Towards Mobile Multi-Display Environments

A Design Exploration
Using Projection-Screen Devices

by

Jessica Rebecca Cauchard

A dissertation submitted to the University of Bristol
in accordance with the requirements for award of the degree of Doctor of Philosophy
in the Faculty of Engineering, Department of Computer Science

June 2013

Word count: ca. 65 800

ABSTRACT

Thanks to miniaturization of display technologies, the recent years have seen the emergence of a new generation of mobile devices containing multiple displays. They are identified as Mobile Multi-Display Environments (MMDEs), building on previous work in the field of Multi-Display Environments. This doctoral work presents the first exploration and classification of this research space. In particular, I identify the case of projection-screen MMDEs, mobile devices containing both projection and screen technologies. The dissertation address the following thesis:

> *Providing re-configurability of displays' relative placements in the heterogeneous MMDE and providing interaction using kinaesthetic cues and spatial memory, users can manage complex and highly cognitively charged tasks as well as complex information management across multiple displays.*

To support this thesis, the dissertation answers research questions around the possibility of synchronous use of the displays given their inherent technological and physical disparities; the optimal relative positioning of the displays; the use of the mobile-projection unit as a secondary display and the projection spaces available around the user.

The contributions of this work are multiple, the main contributions are: case studies evaluating and demonstrating the usefulness of synchronous use of the multiple displays; design guidelines for MMDEs; novel interaction techniques and scenario of use; a mathematical model of perceived depth in the mobile environment; and a series of prototypes and experiments that have been designed to support this work.

The dissertation shows that multiple displays can be used synchronously to improve the device's capabilities in heterogeneous projection-screen MMDEs so users can perform complex tasks across both displays. This dissertation's vision is that mobile devices with multiple displays can become as useful and as widespread as their fixed MDEs.

The results presented in this dissertation further the knowledge of MMDEs.

DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE:.........................

ACKNOWLEDGEMENTS

It takes a long time and an incredible amount of energy to complete a PhD and I feel changed from this experience. I probably would not be here today, the person I am, if not for the incredible people who have helped me through the completion of this dissertation. I would like to use this section to thank those people.

Above all, I would like to thank my family. Maman, Papa, Vous m'avez appris à être curieuse, vous m'avez donné le goût des sciences, du savoir et de la connaissance. Vous m'avez appris à poser des questions et à essayer de comprendre le monde sous tous ses aspects. Vous m'avez appris à travailler dur, à me surpasser et à ne jamais baisser les bras dans l'adversité. Vous m'avez toujours dit qu'il fallait que je travaille pour moi et pas pour les autres. Vous m'avez laissé suivre mes rêves et aidé pour qu'ils se réalisent. Cette thèse n'existerait pas aujourd'hui sans tout cela. Merci d'avoir fait de moi une jeune femme indépendante et d'avoir cru en mes rêves les plus fous. Merci pour votre amour incommensurable et votre soutien permanent. Jérémy, tu es doté d'une incroyable générosité et d'un amour sans limite. Tu as toi aussi toujours respecté mes choix. Merci d'avoir toujours été là pour moi. Je veux que tu saches, que c'est aussi grâce à toi que je suis qui je suis. Je te souhaite que la vie t'amène tout au bout de tes rêves !

I would like to thank my PhD advisors Pr. Mike Fraser and Pr. Sriram Subramanian. Mike and Sri, I would like to thank you both for co-advising me during my PhD. Those years have been quite a ride! You have been there for me when I needed you and you left me alone when I needed space. You respected my choice and helped me follow my ideas. Your continuous support and trust means so much to me. Thank you for everything.

I would also like to thank my PhD examiners, Dr. Kirsten Cater and Pr. Enrico Rukzio. Thank you very much for taking the time to read my dissertation and for your valuable comments that helped shaping this dissertation into its final version.

I would like to address a special thank you to Pr. Nishan Canagarajah, Dean of the faculty of Engineering. Nishan, you have been most supportive in all of my initiatives. We are very lucky at the University of Bristol to have such a positive and enthusiastic person at the head of the Faculty of Engineering. Many thanks for your support.

I obviously would like to thank my colleagues at the Bristol Interaction & Graphics lab and in particular: Izdihar (Izzy) Jamil, Ben Long, Han Teng, and Anne Roudaut. A special thank you to Matt Sutton, Peter Bennett, and Timo Kunkel for helping me with the illustrations in this dissertation. I will miss so many memorable and fun moments from being with you, and I would like to particularly thank those of you who have been my family during my first year in Bristol.

Thank you to the fantastic admin and support staff. Thank you for being there all the time and making things so easy for us. A particular thank you to Andrea, Becky, Caroline, Gina, Hayley, Rachel, Ruth, Sally-Ann, Simon, Rob, Syed, and Tracie. I would not want to forget our wonderful porters, whose smiley faces always instantly made me happy to get into the building.

I had the very special opportunity during my PhD to intern overseas at Microsoft Research Asia in Beijing. I would like to extend all my thanks to my mentor there Dr. Xiang Cao and also to Dr. Desney Tan for giving me this opportunity. Xiang, I really enjoyed working with you and especially brainstorming and bouncing ideas off each other. You are a brilliant scientist and have so much to share. I hope we get the chance to work again together in the future. Many thanks to my brilliant colleagues at MSRA for all those surreal times we had together in Beijing: Dr. Darren Edge, Gunhyuk Park, Teng Han, Pr. Hong Tan, Pr. James Landay, Jesse Kim, Jiawei Gu, Jizhou Yan, Joan Savage, Jun Kato, Dr. Koji Yatani, Luke Vink, Pedro Nakazato, Roger Ibars, Sergio Paolantonio, Sunny, Summer, Weili Shi, Xiaowei Dai, Xin Yu and Yang Zhao.

I have also had the chance to spend some time at the DFKI German Research Centre for Artificial Intelligence in Saarbrücken. I want to say a big thank you to Markus Löchtefeld for collaborating with me on projects, I am very glad we had a chance to work together! Many thanks to Pr. Antonio Krüger for welcoming me in your lab and to Joahnnes Schöning, Sven Gehring, Matthias Böhmer, Maria Isk and Lina Ruiz for making my stay in Saarbrücken so much more enjoyable.

I now would like to thank my mentors. Many thanks to Dr. Daniela Romano for giving me "the research bug" and pushing me into a research path. Many thanks to Dr. Elizabeth Massey, my MentorSET mentor who was one very special encounter. Beth, you helped me decide whether it was the right time or not for me to start a PhD and you helped me make the right choice. I would also like to thank my current mentor, through the MentorNET programme, Dr. Demetrios Karis who has been incredibly supportive during the writing up period.

I now would like to thank two women who have played a special role in my life. Ma Mamie, Andrée Ginette Mielnicki et ma grand-tante Nelly Mielnicki. Vous avez des parcours de vie incroyable, vous êtes toutes deux des femmes fortes et formidables. Vous avez été déracinées et peu de gens peuvent imaginer les parcours que vous avez traversés. Vous êtes restées fortes et humbles. J'espère accomplir autant que vous deux dans ma vie.

At last but not least my incredible friends: Sarah Norris, you are the most amazing friend someone can have. You have been there from beginning to end and it means the world to me. Leslie Sanz, you have known me before and now, after the PhD, we have been through a lot those last few years and we are still going, we climbed a mountain together (literally) and I cannot wait for our next adventure! Sid Rahman, you know how much you helped on an everyday basis, thank you for being so supportive and patient with me. Noam Adani, Bristol would not have been the same without you. Thanks for all those nights you picked me up late from the lab and the ones you convinced me to go out and enjoy life a bit more. Omar Alvi, you are a true friend and you have been from the start. Thanks for supporting me all those years and for believing in me.

Very special thank you to my amazing friends who were there is both fun and difficult moments, to the ones who lived with me, hosted me, endorsed me, came out for drinks and dinners with me, travelled with me, picked me up from work, helped me move home and will always be just a phone call away. Thank you: Christelle Bellot et ses enfants, Daniela Woolfe, Diana Cabrera & Tiago Guizzo, Elizabeth Bales, Jean-Edouard Canton, Jennifer Marlow, Kati & Garry Perez as well as Hinda and Noa, Leah & Dovid Usiskin and their children, Lisa Cowan, Marianthy Riga & Christos Papadopoulos, Melissa & Moshe Baron, Mike McCarthy, Nick Chen, Nathan Yebgui, Orianne Videau, Sarah Esper & Tristan Picamal.

Another special thank you to my friends in Beijing. My experience in China was amazing thanks to you all: Danielle Goldberg, Dini and Shimon Freundlich and their children, Eva Cohen, Huo Yan & Zheng Zhang, Jinjin Ge, Luce Alon Gutierrez and her wonderful family – thank you so much for having me, Michal Tarazi, Michal & Shlomo Freund, Mickael Tanzer, Miriam & Nosson Rodin and their children, Rivka Inglis, Sarrine Bigio, Toby Wilansky & Rui Zhang.

A final special thank you to Anke Brock, Dong-Bach Vo & Elizabeth Bales who have been so present in the last few week of writing up my PhD.

Last but not least, I am so grateful to Nick Chen, Lisa Cowan, Anne Roudaut, Omar Alvi and Sarah Norris who have been proofreading this dissertation.

Partial funding for this work was provided by EPSRC (grant number EP/G058334/1) and MobileVCE (www.mobilevce.com) as part of the User Interactions for Breakthrough Services research program.

DEDICATION

To free education

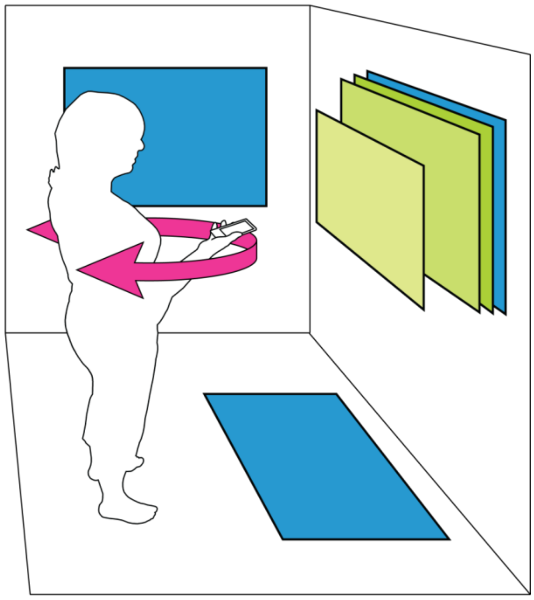
& freedom in education

Jessica Cauchard

CONTENTS

LIST OF FIGURES

List of Tables



Chapter 1
INTRODUCTION

Today is an exciting time for mobile computing research. Mobile phones are not just phones anymore; they are smart platforms to collaborate, share life events, check what is happening around us, find restaurants, and even subway stations. The more sensors are being embedded into phones, the more capabilities the devices offer; and many now also use their phone as camera or in-car GPS instead of having a dedicated device. As those new functionalities arise, displays have become essential to provide users with feedback and input strategy for complex tasks. While the first mobile phones did not have or need a screen, displays have become an established component of today's smartphones.

From the first mobile phones to until a few years ago, the trend was to create devices as small, thin and light as possible, with as many embedded functionalities as possible. Yet, as users long for viewing and interacting with an increasing amount of data on their mobile device; and as usages evolve towards looking at images, maps and watching videos; the trend has reversed and screens have started to increase in sizes and quality, resulting in larger handheld devices.

Another approach to show extra information on a mobile device, other than increasing the screen's size, is the multi-display strategy. It consists in appending an additional display, such as a secondary screen, onto the existing device.

These devices are characterized as Mobile Multi-Display Environments (MMDEs) and are defined in this thesis as:

Any mobile computing environment containing more than one display

Actually, in order to manage the large quantity of on-screen content, some manufacturers and researchers have adopted a multiple-screen strategy. For instance, Nintendo DSi [Nintendo 2011] or Codex [Hinckley 2009] both present multi-display handheld devices for which the screens can be folded one over the other in a clamshell manner to not increase the size form factor when carrying the device.

Finally, another way of incorporating additional display space but without increasing much the device's size is to add a mobile-projection unit. This is now possible, as projectors have now been miniaturized into tiny physical units. They started in 2006 when Symbol Technologies [Stern 2006] presented the first miniaturized projection engine. Since then, many mobile devices, such as phones, cameras, and even tablet PCs; have been fitted with embedded mobile projectors. Mobile projectors present remarkably unique properties as they provide substantial additional display real estate while adding minimal weight and bulkiness to the physical device. They therefore provide a great alternative to increasing screen sizes to expand the available display space.

The reason why MMDEs were created is intrinsically the same for which MDEs have been developed. The concept of MDEs is presented by Hutchings and colleagues [Hutchings 2004a] and the research is initially identified as "Multimon" – for multiple monitors –, it consists in adding one or several secondary monitors to the desktop environment to alleviate problems users were encountering in managing small space to interact with increasing amount of data. Research show that multiple displays allow for users to be more productive, especially for highly cognitively loaded tasks [Czerwinski 2003]; to separate information, applications and tasks across displays; and even to multi-task, by separating work into primary and secondary tasks that are in turn divided across primary and secondary displays [Ringel 2003].

Nevertheless, as the displays embedded on mobile devices have very specific properties due to their portable form factor; most of the existing research in MDEs cannot be directly applied to the mobile environment. For example, the MDE community presents guidelines to how the displays need to be positioned in the environment to better the user experience [Su 2005]. In projection-screen MMDEs, the displays are fixed on the physical device and cannot be re-oriented to follow those guidelines. Designers therefore need to build different systems to manage the alignment of the displays. Another example is that in a MMDE, as the device is potentially constantly moving, the interaction technique needs to be adapted to the current context of the device; whereas in a fixed MDE, the context does not change. In conclusion, although MMDEs have intrinsically been created with the same concept in mind for which MDEs have been developed, MMDEs do not correspond to a mobile version of MDEs and therefore MMDEs cannot be studied as such.

While MMDEs are still at their dawn and have not yet been comprehensively studied, this dissertation envision is that in the future, users will be able to use MMDEs as they use MDEs. Users will be able to realize tasks of the same complexity as they do in the fixed setting; and this through the affordances brought on by the multiple displays.

1.1 SCOPE

This research work considers that three types of MMDEs exist, when considering display composition, as they can be created out of multiple screens, screens and projectors, and multiple projectors. In this dissertation, I specifically designed and studied MMDEs comprising both screen and projection capabilities, which will be referred to as projection-screen MMDEs.

The recent emergence of mobile devices: such as phones, tablets, and cameras that integrate a mobile projector fit within the projection-screen MMDEs category. While those devices are classified as “personal devices”, projection-enabled devices are often considered as devices to support multiple users collaboration using the projection as a shared display. Embedding a mobile-projection unit therefore modifies the affordances and usage of the mobile device and brings to light new considerations such as privacy issues with projecting personal information but also heralds new opportunities to collaborate and share information [Cao 2007].

Those devices are especially interesting as they present a small form factor with a large display real estate. A true interest of such devices lies into using the displays synchronously to exploit the large display real estate to manage, monitor information and multi-task as with their MDEs counterparts. Nonetheless, projection-screen MMDEs are currently being used one display at a time depending on the task. For example, the projector can be used to watch a video or share images while the screen is being used as a traditional phone or camera screen; therefore losing the advantage of having multiple displays and extra screen real estate on a single device.

In spite of the recent research interest in such devices, very few pieces of research actually propose to use the displays synchronously [Greaves 2008, Winkler 2012b]. This is likely due to the current design of the projection-enabled mobile devices where the projection and the screen physical placements on the device do not allow for the displays to be looked at simultaneously and therefore to be interacted upon at the same time.

It is therefore crucial to comprehend how the projection fits within the ecology of a mobile device. This dissertation aims in particular at understanding whether the heterogeneous displays of a projection-screen MMDEs can be used synchronously to help the user achieve complex tasks. It identifies several design issues such as the alignment of the displays, their angular and depth separation as well as their different needs in terms of interaction technique.

1.2 APPROACH

At this time, MMDEs and especially projection-screen MMDEs are being used with the displays in isolation from one another, using either the screen or the projector depending on application and context. This research aims to understand the viability of MMDEs; and whether the multiple displays can be used synchronously. In order to address the challenges encountered in heterogeneous projection-screen MMDE, my approach is divided into two focus areas.

The first focus area studies specific issues with heterogeneous projection-screen MMDEs and more specifically in terms of displays' organisation. This aspect is crucial as for example, if the projection beam is orthogonal to the screen; the user is not able to look at the projection while interacting with the screen. This is especially damageable as, for now, most interaction with the projection involves using the touch screen. The second focus area observes which spaces around the user can be used to interact with the projection. Indeed, while the screen is just being held in the user's hand, the projection can virtually project anywhere and it is critical to identify which interaction zones around the user are suited for displaying projected content and interacting with it.

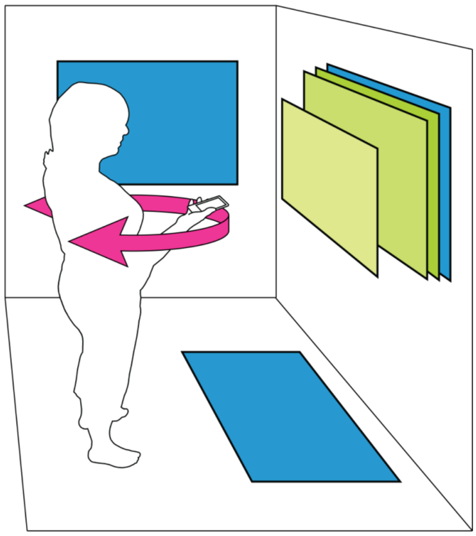


Figure 1.1: Scope of the research: this dissertation investigates various projection spaces around the user: projection on the front, floor, and side (blue), the physical space around the user's body (pink) and the space in depth between the user and the projection surface (green).

I combine this two focus areas, each piece of research studying a specific aspect of the MMDE will also explore one of the identified interaction zone around the user. The various interaction zones are defined in Figure 1.1. This dissertation focuses on the single-user scenario. As shown in this research work, MMDEs are fully applicable to single-user activities and to the scenarios that are addressed in the dissertation. It is therefore critical to understand the challenges of using MMDEs for a single user before investigating research questions due to multi-user interactions and collaboration. This research work will benefit MMDEs' users and enhance their experience when interacting with their personal mobile devices.

One key aspect that was utterly clear and identified early on in this research; is that the traditional arrangement of the mobile-projection unit at the top of the device, displaying content at a 90° angle compared to the screen and currently preferred by manufacturers; is not suited to interact with the screen and the projected content synchronously. A mobile steerable projector was then designed and prototyped; it allows re-arranging the normally fixed configuration between the screen and the projection space. An exploratory study was ran using this prototype to verify if different screen-projector arrangements would be better suited for different tasks.

The literature review on MDEs shows that displays have to be positioned at a certain distance and angle to avoid negative impact on users such as visual separation effects. The second piece of work studied those effects for heterogeneous projection-screen MMDEs where the displays are also separated in depth – as the projection will always appear further away than the screen –. In particular, three possible projection areas were explored (referred as front, floor and side projection and represented in blue in Figure 1.1). It was then investigated whether the projection could be used as a secondary display to the phone as it is the case with multiple displays usage in MDEs. At the same time, a spatial technique was asserted to interact with the MMDE, moving the device along the pink arrow in Figure 1.1. Finally, this dissertation considered exploiting the gap between the user and the projection surface to project information in depth using 3D projection techniques. This would consequently limit the amount of physical projection surface necessary, while projecting the same amount of content, layered in depth (green area in Figure 1.1).

This dissertation also considered back projection, ceiling projection, and of course the emerging area of on-body projection. Yet, it was decided not to integrate them to this research although some of the related work overlaps. Indeed, one can consider that for back projection, since the user has to turn around to see the projection, the condition is therefore similar to front projection that is already covered in this work. While ceiling projection is typically used when the user sits down on an inclinable seat, or lies down and looks at the ceiling, it is an uncomfortable position in the mobile setting so it was decided to leave it outside the scope of this dissertation. Finally, since this research explores visualization and interaction around the user, while on-body projection presents interesting research avenues, it considers different challenges than the ones considered within the scope of this dissertation.

1.3 THESIS AND CONTRIBUTIONS

1.3.1 Thesis

This thesis argues that multiple displays on a single-device can enhance the capabilities of the device and offer a synchronous usage of the multiple displays. It justifies that this is only possible providing that the displays are positioned within specific angles and physical separation between one another and on the assumption that they offer re-configurability depending on context. This work shows that new scenarios of interaction can be created, drawing on the advantages of adding projection capabilities to a mobile device. Single-device MMDEs are asserted as beneficial for single-user use and extremely flexible for use in different scenarios. Finally, this work addresses the different spaces around the user that can be used to interact and display information from a heterogeneous projection-screen MMDE.

In order to address this, the following thesis statement is proposed:

> *Providing re-configurability of displays' relative placements in the heterogeneous MMDE and providing interaction using kinaesthetic cues and spatial memory, users can manage complex and highly cognitively charged tasks as well as complex information management across multiple displays.*

Throughout this dissertation, I will provide support for the thesis statement by presenting my contributions and answering the following four research questions:

- **Research Question 1:** Is synchronous use of the displays effective for mobile multi-display environments?
- **Research Question 2:** How does the relative physical position between the multiple displays affect usability, and what are the optimal relative positions?
- **Research Question 3:** How can the mobile-projection unit be used as a secondary display on a mobile device drawing on the concept of secondary display in fixed multi-display environments?
- **Research Question 4:** How can the space between the user and the projection space be enhanced with additional information?

1.3.2 Contributions

1) A case study that demonstrates the viability of heterogeneous MMDEs for synchronous *use of the displays*

Currently, heterogeneous MMDEs are typically designed for asynchronous use of both displays; therefore losing the opportunity of having additional screen real estate on a small device. The work verifies that a complex task that requires careful attention on both displays is feasible. It is also found that some arrangements of the displays are better suited then others, such as when the screen and projection are in the same field of view. Moreover, users performances are not hindered when the device is handheld; therefore proving the viability of such devices in a fully mobile setting.

2) Design guidelines to design MMDEs in terms of display orientation and the use of virtual workspaces

A mobile steerable projector is prototyped to explore various alignments between the screen and the projector. Results show that different alignments are needed for different contexts of use. For example, when the user is moving, they prefer to project on the floor, as there is no constant wall space available. However, the angle between the screen and the projection depends on how the device is being held by the user – horizontally or inclined –. Various alignments are compared for tasks that demand synchronous use of the displays. Empirical study results show that it is less cognitively demanding for the user if both displays are in the same field of view. Throughout this dissertation, design guidelines for MMDEs are gathered, based on empirical results.

