapting interfaces to larger visual spaces. Hence, we explore how a state-of-the-art desktop environment, in this case, KDE Plasma, can be adjusted to support users working on LHRDs.

In 1997, Swaminathan and Sato [233] called for focusing on particular design requirements for LHRD GUIs. Bi and Balakrishnan [28] compared performing daily work on regular desktop setups with performing the same work on an LHRD. Their results showed that users preferred working on the LHRD. Comparably Rajabiyazdi et al. [202] invited researchers from various disciplines to perform their work on an LHRD. They showed that the LHRD enabled getting insights into data, which had not been possible on a smaller display. However, the authors also highlighted the need to improve GUIs design for LHRDs. The previous Chapter 10, explores content management though participatory design. In contrast, in this chapter, we explore how working prototypes are used and perceived by possible users of LHRDs. On a contextual level, both chapters focus on content

Figure 11.1: The setup used in the evaluation study with the *Curved Zooming*.

management on LHRDs. Hence relevant related work for this chapter is also presented in Chapter 10.

Based on findings of previous work we designed, implemented and evaluated four window alignment techniques enhancing the use of KDE Plasma as desktop environment on LHRDs. We decided to use the KDE Plasma as desktop environment because it allows manipulating the view and behavior of all GUI elements through applications written in C++ and OpenGL, so-called KDE Desktop effects.

The results of the user study show that participants prefer techniques which include new functionality without changing the well-known interface behavior.

(a) Linear Curved Zooming

(b) Curved Zooming

(c) Schematic comparison between Linear Curved Zooming and Curved Zooming.

(d) Window Groups

(e) Window Spinning

(f) Side Pane Navigation
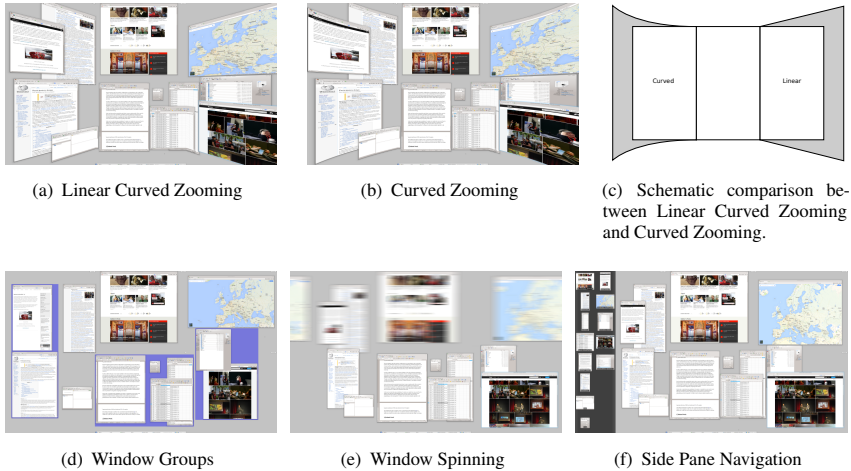
Figure 11.2: a) - c) shows the two implementations of *Curved Zooming* and a sketch representing the behaviour. b) - d) shows the three other window alignment techniques.

11.1 Design

We envision that LHRDs will become commonplace in office environments. We designed four window alignment techniques extending classical window management, assuming future LHRDs will have a size of at least 2×1 m (see Figure 11.1) and a high screen resolution (minimal 88 PPI). We synthesized all four window alignment techniques from previous work:

11.1.1 Curved Zooming

Mackinlay et al. [163] proposed the "perspective wall" which provides details in the center of the display while perspectively decreasing details on the left and the right side. Thereby, the user shall get a better spatial overview of limited screen space. In contrast, Shupp et al. [223] show that performance when working with a large curved screen is better than when using a large flat screen. A curved LHRD has the advantage that the viewing distance is equal over the whole screen space, with all visual content perceived to be the same size. However, curved display

arrangements are not always possible. Due to the physical size of flat LHRDs, content in the periphery is perceived as smaller and might be too small to read. We envision a digital zoom of right and left to overcome the readability issue, where the content displayed in the center has the original size and content in peripheral areas is zoomed. Further, we envision two types of zoom: A constant zoom factor resulting in a *Linear Curved Zooming* (see Figure 11.2(a)) and a squared zoom factor resulting in a *Squared Curved Zooming* (see Figure 11.2(b)).

11.1.2   Side Pane Navigation

Hutchings et al. [108] argue that large screens lead to more open windows at a time. Bezerianos and Balakrishnan [27] show that users tend to separate content on single screens. To keep track of all open windows, we introduce *Side Pane Navigation*, which presents a real-time thumbnail of each window on the left side of the screen (see Figure 11.2(f)). Furthermore, Andrews et al. [12] stated that moving the head is faster than directing the cursor with the mouse. Therefore, we see a need for a shortcut to move the mouse to the *Side Pane Navigation*. As a consequence we implemented a keyboard shortcut to jump to the *Side Pane Navigation* bar. Also, when selecting a window in the *Side Pane Navigation* bar, the cursor jumps to the window and the window will be highlighted.

11.1.3   Window Spinning

Andrews et al. [12] report that LHRDs enable spatial arrangements of information, which changes the way users work and think. However, this requires a physical move to get an overview or to switch focus. In line with Roberson et al.'s [208] Tablecloth, we designed *Window Spinning* to allow content switching without changing the seating position. This enables the user to move the whole screen content to the left and right side. The screen content will be moved when pressing a predefined shortcut combination on the keyboard while moving the mouse in the desired direction, as shown in Figure 11.2(e). If a window moves out of the display, this window will appear on the other side of the display again. Hence, it is possible to "rotate" all windows. While other windows are moved to the focus area, the relative spatial relation between windows remains consistent.

11.1.4   Window Groups

According to Kirsh [122], humans make use of arranging tools and information spatially for quick access and easy understanding. Robertson et al. [207] proposed using a plus-focus approach on desktop computers and group windows by content. Currently non focused groups can be moved to the periphery and will be displayed in smaller size. We adjusted this concept and, designed a technique where it is possible to group multiple windows. These groups are visually highlighted and can be moved as one object. Furthermore, adding and removing windows is possible using shortcuts as well as moving windows within the group. A group is visualized with an underlying colored frame, as shown in Figure 11.2(d).

11.2   Study

We conducted a repeated measures study to collect qualitative feedback and to identify the best-suited parameter values for three out of our four window alignment techniques which allow for configuration through a number of parameters. In detail, we compared linear against curved zoom for the *Curved Zooming* window alignment technique under seven zoom conditions. For the *Side Pane Navigation*, we compared the size of the thumbnails. *Window Spinning* allows splitting the screen into several horizontal areas. Hence, we presented one, two and three areas. *Window Groups* has no adjustable parameters.

We recruited 12 participants (11 male and 1 female) aged between 22 and 39 years ($M = 29.3$, $SD = 5.1$) though our mailing list and on our campus.

11.2.1   Apparatus

The center of the screen was used as the main focus point. Related work shows that a display with a width of up to 2.4 m allows seated office work [150]. Hence, we decided to use three 50 in displays, namely Panasonic TX-50AXW804, with 4K resolution. We arranged the three displays in portrait mode, resulting in a display area of 2.02×1.13 m and a resolution of 6480×3840 pixel. We used Ubuntu 14.04 with KDE Plasma Workspaces 4. The KDE desktop environment provides the possibility to adjust the GUI though so-called "desktop effects". This provides the opportunity to manipulate the GUI for all running applications.

For the user study, we placed a desk and an office chair in front of the setup with an approximate distance of one meter between the chair and the display. For interacting with the system, we provided keyboard and mouse.

11.2.2   Procedure

After welcoming our participants, we asked them to take a seat centered in front of our setup and to fill in a consent form and a demographics questionnaire. We started by showing all window adjustment techniques to the participants. We showed the window alignment techniques in a random order, each with each configuration. We explained each effect before the participants tried interacting with it by using a standardized protocol. During the explanation phase, we did not give participants a specific task. Instead, we opened a high number of windows simultaneously to simulate a work environment with several different tasks and to encourage interacting with different types of content. After exploring the window alignment techniques in the sandbox interaction session, we asked about their preferred technique and parameter values on a 7-point Likert-scale. This was followed by a semi-structured interview.

11.3   Results

First, we analysed if participants rated one window alignment technique over another. Participants rated *Window Spinning* best with $M = 5.83$ ($SD = 1.03$), then *Side Pane Navigation* with $M = 5.75$ ($SD = 1.49$), then *Window Groups* with $M = 5.58$ ($SD = 1.31$), and with the lowest rating *Curved Zooming* $M = 4.25$ ($SD = 1.60$), see Figure 11.3. We further conducted a non-parametric Friedman test of differences among reported measures. However, Friedman's test rendered a χ^2 value of 7.147 which was not statistically significant $p = .067$. Thus we assume that all four window alignment techniques are equally useful. The qualitative feedback indicated in more detail that the participants saw the need for novel UI designs for LHRDs. They liked the window alignment techniques as they mentioned for instance:

> "... without this kind of customization large displays may be not used so effectively" *(P5)*
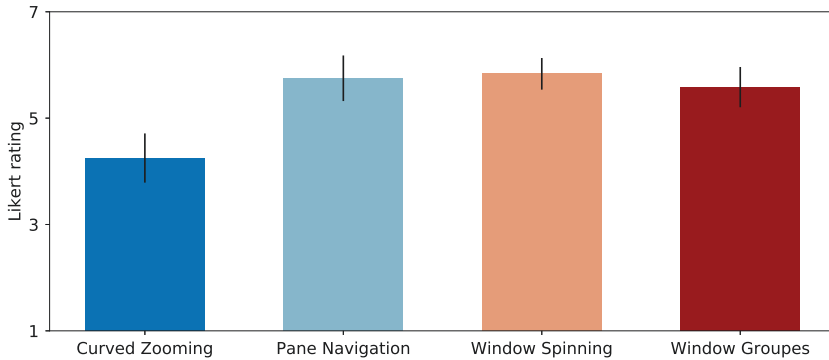
Figure 11.3: Rating how useful the window alignment techniques were perceived by participants (From 1 — "not useful at all" to 7 — "definitely useful"). The error bars show the standard error.

and other statements indicating detailed advantages and possible improvements for each window alignment techniques.

Curved Zooming:
Participants rated *Curved Zooming* less useful than the other window alignment techniques (see Figure 11.3). The main drawback of *Curved Zooming* seems to be the distortion of the content in the peripheral areas left and right. Three participants stated that it was uncomfortable to read distorted text or to work with skewed images. Furthermore, two participants argued that the linear zooming allowed for easier reading than the squared curved zooming. On the other hand, users reflected tha this can also have positive aspects:

> "The gaming experience would be really good with this effect" *(P11)*

and

> "It makes me feel closer to the screen, which is a positive thing" *(P2)*

Four participants argued that this window alignment technique helps to focus on the center of the screen and to keep an overview. These arguments are also represented in the preferred medium zoom level (see Figure 11.4).

To analyze if participants rated one CURVINGTECHNIQUE over the other in respect to the different ZOOMFACTOR we applied the Aligned Rank Transform
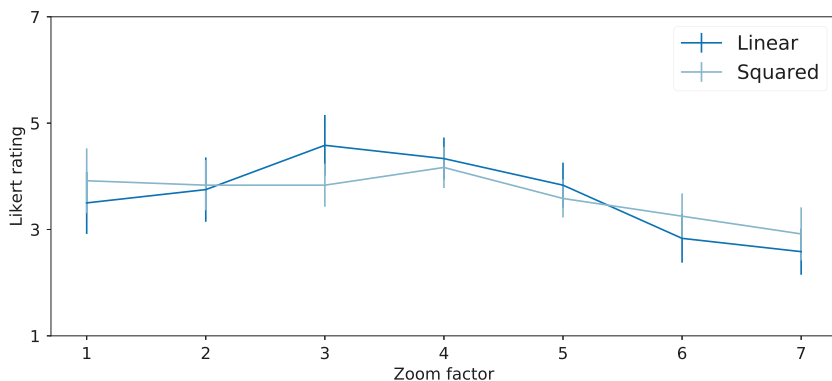
Figure 11.4: Rating of parameter values for *Curved Zooming*. The error bars are showing the standard error.

(ART) [270] procedure to the feasible RATINGs, used the ARTool toolkit[19] to align and rank our data. This allows us to conduct a two-way RM-ANOVA. Our analysis revealed a significant main effect for ZOOMFACTOR ($F_{6,143} = 4.4$, $p < .001$). However, no significant main effect on CURVINGTECHNIQUE ($F_{1,143} = 0.067$, $p = .796$). There was no significant two-way interaction between CURVINGTECH-NIQUE × ZOOMFACTOR ($F_{6,143} = 0.634$, $p = .701$). We further conducted post hoc tests using a Wilcoxon signed-rank test with a Holm-Bonferroni correction. None of the comparisons were statistically significant ($p > .05$).

Side Pane Navigation:
Six participants stated that the *Side Pane Navigation* helped keep track of changes in several windows. Participants also argued that it was easier to keep an overview:

> "[*Side Pane Navigation*] works great for multitasking" *(P11)*

P6 explained that he appreciated that he was not required to recall the positions of single windows.

Participants had different opinions about mouse cursor jumps. While P6 strongly welcomed the reduced cursor travel, P2 stated that the jumps were not intuitive and were irritating. Most participants acknowledged having 10 windows as thumbnails in one column (see Figure 11.5), and four participants argued that the

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[19] http://depts.washington.edu/madlab/proj/art/index.html last accessed: 21-08-2017

Side Pane Navigation required too much space. Furthermore, P3 mentioned that the *Side Pane Navigation* moved the focus point to the left, which required more head movement.

We further conducted a Friedman test of differences among the window count. However, Friedman's test rendered a χ^2 value of 6.836 which was not statistically significant ($p = .145$), see Figure 11.5.

Window Spinning:
Participants rated *Window Spinning* most useful (see Figure 11.3). Six participants argued that this helped to keep focus:

"[*Window Spinning*] is good to keep windows organized" *(P4)*

Participants further stated:

"Windows can be ordered as they would be one group on screen [and then moved entirely]" *(P6)*.