3) A novel interaction scenario using kinaesthetic cues to interact with a MMDE and get additional content displayed around the user

There are two aspects to interacting with a MMDE; the first one consists in changing the content being displayed while the second one focuses on interacting with the content itself. A prototype was created for which users can change the content being displayed on both the screen and the projection simply by moving the device around their body. Results show that for a task that necessitates accessing multiple applications; using kinaesthetic cues over traditional touch screen interaction significantly increased performance – fewer errors and faster task completion time –.

Moreover, 75% of the participants preferred using the projection and screen simultaneously, over the screen only condition. Lastly, users were able to use up to four interaction spaces around their body.

4) A mathematical model of perceived depth for mobile 3D projection

In order to exploit all of the space around the user to project information, the work explored using the gap between user and projection space to project information in the available depth. Because of the lack of previous research work on the perception of depth in 3D mobile environments, a new mathematical model of perceived depth was derived from existing models of perceived depth in fixed stereoscopic 3D environments. The model is verified; and presents over 95% accuracy in a user study.

1.3.3 Summary

The combination of the contributions uncovers that the hypothesis I posited was correct. Actually, Contribution 1 exposes that some arrangements of the displays are better suited for highly cognitively loaded tasks while Contribution 2 shows that in heterogeneous MMDEs, different alignments between the displays suit different context of use. I deduce that the device needs to present reconfigurable display alignments to adapt to the different tasks and contexts. Contribution 3 demonstrates that using kinaesthetic cues and spatial memory empirically significantly improve applications and workspaces switching in MMDEs. User Experience was moreover qualitatively improved in the MMDE over a single screen condition. This proves that by combining kinaesthetic cues and spatial memory, users were able to perform complex tasks and manage information across the multiple devices.

This dissertation presents an exploration of MMDEs, it demonstrates the potential of MMDEs, and especially heterogeneous projection-screen MMDEs. This dissertation shows evidence that multiple displays vastly enhance the usages and affordances of existing mobile devices. Mobile devices' users are then provided with new platforms to perform complex tasks on small devices. This doctoral work corresponds to the first evidence that MMDEs are as powerful as MDEs in the fixed computing environment. Since mobile devices accompany us at all times and increasingly help us with any everyday tasks, mobile users can expect MMDEs will become ubiquitous and even more powerful as mobile projectors become lighter and brighter.

1.4 DISSERTATION WALK-THROUGH

Chapter 2: Background: This chapter presents a review of the literature providing a research context to this dissertation's work. It first describes latest work in the field of mobile projectors. It then investigates existing research in MDEs, including bringing a mobile device to a fixed environment. The following section defines the space of Mobile MDEs and presents existing research work. A classification of MMDEs is then presented in section 2.3.1. This background section is used to inform the design of MMDEs in the following chapters.

Chapter 3: Exploration of MMDEs through Various Display Alignments: In this chapter, the validity of MMDEs is investigated for various alignments between a screen and a projector, in a mobile steerable projection-screen prototype. After detailing the design of the prototype, an exploratory study for different scenarios of use of the projection-enabled mobile device and for the various display arrangements is presented. Finally, various interaction techniques are investigated depending on the relative alignment of the displays.

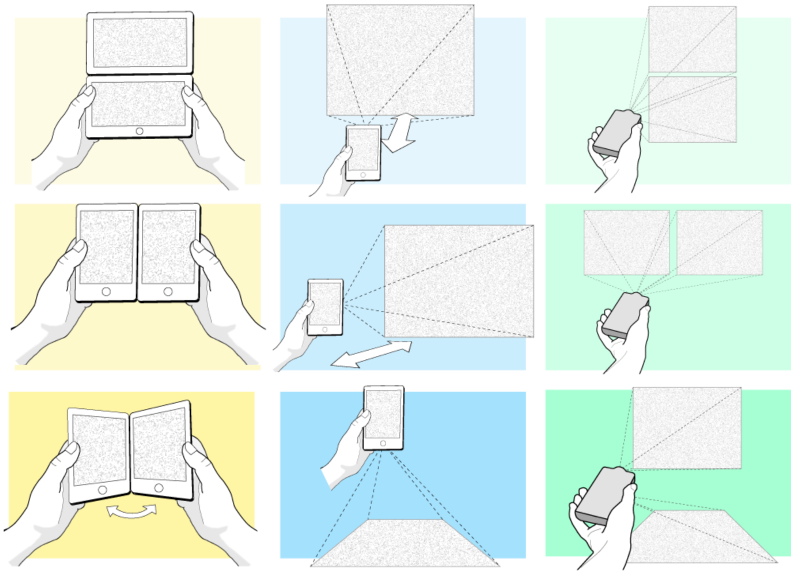
Chapter 4: Alignment and Visual Separation Effects in MMDEs: This chapter introduces a user-study, which evaluates whether the negative effects of visual separation present in fixed MDEs exist in Mobile MDEs and under which circumstances. Three alignments between the screen and the projector are being presented with a projection in front, on the floor or on the side of the user. The results allow drawing design guidelines on the relative position of the multiple displays.

Chapter 5: Secondary Displays in MMDEs: The Case of Virtual Workspaces: This chapter investigates using kinaesthetic cues as well as the space around the user's body to display different information on the MMDE. The use-case chosen for this study is the use of multiple virtual workspaces using the projection as a secondary display. This use-case was chosen as it corresponds to one of the traditional usage of secondary displays in MDEs and so this work can be inspired by previous research work in MDEs.

Chapter 6: Depth and Stereoscopic 3D for Mobile Projectors: This chapter extends the projection space available to the user by taking advantage of layering projection spaces at different depth between the user and the projection space. The chapter presents a new geometrical model for perceived depth in mobile stereoscopic 3D environments based on the existing model of perceived depth for fixed settings. A first user-study determines the validity of the model while a second user study investigates the usefulness of the model in the handheld environment and draws conclusion on interaction design.

Chapter 7: Discussion and Conclusions: This chapter summarizes the work presented in this dissertation. It describes how each research question was answered and reflects on the results obtained. It concludes on the work done, advances the contributions of this dissertation to the research community, and presents a future work section proposing new avenues for research.

Part of the research work presented in this dissertation was published in peer-reviewed conferences and journals, and presented at peer-reviewed workshops. The full list of publications is available in APPENDIX B: Publications. All related video figures are included on the DVD located in the back cover of this dissertation.



Chapter 2
BACKGROUND

The notion of Mobile Multi-Display Environment (MMDE) is being developed within the work presented in this dissertation. This chapter provides an understanding of the research and state-of-the-art that this dissertation is drawing upon. MMDEs are being developed and put to use in many research areas, with literature spanning from the fields of Mobile, Wearable, Ubiquitous, and Pervasive Computing to Augmented Reality. This chapter divides the research covered into four sections: Mobile Projectors, Fixed and Mobile MDEs, and an exploration of the similarities and disparities between fixed and Mobile MDEs.

As presented in the Introduction chapter, the prototypes developed in this dissertation are MMDEs composed of both screen and projection capabilities a.k.a. projection-screen mobile devices (see APPENDIX A: Glossary). The first section of the literature review (2.1) will then present related work on Mobile Projectors. Despite being single-display devices, mobile projectors inform design choices and interaction techniques with mobile projected environments as the ones seen in projection-enabled MMDEs. Therefore, this work can be used as a foundation to designing projection-enabled and more specifically projection-screen MMDEs. It is important to note that this section includes the literature on mobile projection technology only and does not take into account fixed projection systems as they present different characteristics from the ones met in MMDEs.

The second section (2.2) is dedicated to Fixed Multi-Display Environments as they provide an understanding of the challenges encountered by having multiple displays in an environment. This section describes how MDEs have improved computing and identifies challenges with environments containing both homogeneous and heterogeneous displays in terms of visualization and interaction. Environments where a mobile display is brought onto a fixed MDE are also considered.

The third section (2.3) concentrates on defining the MMDE research space. The field is divided into two types of MMDEs, the ones composed of multiple single-display devices that are brought together; and single multi-display devices. Each subsection presents corresponding existing solutions and designs for both homogeneous and heterogeneous MMDEs (see APPENDIX A: Glossary). The section presents a classification of MMDEs based on display type and mobility.

The final section concludes by presenting a list of challenges for designing Mobile MDEs given their similarities and disparities with fixed MDEs.

The research reviewed in this chapter covers the general area of MDEs in both fixed and mobile settings. More specific literature review on steerable projection, proxemics, visual separation, and 3D projection is available at the beginning of the corresponding chapters (Chapters 3 to 6).

2.1 MOBILE PROJECTORS

This PhD dissertation is interested in MMDEs with a focus on projection-screen MMDEs. This section is dedicated to provide an understanding of mobile projectors, which corresponds to mobile devices with a projection as unique display (Figure 2.1). Mobile projectors provide a low-cost portable solution compared to traditional fixed projectors. They can be used instead of a fixed projector, taking advantage of the physical properties of the mobile device. They can be plugged onto phones and run on battery while fixed projectors usually require being connected to a PC or laptop and need constant power supply. Mobile projectors have therefore been heralded as a replacement to fixed projectors, especially in developing countries where access to expensive technology is scarce and power is not available at all time. Mobile projectors are also known as standalone, handheld, ubiquitous or pico-projectors (See APPENDIX A: Glossary). Devices containing a screen in addition to the mobile-projection unit are studied in section 2.3: Mobile Multi-Display Environments. This current section defines how mobile projectors work, for what applications they are most useful, and how to interact with such devices. This literature helped inform the design of projection-enabled MMDEs, which are discussed in the MMDE section of this chapter (2.3).

Figure 2.1: Pico Pocket V3 projector. In order to project at a chosen height, the projector needs to be specifically oriented towards the projection space. The mobile projector can, for example, be rested on a pile of books (Left) or fixed on a tripod (Right).

This section covers the different devices, technologies, applications, and interaction techniques corresponding to the mobile projection space.

2.1.1 Devices and Technology

– " For the first time we have the potential to design portable devices whose display size is not constrained by the size of the device itself." p.2 [Buxton 2004] –

In 2003, Symbol Technologies present one of the first laser mobile projector, a revolution for mobile projection [LaserFocusWorld 2003]. The prototype unit they present measures 28.8 × 16 × 10.8mm and enables projecting images and videos always in focus with a resolution of 640 x 480 pixels and 16 levels of grey. They already envision using this projector as a mobile solution for professionals to project from their laptop or PDA. Around the same time, Reho and Impiö patented the first LED mobile projector [Reho 2003]. Their primary idea is to have an external display for a "data processing device" (e.g. PDA) in order to study information without having to handle the physical device itself. Reho and Impiö envisage many other types of devices that the mobile projector could be plugged into in order to get various types of information. Their vision has been supported by future development in embedded projection technology. The same year, Bove and Sierra present a prototype for an embedded personal projector using vertical cavity surface emitting lasers [Bove 2003].

Technology

There are currently three major technologies operating mobile projectors: Digital Light Processing (DLP), Liquid Crystal on Silicon (LCoS) and Laser-Beam Steering (LBS) [Markets and Markets 2010]. While this background section will not deeply study the technical and functioning aspects of each technology, readers should keep in mind that the various mobile projectors inherit their capabilities depending on the technology they are built upon.

There were around 10 models on the market in 2008 against over a hundred models in 2013 [PicoProjector-Info 2013]. The first available models had very little brightness, contrast, and could only project against a light background in a dark environment. Current models have much higher brightness and contrast (by a factor of 10), and resolution has more than doubled for comparable device sizes. Figure 2.2 presents the evolution of available models in terms of brightness since 2008 and Table 2.1 below presents a classification of the technical characteristics of the presented models using data from [Projector Central 2013].

N#	Brand	Model	Tech.	First ship	Contrast	Brightness (Lumens)	Resolution (max)	Size (in mm)	Weight
1	Optoma	PK101	DLP	Jan 2009	1000:1	11 ANSI	640*480	10*50*100	100gr
2	MiLi	HI-P60	LCoS	Jan 2010	100:1	10 ANSI	640*480	40*70*150	100gr
3	3M	MPro150	LCoS	Jan 2010		15 ANSI	1280x768	20*60*130	200gr
4	Microvision	ShowWX	Laser	Mar 2010		10 ANSI	848*480	20*60*120	100gr
5	Samsung	SP-H03	DLP	Jun 2010	1000:1	30 ANSI	854*480	40*70*60	200gr
6	Aiptek	V50	DLP	Nov 2010	2000:1	50 ANSI	854*480	20x70x130	200 gr
7	Vivitek	Qumi Q2	DLP	July 2011	2500:1	300 ANSI	1600x1200	30*160*100	600 gr
8	Aaxa	P4	DLP	Nov 2011	2000:1	80 ANSI	1280*800	30*70*140	400gr
9	Asus	P1	DLP	Dec 2011	2000:1	200 ANSI	1600x1200	30*120*130	400gr
10	Optoma	PK320	DLP	Feb 2012	1000:1	100 ANSI	1280*800	30*120*70	200gr
11	Brookstone	HDMI Pocket	DLP	July 2012		85 ANSI	854x480	20*100*100	200gr

Table 2.1: Characteristics of the mobile projectors presented in Figure 2.2 using data from [Projector Central 2013]

From Figure 2.2 and Table 2.1, one can see the incredible technological advances that have been made in the past few years. The brightness and contrast are much higher for the same weight and size of device. Nonetheless, slightly bigger and heavier projectors can have much better technical characteristics such as the Vivitek Qumi Q2, item 7 on the picture. This projector is for example equipped with full stereoscopic 3D projection capabilities. Some of the recent mobile projectors even include additional functionalities such as the PhoneSuit LightPlay [PhoneSuit 2013] that runs under Android OS and propose WiFi and internal memory storage amongst other functionalities.

Looking at the trend, it is expected in the near future to see better quality projection for the same form factor, and maybe even some premises of outdoor projection.

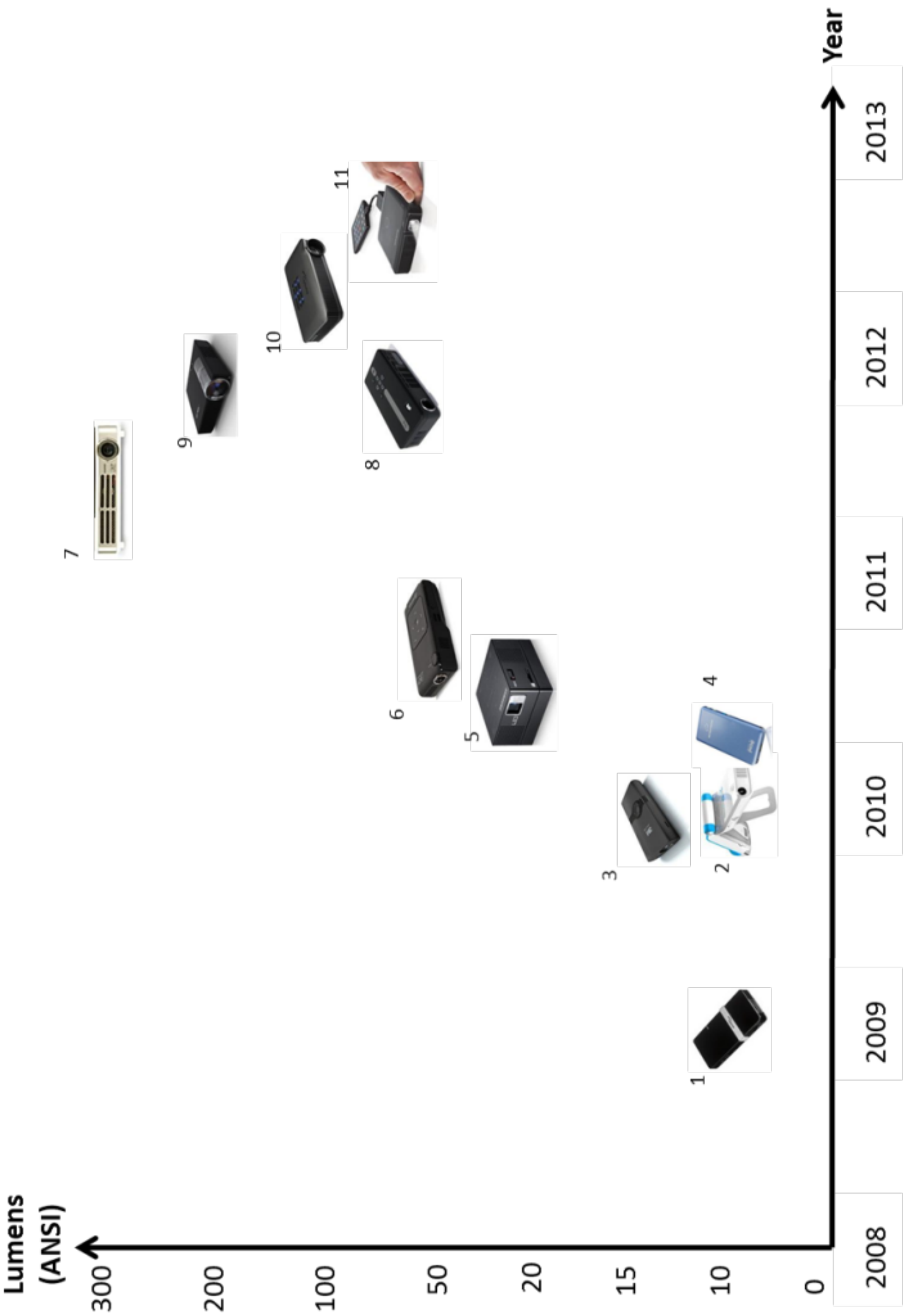


Figure 2.2: Representation of the evolution of mobile projectors in terms of brightness (in Lumens) across time since 2009. The projectors' specifications are detailed in Table 2.1.

Handheld mobile projected display

Raskar et al. propose the first “portable” projector iLamps [Raskar 2003] envisioning a near-future with even smaller and lighter mobile projectors. iLamps is a self-configuring projector that adapts the display shapes to the projection space offering to display on flat surfaces but also on 3D objects. The projector is equipped with a tilt-sensor and a camera to sense its environment where fiducials markers are attached to the objects of interest. Later on, Dao et al. present a semi-automatic real-time calibration technique for handheld mobile projectors [Dao 2007]. Their technique allows keeping the shape of the projection stable and always rectangular using an embedded 3D accelerometer sensor and a digital compass, therefore allowing for an infrastructure free correction. The proposed technique is especially useful as handheld mobile projectors are subject to hand jitter but also to keystone effect when the projection space is not perpendicular to the projection beam. Applying this technique will allow a steady and non-distorted projection.

Characteristics

The main characteristic of mobile projectors over more traditional projectors is that they are portable. This means that they have a smaller form factor and that they are lighter. Most of them are also battery powered when the vast majority of projectors need to be plugged in to a main power supply. There are nonetheless trade-offs for being portable in that the brightness, resolution, and contrast are much lower than with a fixed projector. At this point, it is difficult to use a mobile projector in a non-light-controlled environment, such as outdoors in the daylight.

There are nonetheless major advantages to using projection technology in a mobile device. Firstly, the display size is bigger than the device’s size. Before miniaturized projection, mobile devices were constrained to an input/output area dependent on the size of the device. Now, the device can have a small form factor and still offer a large display area. Secondly, the projection can take any shape, thanks to its transparent boundaries; and any size, as it is not constrained by the device physicality. Additionally, virtually “any” surface can be transformed into a projection area. While users often think of projecting on a white flat surface to get the best image quality out of the projection, projecting on various materials, colours, and shapes actually increases the capabilities of the projection. For example, users can decide to project on their hand, on a surrounding object, or choose to get a distorted image for its aesthetic properties. Depending on the desired effect, one can decide to project on a projection surface rather than on another.

Classification

Rukzio et al. present a classification of mobile projectors in term of their conceptual use [Rukzio 2012]. They present four classification categories: *Peripheral*: self-contained independent device that can be used as secondary or external display; *Handset-integrated*: mobile-projection unit embedded into an existing mobile device with a screen – therefore creating a MMDE; *Wearable*: mobile-projection unit attached to the body; and *Stand-alone*: self-contained independent device that is used on its own and not as a secondary display. While their classification contains all devices, this section presents a different strategy to classify those devices that better suits this dissertation. It starts by presenting the literature on Mobile Projectors in section (2.1) and the literature on MMDEs in section (2.3). Therefore, devices considered as *Peripheral*, *Wearable,* and *Stand-alone* are presented in this section (2.1) and *Handset-integrated* mobile projectors in the MMDE section (2.3).

2.1.2 Applications

Initially mobile projectors have been presented as secondary displays to mobile devices such as laptops and mobile phones. They have been heralded as useful to present data at meetings, share pictures, and watch movies from a mobile device using a large display. Nevertheless, in the past few years, the research community has seen them being used for a wide variety of applications ranging from entertainment to military usage. This section presents the different types of applications for which mobile projectors are being used and focuses, in particular, on single device scenarios.

In Rukzio et al.'s classification [Rukzio 2012], interaction techniques for personal projection are divided into *input* and *output*. The output section includes *anywhere display*, where the user can virtually project anywhere; *spotlight interaction* – or magic lens –, where the projection is used as a window onto a larger virtual world;

augmented reality, when augmented real world objects; and *multi-projector interaction*. While multi-projector interaction is discussed in the MMDE section (2.3), this section concentrates on applications for a single mobile projector. Those applications correspond to one of three visualisation techniques defined by Rukzio et al. and illustrated in Figure 2.3.

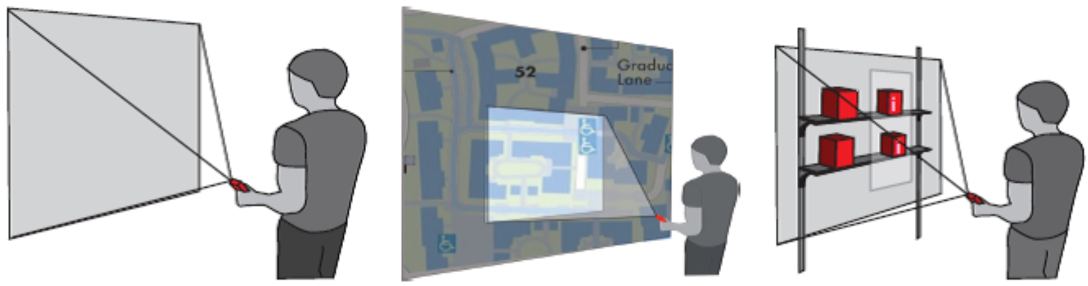


Figure 2.3. The mobile projector visualization technique corresponds to an anywhere display (Left) where all of the content is being projected; to a spotlight interaction technique (Middle) where the projection acts as a window onto a larger virtual world; and to an augmented reality system (Right) where the content is projected to augment physical objects around the user. (Illustration reproduced from [Rukzio 2012]).

Augmented Reality

A particularly relevant scenario is to use the projection as an augmented reality display, as first proposed with iLamps [Raskar 2004] to, for example, augment objects in a warehouse. Similarly, mobile projectors have been used to augment a fuse box [Beardsley 2005], books [Tomitsch 2012], paintings in museums [Kim 2010], bookshelves and supermarket shelves [Löchtefeld 2010], physical maps with Map Torchlight [Schöning 2009] and Marauders Light [Löchtefeld 2009], which projects the position of the user's friends on a physical map using the devices' location data.

Following interaction with physical maps, mobile projectors have been used for navigation applications where users do not need to focus on a screen while walking, which is actually potentially hazardous. Users can instead improve their walking experience by augmenting directions directly into their environment. Pathlight [Wecker 2011] is a projected indoor interface to support navigation in a museum where users navigate to a specific destination by projecting directional arrows depending on their current position and final destination. NaviBeam [Winkler 2011a] is also an indoor navigation system which is applied to shopping malls. The authors conceptualize that the projector would be body-worn and project information on the floor such as a directional line that would indicate direction to the user's destination. Finally, as navigation scenarios already exist with mobile devices, Arning et al. [Arning 2012] propose exploring performance in a mobile projection navigation system compared to a mobile screen interface. They highlight that navigation performance was significantly reduced and that the walking speed would drop using the projected interface. Their results show negative effects when using the projection, due principally to lack of visibility in inadequate lighting conditions and privacy concerns. Yet, they also believe that the novelty of the interface may have been detrimental to the study, and that a longitudinal study is needed to confirm those results, so users will get more time to get used to the projected display.

Mobile projectors have also been used in Augmented Reality (AR) applications as a way to guide the user through a task. For example ClippingLight [Kajiwara 2011] provides an interface for users to take snapshots without having to look through a viewfinder but solely using the projected boundaries. Qualitative results show that participants preferred the projected interface to a traditional camera interface, and quantitative results show that the projected technique was significantly faster. Another example is Löchtefeld et al.'s "guitAR" for which a mobile projector is mounted onto the headstock of a guitar to support learning [Löchtefeld 2011b]. The projection augments the guitars with colours and shapes indicating how the player needs to place their fingers on the instrument; enhancing the learning experience that would usually consists of looking away at a book while trying to place the fingers on the guitar.

AR can also be used for remote assistance, as proposed by Gurevich et al. [Gurevich 2012] with TeleAdvisor. Their system consists in embedding a mobile projector on a mobile robotic arm so that an on-site worker receives active help and feedback from a remote worker who has control over the robotic arm. In a similar context, Suzuki and Klemmer [Suzuki 2012] propose to use TeleTorchlight, a mobile projector and camera unit to support teleworkers by projecting the boundaries corresponding to the camera's field of view so that the worker can precisely identify what information they are filming and sending out to off-site workers. Similarly, Gauglitz et al. [Gauglitz 2012] propose a framework for remote collaboration that takes into consideration the physical environment of the mobile worker. They evaluate their system in a cockpit using a tablet-PC but mention that their framework allows for it to be replaced by a mobile projected display. They mention that the projection would allow direct view on the environment while the tablet presents a decoupled view.

Another AR interface is AnatOnMe [Ni 2011], which is also the first medical application for mobile projectors. AnatOnMe uses the projector as a way for the doctor to communicate information to the patient. The doctor can augment the patient's body by projecting over the limbs while providing explanations, so the patient can visualise their condition and get an understanding without any medical background.

Mobile workers

– "A new mobile UI solution that reduced situational impairment would be highly useful for several kinds of mobile workers[1], especially for outdoor work." p.206 [McFarlane 2009] –

McFarlane and Wilder [McFarlane 2009] exploit the highly mobile properties of the projection to design a supporting user interface for *military stability and support operations*. They believe the properties their system, Interactive dirt, are built on will be applicable to all mobile workers. They argue that projection provides an alternative to mobile devices for which users need to stop their activity in order to interact with the screen. They state that this creates too much of a situational impairment to ensure users' safety during military operations and successfully propose mobile projection as a lightweight and fast-access alternative.

Wearable Projection

The previous sections show that mobile projectors are traditionally used handheld or rested on a flat surface. Yet, given their small size and low weight, they can also be found attached to the user's body.

For example, Blaskó et al. propose embedding the projector on a watch, worn at the user's wrist [Blaskó 2005]. The user could then project on near-by wall surfaces and interact with the projection by manipulating the watch and moving their arm. Their

[1] Here "mobile workers" refer to military personnel on the ground during an operation but the concept is applicable to any workers who use mobile devices on the go.

prototype is however using a stationary projector, simulating a mobile projector that was not available at the time. Following the same idea, SixthSense [Mistry 2009a] propose a “necklace” projector and camera system. The concept is that SixthSense can be used to guide users through different tasks or improve their experience, such as when taking pictures. Mistry et al. also propose in WUW - Wear Ur World [Mistry 2009b] a set of gestures to interact with the wearable projection.

A personal projector, when fixed on the user’s body, can be used as a personal ambient display. For example, Reis and Correia [Reis 2011] project an imaginary friend on the floor that follows users around; similarly to the Tamagotchi virtual pet [Bandai 2010] that users would carry around in the late 90s. The designed imaginary friend taps into the user’s emotions thanks to an electrodermal activity sensor that feels the user’s arousal and behaves according to the user’s movement and emotions; creating a personal ambient display of emotions. Another example is Tweeting Halo [Ng 2010] that proposes a shoulder-mounted mobile projector with the beam pointing towards the ceiling. The projection is used as an extension to the clothing and as a way to express personality or feelings when tweeting messages displayed above their head. Similarly, Leung et al. [Leung 2011] propose projecting Facebook [Facebook 2013] profile information as a way to convey online social identity. Although they encountered some technical constraints and privacy concerns from study participants, they also found that the ambient display was used as a conversation starter. This shows that the “public” projection can be used to trigger socialisation from a personal mobile device.

One issue with body-mounted projection is that the position of the projector on the body as well as the body’s motion is going to affect the quality and the readability of the projected image. Tajimi et al. [Tajimi 2010] therefore propose an image stabilization method for mobile projectors mounted on the user’s body and more particularly on the hip. Their sensor-based method takes the user’s body motion into consideration; stabilizing the image even when the person is walking.

Entertainment

A very interesting aspect of mobile projectors used for games and entertainment is that interaction is usually not limited to moving the projector or interacting with the projection. Instead, researchers have shown interest and creativity in using all the affordances of such devices to create very diverse user experiences.

As the projected content can take any form or shape, some researchers propose projecting a virtual object only, as if the projector was controlling that object alone. Willis propose to interact with the virtual character by moving the projector itself [Willis 2011a]. Their approach is especially interesting as they project some background with the character and the interaction is designed such that the user feels that the background is changing depending on the character's movement; as if the character and its background were not coupled. Their approach is a form of using the projection as input and output. In a similar fashion, PicoPet [Zhao 2011] and Twinkle [Yoshida 2010] propose interaction between the virtual character and the real world. PicoPet [Zhao 2011] is a projected virtual pet that adapts to the environment where it is projected. For example, when projected onto a blue background, the virtual pet starts to swim interpreting the blue background as water. With Twinkle [Yoshida 2010], the projected objects changes depending on the physical interaction between the virtual character and the physical objects, taking into account both motion and collision.

The following two systems propose supporting children's storytelling using mobile projection. In a user study, Åkerman et al. [Åkerman 2011] provide mobile projection systems with pre-recorded animations for a group of three to four children. They show that thanks to their system, children were given opportunities to share and move that they would not have had without a projection or in a fixed computing environment. They therefore encourage the use of mobile projection for such activity. Willis et al. propose HideOut [Willis 2013], an interaction technique with markers hidden on physical objects to support interaction between a mobile projector and nearby objects. They propose applications such as interactive storytelling and mobile games. Sugimoto et al. take the storytelling concept further with GENTORO [Sugimoto 2009] as they propose to use a mobile independent robot in conjunction with the mobile projector. GENTORO allows projecting a virtual path that the physical robot can follow, so that children can control the robots movements using the projection as input. They show that their system encourages creativity and that children could effectively create stories using both virtual and physical elements.

Finally, Winkler et al. propose Wall Play [Winkler 2012a], a game interface that projects on both wall and floor so the user can benefit from a more immersive experience. In a bowling application, the virtual ball is presented on the projection until the user "hooks it"; then the mobile projection is used as a flashlight onto the main game. The interaction is realised through pressing a button and measuring sensor data such as accelerometer and magnetometer. The user plays projecting on the floor and can see the result of their action – such as falling pins – on the floor and wall. It is interesting to note that in this application, different interaction and visualization metaphors are used for different parts of the games.

Acceptability

In many studies, participants complain about privacy issues or worry about acceptability of handheld mobile projection systems. Ko et al. [Ko 2010] raise several issues concerning the impact of the extension of projection to most mobile users. They in particular address environmental and social aspects, such as when the mobile device stops belonging to the user's personal distance, as defined by Hall's proxemics work [Hall 1966], and instead displays into the public zone. They discuss issues about the visibility of the content to others, who may or may not want to see the information and privacy issues about projecting personal content. They mention the limited amount of available public projection spaces, such as how to manage who can project when there is not enough space for all, as well as what acceptable projection spaces are, and whether some projection spaces should be "off-limits", such as the human body. Finally, they discuss light pollution, such as when a passer-by glares at the projection beam by inadvertence, potentially damaging their eyes. Kaufmann and Hitz actually propose the Eye-Shield system [Kaufmann 2011] to prevent bystanders from being blinded by projectors. The systems detects when a person looks towards the device's beam and blocks out the part of the image that will disturb surrounding people.

2.1.3 Interaction Techniques

The previous section demonstrates that mobile projectors are being used for a wide range of applications as output, as well as input. This section shows that there are as many different types of interaction techniques as applications. This section is used to inform heterogeneous projection-screen MMDEs design in the dissertation, keeping in mind that interacting with the projection on its own presents some differences to interacting with multiple displays.

As shown in the previous section, Rukzio et al. present a classification for interaction with personal projection [Rukzio 2012]. This section considers their input section, which is composed of *input on the projector*, *movement of the projector*, *direct interaction with the projection*, and *manipulation of the projection surface*. *Input on the projector* corresponds to techniques consisting in using physical buttons or a wheel on the side of the projector; they will not be presented further as these techniques are usually transferred to MMDEs as interaction on the touch screen and are mentioned in the MMDE section.

Movement of the projector

As mobile projectors contain an increasing number of sensors embedded on the device, such as accelerometers and compass, it is now possible to detect the intrinsic movements of the device. Extrinsic movements corresponding to where the device is moving related to the environment is also possible using sensors such as IR markers. Moving the device itself is one of the first interaction techniques that were put forward for mobile projectors. Indeed, Zoom-and-Pick [Forlines 2005] was, for example, designed especially for mobile projectors, taking into account hand jitter and limited projected resolution. The technique consists in performing a click on a pistol handle while moving the projector itself to select targets on the projected display. The concept of moving the device to zoom in and out is also used by Rapp's Spotlight Navigation [Rapp 2010] and by Löchtefeld et al. [Löchtefeld 2011c] with a semantic zoom affected by moving the device closer or further away from the projected information to interact with the projection, and for example chose the level of details to display.

Willis and Poupyrev [Willis 2010] define the MotionBeam metaphor as a set of interaction techniques using the movement of the projector to affect the projected object. They use a six-degree-of-freedom sensor on the projector to identify intrinsic movements and propose to use metaphors and techniques based on “animation and graphic art”. Finally, Song et al. [Song 2010] propose MouseLight where a projector is embedded on a mouse, and propose bimanual interaction using both a pen and the projection mouse. The interaction is then displaced depending of the position of the mouse or in other words, the projector.

Interaction with the projection

This section is defined as “interaction with the projection” and not “direct interaction” as it considers both direct and indirect interaction techniques with the projected content.

On one hand, Cao et al. [Cao 2006] propose interacting with the projection using a pen and virtual ink, so that the user can annotate projected objects. One of the limitations of their work is that the user will need to hold the projection steady in their non-dominant hand while writing with the dominant hand. Later on, Harrison et al. propose touching the projection directly on the skin [Harrison 2010, Harrison 2012] or on objects held by the user [Harrison 2011], such as a notebook, while the projector is mounted on the user’s shoulder.

On the other hand, Cowan et al. present Shadow Puppets [Cowan 2011], an indirect interaction technique where the user can use the shadow of their fingers on the projection beam to interact with the projected content. Molyneaux et al. present both a direct and indirect interaction technique with the projection [Molyneaux 2012] using two different approaches. The first one RoomProjector relies on a sensing infrastructure composed of four Kinect depth-sensing cameras fixed inside the room. The second one SLAMProjector is infrastructure-free and uses a pro-cam system for shadow and touch interaction on the projection.

Input

The concept of using a projector as both input and output was introduced by Underkoffler et al. through the I/O Bulb, considering a light source as a 1x1-pixel projector [Underkoffler 1999]. Many systems now offer using mobile projectors for both input and output, as described below.

Researchers propose creating augmented the surfaces on the fly without the need for pre-set configuration. For example, the Canesta projection keyboard [Roeber 2003] projects a virtual keyboard on a flat surface; providing an alternative to interacting with mobile devices. More recently, LightTouch™ proposes to turn any flat surface into a virtual keyboard [Light Blue Optics 2010] using wireless connectivity and infrared touch sensing. Both the Canesta projection keyboard and LightTouch propose to use the projection as output but also as input to other mobile devices. The concept is to enhance users' experience compare to typing on small keyboards (physical or touch) embedded on mobile devices. Wilson takes the concept further with PlayAnywhere [Wilson 2005], a mobile projection system that creates an interactive tabletop onto any flat surface using computer vision techniques to interact with the projected content (Figure 2.4). Although their current prototype is not handheld-sized, they envision that in the future, the system could be embedded into a small compact device.

While the projector can be a standalone device, it can also be mounted or embedded into other mobile devices. Song et al. propose PenLight, a pen interface with a mobile projector mounted on the pen [Song 2009]. PenLight allows working on physical documents using multiple virtual layers of content that the projector can overlay on top of the document. Another example is proposed by Do-Lenh and colleagues with Docklamp [Do-Lenh 2009], an augmented lamp composed of a projector-camera system that supports simultaneous augmented digital interaction with traditional paper-based interaction on a desk. Similarly, in LuminAR [Linder 2010] the mobile projector is mounted on an augmented lamp with a robotic arm that can move the projection to different places on the desk. MobileSurface [Zhao 2010] is another example of augmented lamp which allows in-the-air interaction within the projection area.

Finally, PICOntrol [Schmidt 2012a] presents a mobile projector which is actually primarily used as input to electric devices in the user's environment; while the visible projected content is used as feedback to the interaction. Schmidt et al. propose to use the projection beam combined with photo sensors on electric devices for the devices to be commanded via the projection itself. They propose a variety of applications such as controlling a music player or even inputting text using a projected virtual keyboard.

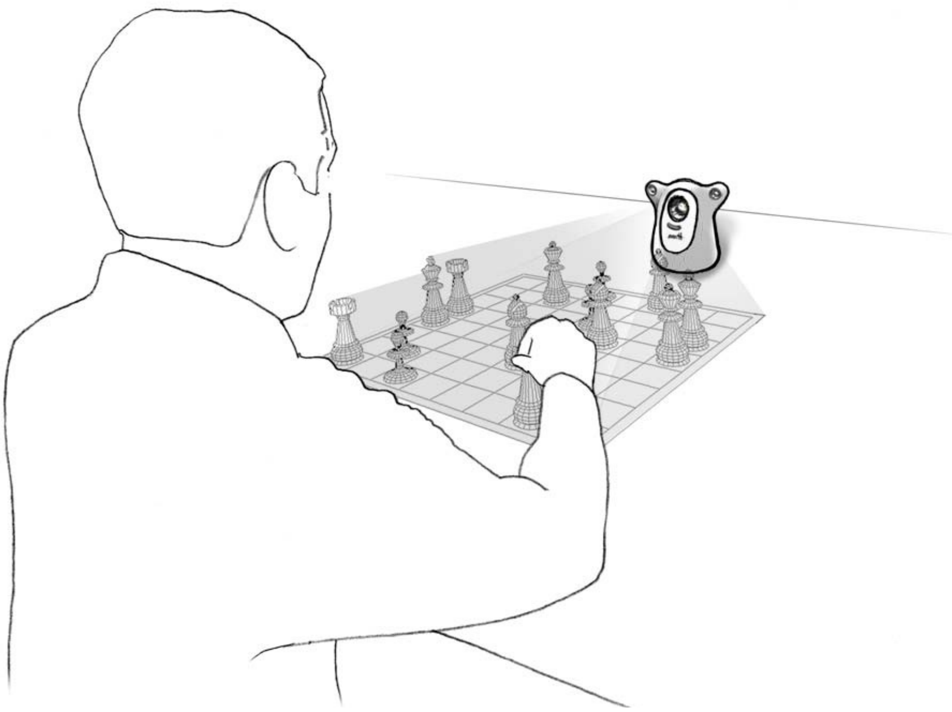


Figure 2.4: Wilson presents a vision of a "compact tabletop projection and sensing system" [Wilson 2005]. This design corresponds to the trend of mobile projection devices that can be rested on a surface and used to interact with the augmented surface.

Manipulation of the projection surface

This paragraph defines a particular case of handheld mobile projection via a movable display screen. The projection is technically handheld but the mobile modality is introduced by the movement of the projection space and not by moving the mobile projector. This case corresponds to moving the projection space while resting the mobile projector on a surface. It is actually a very interesting condition as it is traditionally expected that the projection will move depending on the physical position of the projector and not of the projection space, introducing a reversed interaction paradigm to handheld mobile projection. This section considers the projector either body-mounted or as a standard projector fixed in a room.

Body-worn mobile projection

Mobile projectors are often used as handheld devices. Their small and light form factor also allows them to be body-worn. The mobile projector is then fixed relative to the body while the user moves the projection space thus still achieving mobile projection.

Karitsuka and Sato [Karitsuka 2003] propose wearing a bag pack mounted projector to present personalised information into the user's environment. In their prototyped version, they project onto a notebook that the user is holding or onto a wall in front of the user. Their system is however quite cumbersome due to the size of usable quality "mobile projectors" at that time. Later on, the Cobra system propose a shoulder-mounted projector used together with deformable projection surface held by the user [Ye 2010]. Cobra is used for gaming applications and the deformable screen is used as input to the game. Harisson et al. take the shoulder-mounted projector concept further and propose to display projected content on the user's skin with Skinput [Harrison 2010] as well as on paper held by the user with OmniTouch [Harrison 2011]. In each of these cases, the user moves the projection surface rather than the projector, still providing a mobile projection. Finally, Mistry and Maes' SixthSense [Mistry 2009a] propose wearing a camera-projector necklace to augment the user's environment.

Fixed projectors

Konieczny et al. present a rear projection flexible screen that is tracked in the environment [Konieczny 2005]. The particularity of their work is that they use a projector with a spherical lens that offers a 180-degree field of view and "nearly infinite depth of focus". The user can then move the screen around in the environment but also flex it into different shapes. Konieczny and colleagues propose to use their system to examine the interior of 3D volumes by using the handheld display as if showing virtual slices or more generally to use it as a "magic window" to a virtual environment. When inspecting volumes, the user can explore the volume by positioning the screen at different depth locations. They however note that this becomes tiring when holding the screen steady in the same position for extended period of times and mention the implementation of a "freezing" command so the user could inspect a slice without having to hold the device in a specific position. This is a useful design consideration for handheld mobile projections.

Lee et al. present a novel technique for projecting onto a moveable display inside a room that uses the room's projector both for displaying content and for tracking the display's position [Lee 2005]. They remove the cost for external tracking system and propose an ultra-lightweight and low-cost surface to use as tablet display. They use the bespoke tablet display as a magic lens or as a moveable Focus + Context display. Leung et al. [Leung 2009] provide a similar system which does not require any sensors, instead they use the projector-camera pair as input and output. They detect the position of the projection board thanks to computer vision and image processing technique, and provide real-time tracking and projection on the board.

Li et al. propose using a pro-cam system to project on a handheld flexible display [Li 2012]. They use paper as flexible display; which is an especially interesting choice of projection surface due to its low cost and wide availability. One of the challenges of projecting on paper is that it is a deformable object and that the projection can be skewed due to different effects such as keystone for example. Li et al. overcome this issue by proposing a real-time algorithm to track the 3D surface of the paper using a checker pattern at the back of the paper. They then project a corrected image onto the paper so that the user can freely twist the projection surface.

Huber et al. propose LightBeam [Huber 2012] to project on everyday objects by the user when the mobile projector is rested on a flat surface. They use everyday objects typically available on table or desk to both project on and interact with the projection by physically interacting with objects.

Most of this work requires keeping the projection surface in both the camera and projector field of view. Adding steerability would provide more flexibility but would introduce extra challenges such as keystone effect from the projection.

2.2 Fixed Multi-Display Environments

As presented in this background chapter, Mobile MDEs are very recent environments that have been developed thanks to efforts and research in miniaturisation of displays. Therefore, in order to have a better understanding of MMDEs, it is important to determine what MDEs are and what research questions they have raised.

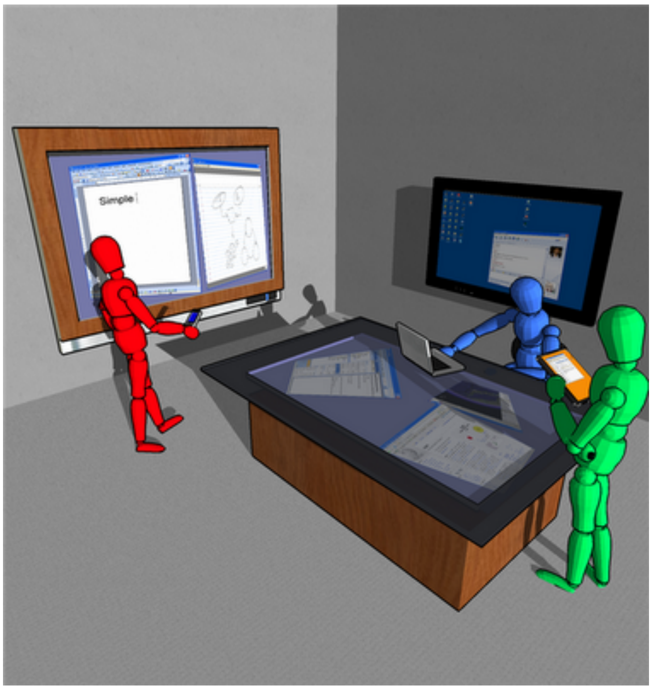


Figure 2.5: Illustration of a MDE. This environment contains both fixed and mobile displays. The fixed displays can be of screen or projection type and positioned either vertically or horizontally. The mobile devices can be laptops, tablets, PDAs, or mobile phones. Traditionally, mobile displays are for personal use and larger displays allow collaboration between the different users in the environment (Illustration of the E-conic system [Nacenta 2007] reproduced with permission from Dr. M. Nacenta).