The *Window Spinning* is particularly helpful when switching between different tasks frequently. The participants were able to move multiple windows in the focus area at once, resulting in less head movement. P3 explained that he liked multiple separately movable areas. This allowed content to be explored in multiple windows on the upper half of the display while combining the gained
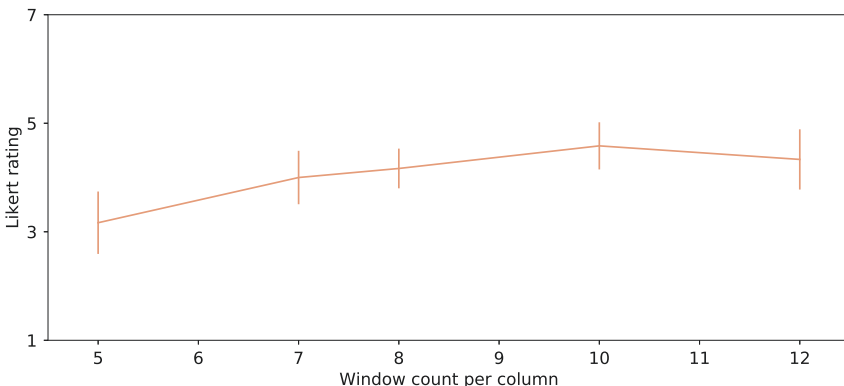
Figure 11.5: Rating of parameter values for *Side Pane Navigation*. The error bars are showing the standard error.

information into a text document in a window in the lower half of the display. Three participants mentioned it could be difficult to oversee the relation between area and window. This was particularly challenging with more than two areas. Hence, participants preferred two areas over one or three. Participants had no negative comments about *Window Spinning*, maybe because it looked like the classical KDE Desktop if the *Window Spinning* interaction is not used.

We statistically compared the rating of one, two and three spinning bands $M = 5.3$ ($SD = 1.4$), $M = 5.58$ ($SD = 0.8$), and $M = 3.75$ ($SD = 1.7$) respectively. We further conducted a non-parametric Friedman test of differences among the spinning bands. However, Friedman's test rendered a χ^2 value of 5.209 which was not statistically significant ($p = .074$). However, the descriptive statistic suggests that two spinning bands are optimal.

Window Groups:
Participants rated *Window Groups* less useful than *Window Spinning* and *Side Pane Navigation* (see Figure 11.3). The concept behind *Window Groups* was well known to the participants. Hence, four participants assumed that this was the natural adjustment of virtual desktops for LHRDs. Similar to when using virtual desktops, participants would use *Window Groups* to classify different tasks they were working on, for instance one participant stated:

> "[I would group] windows which belong to each other logically, for instance to accomplish one specific task" *(P2)*.

In particular, P8 would use this for office work. Overall, participants perceived grouping windows to be intuitive. Participants did not mention any criticism or possible improvements.

11.4 Discussion and Conclusion

In this chapter, we have presented four novel window alignment techniques for LHRD workplaces synthesized from related work and their evaluation. Based on our inquiry, we can observe that well-explored window alignment techniques for desktop environments are not automatically applicable for LHRDs. The results show that users of LHRDs appreciate window alignment techniques with enhanced support for window management. Thereby, managing the user's focus and attention is the key challenge for such window alignment techniques. The feedback related to *Curved Zooming* and *Side Pane Navigation* shows that

breaking well-established techniques was not appreciated by participants. Despite the fact that the participants described *Curved Zooming* as more immersive and supporting focus better, they were disturbed by the distortion. In the case of *Side Pane Navigation*, some participants were confused by the abrupt jumps of the mouse cursor and did not appreciate the shorter mouse movements. Consequently, future interaction techniques for LHRDs should consider that task immersion, arrangement, visibility and legacy issues need to be balanced according to the task before the user.

Participants argued that *Side Pane Navigation* lowered the need for recalling the window positions. This would allow users to draw more attention to the actual task, instead of on the positions of windows. However, if windows are arranged linearly or without spatial meaning, users would not utilize the posibility of LHRDs to relate information spatially on display. Kirsh [122] described the human ability to arrange information with spatial meaning a one key aspect to successfully explore information.

Participants preferred window alignment techniques which resembled traditional desktop patterns i.e. *Window Spinning* or *Window Groups*. Both window alignment techniques were perceived as providing additional support without changing the well-known UI behavior. In particular, *Window Spinning* was appreciated because it allowed switching focus without reordering all windows and the underlining structure when switching focus. This shows that legacy issues are likely to prevail when performing tasks which are already commonplace when, possibly, users transition to LHRDs. Due to this, augmenting existing window alignment techniques appears to be an effective way of designing window alignment techniques for LHRD-Interfaces used for office work. In contrast, for scenarios which are not adequately supported through desktop setups, related work shows that radically novel window alignment techniques are beneficial.

The small number of participants and the setup of a controlled lab study impacts the results of our study. For future development, more detailed user feedback is needed, preferably collected in a field study. However, even with a small number of participants, we were able to identify several improvements for future investigation and development.

We conclude that novel GUIs for LHRDs have to support a transition from classical desktop GUIs to new paradigms facing larger display spaces. Thereby these interfaces should enable users to work with familiar patterns and offer novel patterns at the same time.

Chapter 12

Reading Applications

Extended display space offers the chance to design novel representations for information. Data with an inherent spatial meaning, like maps, enable ease in utilizing the advantages of LHRDs. However, GUIs for interacting with data without a natural spatial meaning, require a careful design process. Today, we see well-designed viewing applications for eBooks and PDF documents for small displays such as smartphones and tablets. Such applications are also available for desktop-sizeed displays. However, there is little work on document viewing on LHRDs, albeit page-based documents being one of the most important information sources. These documents have commonly more than 100 pages [5]. Furthermore, users work with multiple documents in parallel. As described in the vision in Section 2.1, one central work task is and will be to make well-informed decisions. The information required for the decision making is often available as text-based documents. Digital functions such as search and highlight functions support knowledge extraction from digital documents already today. In contrast, paper-based documents have the advantage that pages can be easily rearranged and visually aligned [189]. Now, LHRDs have the potential to combine these two advantages and enhance the process of knowledge work. Additionally, document viewers for LHRDs could enable users to explore documents in different body postures. This might help users to stay engaged over a longer period.

Since ancient times, text documents, including also artwork and figures, have been designed for page-based layouts. With the invention of printing technology, page-based documents have become commonplace and are an essential element of office environments. Over thousands of years written books had been the

only way to store and access knowledge at a later point in time. With libraries societies have created places to provide and large amounts of knowledge. With the description of the Memex, Vannevar Bush [38] envisioned a device to compress all books and easily access them. Today, most documents are digitally accessible. Hypertext allows providing fast access references to related documents. In particular document types such as Hypertext Markup Language (html) or electronic publication (epub) provide more freedom than page-based layouts and hand over more responsibility for the layout to the rendering application. At the same time digital documents lack tangibility [189] and challenge culturally well-established ways of knowledge communication. The transformation from printed documents to digital and interactive knowledge providers is an ongoing research topic in human-computer interaction [191].