Figure 2.5 illustrates an example of MDEs composed of both fixed displays and mobile displays. MDEs come in a wide variety of form and complexity. They can be composed of only two fixed displays that have the same size and resolution or of many displays with very different properties. This section presents a brief literature review of fixed MDEs that can help inform design of Mobile MDEs. Specific characteristics such as steerability, visual separation effects, and 3D environments will be described individually in the respective chapters of the dissertation.

2.2.1 Vision of MDEs

In 1998, Raskar et al. presents their vision of *The office of the future* [Raskar 1998]. They envision that any surface in an office could potentially be used as a display but also that any item or person in the office could be "scanned" and be used in a virtual environment. They present not only this vision but also the technologies to realise it.

Technologies presented include high-resolution displays as well as smart cameras and projectors, thus creating a heterogeneous MDE. Their vision has actually come true to a certain extent in current meeting spaces.

MDEs are initially presented in meeting and conference rooms as a way to support collaboration between the different users. The displays can be screens, projectors, or both; each presenting their own advantages and challenges regarding interacting with the displayed content. Most applications of MDEs are about supporting collaboration in a co-located environment. Hutchings [Hutchings 2006] presents some of the reasons why users prefer to divide information across multiple displays into multiple spaces. They found that users were worried that sensitive or private information could be communicated and this is where using a personal mobile device in the environment would help keeping sensitive information on a small personal display while sharing public information on larger displays.

As users bring an increasing number of personal electronic devices into these rooms such as laptops, PDAs, and smartphones, MDEs have started to adapt, including mobile devices into the environment and catering for them in terms of interaction and visualization techniques. Additionally, displays have become ubiquitous and can be found virtually everywhere: offices, trains or planes, streets, and even building facades. A MDE can be created by having a personal device communicate with any of those ubiquitous displays. While MDEs are often considered as a way to support multi-user collaboration, there are also many cases in which they are being used for a single user, such as when working at a desk with multiple monitors [Ringel 2003] or when adding a secondary screen to improve TV watching experience [Cesar 2008].

Since this dissertation focuses on MMDEs in single-user scenarios, the literature review discussed in this section will primarily focus on MDEs for single users.

2.2.2 Effects of MDEs Usage

As discussed above, the presence of multiple displays in a computing environment generates additional functionalities that do not exist in single-display environments.

Nonetheless, these configurations also induce new issues for users, beyond interaction-related issues. This section focuses on the effects of MDEs on users.

One usage of combining several monitors is to create a large tiled display. In this scenario, homogeneous displays – same size and resolution – are selected to create a consistent large display. Despite this homogeneity, the bezels around each individual monitor create an interior bezel to the large tiled display and cause physical discontinuity. Bi et al. investigates the effects of those interior bezels [Bi 2010]. They found out that interior bezels have no negative effect on visual search when data is displayed fully on one monitor or another but that splitting data across bezels is detrimental to usability. They also found that users applied a different search strategy depending on the number of bezels. In terms of interaction, they note that bezels are detrimental to steering across displays but not to selecting an item on a given screen.

Rashid et al. identify a list of factors influencing visual separation switches in multi-display user interfaces [Rashid 2012]. They first present a taxonomy for MDEs based on previous research with five main factors that affect attention switching: *display contiguity*: whether the displays are separated by bezels or distance and/or depth; *angular coverage*: the angular size covered by the multiple displays for a single user; *content coordination*: corresponds to how the data on the different displays is semantically connected; *input directness*: type of input provided in the MDE; and *input-display correspondence*: that is linked to input directness. Some of their main findings are that depth separation between displays can be detrimental to the users while bezels do not affect performance apart for steering across bezels as proved by Bi et al. [Bi 2010]. They also expect that MDEs with wider angular coverage will require more attention switching. They finally advance that the type of input has to be a good fit for the task performed not to demand extra attention from the user.

Specific effects on users such as the size of the displays, bezels, angular separation and visual separation effects can be found in section (4.2).

2.2.3 One Large vs. Multiple Small Monitors

Traditionally office desks are composed of a desktop computer and one or several monitors, thus creating a MDE. Users take advantage of the multiple monitors and added screen real estate to partition information such as to visualize multiple documents at the same time; to manage multiple applications, and to monitor changes on the system in their peripheral view [Grudin 2001, Ringel 2003].

As MDEs started to emerge, a main research question appeared wondering if multiple displays would perform better than a single display or than a larger display space. Hutchings et al. [Hutchings 2004b] first compare how users manage display space and windows in both single and multiple monitor conditions. They find that multiple monitor users will need less window switching and that the additional display surface can be used for peripheral information that is not occluded anymore by the current window and can instead be positioned on another display. Bi and Balakrishnan [Bi 2009] then present a week-long field study and compare usages of a very large display (16’ wide x 6’ high) to a single and a dual-display condition. Results show that in both the large display and dual-display conditions, users partitioned applications into a focal and peripheral regions. They find that the focal region is used for primary tasks when the peripheral regions are used for secondary tasks. Results show that participants suffered from visual discontinuity because of the bezels in the dual-display condition. Overall, users preferred the large display condition and mentioned enjoying the immersive aspect of it. Jakobsen et al. [Jakobsen 2011] propose to identify how display sizes actually affect visualizations usability. In particular, they run a user study for three interaction techniques: focus+context, overview+detail, and zooming techniques, using a map navigation task. They find that the choice of interaction technique depends on the display size as, for example, overview+detail performed best but required more movements than focus+context on large displays. They note that focus+context performed poorly on small displays and should therefore be preferred on larger displays.

2.2.4 Applications

There are many applications to MDEs, which go beyond display sharing across multiple devices in a co-located environment. For example, the CAVE [Cruz-Neira 1992] propose an immersive virtual reality environment composed of usually four wall- and floor-sized displays. The displays are actually projection surfaces equipped with rear stereoscopic projection. The combination of the displays creates a virtual reality room where all displays seem to be just one continuous immersive display.

Some other systems propose combining multiple projectors to create 3D displays [Raskar 1999] and enable augmented-reality applications, such as reproducing complex shading over existing physical objects as in Shader Lamps [Raskar 2001] and augmenting tangible objects to then interact with them using a projector-camera solution, as in Molyneaux et al.'s Projected Interfaces [Molyneaux 2009].

Other research works propose augmenting users workspaces such as Wellner's DigitalDesk [Wellner 1993], which interacts with paper and a projector positioned above the desk. This work corresponds to the premises of tabletops and multiple displays on a desk, such as when bringing a mobile device onto an interactive workspace. The projector is combined to a camera so the user can benefit from the affordances of both the physical and the digital environment.

Multiple displays can also be used for different applications within the environment, for example, Chan et al. [Chan 2010] propose using multiple projectors to project in both the visible and the infrared spectrums. Users can then see the projected output while interacting with mobile devices that perceive the infrared markers, therefore allowing transparent interaction between the mobile device and the projected environment.

2.2.5 Interaction Techniques

This section presents the main interaction techniques and challenges when interacting with a MDE that can then be considered when designing MMDEs. It is a presentation of the main techniques and not an exhaustive list of all interaction techniques.

Rekimoto introduces *Pick-and-drop* [Rekimoto 1997] as a technique consisting in manipulating digital objects as if manipulating physical objects by "simply" picking the object from its source and dropping it to its destination. The technique presented is revolutionary and propose a direct manipulation interaction technique for multiple devices. The system proposes pick-and-drop on mobile devices such as PDAs using a physical pen. Baudisch et al. propose using pen as well as touch metaphor in the *Drag-and-Pop* and *Drag-and-Pick* [Baudisch 2003a] interaction techniques. The techniques allow accessing data that would be hidden behind a bezel of another display or that would normally be too far away from the user for them to interact with the content. Hinckley et al. also propose using the pen metaphor in *Stitching* [Hinckley 2004]. They propose that pen gesture spans across multiple displays, crossing bezels and displayless space, so a cursor or any digital object can be moved from one display to another. Stitching establishes the spatial relationship between the displays and calculates the pen movement's curve to infer the position of the cursor on the second screen. A drawback of this technique is that the cursor gives the impression of "jumping" from one display to another.

Some researchers propose interacting in the MDE using a mouse or a pointer. One main issue in MDE is that there is a gap or a bezel between the displays so the mouse or cursor movement does not appear continuous to the user. This problem is enhanced in heterogeneous environments where displays have different sizes and properties, and there is no common border. *Mighty Mouse* [Booth 2002] proposes a user interface based on VNC protocol, considering that the devices in the environments are all linked through a network, so that the user can use any device as input to output on any other device in the MDE. The software registers the spatial arrangements of the displays and when the cursor moves out of the boundary of a display, it appears on the next display corresponding to the described alignment.

Baudisch et al. then present *Mouse Ether* [Baudisch 2004], taking into account the horizontal and vertical offsets between multiple monitors. Previously, users would see the mouse cursor "jump" up or down – stitching technique – when moving across displays with different sizes, while *Mouse Ether* applies graphical transformations to the cursor so the movement looks continuous to the user. Mouse Ether significantly improved target acquisition performance. Benko and Feiner take the concept further and introduce additional pointer wrapping with *Multi-Monitor Mouse* (M^3) in the homogeneous MDE [Benko 2005], later extended to the heterogeneous MDE [Benko 2007b]; where users can switch the display they are currently working on, while the mouse moves to the corresponding location on the new display. They find that M^3 highly improves user experience, and that in the heterogeneous environment the benefits of the techniques were proportional to the distance between displays and the “visual–device space mismatch between monitors”.

With *Perspective cursor*, Nacenta et al. [Nacenta 2006] propose to take into account the user’s perspective of the MDE to let the user interact across the multiple displays. In a controlled study, they show that perspective-enabled interaction techniques improved performance in pointing tasks, especially when the displays are situated at large distances from one another. Later on Nacenta et al. present a taxonomy to classify “cross-display object movement techniques according to three dimensions: the referential domain that determines how displays are selected, the relationship of the input space to the display configuration, and the control paradigm for executing the movement” (p.3) [Nacenta 2009]. Their taxonomy help determine what interaction technique is best suited depending on the characteristics of the MDE.

Heider et al. [Heider 2007] propose a dynamic MDE with automatic display mapping where the position of information is automatically computed by the system. They also account for screens and projectors differentiating them as Displays or Surfaces, as a steerable projector could for example steer to the best surface. They argue that their technique improves user experience in a MDE as this solves problems such as display control (i.e., which user controls the display) and simplifies the interface where a user would have to find the best display to show information.

Lee et al. propose a gesture based interface Select-and-point [Lee 2008a] that consists in selecting a document on the mobile screen and pointing towards the large display to display information. Spotlight [Khan 2005], is an interaction technique to direct users’ attention to a specific area on a large display by “putting the light” on that specific area. The entire display space is darkened except for a circular region around the cursor. Users’ attention is then directed towards the spotlight. Finally focus+context screens [Baudisch 2001] is combines both low and high resolution displays, so the user can visualize specific areas at high resolution compare to the rest of the display, keeping the same display scale.

2.2.6 Mobile Component in a MDE

This section explores background literature corresponding to bringing a mobile device into a fixed MDE. As mobile devices are ubiquitous devices containing personal data, users want to be given the possibility to interact within larger infrastructure using their own personal devices. Additionally, with the development of ubiquitous computing, there are more and more electronic devices present in the environment, which could potentially be used in conjunction with a mobile device. This section concentrates primarily on single-user scenarios as these correspond to the focus of the dissertation.

Myers propose that mobile devices can be used to interoperate with other mobile devices and to control electronic devices situated in the vicinity of the user [Myers 2002]. He introduces and implements the concept of multi-machine user interfaces; considering that depending on task, it may be better suited to share interaction across devices. He also envisions that the mobile device can be used to interact with the larger display, sharing public information and retaining personal data. Dix and Sas propose a framework for mobile devices use with public displays [Dix 2010]. They identify key elements of each display, show the complementarity of the devices, and argue that many factors influence the ways in which the mobile device interacts with the public display including: situated display size, interaction technique, and context (e.g. number of people within the vicinity of the public display).

Applications

There are many potential applications when using mobile devices in a MDE. One motivation is to share information from a personal device to a public or semi-public display [Myers 1998, Greenberg 1999, Cheverst 2005]. The large display can also be used to play a game as proposed in Flashlight jigsaw [Cao 2008] or as input to interacting on a whiteboard [Rekimoto 1998].

While mobile devices can be used with existing computing infrastructure, such as computer screens, wall-mounted displays and tabletops, they can also be used to interact with TVs. Robertson et al. [Robertson 1996] propose using a PDA to interact with the services of an interactive television (ITV). Through infrared connection, they propose partitioning information across the displays; using the PDA screen for input and text information, and the TV screen to display larger images.

More recently, Cesar et al. [Cesar 2008] present interaction techniques for using a mobile device as secondary screen in ITV environments. They identify four usages in particular: *control*, *enrich*, *share*, and *transfer television content*. Alfaro et al. propose Surround Vision [Alfaro 2011], a mobile device used as a secondary screen that allows the user to have a different view on the mobile device than the one being displayed on the TV screen. The user can change view by moving the spatially aware mobile device. Finally, Holmes et al. [Holmes 2012] evaluate that in a television and secondary mobile screen environments, around 30% of the visual attention is directed towards the mobile device and the average gaze length on the TV is significantly decreased. The TV experience is therefore highly modified and introducing a mobile device in such environments needs to be carefully considered both in terms of display visualization and interaction technique.

Device discovery

As seen in the previous section, one challenge in interacting with MDE is the ability to map the physical positions of the displays onto the computing environment. Adding a mobile device to an existing MDE raises additional interaction challenges. Firstly, the device needs to be informed that it can now communicate with the other displays in the environment and, vice-versa, the environment needs to be informed that a mobile device has just been brought in. Secondly, since the mobile is brought to the environment, users need an effective interface to identify what display they are actually using.

Several systems have been tested for the user to identify and select which device in the environment they want to interact with from their personal device. Some interfaces propose lists of devices ordered alphabetically, or using some spatial data, while some interfaces propose an iconic menu with an organisation of the icons corresponding to the physical layout of the devices. Gostner et al. [Gostner 2008] for instance test two types of spatial interfaces against an alphabetical list of the various devices in a room. They find that participants preferred using an iconic menu with the icons' positions matching the real-world physical positions. However using a linear list with a spatial reference was actually detrimental to performance. Gellersen et al. then propose the RELATE interaction model [Gellersen 2009] which is designed to support impromptu collaboration using a relative positioning system which does not require a full tracking infrastructure. They also test the three interface types and find a user preference towards the iconic map although quantitative results were similar using the three interfaces. Both studies show a user preference towards using spatial interfaces matching the physical layout of the devices

Pering et al. developed Elope, a RFID-based system that allows smooth interaction between a personal device and other devices in an environment [Pering 2005]. The concept of Elope is to simplify user interaction as much as possible. Instead of selecting which device to interact with, users would scan an object with a RFID tag to signal their intention and trigger interaction. For example, scanning a remote control informs the system that the user is about to give a presentation; the system would then put the presentation up on the large display. This system is ideal in a meeting room where people come in with personal devices and for which some pre-determined actions could be implemented. However it seems less suitable for serendipitous use of mobile devices in public environments, in which case some of the techniques presented in the previous paragraph are more applicable.

Want et al. present a technique for *Dynamic Composable Computing* which enables to wirelessly link mobile personal devices to other devices available in the environment as a way to "easily and seamlessly extend the capabilities" (p.1) [Want 2008] of mobile personal devices. They propose not only to connect the devices, but also to compose an environment. Users could therefore choose whether they want to reach a specific device or functionality. From the interface, they can decide to view the files from one device on the display of another device in one movement only using the "join-the-dots" metaphor. The interface consists in a visual representation of the available devices and functionalities for which the user can draw a line between the services and the destination.

Interaction frameworks

Rekimoto et al. present a framework to smoothly exchange data between personal devices and surrounding computing infrastructure. *Augmented Surfaces* [Rekimoto

1999], allow users to transfer personal data onto shared workspaces in multi-user collaboration setting. Two interaction techniques are presented: Hyperdragging and Anchored cursor; which rely on the physical positions of the display spaces to offer spatially continuous interaction. Finally Rekimoto et al. propose tagging physical objects within the interaction space with markers so that the digital content associated can be brought into the MDE.

The Interactive Workspaces Project presents iRoom [Johanson 2002] an intelligent room for multiple users and devices to interact with. Within iRoom, Johanson et al. present iROS, a distributed software platform for interacting with the multiple displays. iROS aims to support cross-platform interaction between the various devices in the room as each component – phones, PDAs, laptops – comes with its own, potentially proprietary, operating system, and software components. The system also proposes cross-platform user interface across the devices in the room.

Paek and colleagues present a platform for interactive shared displays where input can come from any mobile devices in the vicinity [Paek 2004]. While other systems propose interaction using mobile devices for a specific application on the shared display, this work has the particularity to propose a flexible platform where users can port their existing applications onto the shared display. The platform is based on XML-type requests and various input and output modules. Building on the same concept, *ModControl* [Deller 2011] is presented as a flexible and personalized XML communication framework for a mobile device and a larger display to communicate as a client-server application. The framework offers to add various modules to the connection depending on the user's needs and to give flexibility to the devices and to the interface. For example, a *mouse emulation module* allows the mobile device's touch screen to be used as input to the cursor on the large display.

While many frameworks are specific to interacting within a room or an existing workspace, Olwal presents *LightSense* [Olwal 2006], a technique using mobile devices on any display wherever they are located. *LightSense* tracks cell phones LEDs to use them as spatially aware handheld devices to interact with other displays. The tracking can either be done by placing a camera behind the screen in rear-projected displays – such as tabletops – and using computing vision to track the light source; or by placing some markers behind the screen – such as light dependent resistors – that are triggered by the light source. This technique does not require any modification to handheld devices. In a similar manner, a mobile projector could also be used as light source.

Interaction metaphors

This section develops the main interaction metaphors to using a mobile device in a MDE. Ballagas et al. [Ballagas 2006] survey such interaction techniques and classify them in terms of Position – of the mobile compare to the fixed environment –, Orientation, and Selection – techniques to select an item –. The classification presented below differs as it is according to user-centred interaction metaphors; nonetheless it covers similar aspect of the background literature.

Several researchers propose using gestures to interact with a mobile device in a MDE. For example, Dachselt and Buchholz [Dachselt 2009] show that simple set of gestures based on tilting and throwing can be very powerful to interact between a mobile phone and a larger display. Kray et al. [Kray 2010] propose a user-centric approach to define gestures to connect a mobile device with a larger screen – public display or tabletop –. In a user study, twenty-three participants were asked to perform a gesture with their phone that they found would be most appropriate for specific activities such as sending a media file from the phone to another screen or downloading an application towards the phone. They find that users were able to perform gestures and that the majority of the gestures performed included a change in relative distance between the mobile device and the large display. However, by moving the phone towards the larger display or by rotating it, the user will lose visual feedback on the phone's screen.

Another interaction metaphor presented by Bier et al. is the *Magic lens* technique [Bier 1993], which can be applied to a mobile device on a larger screen by using the mobile screen over the larger display. The mobile screen behaves as a "viewing filter" – such as a zoom – of the main displayed image. Such devices are traditionally spatially aware so the image displayed on the screen corresponds to the part of the image that is occluded by the mobile display. Magic lenses are now even proposed as a way to access 3D content in virtual environments [Brown 2006].

Another way to interact in-between the devices, is by performing touch gestures. Boring et al. [Boring 2010] propose touching the screen of the mobile device to interact with the larger display using a live video of the larger display. Touch &

Interact [Hardy 2008] and PhoneTouch [Schmidt 2010] propose a different touch metaphor where the physical mobile device is used to touch the larger display surface, in order to enable selection of screen objects and easy transfers of data in a Pick&Drop fashion [Schmidt 2010]. In later work, Schmidt et al. introduce additional interaction techniques such as recognizing which phone touched the surface, using a virtual lock on personal data on shared screens, and even using interaction menu on the phone while interacting on the large display [Schmidt 2012b]. Finally, Xu et al. propose Plug&Touch [Xu 2012] where a phone's on-screen information can be displayed on a larger TV screen. The system then allows using the camera at the back of the mobile device to identify user's touch on the TV. Their system however necessitates pre-calibration between the mobile and fixed displays, therefore impairing mobility.

Lee et al. present a gesture-based interface to connect multiple mobile devices in a heterogeneous MDE [Lee 2009]. Their gestures are however bare-hand and not performed through gesturing with the mobile device, so the user can still use the mobile screen when performing the interaction.

Ubiquitous cursor [Xiao 2011] allows moving objects from one display to another in a highly heterogeneous MDE composed of both mobile and fixed displays using a mouse. Xiao et al. investigate whether direct feedback is better suited than indirect feedback for such environments. They find that direct cursor feedback, where the cursor is displayed everywhere in the room, on a perspective-based interaction technique performed significantly faster. This shows that mouse interaction is possible with a MDE integrating mobile devices providing that the devices are not handheld but rested on a surface. Slay and Thomas [Slay 2006] propose a specific control device to interact in heterogeneous MDEs. Their control device is composed of a PDA and a sensor pack. The user interacts with the PDA screen using a stylus. Slay and Thomas compare the performance against a wireless gyroscopic mouse and a traditional mouse. They find that with training, users performed better using the control device, in a task such as navigating across the displays. Instead, the traditional mouse performed better before training. Finally, McCallum propose ARC-Pad [McCallum 2009], an interface to move a cursor on a large display by touching the mobile phone's screen. The cursor can then "jump" from one area of the screen to the other, rather than using a direct mapping of the cursor's movement to the phone that has a small screen real estate.

2.3 MOBILE MULTI-DISPLAY ENVIRONMENTS

The first mobile devices, such as mobile phones, were a tremendous achievement in terms of miniaturization of computing technologies but were still quite cumbersome for users. For years, research has focused on miniaturizing computing power, embedding sensors, and developing lightweight materials, to make portable devices as small and light as possible. As more and more sensors are being embedded on devices, people can now access a very large amount of data from their handheld devices and then require additional screen real estate. The trend has then turned around, and in the last few years, the market has seen the emergence of much larger embedded screens.

Figure 2.6: Example of a *single-device-multi-display* environment: The Nikon Coolpix S1000pj camera [Nikon 2010] that contains both projection and screen technologies. The displays are embedded within the device in a way that the dual-display capability does not impair the portability of the device in a way a larger physical display would.

Another popular avenue to display additional information on small devices is to add another display on the existing device, such as an additional screen or projector (Figure 2.6). Proof is that clamshell phones, handheld dual-display game consoles, projection-enabled tablet PCs and cameras are steadily increasing the number and forms of multi-display mobile devices. Such devices operate by providing visual information on different displays. Those devices are named Mobile Multi-Display Environments (MMDE) and defined as:

Any mobile computing environment containing more than one display.

Please note that a MMDE can also be created by concatenating multiple single-display devices. Since users possess an increasing number of personal devices, they will need at times to use those devices simultaneously, thus creating a MMDE on the spot.

This section presents a literature review of the different devices, technologies, and the state of the art of research being conducted on such devices with an accent on the composition of the environment and the management of the displays. The following two types of displays are considered, regardless of the technology they rely on: *screens* and *projectors* as they correspond to the principal types of displays found in MMDEs.

This section has a focus on displays that are being used synchronously by a single user. The classification of MMDEs (2.3.1) shows that this work will focus exclusively on single-device-multi-display MMDEs. Those are personal mobile devices fitted with multiple displays. It is therefore critical to understand how a single user can actually interact with their personal device before looking into multi-user scenarios.

This section first introduces a classification of MMDEs (2.3.1), before presenting the literature related to multiple-device MMDEs (2.3.2) and single-device MMDEs (2.3.3). Systems presented will help inform design choices for this research work.

2.3.1 Classification for MMDEs

This section presents a classification for MMDEs with specific definitions for the different classes of MMDEs. It also motivates the type of MMDEs that this dissertation will focus on. Fixed MDEs are considered earlier in section (2.2). This section also refers to the Glossary available in Appendix A.

Partially vs. Fully Mobile

- *Partially Mobile MDEs* correspond to environments where a mobile device is imported inside a fixed MDE, such as when a PDA is used in conjunction with shared public displays [Greenberg 1999]. Although outside the scope of this research, these environments can inform future design, so they will be briefly discussed in the Background section 2.2.6: Mobile Component in a MDE.

- *Fully Mobile MDEs* are environments that support more than one display and that are composed of one or several mobile devices. Fully Mobile MDEs can then be separated into two categories: *Multi-device-single-display* and *Single-device-multi-display*

Fully Mobile MDEs

Fully Mobile MDEs are particularly interesting as they correspond to either: one mobile unit that contains multiple displays, or to the composition of multiple single-display mobile devices. As such, they can be divided into two categories *multi-device-single-display* and *single-device-multi-display*.

Multi-device-single-display

Mobile *multi-device-single-display* environments are created when individual single-display mobile devices are brought together to create a new MMDE. Many examples of these environments are presented in the previous sections under 2.3.2: *Multiple Devices*. To summarize a few examples; Lyons et al. [Lyons 2009a] presented a technique that uses a network to link multiple single-display devices in order to share co-located display spaces. Another example is Cao et al.'s interaction technique for individual mobile projectors to interact simultaneously [Cao 2007]. Finally, Siftables [Merrill 2007] provide a set of tangible interactive objects, each equipped with a single display that can be combined in order to manipulate data and information.

Single-device-multi-display

Mobile *single-device-multi-display* environments correspond to single mobile devices that contain multiple displays. This type of environment has gained a lot of popularity with the miniaturization of screens and the growth of mobile-projection units in existing devices. Those devices are presented in the previous sections under 2.3.3: *Single Device*. To review a few examples, Sony presents a camcorder that contains a screen and a mobile-projection unit [Sony 2011]. Another example is *Z-agon*, a cube-shaped device with a screen on each face [Matsumoto 2006].

Multi-device-multi-display

Mobile *multi-device-multi-display* environments are a composition of multiple *single-device-multi-display* environments. They present a combination of the challenges encountered in the two previous categories. Such environments are still marginal in the literature but can easily be envisioned. For example, if two users were collaborating using one projector phone each, they would be creating a *multi-device-multi-display* environment. These environments will gain more understanding through the study of the *single-device-multi-display* devices that compose them.

Comparison

Although both *multi-device-single-display* and *single-device-multi-display* categories present interesting challenges and research questions, in this dissertation, the work will focus exclusively on *single-device-multi-display environments*.

As a matter of fact, this dissertation is interested in how the position and alignments of the displays allow synchronous use of the display surfaces. In a multi-device environment, each individual display can easily be reconfigured as each display belongs to a separate device and can easily be moved and re-oriented by simply moving the devices themselves. The *multi-device-single-display* environment then created is easily adjustable and can be adapted to the desired situation. Intuitively, users can then reduce visual separation effects.

In single-device environments however, displays have traditionally been fixed relative to one another, such as with mobile projector phones where the projection lens is normally fixed at an orthogonal angle to the phone's screen. While some research propose reconfigurable multi-display layout, such as the Codex [Hinckley 2009] where two screens are hinged and can be rearranged into different positions; most single-device environments do not allow the user to rearrange displays in order to simultaneously visualise information.

As *single-device-multi-display* environments have started to be commercialized, it is critical to understand how the multiple displays can be used synchronously despite the challenges and constraints arising from multiple displays being embedded into a single device. This dissertation will therefore focus on those environments.

Classification

There is a fixed number of ways to position displays together in a *single-device-multi-display* mobile environment.

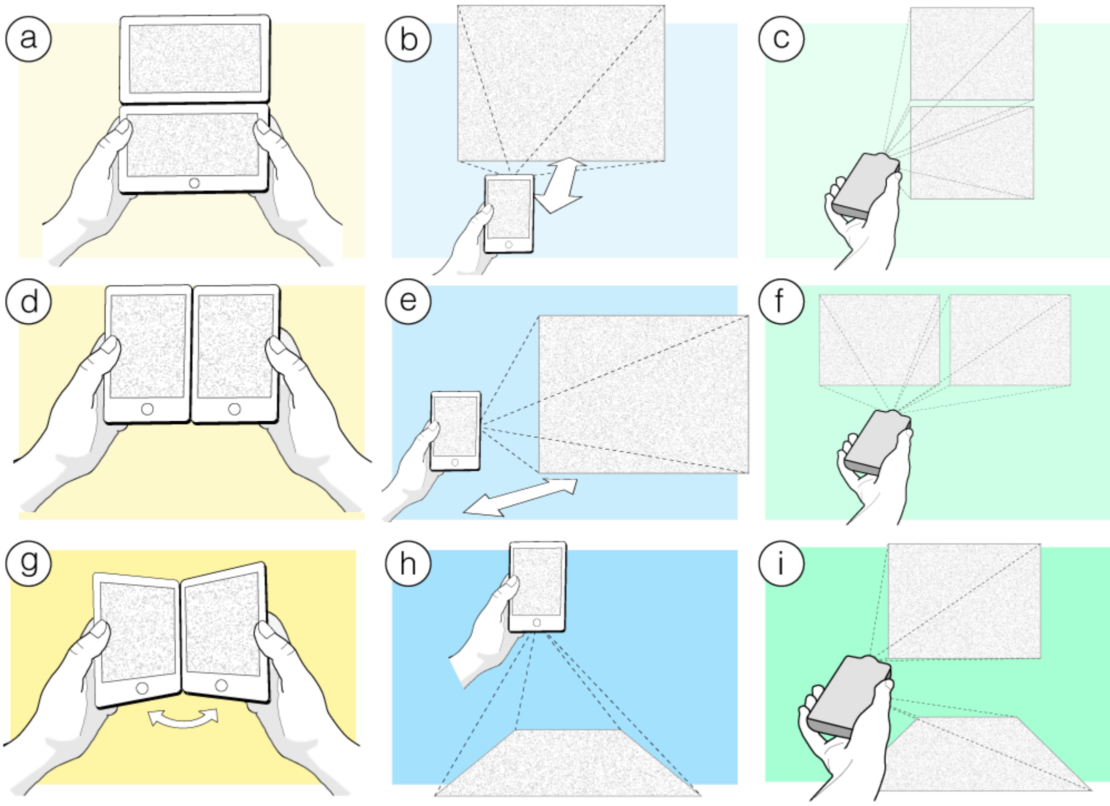


Figure 2.7: Possible layouts for two displays on a mobile device for different types of displays: Left: screen-screen (a,d,g); Middle: screen-projector (b,e,h); Right: projector-projector (c,f,i) [Cauchard 2011].

The displays can either be separated by:

- distance vertically (Figure 2.7 a,b,c),
- distance horizontally (Figure 2.7 d,e,f),
- an angle (Figure 2.7 g,h,i) or
- Any combination of those conditions.

The distance that separates the displays will vary depending on the devices' design: from a few centimeters wide such as the size of a bezel or a hinge (Figure 2.7 Left column), up to a few meters wide in the case of a projector enhanced device (Figure 2.7 Middle and Right columns).

When the displays are separated by an angle (Figure 2.7 g,h,i), *this angle* can be of any value (0-360°) along any axis in the cartesian space.

This physical separation in distance and angle can be either fixed or reconfigurable depending on the design of the device.

In the screen-projector cases (Figure 2.7 b,e,h) the displays are always further separated in distance in depth due to the inherent properties of each display. There may also be depth separation in the projector-projector cases (Figure 2.7 c,f,i) depending on the choice and availability of projection spaces.

Type of displays

There are different types of displays including: screens, projectors, 2D displays, 3D displays, touch-enabled or simple display screens. In this dissertation, when the multiple devices of a MMDE are of the same display technology, the environment is named homogeneous. On the contrary, when the display technologies are different, the environment is considered heterogeneous (See APPENDIX A: Glossary).

Number of displays

When a *single-device-multi-display* mobile device is composed of more than two displays, the displays can be studied as pairs of displays, in terms of their relationship to one another. Therefore, a fictive device containing three screens (A, B, and C) would be studied in terms of three pairs of screens (A&B, B&C, and A&C). This dissertation will then focus on dual-display MMDEs.

Figure 2.7 presents an exhaustive list of the different types of MMDEs that can be created for a pair of displays. The MMDE can be composed of two screens (Left column), a screen and a projector (Middle column) or two projectors (Right column).

As demonstrated in the literature, the space of multiple screens has been relatively well investigated while the space of multiple projectors presents few devices and examples. This dissertation will focus on the space of projection-screen MMDEs (i.e. composed of screen and projection technologies). This topic is especially interesting as it corresponds to heterogeneous MMDEs and presents some first-hand challenges due to the disparity of the displays. It is more likely that investigating this complex space will allow generalizing some of the findings to the more general MMDE space.

2.3.2 Multiple Devices

MMDEs can be composed by bringing together multiple single-display mobile devices, in the same way that fixed MDEs are created. In particular, it concentrates on multiple devices used by a single user and not on environments supporting multiple-user collaboration, as this dissertation focuses on single-user scenarios.

Usage

To get a better understanding of multiple devices use by single users, Dearman and Pierce [Dearman 2008] investigate the reasons behind using multiple devices together and how people use those devices. They present four main findings: some activities span across multiple devices; users assign specific roles to the devices depending on, for example, their form factor and interaction techniques; work and personal activities are managed across multiple devices; and users manage data across devices in various ways. They also note that sometimes people use multiple devices simultaneously when they transition from an older device to a newer one; often repurposing the older device.

Similarly, Oulasvirta and Sumari [Oulasvirta 2007] present a field study to understand how mobile information workers use multiple mobile devices at work. They argue that the workers often changed the devices configuration. Many used either one device or the other for reasons as varied as: the suitability of the display and available interaction technique; the time it takes to start their work on a device – it is faster to look at some information on a phone rather than start a laptop to do the same action –; and even for security purposes. Moreover, they also mentioned people would use the multiple devices to multi-task, which is actually a way of using the displays synchronously. In both research, all the devices studied are single-display.

Synchronous or asynchronous use of the displays

Displays can be used in a synchronous manner – when the displays are used conjointly – or in an asynchronous manner – when the displays are used separately, one or the other depending on the task at hand.

In the case of multiple devices, the individual devices' displays can be used combined to create a larger or a better quality display. This is especially the case in homogeneous MMDEs, composed of multiple screens or multiple projectors, as the displays can easily be arranged around each other. For example, Schwarz et al. [Schwarz 2012], propose to use the Phone as Pixel ; meaning creating large ad-hoc displays from co-located mobile devices' screens. Their implementation can aggregate potentially any number of devices of any size and shape using only the web browser and Internet access of the device, as well as a camera and vision-based technique to determine the relative position of the displays. Moreover, Cao et al. [Cao 2007] and Raskar et al. [Raskar 2003] both propose using multiple mobile projectors together to create enlarged display area, while Amiri et al. [Amiri 2012] propose displaying a higher quality projection by aggregating multiple mobile projectors.

In projection-screen MMDE, it is not straightforward how a larger combined display can be created out of the heterogeneous environment. In most cases, a mobile projector is added to an existing screen-only device and used instead of the screen for specific applications, such as when more display real estate is needed. In most scenarios, the mobile projection is used to support multiple users and is not considered for single-user scenario. For instance, View & Share [Greaves 2009] allows co-located users to share data on a large mobile projected display instead of a small-size screen. The projection then takes over from the screen as primary display.

Interestingly enough, multiple mobile projectors can be combined to create a large display while keeping the projection surfaces disconnected. This is what was presented in the Helicopter Boyz dance performance [Helicopter Boyz 2010] where children were dressed in suits covered with twelve mobile projectors that projected images, which positions reflected the children's movements. The mobile projectors were used as an extension to the body, creating at times a large disconnected image and at other times, a set of separate projected images.

Applications

Multiple displays brought together can be used for various applications for single-users such as partitioning information, managing applications, and even visualizing multiple pieces of information simultaneously. The displays can be used synchronously or asynchronously depending on the needs of the application.

In the literature, multiple-screen environments are very often used synchronously. For instance, multiple screens have been used for watching videos across multiple displays [Shen 2007]; sharing pictures – or in principle any data – across devices [Kray 2009]; and enhancing single-user reading experience as in CloudBooks [Pearson 2011]. When the displays are used separately, the user chooses which device is most appropriate depending on context. For example, in a projector phone, the user may use the screen to write a text message and the projection to watch images. However, in some scenarios, it may not be straightforward to the user which display is most appropriate to use, such as when the displays are body-worn. Ota et al. then propose [Ota 2010] a context-based methodology that automatically defines what projection to use in a wearable multi-projector scenario.

Another application for a mobile projector is to use it instead of a fixed projector, taking advantage of the physical properties of the mobile device. Mobile projectors provide a low-cost portable solution compared to fixed projectors. Additionally, they can be plugged onto phones and run on a battery while fixed projectors require a PC or laptop and constant power supply. Mobile projectors have therefore been heralded as a replacement to fixed projectors in developing countries where access to technology is scarce and power is not available at all time. Mathur et al. [Mathur 2011] present a field study in rural India in a school and a healthcare environment to show the need for devices such as projection-enabled mobile devices (projector phones in their study). They argue that thanks to the simplicity of the interface, participants could author content regardless of their education level and were very enthusiast about the possibilities of using projection-enabled devices.

As mobile projectors have been shown in the previous section to be usable as input, Hosoi and colleagues propose controlling a robot through one or multiple mobile projectors [Hosoi 2007a, 2007b]. In CoGAME, they propose manipulating a mobile robot by using multiple mobile projectors. They propose projecting a path that the robot will follow. In their scenario, the multiple projectors correspond to multiple users, so the users can collaborate through the projection. However, one could imagine a two-hand interaction with two projectors where the user would increase the path length by concatenating the projections.

Interaction

There are two aspects to interacting with multiple displays brought together. One aspect is how to pair the devices so that they can form a MMDE and the other aspect is to understand how users can interact with the newly created environment.

Pairing the devices

Hazas et al. [Hazas 2005] propose *Relate*, a framework using ultrasonic sensing through a network of USB dongles to get mobile devices to connect together and automatically acquire relative positions of the mobile devices – laptops – without needing an external infrastructure. Kortuem et al. [Kortuem 2005] build upon the *Relate* system by introducing a user interface as a set of spatial widgets to the existing infrastructure. Lyons et al. [Lyons 2009b] explore using sensors embedded on mobile devices to facilitate devices discovery through spatial sensing providing context-aware composition of multiple devices. They use an array of sensors such as accelerometer, gyroscope and magnetometer and actuators to identify the location of the device. Once the displays have been sensed, they can be used together to, for example, compose a new larger display.

Lyons et al. propose the *Dynamic Composable Computing* approach [Lyons 2009a] to wirelessly combine multiple single-display mobile devices to share co-located displays space. This technique allows users to gain a larger display real estate by combining co-located mobile devices' screens; it also allows users to run legacy applications on the newly created composed display. Schmitz et al. [Schmitz 2010] propose a framework to bring multiple single-screen devices together to create a larger display but also to interact with this newly created display using multi-touch technology from the touch screens they are composed of. They propose both manual and automatic calibrations of the displays. Technically, one device is chosen as host to the other "client" devices which relative location to the "host" is used to create the new viewport. Their system allows the devices to be physically right by each other or even slightly apart as when three devices are put together in a triangle shape.

Lucero et al. [Lucero 2013] propose to connect phones together by using the proximity of the devices and touch interaction (Figure 2.8). Once the devices are paired, the user receives audio-tactile feedback. This solution has a great advantage that users are certain that they are connecting to the right device since they do not refer to it by clicking on a list of devices' names for example but by instead using its physicality.

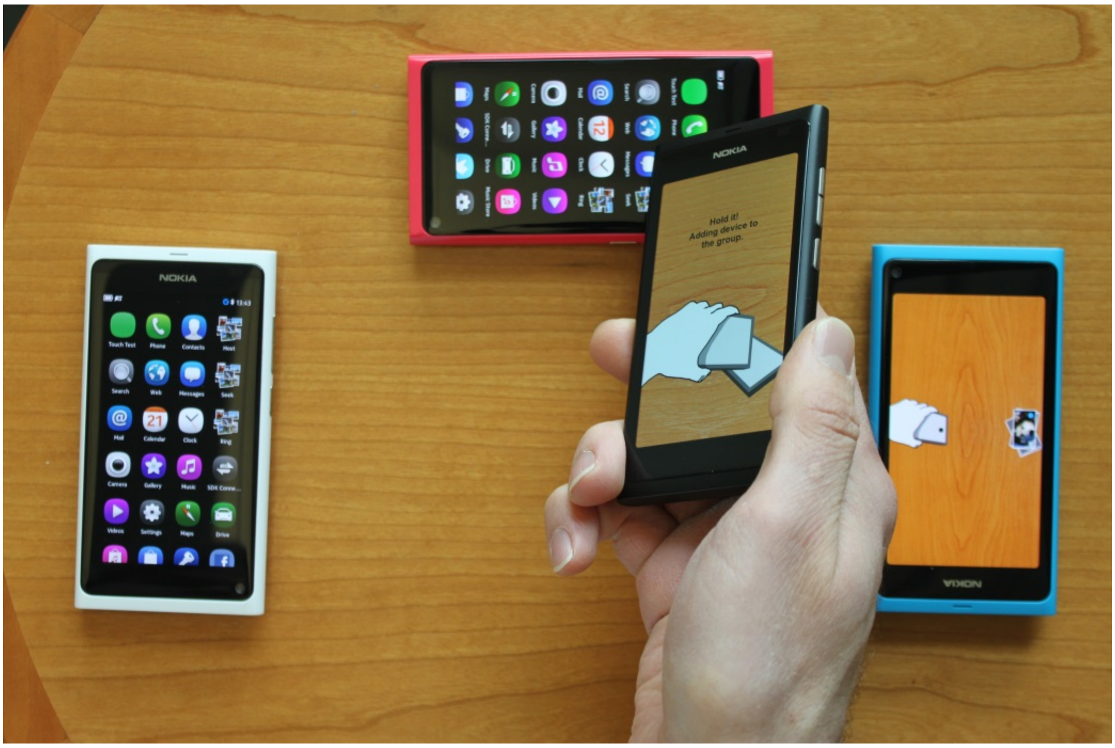


Figure 2.8: MMDE composed of multiple devices each with one screen. In this example, the user connects the devices together by bring one device over the other and using touch input. (Illustration reproduced from [Lucero 2013] with permission from Dr. A. Lucero).

Finally, as there is little work on pairing projectors together for single-user scenario, the paragraph will describe the SidebySide solution [Willis 2011b] even though the system was initially designed for multiple-user scenarios. SidebySide propose playing a projected game using two mobile projectors. Projected invisible fiducial markers in the near-infrared spectrum are used to determine the position of the visible projection relative to one another. The great advantage of their system is that it embeds an IR camera and therefore does not require any additional sensing infrastructure. It is fully portable and capable of creating ad-hoc interactive surfaces.

Interacting with the content

In terms of interacting with the larger display created from bringing the devices together; Kurdyukova et al. [Kurdyukova 2012] propose using iPad's gestures to transfer data in between two screens – two iPads –. They note that the flat shape of the device makes it easier to use physical-touch based gestures and restricts the use of spatial gestures. Pierce et Nichols [Pierce 2008] propose an infrastructure based on instant-messaging that extends applications' user interfaces across multiple devices in a MMDE. Finally, Yatani et al. propose Toss-it [Yatani 2005], an interaction technique allowing users to send information from a mobile device to another using a swing or toss action. Although their interface is planned for multi-users, it could be transferred to the single-user MDE. While research work can be found looking at specific interaction techniques in MMDEs to support multi-users using proxemics and devices' orientation [Marquardt 2012], there is little work focusing on single-user scenarios.

When interacting with two devices, such as a phone and a mobile projector, there are currently no specific interfaces adapted to when the devices are coupled. The phone has its own interaction technique and so has the mobile projector. Some manufacturers propose a phone app to interact with the projection but there is limited research for when the devices are decoupled. Interaction specific to projector phones as a single device will be presented in the next section (2.3.3).

One issue when using a projection-screen MMDE is that the screen and the mobile-projection unit are physically fixed to one another, so that the projection is affected when manipulating the mobile device. Baur et al. [Baur 2012] propose an alternative to screen and projection by simulating a projection over a fixed screen. The "Virtual Projection" is still connected to the screen, as the phone's camera is used to map the position of the virtual window. Manipulations are then possible on the virtual projection without needing to move away from the screen to increase the projection size for example. However, a major drawback of this system is that the Virtual Projection is limited to the screen physicality, therefore losing the advantage of having a border-less and potentially very large projection space that mobile projection traditionally offers.

Physical affordances

Opportunities however go beyond connecting two displays together. Siftables [Merrill 2007] and Stackables [Klum 2012] both present examples of using tangible interactive objects containing a single screen each, which can be combined in order to manipulate data and information. Girouard et al. propose DisplayStacks [Girouard 2012], a new generation of thin-film flexible digital screens that can be used with affordances similar to paper. The displays can then be piled, stacked, and overlapped linearly.

Billinghurst et al. [Billinghurst 2002] present a system which is not based on the traditional understanding of screens but that is definitely worth mentioning here. They propose holding physical display surfaces – cardboards with markers – where Augmented Reality data is displayed. The system presents multiple “screens” and the visualization happens through the Head Mounted Display (HMD). The user can interact with the multiple physical display surfaces while visualizing the AR world.