A large number of documents still make use of the structuring element of page-based layouts and present content in page-defining file types such as PDF. All publicly available PDF viewers present documents either linearly arranged or in a grid layout. Thereby, the use the advantages of large display spaces is inefficient. We explore how PDF viewers can present page-based documents on LHRDs and utilize the full display space, where the user can see several pages at the same time and visually compare and relate content on multiple pages. Thereby, there is a potential to support extracting information out of digital documents. To create a consistent scenario, we focus on reading scientific literature. This limits users' requirements to a smaller set of functionalities, while still allowing us to illustrate the advantage of LHRDs for document viewers.

This chapter is based on the planned publication: L. Lischke, M. Altmann, M. Hurler, A. Bernhardt, P. W. Woźniak and A. Schmidt. Enhancing Document Exploration on Large High-Resolution Displays.

12.1   Related Work

In this section, we discuss previous work on document management and reading applications. Thereby, we focus particularly on supporting insight gaining through spatial arrangements. Document navigation is a central task in understanding complex contexts. In the project Data Mountain, Robertson et al. [206] explored the use of 3D document grouping. Data Mountain allows storing web pages as thumbnails on a 3D layout grid, instead of traditional bookmarks. The comparison

between the traditional bookmark lists and Data Mountain revealed benefits such as faster document retrieval.

O'Hara and Sellen [189] analyzed reading on paper and screen. The authors highlight the structuring function of paper layout for text documents. Furthermore, on paper reading enables arranging pages spatially and juxtaposing variable pages. Hence, the authors conclude that document viewers require flexibility and control for spatial layouts. Furthermore, the authors argue that document viewers will benefit from larger display spaces, because of the ability to arrange content spatially. However, surprisingly little work has focused on designing document viewers for LHRDs.

Alexander and Cockburn [5] showed, that navigation is the most performed task in text editing and viewing applications. Hence, Cockburn et al. [43] followed the argumentation of O'Hara and Sellen [189] that scrolling increases the workload and can lead to negative user experience. To overcome this challenge, Cockburn et al. [43] implemented a space-filling thumbnail viewer to display a large number of pages at once. Based on the visualization technique of space filling thumbnails, Gutwin et al. [89], presented a document viewer for spatially-stable document overview. This document viewer provides an overview of whole documents without scrolling. The authors showed in a field study that this supports visual search and relocating particular content. The overview of documents enables fast visual search and communicate the position of tables, figures, and paragraphs well. In Chapter 4, we showed that users could perform fast visual search tasks, even on large surfaces. Hence, we assume that space-filling thumbnails and spatial-stable document overviews would benefit from LHRDs.

The work presented by Cockburn et al. [43] and Gutwin et al. [89] demonstrate the clear benefit of spatiality for document viewers. However, the arrangement of the single pages is not flexible and does not allow juxtapostion of arbitrary pages. Hornbæk Frøkjær [106] compared the usability of three document viewers. The results of their study with 20 participants showed that participants performed best when the overview of the document together with a detailed view was displayed. In contrast UI displaying only the text in a linear manner or fisheye mode was less effective. This points again, to the importance of providing an overview of the whole document as well as keeping the document structure.

12.2 Focus Group on GUI Design

To understand user expectations for document viewers for LHRDs, we conducted a focus group on reading applications for scientific documents. We invited five participants (one female, four male), through our campus mailing list and by word-of-mouth advertising to participate. The participants were aged between 26 and 30 ($M = 27.2$, $SD = 1.92$) and were students writing final theses. As compensation, we provided snacks and refreshments.

12.2.1 Procedure

After welcoming all participants, we explained the topic and procedure of the focus group. First, we asked them to read and sign the consent form granting the permission to audio and video record the session. We started the session with a period of 15 min to sketch, individually, ideas of how to use the display space for working with scientific documents. We provided pens and paper to sketch GUIs. To explore the design space widely, we did not define whether the application would be used in a seated scenario or when the user is standing and walking in front of the display. Furthermore, we made no determination about the input technique and followed participants assumptions.

Afterwards, we asked the participants to present and discuss their ideas in a 30 min session. Inspired by the design workshop conducted by Knudsen et al. [128], we prepared a whiteboard in the size of an LHRD. We asked the participants to imagine the whiteboard as LHRD. We ask them to assume that they are using an LHRD for working with related work to their work. To sketch the GUI design, we provided exemplary scientific publications and printouts representing related publications. All printouts were presented on paper in original size. We provided magnets to mount the papers on the whiteboard and board markers to draw additional GUI elements.

12.2.2 Results

All of the designed GUIs put the primary document in the center of the display space. When participants assumed a scenario where the user was standing in front of the display they preferred aligning all pages of the document horizontally over the whole display space. Thereby, the primary document would be presented
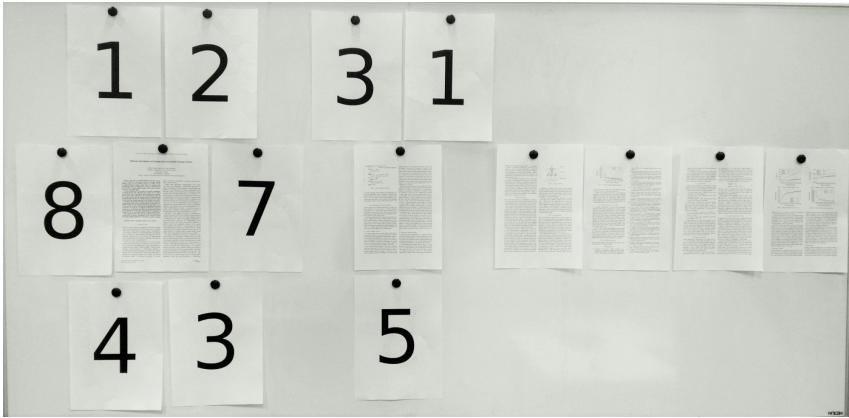
Figure 12.1: Sketched GUI design during the focus group session. The GUI presents the primary document aligned horizontally, with related documents displayed above and below.

at users eye height for comfortable reading. When a document contained more pages than the display space would allow the participants assumed horizontal scrolling. The space above and below the document would be used to display cited or related documents (see Figure 12.1).

For scenarios where the user was mostly sitting in front of the LHRD, the primary document would also be displayed in the center of the display. However, the pages would be aligned vertical, with two pages horizontal next to each other. Here, participants assumed vertically scrolling. The participants had different opinions about separating pages from the main document and inserting other pages in between for comparison of paragraphs. The disadvantage of separating particular pages would be that the overview over the full document would not be visible anymore.

Additionally, participants saw the need to add more functionality. This included functions to annotate documents and highlight text. Furthermore, participants asked for the possibility to view other content, such as web pages to compare content from a large variety of sources.
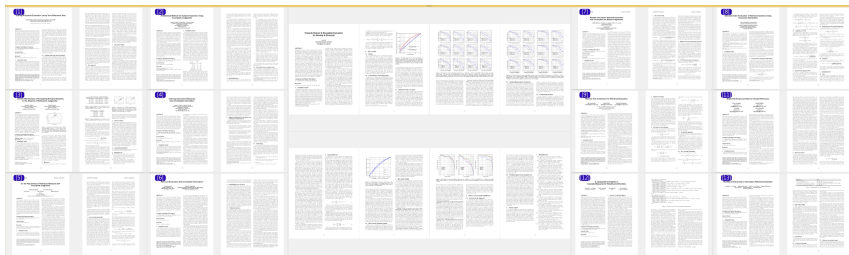
Figure 12.2: Screenshot of Prototype P1. In the centre area the primary document is viewed, while cited papers are displayed on the left and right.