2.3.3 Single Device

This section covers MMDEs composed of multiple displays on a single device. As those devices are still new on the market, many research works simulate the single-device configuration using multiple devices, such as a mobile projector and a phone emulating an integrated mobile projector phone. As prototypes are designed as single-devices with respect to physical affordances and limitations; those prototypes are then considered single-device environments and are presented as such in this section. In particular, this section considers the alignments of the displays, and if the scenarios allow the displays to be used synchronously or asynchronously. This section exposes that the asynchronous use of the displays is sometimes due to the position of the displays on the mobile device, which does not allow users to look at both displays simultaneously.

Projection-enabled mobile devices

The first devices that appeared with an embedded mobile-projection unit on top of a screen were projector phones, such as the Samsung MBP200 [Davies 2009] that was first presented at CES 2009. Projector phones were initially marketed for business presentations where people would have a quick and easy access to content that could be shared on the projection on the spot. They were also introduced as a way to share multimedia content such as photos and videos between multiple co-located users. Recently, projectors started to be embedded into other personal mobile devices already containing a screen such as: cameras, e.g. Nikon Coolpix S1000pj [Nikon 2010]; video cameras, e.g. Sony Handycams [Honig 2013]; tablet PCs, e.g. SmartDevices SmartQ U7 [Smart Q 2013] (Figure 2.9); and more recently laptops, e.g. Fujitsu Lifebook S761/C [Savov 2011]. It is expected that the market for projector phones will grow to 20 million units by 2015 [Dickson 2010].

Figure 2.9: Picture of the projection-enabled tablet SmartDevices® SmartQ U7 [Smart Q 2013]. This Tablet PC contains both a screen and a DLP mobile-projection unit, creating a MMDE. The alignment between the screen and mobile-projection unit presents a fixed 90° angle, separating the displays by an orthogonal plane.

Applications

Since screens and projectors have very different affordances and capabilities, the applications for which a mobile device containing two screens will differ from a device containing two projectors or a screen and a projector.

The multiple screens on a single-device MMDE are traditionally used conjointly to offer added display surface to the user and as a way to manage information across the displays. In many situations, they present an extension to current use of mobile devices. They have been used for a variety of applications, such as gaming [Nintendo 2011], reading [Chen 2008], text editing [Masoodian 2004], augmenting a watch into a multiple-screen device [Lyons 2012]; and enabling 3D visualization [Harish 2009].

When considering MMDEs composed of multiple projectors, there is a gap in the literature, as very few systems actually exist. Existing systems include a conceptual projected desktop environment from a mobile device [Aamoth 2010], a dual-projection alarm-clock [Discovery Communications 2013] and also research investigating using dual-projection to create stereoscopic images [Inami 2000, Krum 2012]. Those devices are further detailed in the *Synchronous use of displays* section.

Regarding projection-screen MMDEs; researchers have proposed to study how those devices are actually being used. In a short-term field study, Wilson et al. note that participants found the projection most useful when in public environments [Wilson 2012b]. Users projected on varied surfaces including walls, desks/tables, paper, PC monitors, floor, ceiling, objects, other people, and even windows. They observe that some content – such as maps – actually requires flat surfaces to be usable. During the study, users raised concerns about personal data and privacy issues when reading personal data on the projection, despite the fictional nature of the content. A longer-term field study aims at exploring how projector phones are actually being used "in the wild" [Cowan 2012]. Cowan et al. find that usage scenarios can be divided into three categories: *private, semi-private,* and *public;* which suggests that the nature of the projection display itself changes the way the personal mobile devices are perceived by users. People reported using the device either handheld or rested on a piece of furniture, when watching a movie for example. As per the Wilson et al.'s work, participants projected on many projection spaces; moreover the projection was used as a way of sharing experiences and getting attention from others around them. Some noted that when moving the phone they would sometimes accidentally shine the projector over people or in a public plane and noticed that it was disrupting. Cowan et al. note that the usage and possibilities for projector phones go way beyond the ones for which the devices were initially marketed.

Greaves et al. [Greaves 2008] present two applications for projector phones: picture browsing and map interaction. They propose using three display configurations: screen-only, projection-only and both displays to interact with their applications. The same prototype is used by Hang et al. [Hang 2008] to study map interaction. They show that the projection, thanks to its larger display size, improved users' performance when navigating through maps but that the unsteadiness of the projection would affect it in a negative way. However, their prototype is mounted on a frame using a piece of elastic and the projection jitter could be heavier than hand jitter. They also show that text input should be performed on the screen rather than the projector. Finally, they note that participants preferred using the displays simultaneously.

Asynchronous use of displays

A major reason why displays are used asynchronously in mobile devices is due to the physical limitations of the device itself. For example, some mobile devices feature multiple screens situated on different parts of the device, such as clamshell phones where a screen is located inside the phone and the other outside as on the LG LX-150 (Figure 2.10). The external screen has appeared on clamshell mobile phones so that users would not have to operate the phone (i.e., open it) to know its status. For instance, when receiving a call, the caller id would be presented on the external screen, which would then act as a secondary display. Nakamura proposes Reversible display [Nakamura 2005], a dual-screen prototype where two screens are attached back-to-back. They propose to map the virtual object displayed to the physical object, using front and back view, so one screen displays the front of an object while the other displays the back. The displays are then paired and operated together while they cannot be seen at the same time. In the presented systems, the user does not benefit from having additional display real estate from the multiple screens, as both screens cannot be located in the user's field of view at the same time.

Devices composed of a screen and a mobile-projection unit are currently manufactured with the mobile-projection unit at the top of the screen, creating a 90° separation angle between the screen and the projection and therefore adding an angular plane between the displays. As a result, users cannot look at both the screen and the projection since they cannot be in the user's field of view at the same time. Most applications then propose to use either the phone or the projection depending on application and context, while other applications propose switching from a display to the other to interact with the system. For example, Robinson et al. propose PicoTales [Robinson 2012], a prototype to author animated stories from the screen and that can be displayed on a larger display through the projection. The displays are then used complementarily.

Figure 2.10. Pictures of a clamshell mobile phone LG LX-150 opened and closed. The device presents two screens, one on the outside to notify users when the device is closed and one inside for the user to interact with the phone. Because of form factor the user cannot use both screens simultaneously and thus cannot easily benefit from the additional screen real estate. ©LG.

Another example of asynchronous use of the displays in projection-screen MMDEs is to interact with the projected display during a call, as proposed by Winkler et al. [Winkler 2011b]. The system offers projecting information on a desk during a phone conversation when the device is held by the caller's ear. This scenario makes use of one display at a time and not both of them synchronously; it chooses to use the projected display when the physical device is outside the user's field of view.

Projection-screen devices correspond to highly heterogeneous devices since the screen and the projection have very different display properties, including display size; resolution; brightness; contrast; colour accuracy; and physical shape. They are especially interesting because of this heterogeneity between the displays. These devices offer a larger projected display, in addition to the existing screen display.

Synchronous use of displays

The previous subsection presented dual-screen devices where each screen was used independently from the other. Nintendo DSi [Nintendo 2011] is one of the first examples of displays being used synchronously. The displays are positioned one above the other and one screen is used for display only while the second one is used as display and touch input. In the 3Ds version, one screen presents a 2D display with touch input and the second screen offers 3D display technology.

The *Applications* section described applications to multi-display devices such as Chen et al.'s flexible and reconfigurable dual-screen e-book reader [Chen 2008]. They show that their "multi-slate" prototype presents advantages over a single-display device by, for example, providing better support to navigate through documents. They also propose using the two displays to show separate information, therefore compartmenting information across the displays and improving multi-document reading experience. Hinckley et al. then propose *Codex* [Hinckley 2009] as a dual screen tablet computer where the screens are separated with a hinge. The authors argue that *Codex* offers various functionalities depending on the arrangements between the displays and therefore propose a set of postures. For example, they advance single-user scenarios when the displays are located in the same field of view and multi-user scenarios when the displays cannot be seen alongside.

Nonetheless, MMDEs are not limited to dual-display devices and can present more than two displays. As such, there are cubic displays [Matsumoto 2006] or even icosahedron shaped displays [Poupyrev 2006] that consist in multifaceted devices with a screen fitted on each face; hence six displays put together in the cubic display example. Users can then visualize multiple pieces of information on the various faces. Yet, while information is displayed on all screens, not all information can be accessed at once. Indeed, the user cannot see the front and the back of the cube at once, since only up to three faces can be seen at one time. Other cubic displays propose to transform the cube into a 3D display where the image appears as if inside the cube without the need for special glasses [Harish 2009, Lopez-Gulliver 2009, Stavness 2010]. Finally, Alexander et al. propose Tilt displays [Alexander 2012b], a 3x3 small screens prototype, where the screens can be tilted to give users extra information on the displayed image such as the shape of a terrain.

Recently, researchers introduced the concept of foldable displays. They envision screens that are not rigid any longer and become foldable [Lee 2008b, Khalilbeigi 2012] or even rollable display surfaces [Khalilbeigi 2011]. Those displays are not constrained by fixed size and rigidity and can instead be resized depending on users' needs. Although, not actually composed of multiple displays, this category of devices is still presented in this section, as the screen can be folded into multiple displays. Its affordances and reconfigurability are also an inspiring technique for interacting with multiple displays on a single device. Moreover, Khalilbeigi et al. propose reconfiguring dual-foldable screens in a similar way as Codex propose reconfiguring rigid mobile screens [Hinckley 2009]. Yet, in both Lee et al. and Khalilbeigi et al.'s work, the display is prototyped using a ceiling mounted projector. It can be envisioned that the same work can be realised using a body-mounted projector and a mobile projection surface as presented in the previous section on Mobile Projectors.

While the previous systems observed multiple screens, this paragraph describes synchronous use-cases for devices with multiple projectors. Bonfire [Kane 2009] adds two mobile projectors to a laptop in order to create a mobile augmented desktop environment. The projectors are mounted on each side of the laptop and coupled with cameras so the projection can be used as both input and output. They argue that the projection can augment physical objects by the laptop, so that each respective projection would be in charge of the objects within their respective camera's field of view. Likewise, the Mozilla Sea Bird concept phone [Aamoth 2010] is equipped with two projectors located on each side of the device. They propose two use-cases.

Figure 2.11: Mozilla Sea Bird concept phone [Aamoth 2010] is equipped with dual mobile-projection units. The projectors can be used to project a keyboard on the side of the device (Left) or to give a laptop impression (Right)

In the first scenario, each side projector displays half of a touch-enabled laser keyboard, so users can type while keeping an eye on the screen in the centre (Figure 2.11 Left). The second scenario envisions replacing laptops by mobile phones by projecting a desktop environment – monitor and keyboard – from the phone that would be placed on a docking station (Figure 2.11 Right). They show how mobile projectors can empower and enhance capabilities of existing mobile devices and how various placements of the projectors and alignments between the displays can be used for different functionalities, aspect that is exploited in Chapter 3: *Exploration of MMDEs through Various Display Alignments*.

Figure 2.12: Left: Space Projection alarm clock and its two mobile-projection units on a hinge. Right: Discovery Kids Rocketship Projection Alarm Clock displaying the time and a background image from two separate mobile-projection units ©Discovery Channel

Additionally, dual mobile projectors alarm clocks intended for ceiling projection [Hall 2007, Discovery Communications 2013] can be found on the market; for which one projector beams a background image while the second superimposes current time over the background image (Figure 2.12 Right). The Discovery Space projection alarm clock (Figure 2.12 Left) can additionally project at various locations by rotating the hinge where the projectors are located. Specific literature on steerable projection is discussed in Chapter 3 Exploration of MMDEs through Various Display Alignments.

Finally, multiple mobile projectors can be used synchronously by superposing images in order to create a stereoscopic image. Both Inami et al. [Inami 2000] and Krum et al. [Krum 2012] propose using two mobile projectors embedded onto a helmet to create a perspective corrected stereoscopic image using reflective film on the projection surface.

Interaction techniques

In terms of interaction technique, Kaufmann and Hitz propose using the projection as a window onto a very large virtual workspace [Kaufmann 2012]; based on the peephole concept for mobile devices [Yee 2003]. While their technique mentions projector phones, it only requires the use of the mobile-projection unit and is therefore more appropriate for mobile projection (section 2.1). Sugimoto et al. propose Hotaru [Sugimoto 2005] as a set of manipulation techniques for projection-enabled devices. They propose direct interaction on the projection surface and recognize finger movements such as click, drag, and release. Their prototype was implemented with camera and projection positioned above the user to recognize hand movements. More research needs to address the robustness of the system in a truly mobile environment where both camera and projector are embedded onto the mobile device.

Because of the limited screen real estate on mobile devices, occlusion is a major problem when interacting with handheld devices. Wigdor et al. propose Lucid Touch [Wigdor 2007], a mobile device where multiple displays are stacked above each other so the user can interact at the back of the device and see their action by "pseudo-transparency" on the main display where the system overlays an image of the user's hands interacting at the back of the device. Winkler et al. [Winkler 2012b] propose mid-air pointing as a way to interact with a projection-screen mobile device and smoothly transition from interacting with the screen to interacting with the projection. They find that interacting behind the projector phone, and pointing at the projection yielded better results than interacting at the front or on the side of the device. They show that mobile applications benefited from the projected display and that there is a need for application-specific interaction techniques. They conclude that touch and mid-air pointing on both displays are suitable techniques for those environments.

Finally, Lyons et al. present *Facet*, a multi-screen watch [Lyons 2012] and propose multi-touch interaction via synchronous single-touch on multiple screens; supporting specific sets of gestures, such as pinching or touching three screens synchronously.

This section focussed on defining the scope and presenting the literature on MMDEs. In particular, it includes a classification of MMDEs. The following section presents some similarities and disparities between fixed and Mobile MDEs that will help inform the design of MMDEs.

2.4 Similarities and Disparities Between Fixed and Mobile MDEs

This section concludes the Background chapter and discusses some of the main findings and challenges for single-device MMDEs that appeared in this background chapter. From this point on, for simplification purposes, the term MMDE will refer to fully mobile single-device MMDEs.

- Synchronous use of displays in MMDEs

The literature shows that multiple monitor environments are primarily designed for synchronous use of the displays, while MDEs are designed either for synchronous or asynchronous use of the displays. Regardless of the usage scenario, adapted interaction techniques have been developed so that users can easily move information from a display to another and interact with the displayed content regardless of its position in the environment. The literature shows that homogeneous MMDEs often offer synchronous use of the displays. While, heterogeneous MMDEs, such as projection-screen devices, are often designed for asynchronous use of the displays, considering that users will chose what display to use depending on their context. Heterogeneous MMDEs therefore relinquish their advantage of having multiple displays and additional screen real estate, as the displays are not used synchronously. This is especially damageable as screens on Mobile MDEs are particularly small and do not allow easy access to all types of content, such as maps that benefit from being displayed on larger spaces.

In this dissertation, the presented doctoral work will investigate whether it is possible to use the multiple displays synchronously. The work will present multiple projection-screen MMDEs designs and prototypes, so users can benefit from the additional display real estate in such environments.

- Displays alignment in MMDEs

In the Fixed Multi-Display Environments section, previous work shows that MDEs provide users with effective solutions to compartmentalize and manage workspaces, as well as applications, across multiple displays. Users traditionally decompose their work into primary work, which is often positioned in the focal region of the user; and secondary tasks, that are positioned in peripheral regions. Literature shows that the position and alignment of the displays play a role in the usability and user experience, where large angles and spaces between displays create attention splits and add cognitive load on users. User interaction techniques are also adapted to manage bezels and displayless areas in-between displays. Moreover, background research shows that synchronous use of displays in MMDEs occurs when the multiple displays are positioned in the same user's field of view. However, previous work inform that current designs of projection-enabled MMDEs do not allow the multiple displays to be present in user's field of view at once. This may potentially be preventing simultaneous visualization and interaction with the heterogeneous displays and may be affecting effective use of heterogeneous MMDEs.

This dissertation will therefore explore display alignments and whether problems that occur when displays are misaligned in MDEs are translated into the MMDE space.

- Interaction techniques in MMDEs

Previous work presents a plethora of interaction techniques that have been specifically developed for MDEs. Nacenta et al. even propose a framework to determine which interaction is best suited depending on the context of the MDE [Nacenta 2009]. Yet, few techniques have been specifically developed for interacting with MMDEs. As MMDEs present devices with physical characteristics very different from their fixed counterpart, it is not clear whether interaction techniques developed for MDEs can be applied – directly and even indirectly – to MMDEs. Additionally, it can be noticed that interaction techniques specially developed for MMDEs concerned screen-only MMDEs and not projectors only, or screen-projector MMDEs. Currently, very little interaction is actually proposed with the embedded projected display and it usually stems from research on mobile projection and does not take into account the affordances of the screen on the device.

This dissertation primarily focuses on visualization and identifies the feasibility and opportunities of the MMDE. Naturally, it is crucial to first identify whether the displays can effectively be used synchronously before developing interaction techniques specific to this space. The work and prototypes in this dissertation will nevertheless provide directions and guidelines for interaction designers to explore this avenue in future work.

- From mobile projection to heterogeneous MMDEs

This background section highlights the wealth of the mobile projection space where the projection is used for a very wide range of applications and domains. Mobile projectors can be used as a way to augment the world, enhance user experience in mobile situations, express emotions through wearable ambient displays, and even as input to other electronic devices. Application domains also vary tremendously from supporting doctors, teachers, learners, and even soldiers. This shows the potential and the extent to which projection-enabled mobile devices can enhance users' daily lives.

This doctoral work concentrates on fundamental and ground aspects of MMDEs, and more specifically projection-enabled MMDEs, and does not limit its study to a specific application area. It is nonetheless essential to keep in mind how applicable those devices are.

- Multiple Projectors MMDEs

Background research shows a gap in the multiple-projectors (single-device) MMDEs where very few devices have actually been developed, researched, and even manufactured; compared to other types of MMDEs. Despite, many research projects propose using multiple projectors for multiple users, therefore on separate mobile devices. The lack of single-device multiple-projectors MMDEs can be partly explained by the fact that there are additional technical constraints when using multiple projectors compare to multiple screens on a single device. This can also be explained by the fact that mobile screens have been available on the market longer than mobile projectors, therefore presenting a more mature category of products both in terms of display quality and interaction technology. In the future, it can be envisioned that multiple projectors will be fitted on mobile devices in the same way that multiple cameras are now fitted on phones; therefore considering asynchronous usage scenarios. Moreover, synchronous usage would allow even larger "everywhere" projections from small mobile devices.

While these aspects will not be directly studied in this dissertation, it identifies a research gap in the literature within this design space.

- Space paradigm around the user

Previous work shows that users can project on a variety of physical spaces around their body such as a wall, a desk, the floor, and even the ceiling. In MMDEs, however, as the angle between the projection and the screen is traditionally fixed, it is not clear what projection spaces can be used. For example, when projecting on the floor, the user would not be able to look at the screen any longer, and therefore interact with the projection via the touch screen, as currently proposed by manufacturers. To conclude, at this point in time, the different interaction and projection spaces around the user need to be investigated for MMDEs.

As this doctoral work investigates different aspects of MMDEs, each study will also investigate a space around the user to identify which physical spaces can be used for projection.

2.5 SUMMARY

This chapter presented general background literature relevant to the research conducted in this dissertation, while more specific state-of-the-art literature is presented in the corresponding dissertation chapters. This background chapter first presented previous work on mobile projection and then defined the space of fixed and Mobile MDEs before presenting a classification of the MMDEs research space. Finally, this chapter ends with a discussion on the findings and challenges in designing MMDEs. In the rest of this document, and in view of simplification, the term MMDE is used to qualify fully mobile single-device MMDE.

The following chapter presents an exploration of the design opportunities of heterogeneous projection-screen MMDEs in terms of alignments of the displays. In particular, it presents a steerable mobile projection prototype that is used in an exploratory study to determine the preferred projection offset angle for different tasks. Two interaction techniques are then implemented, considering interaction scenarios were the projector and camera can be either coupled in the same field of view or decoupled (i.e. in different fields of view).

Chapter 3
EXPLORATION OF MMDES THROUGH VARIOUS DISPLAY ALIGNMENTS

Chapter 2 presents the literature on Mobile projectors, fixed and Mobile Multi-Display Environments. In particular, it defines the scope of MMDEs: how they are designed; what technology they rely on; and what research has already been conducted in this field so far. Furthermore, a classification of MMDEs is introduced and it is identified that this dissertation will in particular address MMDEs composed of heterogeneous displays.

This chapter[1] explores the design opportunities brought by combining a screen and a projector, in an instance of a heterogeneous projection-screen MMDE. It first presents specific related work and shows that the traditional arrangement of the screen and the projector in a mobile device is not always suited and that steerable projection could help resolve this issue. A mobile steerable projection prototype is built and used to run an exploratory study that determine preferences for offset angle between the two

[1] Part of the material in this chapter was published in the PUC journal [Cauchard 2012a] and in the UbiProjection workshop at Pervasive [Cauchard 2010].

displays depending on application context. The study shows that different screen-projector alignments are needed for different tasks and that participants would want to use different angles between the displays depending on the context of use. Conclusions are drawn on this study to inspire novel interaction paradigms for mobile steerable projection systems. A second study explores projections that are "touched" with the hand or foot, as well as projections that detect user's hand or foot movements in front of the device's camera as input to the projection. Results prove that different interaction techniques are needed depending if the projector and embedded camera are aligned or misaligned. Finally, the chapter is concluded by a discussion on the study results and future work. This chapter provides a better understanding of the challenges arising when studying heterogeneous projection-screen MMDEs and will help ground the research directions for the rest of the dissertation.

3.1 INTRODUCTION

From the Background section, it was identified that one of the main challenges in single-user MDEs – fixed and mobile – is the synchronous use of the displays. While in the fixed environment, there are guidelines to how the displays need to be positioned to be used synchronously [Su 2005] and a wide body of research on interaction techniques specific to those environments (section 2.2.5); very little work considers this aspect in mobile devices. Furthermore, in the mobile environment, very few systems actually allow synchronous use of the displays by a single user.

The work presented in this chapter aims at filling this gap by exploring the advantages of having multiple displays in a single mobile device. Chapter 2 demonstrates that most heterogeneous MMDEs are conceived with the idea that the user will use either one display or another depending on the context. For example, the Sony camera-projector [Sony 2011] is designed for users look at the screen when taking a photo and at the projection to look at the photos. In the future one could imagine projecting extra information on the background while taking pictures using the screen. The displays would be used simultaneously. The current design works against the benefits of having additional display real estate on a small device; in spite of having a device that allows a display space larger than the device itself, and that can potentially project anywhere.