12.3 Prototypes

Based on the results of the focus group we developed two working prototypes. Both applications were implemented in C# for Windows. For displaying the document pages of the PDF documents, we used the Adobe Acrobat Reader as Component Object Model (COM) component. The applications were optimized for our display setup, with a size of approximately 4×1.1 m, with a resolution of $12,960 \times 3840$ pixel.

12.3.1 Prototype P1

P1 displays the primary document in the center of the display (see Figure 12.2). Thereby, the document is displayed in a grid layout with two rows and four columns. If required the pages are vertically scrollable. This view requires ⅓ of the full application window. The left and the right ⅓ spaces are used to view related documents. Each side provides space to view the first two pages of six additional documents. Each of these document views can be scrolled separately. To open a document at one of these positions, the user performs a right click to open a dialogue to select the document. As a default, the application presents all cited publications.

12.3.2 Prototype P2

Similarly to P1, P2 displays the primary document in the center of the display (see Figure 12.3), but in contrast to P1, only ⅙ of the space in the middle of the
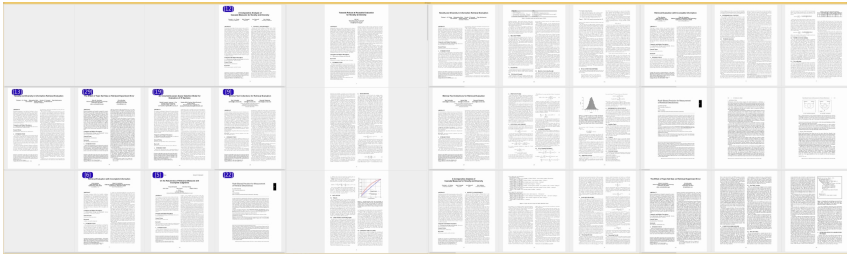
Figure 12.3: Screenshot of the Prototype P2. In the centre area the primary document is viewed, while previews of cited paper are displayed on the left. Additional documents are displayed on the right side.

display is used for this document. All pages of the primary document are aligned below each other. To navigate within this document, the pages are vertically scrollable. Next to each page of the primary document on the left-hand side are all front pages of the documents cited on this page displayed. On the right side of the primary document is space to open other documents. Users can have full access to the cited documents on the left side by dragging and dropping the first page to one of the six areas on the right side. These six document containers are displayed on ½ of the full display space. Each of the six document containers displays three pages of a document horizontally aligned.

12.4   User Study

In order to build an understanding of how GUIs for document viewing on LHRDs should be designed, we compared the two implemented prototypes to a state-of-the-art application, in this case, Mendeley. We invited 12 participants aged between 22 and 28 years ($M = 25.25$, $SD = 1.96$) through our campus mailing list and by word-of-mouth advertising. All participants received refreshments as compensation for their effort.

We designed three sets document related tasks each including four questions. These tasks were either solvable by skimming the primary document or browsing additionally documents. An example task was: "Name the heading of the sub-section." "Or count the number of Figures in the cited paper number 21." We randomized the combination of task set and prototype per participant.
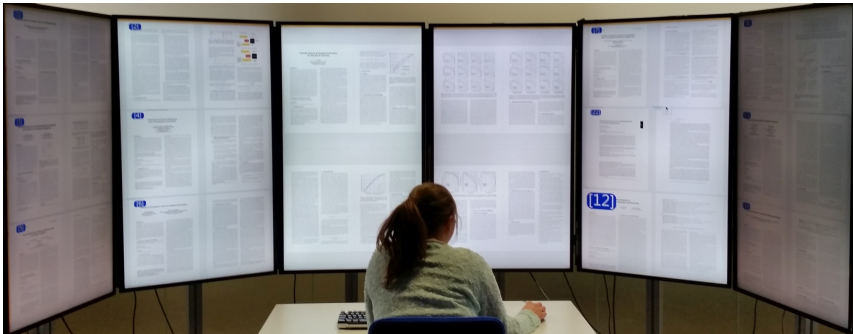
Figure 12.4: A participant is using Prototype P1 on the study apparatus.

Every participant used all applications on a 4.04 m wide and 1.1 m high LHRD. This display had a total screen resolution of 12960×3840 pixel. The LHRD was built out of six 50 in 4K Panasonic TX-50AXW804 screens aligned in portrait mode. To provide equal viewing distances, the screens were arranged in a semicircle in front of the desk (see Figure 12.4). A Microsoft Windows 8.1 workstation drove all six screens and executed the applications.

To compare the three applications, we measured TCT, perceived workload, measured by the raw NASA-TLX [93, 94] questionnaire, and usability rated on the System Usability Scale (SUS) [37] questionnaire.

After welcoming each participant, we introduced the purpose of the study, invited them to take a seat in front of the setup and asked them to read and sign the consent form. Afterwards, we presented all three applications and asked them to familiarize themselves with all three applications. As soon as the participant felt comfortable with all applications, we explained the tasks for the first application. We used a Latin-square order to vary the order of used applications to avoid learning effects. After performing all four task with one application, we asked the participant to rate the effort with the NASA-TLX questionnaire and the usability on the SUS.

12.5   Results

To compare the three applications, we analysed the measurements collected during the user study.

Task Completion Time (TCT)
TCT was shortest when participants used P1 ($M = 266.30\,$s, $SD = 78.46$), followed by P2 ($M = 328.58\,$s, $SD = 69.59$) and Mendeley ($M = 345.56\,$s $SD = 96.56$). A RM-ANOVA revealed no statistically significant difference between the applications in terms of TCT ($F_{2,23} = 2.682, p = .09$).

Perceived Workload (raw NASA-TLX)
The overall average workload was $M = 37$ ($SD = 18.35$). A RM-ANOVA revealed no statistically significant difference between the applications in terms of workload ($F_{2,16} = 0.28, p = .76$).

System Usability Scale (SUS)
The highest SUS rating had P1 ($M = 87.11, SD = 13.19$), followed by P2 ($M = 80.83, SD = 17.37$) and Mendeley ($M = 70.56, SD = 19.35$). A Friedman's test revealed no statistically significant differences between the three prototypes ($\chi^2 = 4.7647, p = .09$).

12.6   Discussion

Layout elements such as headings and paragraphs are important for structuring text documents. Physical pages provide further provide a structure to longer text documents. This element also plays an important role for digital documents and is transformed to a digital metaphor. O'Hara and Sellen [189] argued that the ability to sort and to spread physical pages supports the understanding process of printed documents. LHRDs have the potential to enable the user to spread digital documents on a large display space.