Furthermore, the physical placement of the mobile-projection unit inside the device is critical to the usability of the MMDE and this aspect is explored as a research and design opportunity. Actually, while mobile projectors are being heralded as a new opportunity for co-located collaboration [Cao 2007]; it remains unclear how these projected displays fit alongside the existing hardware ecology of the mobile device. This is how personal projectors offer one of the first design challenges for MMDEs. Indeed, the ways in which mobile projectors are physically positioned in the device will affect the use of the other components of the mobile unit: both inputs (such as keyboards or cameras) and outputs (such as screens or vibrotactile motors). This creates new challenges for the role of the traditional mobile device’s screen, particularly with regard to its placement relative to the projection.

This chapter presents specific background literature on display arrangements, steerable projection, and adapted user interaction techniques (3.2). It shows that there is currently no related work motivating the relative placements of multiple displays in MMDEs, while Chapter 2 shows that this aspect is critical when interacting in MDEs. This chapter therefore explores different alignments between the screen and the mobile-projection unit through the design of the first mobile steerable projector prototype (3.4). Results show that different angular orientations between the displays are needed for different contexts and uses (3.5). Specific interaction techniques are then implemented (3.6) for different placements of the projection-unit within the mobile device and an exploratory study determine their effects on users. Results show that the interaction technique to be used depends on the position of the mobile-projection unit relative to sensors such as the camera (3.7). The chapter concludes with a discussion of the results and suggestions for future work (3.8).

3.2 BACKGROUND

This section presents the motivation behind this chapter’s work as well as specific literature review on display arrangements in between multiple displays in the mobile environment, the orientation of the mobile projector, steerable projection, and interaction techniques for projection-enabled mobile devices.

3.2.1 Displays Arrangements

A number of possible designs might be used to control the relationship between two displays in an optimal manner. In commercialized projector phones, the mobile-projection unit is typically mounted above the screen with a horizontal projector throw. This generates a fixed orthogonal angle between the screen and the projection, making it difficult for the person holding the device to see the screen and projection simultaneously, or even to rapidly interleave between them. This might not be an issue if, for example, each display were used separately – the projector for public interactions and the screen for private ones.

This ‘traditional’ configuration of fixed mobile-projection unit within the device may be unsuited to many tasks because it couples the orientation of the device to the management of the projection space, preventing users from easily and simultaneously using the mobile device and looking at the projection. For example, this fixed arrangement of displays would preclude new opportunities that exploit both displays simultaneously; as Hang et al. [Hang 2008] demonstrate the advantage of using both a projector and a screen for specific applications such as text input. With synchronous dual-displays, users can also decide which data they want to keep private and which data they want to share on the other display at the same time. The Codex device [Hinckley 2009] for example describes an alternative to separating, interleaving or switching off displays with a device that possesses a range of ‘postures’ corresponding to different operational modes identified through the hinge angle.

An alternative dual-display configuration might be to physically separate the mobile-projection unit from the device to support the dynamic juxtaposition of the displays. However, physically separating displays imposes increased demands on user control, cost, power, additional hardware to send video signals, and prevents the projector from easily benefiting from the device’s existing input capabilities such as accelerometers and touch screens. It obviously loses the interests of the single-device environment.

In terms of orienting the projection, applications such as presentation viewing might benefit from being projected on a wall. However, an Augmented Reality (AR) application guiding the user through streets, such as the Nearest Tube Application [Acrossair 2009], might benefit from being projected directly on the pavement, where users can interact with the application by stepping onto directional arrows. Similarly, it is interesting to note the 90° angle between the screen and the projection beam in the AR project Map Torchlight [Schöning 2009], which connects a mobile phone and projector in a fixed alternative configuration, although it does not respond to the problems of contextually adapting the projection angle.

3.2.2 Steerable Projection

According to Ashdown and Sato [Ashdown 2005] p.1 “a steerable projector is a projector whose beam can be moved under computer control”. Steerable projectors allow to project content virtually anywhere in a room, such as the “Everywhere Displays” [Pinhanez 2001] that transforms any projection space into an interactive touch interface [Pinhanez 2003b]. They can also project on any object or surface in the environment and adapt to the user’s needs in terms of interaction [Pingali 2003]. In the case of personal steerable projectors, users should be able to choose relative display angles that are best suited for them depending on the context.

It is expected that some offsets are better suited than others for particular tasks or applications, these correspond to the “difficulties in handling the context switch” described by Hang et al. [Hang 2008] p.214. One difficulty in switching contexts may be that mobile phones or PDAs contain private data such as contact details, personal information, text messages, emails, or pictures. In the case of projector phones, the projection can be used in conjunction with the screen by either cloning the displays or by displaying complementary information across both displays. Cao et al. address potential privacy issues with a permission control system, in which data is either public, semi-public or private, and get displayed accordingly [Cao 2007].

A steerable projector offers a solution in which displaying such categories of information determines or is determined by the spatial relationships between a private and public display. Users can choose where to display information, for example, they can decide to project on a large projection space (public) in front of them or on a smaller one on a desk for more controlled semi-private sharing. Also, a specific projection angle might be more adapted to respond to the physical constraints of the projection surfaces available as discussed later in this chapter. For example, on a train an appropriate projection space might be the folding tray attached to the rear of the seat in front. Thus, it is expected that the optimal projection angle will depend on criteria such as the nature of the application displayed on the screen, the privacy settings, and the environment. The privacy settings are determined in terms of data privacy as well as in terms of private/public spaces. Yet, there is currently little principled information on mechanisms or preferences for projected display use. To explore this emerging design space, the focus was put on observing the angle between a screen and a mobile-projection unit coupled in the same mobile device. The steerable mobile projector prototype designed is presented in the Prototype section below.

3.2.3 Interaction Techniques

Several projects have explored input techniques for mobile or wearable projection systems. However, at this time interactions with projections from these devices are limited in a couple of key ways. Firstly, the device's hardware ecology itself may prevent users from managing the device where and how they want to. For instance, the Light Touch™ projected keyboard [Light Blue Optics 2010] needs to be put down on a flat surface at hand reach in order for the user to interact with it, cutting down on its mobile capability. Similarly, the Skinput interface [Harrison 2010] requires the device to be fixed on the user's body and for the user to not move their body relatively to the projection so their skin can be used as an input surface.

Influence of alignment

The fixed or worn projection can make it difficult to rapidly choose and use appropriate interactive surfaces as the user moves through the environment. Additionally, the fixed relationship between the camera and the projector assumes that the interaction should be aligned, in some way, to the projection. For instance, Mistry and Maes [Mistry 2009a] present a technique based on mid-air interaction where users can gesture to a camera worn around the neck and Cao et al. [Cao 2007] use a combination of two buttons attached to the mobile projector as input.

The relative placement of input and output capabilities on handheld mobile devices could create significant problems for interacting with projections. Rukzio and Holleis

[Rukzio 2010] and Löchtefeld et al. [Löchtefeld 2011c], for example, both raise this issue for different alignments of the mobile-projection unit and the camera in a projector phone. Moreover, if a touch screen and mobile-projection unit are not aligned on a device, then the use of the touch screen as input to the projection is virtually impossible. Recognising this problem, steerable projectors have emerged such as the S-Vision prototype [S-Vision 2010] that, equipped with a hinge, can be sat on any surface and project at different heights, regardless of the device's own position.

Characteristics of Interaction with Handheld Mobile Projectors

Interaction techniques for steerable projections have to be flexible enough to support the use of different projection surfaces: from the traditional wall projection, to projecting on a table or even on the floor. Pinhanez et al. propose using a steerable-projector camera system to interact with the projection in the fixed environment [Pinhanez 2003a]. In the mobile environment however, some features require of the MMDE to be held in a steady position; so the projections' interaction techniques need to be viable when the device is being held. Indeed, the main advantage of handheld steerable projectors is that they are fully mobile and therefore should not require the device to be placed on a stable surface to be used.

The study that is described and presented below in: *Study 1: Projection-Device Orientation* presents a touch screen input as per the research literature and as is available in most commercialised projection-enabled mobile devices. However, current touch screen technologies mostly give visual feedback and are not always practical for 'on the move' interaction in which users might not want to look at the screen in order to interact with the application. Furthermore, small touch screens preclude synchronous shared interaction between pairs or groups with a projection. A good technique for 'on the move' interaction would also allow unconstrained movement with no additional sensors or physical tags.

Interaction techniques for mobile projection

In order to control the projection without the touch screen and the physicality of the device; designers need to consider how to 'click' or select content as well as move a cursor or point of focus. Several selection techniques have been proposed in the literature for various gesture interaction systems. One possibility is the user's hand dwelling over the item they want to select beyond some fixed length of time. The dwell selection technique consists in hovering the hand over the projection space and is derived from Kirstein and Müller's pointing technique [Kirstein 1998]. Another possibility would be to put a reflective surface on the user's body part that can easily be recognised by a camera, such as the "spotlight from tape on a [...] boot" ([McFarlane 2009] p.212) in the Interactive Dirt system. Another example is the use of a vision-based technique to recognise hand shape, such as the pinch gestures proposed by Wilson [Wilson 2006]. These techniques require the user to learn a set of gestures to use the system.

Finally, another solution would be to use a camera-vision system associated with the projection in order to recognise the distance between the user's hand or foot and the projected image; a selection could be made when the user touches the projection space itself as presented for interacting with Steerable Projected Displays [Hartman 2002, Kjeldsen 2002]. This techniques is more commonly used with fixed position depth cameras alongside interactive projection surfaces [Benko 2008, Wilson 2012a].

Lastly, feet can also be considered in such interaction as any body parts. This interaction type has been proposed for input with interactive floors [Augsten 2010] but also as a way to provide eyes-and-hands-free interaction with mobile devices [Scott 2010]. Work that is more recent has looked at different foot gestures to interact with mobile devices [Han 2011, Alexander 2012a, Matsuda 2012].

Interaction techniques for mobile steerable projection

The Prototype section describes a steerable mobile projector and suggests that the user could employ different body parts to produce interactive input. Direct interaction techniques were explored (section 3.6: Interaction Techniques) using hands and feet depending on the angle of projection, as these provide the greatest reaching range to touch a projection originating from a handheld mobile device.

As well as considering the body as direct input, the alignment between the projector and the camera was configured to track the hands or feet for indirect interaction. Since the projector's throw angle can be changed, designers may consider fixing the camera to the projector's steering mechanism so that they are always aligned. However, as with the study tasks described in section 3.5, interaction designers may also wish to consider situations in which the control space and projection space are misaligned and so make the camera independently steerable. This would allow users to control their projection without detracting from the projected content or without being noticed, as in Montero et al.'s secretive gesture [Montero 2010]. Thus, one may design a system to allow the interactive and projection spaces to be deliberately aligned or misaligned at particular points in a task.

3.3 APPROACH

Drawing on the innovative examples from the Background literature, a generalised approach to the configuration issues between the heterogeneous displays is suggested by using steerable mobile projection. In this configuration, both the displays and their inputs can be reoriented with regard to one another on the same device in order to create different juxtapositions and arrangements that suit particular tasks. For this purpose, a steerable projection-screen device was prototyped, for which the orientation of the projection beam can be modified by entering a specific angle on the touch screen interface. The alignment between the two displays is then modified at the click of a button.

The prototyped system is flexible enough so that automatic steering could be added depending on sensors input such as an accelerometer or a compass. This prototype was used in the first (of two) user study. Two interaction techniques were then designed to add interactivity to the device. They required updating the prototype with a different mobile device equipped with better processor capabilities to provide real-time input.

Section 3.4: Prototype describes the technical implementations of the dynamically steerable projection-screen device and section 3.6: Interaction Techniques describes the implementation of the specific interaction techniques.

The first study then demonstrates the requirement for such an approach and determines initial preferences for display offset depending on application context. Conclusions are drawn on this study to inspire novel interaction paradigms for combining such steerable projection systems with interactivity. The interaction techniques adapt to situations in which a variety of projection surfaces may be selected, and a variety of input techniques may be used depending on a user's choice of alignment or misalignment with the projection beam. A second study explores projections that are touched with the hand or foot, as well as projections that detect user's hand or foot movements in front of the device's camera as input to the projection.

3.4 PROTOTYPE

The prototype was implemented using a Samsung Omnia HD i8910[1] (running Symbian 5th Edition OS) and a mobile projector (Pico Pocket V3 Projector). The device is assembled together to simulate a *single-device-multi-display* environment.

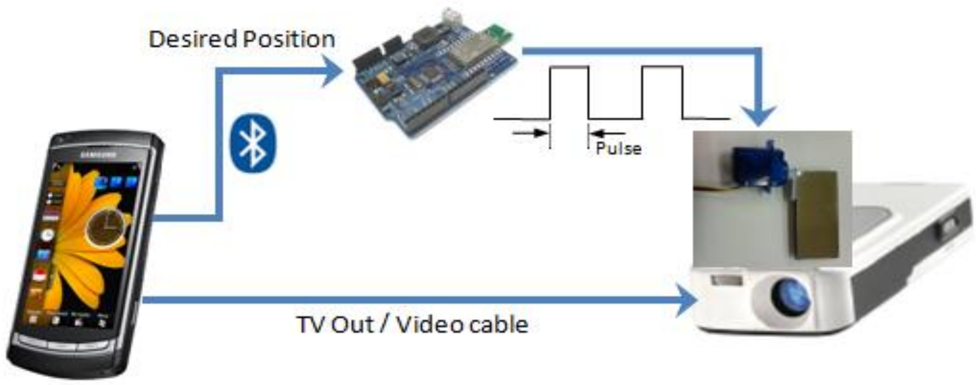


Figure 3.1: Architecture of the steerable projection-screen prototype using a mobile phone, mobile projector and an Arduino board. The phone sends information to the Arduino board via BT giving the desired position of the projection beam. The board modify the Pulse Width Modulation of the signal sent to the servomotor to modify its rotational position. A mirror is fixed on the servomotor that is fixed above the mobile projector's lens. The direction of the projection beam is modified via the rotating mirror. The mobile projector is plugged on the phone's TV Output via a bespoke video cable.

The phone and the mobile projector communicate through a bespoke TV-out/mono cable. This prototype is fully portable and the architecture (Figure 3.1) can be used with any mobile phone equipped with TV-out capability. The prototype can also be used with any mobile projector with Composite Video input. For this example, a mirror was incorporated at the top of the mobile projector's lens, based on Pinhanez' Everywhere Display projector [Pinhanez 2001] but adapting their design to mobile use.

[1] After user study 1, the Samsung Omnia HD was replaced by a Nokia N900 for its computational power

Although a final design would mount the lens on a pivoting head inside the device and/or use an array of steerable Micro-Electro-Mechanical Systems (MEMS) mirrors; for the proof-of-concept, a single larger mirror was cut and attached to a micro servomotor (Hitec HS-55) which is controlled by an Arduino Bluetooth microcontroller. Figure 3.2 illustrates the prototype with the protective cover removed to see the electronics inside the black box.

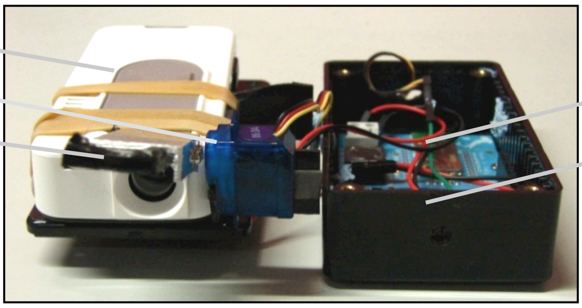


Figure 3.2: Prototype disassembled to show components. The electronic components of the system: Arduino board and the battery are protected inside a plastic case. On this picture, the top of the plastic case is removed

The user selects the angle of the mirror through the touch screen; the application then wirelessly sends information to the electronic board that adjusts the mirror's position accordingly (Figure 3.3).

The presented prototype automates the selection of different projected orientations. Although manual projection systems such as WowWee's Cinemin Swivel [Wowwee 2010] are more straightforward to implement; automated steerable designs offer more possibilities. These include: readjusting the projection's position; keeping the position still even if the user's hand is moving (such as using accelerometers to perform tilt compensation); automatically finding the optimal projection surface; and even moving the projection itself (for example to indicate directions or to adapt to coarse changes in the user's position such as lying down).

```
from bluetooth import *
from appuifw import *

def bt_connect():
    global sock
    arduino_addr='00:07:80:90:8A:33'  #Arduino BT address
    sock=BluetoothSocket(RFCOMM)
    target=(arduino_addr,1) #serial connection to Arduino BT
    sock.connect(target)

def bt_send_data():
    global sock
    #find a way to query the data
    data = appuifw.query(u"Type an angle:", "number")
    sock.send(chr(data))

bt_connect()
bt_send_data()
sock.close()
```

Figure 3.3: Snippet of the application used to send the position of the motor to the Arduino board in Bluetooth – written in Python for the S60 mobile platform.

Steerable projection is affected by standard projection issues such as keystone. If the system makes use of a mirror, then the lens needs to be kept as close to the mirror as possible in order to minimise distortion. In this prototype, the keystone distortion is avoided by sending a signal to the projector at a lower resolution than the maximum resolution. This reduces distortion at the extremities of the image but also reduces the overall scale. Steerable projection systems may also present difficulties with focus although mobile laser projection technology mitigates this problem.

3.5 Study 1: Projection-Device Orientation

This exploratory study aims to determine to what extent steerable mobile projection is important for supporting different uses of projector phones, as they are the most common type of projection-screen MMDEs at this time. Although it was then decided to focus exclusively on single-user scenarios for MMDEs, this study was the first exploration of the space and was run for both single users and pair of users in order to identify potential challenges faced by single users compare to pairs.

This initial exploration aims to determine whether different angles between the mobile device's screen and the projection beam are suited to different tasks. Three simple tasks were designed for participants, during which the selection of different projection angles was monitored. It was hypothesised that:

> H1: *Participants prefer different orientations between the screen and the projection for different tasks.*
>
> It is expected that different orientations are better suited for different tasks.
>
> H2: *Participants prefer the floor projection angle while on the move.*
>
> The reason behind is that in the mobile condition, users will not always have a constant wall space to project on.
>
> H3: *Participants prefer the desk projection angle to read the email aloud*
>
> It is hypothesised that users will feel more comfortable when displaying private information, such as an email, on a desk.

3.5.1 Study Design

Twenty-one people between 22 and 40 years old were recruited to test the prototype, seven working as individuals and fourteen working in pairs (4 pairs were unisex and 3 were of mixed gender). All participants were regular mobile phone users, a minority were already smartphone owners, and none had ever seen or used a mobile projector.

Individual participants and pairs performed each task using one device only. While the prototype can support steering to any angle, the experiment software was implemented with a choice of three pre-determined projection angles, labelled as: Wall Projection, Desk projection and Floor projection (Figure 3.4). Wall projection corresponds to a horizontal projection, identical to the one available on current mobile projector phones. Desk and Floor projections respectively correspond to a 30° and 50° downward inclination.

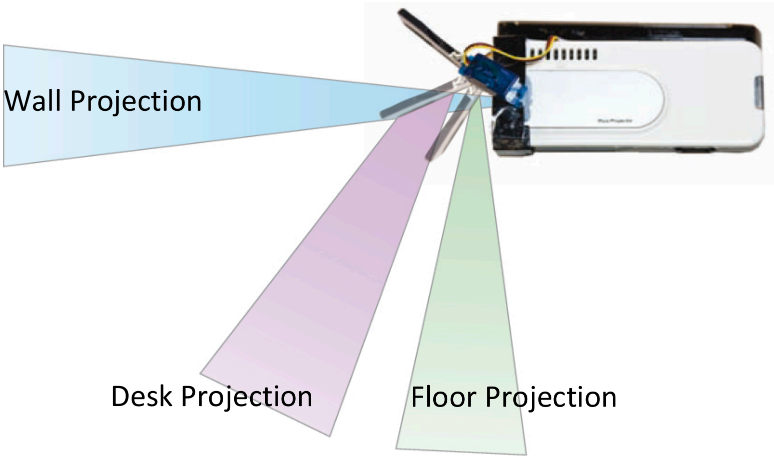


Figure 3.4: Superposed photographs of the steerable prototype (left-side view) at different projection angles with a reproduction of the position of the beam according to the mirror's orientation. The study presents three different angles labelled: Wall, Desk & Floor Projection.

3.5.2 Procedure

The interface for switching angle is very simple, providing a single 'angle' button at the bottom left of the touch screen that opens a pop-up menu with three choices: Wall, Desk or Floor, obviously corresponding to the angle of the same name. The projection angles were purposely given names and not displayed as the number of degree they correspond to so they would be more meaningful to the users. As this could have been confusing for participants, it was therefore emphasised that they could project wherever they wanted, regardless the name of the angle.

Each session lasted between 30 and 45 minutes. During the first part of the session, the prototype was demonstrated to each participant (individuals or pairs). Participants used the prototype until they were familiar with the system. Since the interface was very straightforward, only two touches to change angle, participants were rapidly confident to use the system on their own. In the case of pair participants, only one user would hold the device, and in some cases, participants decided to take turns regarding who was holding the device during the experiment.

Participants were given a set of tasks and asked for each of them to choose the projection angle they felt most comfortable with in order to complete that specific task. It was made clear that the participants should complete the task in their own time and that they could choose any surface to project.

The tasks were chosen to include a spread of demands from keeping the projection very still to observing as much detail as possible through to using the projection on the move (mobile condition). In order to test the hypotheses, three tasks were designed, which could be used for personal projection, and the observer recorded the extent to which preferences for particular angles were shown. The three tasks were:

- *Spot the difference*. Participants projected two images (Figure 3.5) and had to spot at least five differences between them. It was expected that this task would highlight different needs between individuals and pairs.
- *Reading*. Participants had to read aloud an email displayed on the projection. This task required the user to keep the prototype very steady while concentrating on the projected image. It was expected that it would highlight considerations for privacy.
- *Navigation*. Participants had to follow projected arrows (Figure 3.6) to help them navigate between two points across a maze. They were walking while holding the device and interacting with it using the touch screen. It was expected that motion would challenge the participants to find new projection spaces in a continuous manner.

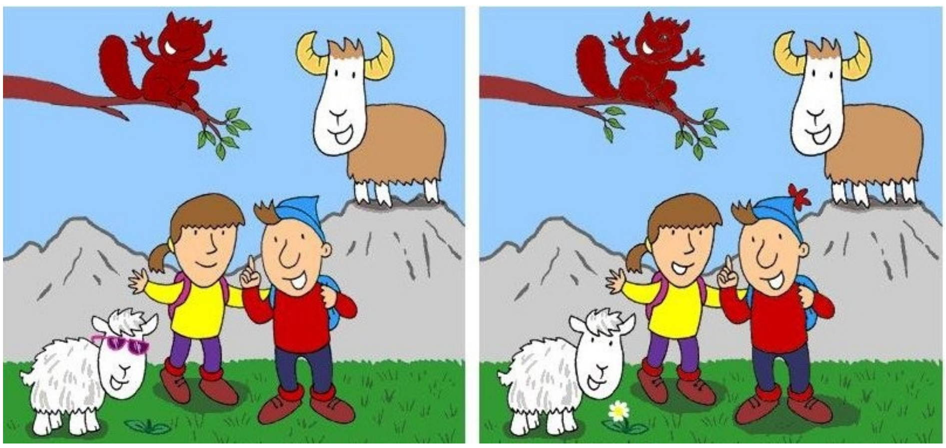


Figure 3.5: Pair of images used in the *Spot the difference* task. The images were projected side-by-side on the projection. The images feature more than five differences but because of the limited resolution of the mobile projector, participants were asked to find only five.