The quantitative measurements in our user study could not reveal statistically significant differences between the three applications. However, the results indicate that O'Hara and Sellen's [189] hypothesis that working with documents can be enhanced by larger display spaces is true. The ability to see multiple pages and documents simultaneously may support sensemaking. Furthermore, participants rated the usability of early prototypes for document viewers on LHRDs highly. This reveals the requirement of differed GUI style guides for desktop interfaces and interfaces for LHRDs.

Our prototypes use the available display space better than desktop applications (in this case Mendeley). In particular, P1 seems to provide a good relation of flexibility and guidance. In this work, we particularly focused on document viewers for scientific documents. This enables us to reduce the required flexibility

of the GUI. For general document viewers, there might be the need for other document layouts. To compare content on multiple pages, GUIs might need to provide the functionality to move pages individually on the whole workspace. However, this freedom could increase the complexity of the application. Due to this, providing a high usability might be challenging. Future work should in the next step conduct a larger user study to compare the prototypes. In a second step, the results should be generalized for document readers for LHRDs and other types of applications.

12.7 Conclusion

Through our design process, we developed two working prototypes for displaying scientific documents. In a user study with 12 participants, we were able to show that our P1 enabled users to extract relevant information faster than using professional tools designed for classical desktop setups. Additionally, participants rated the usability of P1 significantly higher than the usability of the professional tool Mendeley when working on an LHRD.

In future work, it will be important to understand how to utilize the advantages of LHRDs for document viewing in a large variety of use cases. The key challenge is to provide structured guidance to use the space efficiently and thereby enable relating information spread over multiple documents or pages.

V

CONCLUSION AND FUTURE WORK

Chapter 13

Conclusion

Throughout this thesis we have focused on interacting with LHRDs in work environments. This Chapter provides an overview and reflection of our research results. We follow the structure of the research questions and the thesis itself. The focused aspects are derived from the ACM SIGCHI Curricula for Human-Computer Interaction [101].

13.1   Summary of Research Contributions

As discussed in the introduction, humans have utilized physically large visual spaces for hundreds of years for accessing information and impressing others. With the success of graphical computing and due to technical limitations, work-flows have changed in such a way that they are suitable to perform on physically small visual spaces (i.e., desktop screens). This is, in particular, challenging for data exploration, sense making and decision making because for such tasks humans have to relate different and often complex aspects to each other. With advances in computing and display technology, we are now at the cutting edge where it will be soon feasible for many scenarios to build and use LHRDs. However, to build successful LHRD workplaces, well-suited interaction concepts are required. As presented in the introduction (see Chapter 1), research has early envisioned LHRD environments and showcased advantages. In the following, we show how this thesis extends this knowledge. In particular, we address the

following areas: 1) Current state and challenges for LHRD design; 2) Perception of visual content on LHRDs; 3) Enhanced input techniques for interacting with LHRD; and 4) GUI design for LHRD.

RQ1 - Current state and challenges for LHRD design

In Section 2.2, we presented interviews with interaction designers and information visualization experts, focusing on information visualization and LHRD setups. We learned that most designed interfaces are for public settings, and businesses often avoid the risk of investing in interfaces for LHRDs in office environments. Here research can identify benefits and design opportunities of such interfaces and reduce the business risks. Furthermore, in practice, direct touch is the most common input technique for LHRDs. Here research, presented in this thesis (see Part III) can offer a larger diversity.

The identified challenges in designing LHRD environments are also reflected in their daily use. In Section 2.3, we reported on a contextual inquiry in a public transport control room. Control rooms are one of the few environments where LHRDs are commonly used today. Through our inquiry we learned that staff members would appreciate even more display space then they have available today. This supports the general motivation of this thesis, that LHRDs can enhance work processes and data exploration in office environments. However, we observed input challenges and unexpected GUI behavior at the control desks. Users reported the loss of the cursor, long distances between the cursor and desired targets and misinterpretation of input focus. Furthermore, visual content did not always appear at the expected position and was thereby hard to recognize. Additionally, arranging content on large spaces creates large effort. This shows that more research on input techniques for LHRDs and designing GUIs for LHRDs is required.

RQ2 - People interacting with LHRDs

Two fundamental questions for building LHRDs efficiently are how the visual resolution influences the interaction (RQ2.1) and how the physical space influences the interaction (RQ2.2). In Chapter 3, we showed that users could distinguish between all tested (up to 359 PPI) resolutions and rate the media quality inline, although we could not show any influence of the visual resolution on the task performance. However, every study session was shorter than an hour. This raises

the question of whether the perceived low media quality could cause fatigue and thereby affect the task performance over a longer period of time (e.g. a full work day). Finally, designers of LHRD setups have to balance higher display resolution, increasing the perceived quality and higher technical complexity and thereby higher costs.

In Chapter 4, we focused on RQ2.2 and compared text-based visual search tasks on various display sizes. The results showed that humans could manage to interact with large amounts of visual data without being overwhelmed. Furthermore, we showed that users perceive more physical effort when the display is wider than 2.4 m. This might be caused by more required body movement. When designing office environments, this should be considered to motivate users to perform more body movement. On the other hand, there is the risk that too much-required movement could cause undesired fatigue. These findings should be expanded by a principle model of visual search on large surfaces. This would help to predict how long users need to recognize specific visual elements and could influence future GUI design for LHRDs.

The physically large display spaces are predestined for multiuser interaction. Multiuser scenarios can either be collaborative, individual working or competitive scenarios. In Chapter 5, we focused on how multiple users utilize the space in front of an LHRD (RQ2.3). The results of a lab study showed different movement patterns depending on the scenario. When users collaborated, they utilized the full display space and they stood close together when competing. This should be considered when designing GUIs. When users collaborate, all content should be distributed over the full display space. In contrast, in competitive situations, all users need to be able to see relevant information closely together. Furthermore, the different scenarios also influence how the space around the LHRD should be designed. In competitive scenarios, the users aim to get a better overview of the content through stepping back, and increased body movement. Hence, the physical space around the display should be larger when users are competing.

RQ3 - Advanced input techniques for interacting with LHRDs

We learned from RQ1, that common desktop input techniques are not necessarily well-suited for input on LHRDs. In practice, the mismatch of the visually focused area and input focus, visual loss of the cursor as well as long distances between cursor and target position seem to be challenging.

Utilizing the user's gaze position to overcome these challenges is a promising approach. In Chapter 6, we focused on the question of whether eye-tracking based interaction can enhance pointing on LHRDs (RQ3.1). We showed that repositioning the cursor to the current gaze position (MAGIC pointing) can lower the target acquisition for distant pointing targets. In particular, when the user is unaware of the target position, MAGIC pointing supports the target acquisition. However, when the user was aware of cursor and target position, we were not able to show an advantage of MAGIC pointing over mouse pointing. Hence, we can conclude that eye-tracking based interaction can enhance pointing tasks when the user has to search for the cursor or the target visually. Additionally, the presented user studies identified technical challenges for eye-tracking-based interaction techniques. We used a head-mounted eye-tracker, which observed both eyes with infra-red cameras. Both cameras partly occluded the field of view, which could have distracted the user and cause more head movement. Furthermore, we observed that the performed head movement required to utilize the full physical display space affected the calibration of the eye-tracker. Both issues require more future research in sensing technology.

Besides utilizing a user's gaze point for interaction, mid-air gestures could help overcoming interaction challenges with LHRDs. Hence, we focused in Chapter 7 on designing mid-air gesture sets for interaction with window managers (RQ3.2). Through user-defined gesture studies [269], we designed two gesture sets, enabling users to interact on large spaces through mid-air gestures and perform fine-grained, high precision input with the mouse. Gesture commands for changing the input focus and repositioning the cursor enabled the user to focus more on the content than the input technique limitations. Furthermore, these gesture sets have the potential to motivate the user to more physical movement while interacting with content displayed on an LHRD. Thereby the usage of these gestures could have a positive well-being effect [80]. Additionally, we analyzed the influence of the legacy bias [179] on the proposed gestures. The results show that there is only a small influence of knowledge about other input techniques. Future work should evaluate these gesture sets regarding efficiency and UX.

When multiple users interact with one LHRD simultaneously different interests and requested views can lead to potential conflicts (see Section 2.2). In Chapter 8, we focused on the question of whether LHRD-tablet combinations can enhance multiuser interaction (RQ3.3). Combining an LHRD with multiple tablets offers the possibility of using a shared common view on the LHRD and a personal working space on the tablet. The results of the user study show that such a shared interface can lower the perceived workload for data explorations. Currently, all research prototypes for LHRD multidevice interaction use tailor-made interfaces

with custom interaction patterns. For future application designs, it will be important to define design guidelines for multiuser multidevice interaction including LHRDs. From a technological point of view, current web-technology, used for the implementation of Pac-Many, presented in Chapter 5 and for the CIMPLEX VIS Framework[20], allows to build such applications easily.

The physical size and the visual resolution of LHRDs can hold the full visual attention of the user. To utilize these attributes of LHRDs optimally, the user should not be distracted. Hence we explore how input techniques can provide non-visual feedback to enhance input (RQ3.4). In Chapter 9, we contribute the design of a first working prototype of a variable movement resistance slider for discrete data input. Furthermore, we showed through a controlled lab study that variable movement resistance feedback supports value input when the user cannot look at the input device. When no visual attention is required on the input device, the user has more capacity to focus on the actual content on display. Based on this contribution, we see three directions for future research: First, the design of our slider input device is driven by technical constraints. Here it would be interesting to analyze various form factors. For more complex input multiple sliders could be integrated into one device. However, such an input device is not yet developed and tested. Second, with this Chapter, we provide a starting point and evaluate only one pattern of movement resistance feedback. However, the hardware design of our apparatus allows flexible programming of the provided feedback. Hence, it would be interesting to design and compare various feedback patterns. Third, we have demonstrated a performance increase on an abstract pointing task, it would be valuable to evaluate this input and feedback method with a real-world task. Here, integration into the CIMLPEX VIS Framework would be interesting, because small value adjustments can cause a relevant effect on disease spread models, for example.

RQ4 - Designing well-suited GUIs for LHRDs

The analysis of today's design approaches and the usage of LHRDs show the requirement of novel design guidelines for GUIs for LHRDs.

In Chapter 10 we identified though a participatory design process how possible users of LHRDs envision their LHRD work environment (RQ4.1). An LHRD working desk has the single screen elements symmetrically aligned. Some participants argued further for areas that allow standing in front of the display. They

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[20] www.youtube.com/watch?v=pkAmdQPKVZQ

envisioned using these areas mostly for creative tasks or discussing displayed information with others and only on these areas would they want to be able to perform touch input.

In a second step, we asked participants in the participatory design process how they would use the available display space. They assumed they would mostly work focused in the center of the display, while additional information would be displayed in the left and right peripheral areas. Personal communication tools would be placed in the area above the focused working area, where incoming notifications could be checked quickly but not be in the field of view when working. This would allow users to navigate physically between different tasks. In Chapter 11, we analyzed proposed GUI design patterns for window manager on LHRDs as a working prototype in a lab study. Here, the results showed that participants prefer techniques which provide additional functionality without breaking traditional concepts. However, the approach to build on existing window concepts has the limitation that fundamentally different approaches are not respected in the design process, but might have a higher potential.

In Chapter 12, we finally explored how applications can benefit from extended display space. We explore this on the example use case of a page based document reader for scientific publications. First preliminary results indicated that the ability to see multiple documents simultaneously enhance the sense making process. Future work should aim to explore more use cases where LHRDs are beneficial and define general guidelines for GUIs for LHRDs.

Summary

To utilize the advantages of LHRDs for knowledge work, UIs have to support the user to manage the abundant display space. This is relevant for input techniques and GUIs. Input techniques should be aware on which area of the display the user is focusing. Additionally, input techniques should enable users to move while interacting. Also, GUIs should support users to arrange the display space in a meaningful way. The extended display space allows spreading content spatially. This enables the user to get deeper insights.

Chapter 14

Future Work

This thesis provides a set of contributions towards improving interaction with LHRD workplaces. While conducting the research, we identified various challenges beyond the work presented here, which we will describe in this Chapter. We follow the structure of the thesis and cluster the future research challenges in the following areas: First, required technological improvements. Here the required research effort might be not in human-computer interaction (HCI). Second, research opportunities for understanding human behavior interacting with LHRDs. Third, challenges for input techniques and finally opportunities for designing and evaluating GUIs.

14.1 Required Improvements in Technology

Even though complexity and costs for computing power and displays increased massively over the last decades, building an LHRD is still not possible out of the box. These setups require continuous maintenance, which increases the effort. This is particularly challenging when relative resolutions comparable to desktop displays or even mobile devices are pursued. Only further increase in computing power and advances in display technology will enable the breakthrough of LHRDs in office environments. We assume that technological advances to build LHRDs for various settings will be reached within the next decade.

For novel input techniques, sensor technology has to be improved further. In Chapter 6, we showed that the performance of MAGIC pointing is highly depending on the calibration of the eye-tracker. Through the large size of the display the user rotates the head frequently, which affects the accuracy negatively. Here high precision eye-trackers which are effortless to calibrate and comfortable to wear are required. These will allow users to perform pointing tasks efficiently and move the input focus for other input devices intuitively, and can support the system to guide the users to unrecognized content.

14.2 Modelling Human Vision, Perception, and Movement

In Chapter 3, we showed that users perceive various visual resolutions differently. However, we were not able to show an effect on task performance. In combination with study results by Mayr et al. [175], we argue that the visual resolution might influence the performance when working longer with one resolution. While working with a low resolution for one hour might be not an issue, a full working day with a low resolution might create high fatigue. However, designing a controlled lab study to analyze the influence of the visual resolution, is challenging. First, an artificial task which can be solved in several hours will create a high demand for the participants and thereby create noise in the collected data. Furthermore, the effort of participating in a controlled user study like this would be extremely high in comparison to typical studies conducted in HCI. Hence, we would recommend a less controlled in-the-wild study approach. Participants could be invited to perform their daily work on a specific display with a defined visual resolution for a longer period of time. After the period of time, another resolution could be tested. To compare these various sessions, the display usage and performed input could be logged. Furthermore, we would ask participants to rate their experience on surveys. The visual resolution of the human eye together with the distance between the user and the display creates an upper boundary for the required resolution. However, a detailed understanding of the influence of resolution below this upper boundary would allow us to build more efficient LHRDs.

To gain a deeper understanding of how display size effects performance and behavior, it would be valuable to conduct a study with comparable study design as described above. In contrast to using the visual resolution as independed variable here the display size would be used as independed variable. Furthermore, modeling visual search for various stimuli on LHRDs would allow predicting how

long users need to detect visual elements and could influence future GUI designs. For smaller displays, Gutwin et al. [88] presented comparable work. A detailed understanding of the influence of the physical size of visual space would allow identifying the optimal display size. Here, we would expect that the optimal size depends on various factors. First, physical setup will influence the size of the optimal setup. When the user can move in front of the setup, the trade-off between physical navigation and fatigue could be most important. Second, the number of users working separately, together or competitive influences the optimal size. Finally, the displayed content impacts the optimal size of the display.

LHRDs enable users to work comfortably in various body postures. Changing the posture or even moving while interacting can be possible. This could lead to more body movement while working and thereby improve user's well-being and health [80]. However, this leads to two open research opportunities for HCI research. First, interfaces should motivate or trigger users to move while working on an LHRD without annoying or distracting the user. Second, when the user is working in various body postures, the distance and the viewing angle to the display might change. Furthermore, not all input techniques are equally suitable for all body postures. Hence, interfaces need to detect changes in the body posture and to adjust visual representation and activated input technique.

14.3 Challenges for Input on LHRDs

In Chapter 6, we showed that MAGIC pointing can enhance pointing tasks on LHRDs. Other eye-tracking based interaction techniques for LHRDs are under-explored so far. The system knowledge of where the user is looking allows an approximation of what content has been recognized by the user. The system could use this knowledge to guide a user's attention while interacting. This would help to ensure that the user does not dismiss important information. Additionally, the system could summarize recognized content for later review. This could help the user to gain a deeper understanding of complex relations in large data sets. Furthermore, combinations of eye tracking-based interaction with second device interaction seem to be promising, and only a few publications have started to explore this area (e.g. [245]). Thereby, content could be selected through user's eye gaze, and complex manipulations could be performed on second screen devices. The content selection through eye gaze could also be used to select subsets of the data presented on the LHRD for later work on the private device.

In Chapter 7, we presented two gesture sets for interacting with window managers on LHRDs. Future work should implement robust gesture recognizer and evaluate these gesture sets. Therefore, well-suited measurements have to be identified. Work by Rico and Brewster [205] could be a starting point to define the measurements. Besides analyzing TCT and ER, ease of use and fatigue should be considered. Furthermore, it should be analyzed how these gestures motivate more movement while working. We assume that well-designed mid-air gestures as additional input technique have the potential to keep the user more engaged and more active during the data exploration. This could have a positive impact on the data exploration itself, as well as on user's well-being.

In Chapter 9, we showed that variable movement resistance feedback improves discrete value input when no direct visual feedback is provided. Future work should explore how this could be used for exploring complex models, where small parameter changes can have a large effect on the simulation. As application would an exploration tool such as the CIMPLEX VIS Framework[21] be well suited. Here it would be possible to analyze the presented slider device in combination with a real-world task. Furthermore, extended input devices with several physical sliders and various feedback functions could be tested. We assume that additional haptic feedback on the input device helps to compare visual results of models with different parameters. This will help various stakeholders to make use of complex scientific models for sense making.

14.4   Challenges for GUIs for LHRDs

In this thesis, we explored how window managers for LHRDs should be designed and which additional functionality is required (see Part IV). Thereby we identified possibilities to enhance the interaction with LHRDs for common office tasks. The advantage of this approach is that users feel familiar with the fundamental concepts and metaphors. This enables users easily to adapt their work environment to an LHRD workspace. However, we did not show that the metaphor of windows, in general, is optimal for LHRDs. It is possible that other concepts and metaphors support the user better to utilize the advantages of LHRDs. Here an open design exploration is required to identify optimal metaphors. Additionally, more applications for various data exploration and office tasks for LHRD should be designed and evaluated to show possible benefits of LHRDs. Here, in particular, the ability to relate content spatially and display different views is fundamental.

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[21] `www.youtube.com/watch?v=pkAmdQPKVZQ`

The challenge in designing and evaluating applications for LHRDs is that neither prototyping nor evaluation methods for LHRDs-applications are developed yet (see Section 2.2). Prototyping LHRD applications is always challenged though limited prototyping space. Either prototypes need to be miniaturized or they require large spaces. On the one hand, these large spaces are often not available. On the other, miniaturized prototypes are often not able to communicate functions or appearance. Evaluating GUIs for data exploration on LHRDs is challenging, because adequate tasks utilizing the full display space are highly complex and require more time than average lab study sessions in HCI. Through this high complexity, the task performance is also highly dependent on the participants. Hence, for the success of LHRDs, we need to develop well-suited prototyping and efficient evaluation methods.

In the last few years, the industry has released advanced augmented reality (AR) and virtual reality (VR) headsets. The availability and quality of these headsets triggered an interest in these headsets in research and commercial products. Both AR/ VR applications and LHRDs have the advantage to provide large digital views for the users. The ability to present abundant virtual visual spaces with lower technological complexity questions the advantages of LHRDs. Research shows an increasing interest in enhancing office tasks in AR and VR (e.g., [84, 127]). Hence, both research areas focus partly on the same challenge of how to design abundant visual information space. However, we hypothesize, in line with Jacucci [112], that current VR solutions lack in enabling social interaction. Also, AR solutions provide the challenge that collaborating users have to rely on the technology that the content they see is the same. Hence, we assume that LHRDs will outperform AR and VR solution in collaborative settings in the next decade. To prove the hypothesis, future work should compare AR and VR solutions to LHRD solutions for office tasks, data exploration, and sense making.

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Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12. Juli 2011, § 8, Abs. 2 Pkt. 5.)

Hiermit erkläre ich an Eides statt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

Stuttgart, den

Lars Michael Lischke

Lars Lischke
Interacting with Large High-Resolution Display Workplaces

Large visual spaces provide a unique opportunity to communicate large and complex pieces of information; hence, they have been used for hundreds of years for varied content including maps, public notifications and artwork. Understanding and evaluating complex information will become a fundamental part of any office work. Large high-resolution displays (LHRDs) have the potential to further enhance the traditional advantages of large visual spaces and combine them with modern computing technology, thus becoming an essential tool for understanding and communicating data in future office environments. For successful deployment of LHRDs in office environments, well-suited interaction concepts are required.

In this thesis, we build an understanding of how concepts for interaction with LHRDs in office environments could be designed. From the human-computer interaction (HCI) perspective three aspects are fundamental: (1) The way humans perceive and react to large visual spaces is essential for interaction with content displayed on LHRDs. (2) LHRDs require adequate input techniques. (3) The actual content requires well-designed graphical user interfaces (GUIs) and suitable input techniques. Perceptions influence how users can perform input on LHRD setups, which sets boundaries for the design of GUIs for LHRDs. Furthermore, the input technique has to be reflected in the design of the GUI.