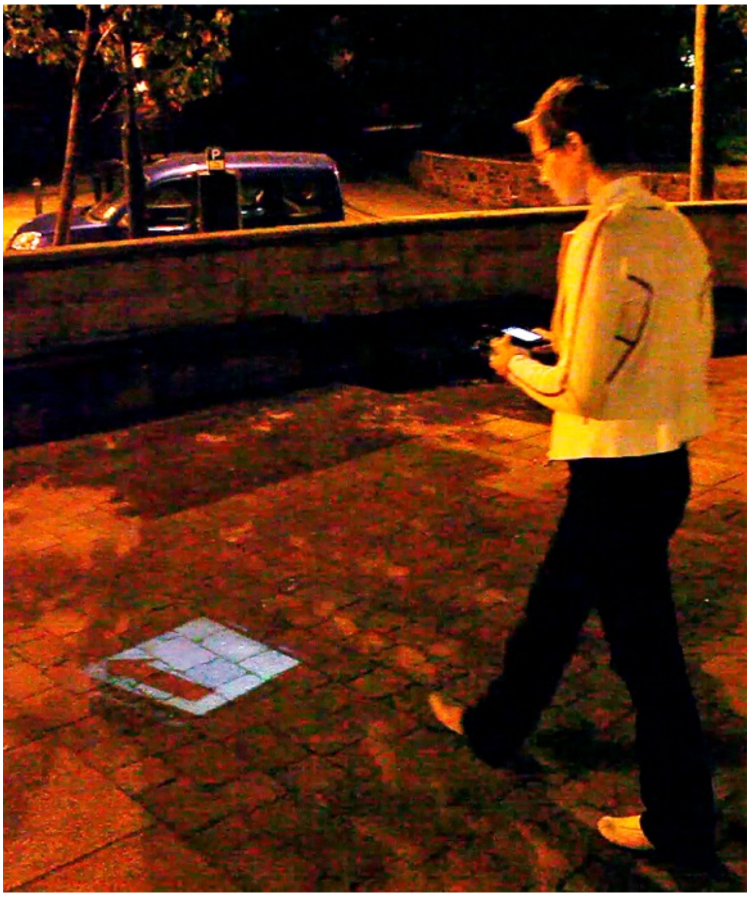


Figure 3.6: Navigation task: Participants had to follow directional arrows to direct themselves through a maze. The experiment was conducted indoor in a dim light controlled environment. The arrows were presented in a timely fashion without the use of an indoor navigation system

The observer monitored if and how often participants changed angles during tasks, between tasks, and for what reasons in a questionnaire. Participants' behaviours were observed during the sessions using a think-aloud protocol (and listening to conversations between the pairs) and a semi-structured interview was conducted after the completion of the tasks to gather qualitative results. Participants identified and explained their angle preferences for each task. They were then given an opportunity to express their opinion on the device, and asked if they would use it if available and in which situations.

3.5.3 Results

Firstly, participants were very enthusiastic about the user study and very excited to try out the prototype. They grasped the concept of steerable projection spaces quickly and showed no difficulty using the touch screen to switch angles. As expected, some participants found the low quality of resolution and contrast as well as keystone effects limiting. For each task, a Pearson's chi-square test was conducted to identify whether preferences of viewing angle were significantly different from random choice for the task. Observations on the detail of participants' selected angles were also recorded.

Figure 3.7: A Pair of participants performing the Spot the difference task. Left: Participants are using the *Wall* projection angle. Right: Participants are using the *Desk* projection angle and the participant who is not holding the device points at the difference on the projection on the desk.

Task 1: Spot the difference

A Pearson's chi-square test indicated a significant difference between the observed and expected frequency of angle that participants felt comfortable with ($\chi^2 = 7.43,\ df = 2,\ p < .05$). The majority (57%) selected *Wall* projection (Figure 3.7 Left), with the remainder (43%) selecting *Desk* projection (Figure 3.7 Right) and none selecting *Floor* projection.

For pairs, one participant typically held the device while the other pointed at the differences (Figure 3.7 Right); some participants used the shadow of their fingers on the beam to point to details of the image. Most participants tried completing the task with different angles, and some changed angles during the task. Most participants looked for an angle they were comfortable with at the beginning of each tasks + explain that they kept it

Participants reported that the *Desk* projection was chosen because it was closer and easier to point at and touch the projected image. The *Wall* projection was chosen as a natural physical position, with more control over the projection size. Most participants (70%) said they would be likely to change angle depending on various factors, including: surfaces available to project on, number of people they would want to show an image to, and how simple it would be to change angle.

Task 2: Reading

A chi-square test showed a significant difference between the observed and expected frequency of angle selected ($\chi^2 = 7.43,\ df = 2,\ p < .05$). The majority (57%) selected *Desk* projection, with the remainder (43%) selecting *Wall* projection and none selecting *Floor* projection.

As expected, reading an email aloud raised some privacy concerns. The choice of reading task for email was perhaps even distracting as some said they would not use the projection at all for reading email, while others believed that they would only use it in private or semi-private places. The *Wall* projection was described as being "more comfortable", with no need to bend one's neck, just looking straight ahead. However, participants also indicated that they would switch to *Desk* projection if they were in a more public place. This confirms that the projection space itself can be used as a way to manage privacy. *Desk* projection was also chosen because participants found the horizontal surface to be the most sensible place to read. A number of participants commented that they would like to pre-set a "reading angle" on their personal device.

Task 3: Navigation

A chi-square test showed a significant difference between the observed and expected frequency of angle selected ($\chi^2 = 10.86,\ df = 2,\ p < .01$). The majority (71%) selected *Desk* projection, with the remainder (29%) selecting *Floor* projection and none selecting *Wall* projection.

All participants used the floor[1], as projection surface for the directional arrows as there was no adequate continuous wall space while walking. The choice between *Floor* or *Desk* projection angle seemed dependent on how participants were naturally holding the device: horizontally (*Desk* projection preferred) or tilted upwards (*Floor* projection preferred). When the device was held horizontally, *Floor* projection was very close to the body and participants did not feel comfortable walking while looking at their feet.

On the other hand, when the device was tilted, participants found the *Floor* angle approximately suitable. They commented that it should be easily adjustable, depending on factors such as:

- Number of people around. For example, they could use a short angle in a crowded place, so the projection would be closer to them
- Terrain. For example, going up hill will require the projection to be further away from the user and down hill would require it closer.
- Speed. The projection distance would need to be adjusted to the speed. For example, a runner would want the projection further away from their body compare to a person walking.

Participants also commented that in general it was tricky to simultaneously walk along the path and control the projection through the touch screen. In most cases, they had to stop walking to change the projection angle, then to resume the task with the new projected angle.

Additional Results

Results were collapsed across all tasks to test whether there was an overall preference for a particular projection angle. A chi-square test showed a significant difference between the observed and expected frequency of angle selected ($\chi^2 = 14.29,\ df = 2,\ p < .001$). Across all tasks, the majority selected *Desk* projection (57%), followed by *Wall* projection (33%), and finally *Floor* projection (10%).

This small-scale study did not have the statistical power to make definitive conclusions about significant differences between individual and pair behaviours. However,

[1] The word "floor" refers to the physical ground, while "*Floor*" refers to the angle used on the prototype.

discussions during the interview indicated that pair interactions heightened a focus on privacy issues. Moreover, pairs appeared to change projection angle more frequently. This may have been to achieve the more complex task of balancing a co-participant's changing viewing requirements with the user's own viewing requirements.

3.5.4 Discussion

In terms of the initial hypotheses:

> H1: *Participants prefer different orientations between the screen and the projection for different tasks.*

H1 was verified as evidence was found that the task being undertaken affects the projected orientation requirements and therefore that different tasks from the selected activities will produce different preference results. For the selected tasks, the overall preferred projection-screen coupling angle was *Desk* (30º), and not the *Wall* angle (0º) currently preferred by mobile projection-screen devices' manufacturers.

> H2: *Participants prefer the floor projection angle while on the move.*

H2 was partially verified. In the task that included user mobility, all users decided to project on the floor. Yet, most participants used the *Desk* angle and not the *Floor* angle to project onto the floor. As explained in the results section, this is mostly dependent on how people hold the device in their hand: inclined or flat. Moreover, the angle currently chosen by manufacturers, *Wall* configuration was not used at all in the mobile task.

> H3: *Participants prefer the desk projection angle to read the email aloud.*

H3 was partially verified. Reading an email read privacy concerns and some users mentioned that they would not project personal data on a projected screen as they felt it would become too public. Participants did confirm that they would switch to *Desk* projection in a more public area although most felt it was more comfortable to project on the wall. For some participants *Desk* projection was the most sensible place to read.

The experiment was deliberately run in a room where many types of projection surfaces (such as whiteboards and desks) were available, so users could decide their ideal projection surface for each task. Every single participant, at some point, changed angle to accomplish the tasks. They all agreed that they would use different angles depending on the context or the application that they were using. Thus, there were strong observational and statistical evidence for the benefits of steerable projection. Participants also provided some interesting suggestion for future designs, including the idea that coupling angles could be automatically recognised by the device depending on the chosen application, controlled at a sub-degree level using analogue controls, and many participants suggested preset favourite angles for given tasks along with other device profile settings. While all participants managed to complete the reading task, some had to find a comfortable distance between themselves and the projection surface – where the letters would be big enough to be read and the image resolution still good enough to read comfortably. None complained of hand jitter affecting them from reading the text.

Finally, the relationship between steerable projection and interactivity – restricting control of the projection to the screen – meant that participants had to iterate between the screen and the projection for control. This issue was particularly prominent in the navigation case where moving compounded the difficulties. It was also particularly observable in studies with pairs where participants had to iterate between angles, often to balance the needs of the user and the observer. It was observed that using projection surfaces that are far away from the hands, such as floor projection, imposes increased demands on the design of suitable interaction techniques for these settings. The following section explores how these implications have inspired the design of interaction techniques for steerable projections.

3.6 INTERACTION TECHNIQUES

In order to demonstrate the capabilities of interactive steerable mobile projection systems, the steerable projection system presented in the above *Prototype* section and used in *Study 1: Projection-Device Orientation*, was updated to support hand and foot tracking through the device's camera. The tracking is realised through real-time vision-based algorithms that make use of the OpenCV library directly running on the Nokia N900 phone. Han Teng (University of Bristol) designed this tracking software. I conducted all other implementation and drove the research. The system is completely autonomous and does not require server-side processing. Although an independently steerable camera was not built; yet, it was decided not to fix the camera relatively to the projector in order to explore different alignment settings for the interaction. The angle between the camera and the projector can currently be changed manually – since the prototypes uses the phone's camera, the angle is between the phone's body and the mobile projector.

Two settings were designed in software: the first corresponds to the camera and projector being aligned, while the second setting corresponds to the camera and projector being misaligned. In addition, different interaction techniques were implemented to respond to the challenges of the different alignment settings. In both cases, a vision-based algorithm, explained below, is used to recognise the colour, shape, and contour of the hand and foot. This ensures that other objects in the environment do not trigger interaction. Examples of these techniques in use can be found in Study 2: Early Investigation of example Applications.

Algorithm for aligned Camera-Projector

In this setting, the camera's interaction space matches the projection space, which means that the camera 'sees' the projected image. The technique implemented for this setting corresponds to a dwell-threshold based selection technique using the hand or foot of the user. This is particularly suitable since the user looks at the same space as the camera; moreover, there is no need for a cursor since this is a direct manipulation within the projection.

In terms of the algorithm itself, the contour and position of user's hand or foot are detected using colour segmentation, frame by frame, with the OpenCV library. Colour segmentation is a commonly used method to separate human body parts from the background [Manresa 2005]. Moreover, this method does not require excessive processing power and can be used in real-time on a phone without limiting other processor demands. The HSV colour space [Tsang 1996] was used to set a range of colours that would correspond to skin colour for hand recognition and tracking. In the case of foot tracking, for the purposes of this demonstration, a dark range of colours was used, imposing the limitation that the user had to wear dark shoes (although more sophisticated algorithms could be implemented). HSV colour model is especially helpful to analyse the image information with non-uniform lighting conditions. Once the hand or foot is recognised, the algorithm separates the contour from the rest of the background (segmentation stage), allowing the software to easily determine the position of the user's hand or foot (Figure 3.8). When exploring this design, environmental factors such as indoor lighting, and the projection background colour were kept under-control in order to reduce the image noise and increase the stability of the recognition algorithm; again, more stable algorithms are possible beyond this demonstration, although real-time responses of these will trade-off against locally available processor capacity.

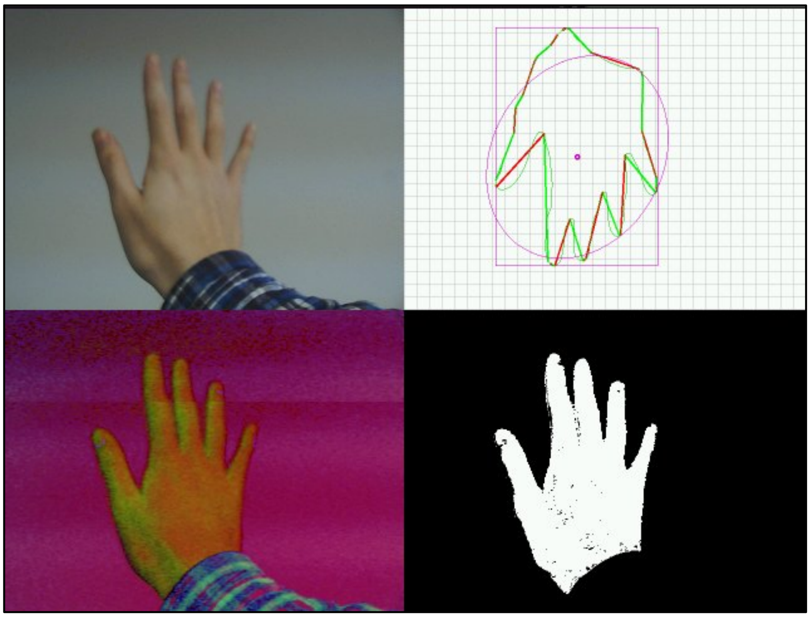


Figure 3.8: Hand detection with OpenCV: The hand is first detected using skin colour and contour and the image is then segmented to remove the background.

Once the hand (or foot) is detected, the algorithm needs to check what is being selected on the projection. The selection starts as soon as the user's hand (or foot) is detected inside the camera's field of view. There are two steps to this selection process. First, the algorithm checks if the detected contour is decreasing in size, implying that the hand (or foot) is moving towards the projection and further away from the camera. This strategy allows the system to differentiate the intention to touch from other movements. After a few frames of the contour decreasing in size, the algorithm checks if the hand (or foot) stays still for more than 10 frames. The refresh-rate of the device's camera used is 20fps in order to guarantee the fluency of gesture detection, so the dwell-threshold time is half a second (0.5s). In practice, the selection time is to some extent increased due to the processing required. The suitability of this dwell time was determined empirically using the system. Once the selection is confirmed, the position of the hand (or foot) is compared to the position of items that can be selected on the projection space; the corresponding item is then selected (Figure 3.9).

Figure 3.9: User interacting with their foot by stepping on the projection. The prototype's camera and projector are both aligned towards the floor. The camera image is compared to the position of the foot enabling the user to select an item on a menu by stepping on it.

Algorithm for misaligned Camera-Projector

In this setting, the camera and the projector are misaligned, which means that the camera's interaction space and the projection space are different. The technique used in this setting involves a gesture recognition algorithm. An indirect selection technique would require implementing a cursor to determine the position of the hand (or foot) relative to the projection. A set of many different gestures could be implemented in the same manner; two gestures were implemented as a proof of concept that gestures can be used for misaligned camera-projector arrangements. The implemented gestures are a waving gesture (with hand or foot) from left to right and the same gesture from right to left (Figure 3.10).

Figure 3.10: Hand waving gesture performed to navigate through pictures from left to right to go to the next picture and from right to left to go back to the previous picture.

The hand (or foot) is detected in the same way as for the algorithm presented in the *Algorithm for aligned Camera-Projector* section. In order to check the movement of the hand (or foot), the algorithm sequentially calculates the contour's coordinate along the x-axis. If the value keeps increasing at each frame for a few frames in a row (rate used is 10fps), then the application recognises that the user is waving from left to right (or from right to left if the value keeps decreasing). One of the limitations of this algorithm is that the user has to move their hand or foot out of the camera's field of view between two actions so that involuntary movements are not considered as input.

3.7 Study 2: Early Investigation of Example Applications

This exploration investigates benefits and trade-offs of the two interaction techniques that were implemented for steerable mobile projection systems (The techniques and respective implementation are described in 3.6: Interaction Techniques).

Figure 3.11: Example of applications for interacting with: Aligned projection and camera by a) touching the projection; b) stepping on it and Misaligned projection and camera by c) waving or d) kicking in front of the projection

The first application (Figure 3.11 a & b) is an Easter Egg Hunt game, which aligns projector and camera in order to enable touch with hand or foot on the projection. In the second application, a presentation support tool (Figure 3.11 c & d), the camera and the projection are intentionally misaligned, so that the camera can detect foot movement when projecting on the wall or hand movement when projecting at any height. The next sections describe these applications and then discuss informal experiences using them to highlight the benefits and drawbacks of these interaction techniques in steerable projection settings.

3.7.1 Aligned: an Easter Egg Hunt Augmented Reality Game

An augmented version of the traditional Easter egg hunt game was implemented using the mobile projection system where virtual clues lead to actual chocolate eggs. Each egg has a location clue that is given to the participant on the projected image. Besides, the projection beam itself gives another clue by displaying at the height at which the egg is hidden. A picture is stuck onto each chocolate egg. When the participant finds the egg, they need to select the corresponding picture on the projection in order to access the next clue. When the game starts, the rules are explained and the user is informed that both hands and feet can be used to interact with the projected image (Figure 3.12 Left). The idea is to use the hand when the projection falls on a nearby flat surface such as table, and the foot for a floor projection (Figure 3.12 Right). When the user selects the correct image, the projector steers to the next clue.

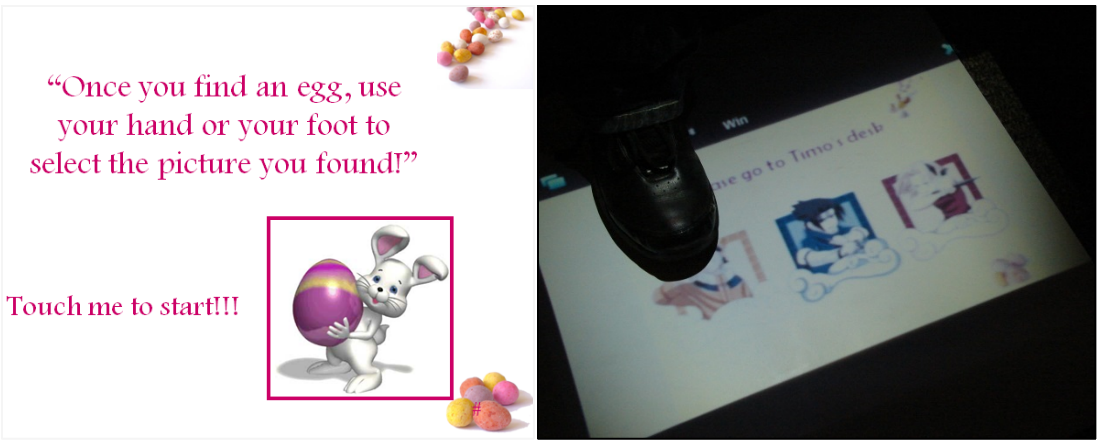


Figure 3.12: Easter Egg Hunt Augmented Reality game using the mobile projector's beam orientation as clue to finding the next egg and the projection as input when the egg is found. Left: Screenshot of one of the projected images explaining the game to the participant. Right: The participant is selecting the icon by stepping on the image.

3.7.2 Misaligned: a Presentation Support Tool

A second application was developed in which the user navigates through a series of pictures or slides and looks at the next or previous item by moving their hand or foot in front of the camera. This interface can be used for changing slides during a presentation or for browsing photos together in a group. For this application, the camera is in a fixed position. The user's hand or foot movement is used to provide input by waving from left to right (forward navigation) or from right to left (backward navigation) in front of the camera.

3.7.3 Findings

In the case where the camera and projector are aligned, touch interaction with the 'spare' hand not holding the device requires the user to get close enough to the projection to be able to touch it. This process was sometimes difficult since the projection reduces in size as the throw is reduced to arm's length (Figure 3.13); in some cases, the user could not get close enough to reach the projection, for example when objects (such as a desk) were obstructing the way between the user and the wall.

Figure 3.13: Projection-Camera aligned scenario. The user is "touching" the projection surface to select an object on the projected image.

Thus, in this Easter Egg Hunt application, with the camera and projector aligned, hand-based interaction was the least easy to use. Foot-based interaction on the other hand was very easy to use, because the throw distance is significantly greater and therefore makes it simple to adjust the projection and foot into a comfortable juxtaposition.

When the camera and projectors are misaligned, as in the presentation application, the movements of the hand and foot allow discrete interaction, opening up many possibilities. The users could intuitively navigate through pictures forth and back by sliding their hands/feet respectively from the left to the right or the right to the left. Although this design was intended to support individual interaction, the device could be held in such a way as to project in a direction and provide a new interaction space to allow someone else to change the slide currently displayed, without holding the device.

The implemented technique that recognises the shape of the hand or foot worked well and dwelling is an intuitive interaction technique to use. In order to provide predictable interactivity, the dwell time needs to be relatively short for the user to have the patience to hold their gesture in place. When the camera and projector are misaligned, it can be difficult to select particular objects without any feedback that conveys the camera-projector mapping, suggesting a cursor on the projection that provides a point of reference.

3.8 Future Work & Discussion

This work opens up new avenues for research into both heterogeneous projection-screen MMDEs and personal projection functionality. This section presents avenues for future work and discussion on the chapter.

3.8.1 Future Work

Interaction technique

This chapter identifies several interaction techniques that are suited for mobile projection and that can be used in the MDE. The study even highlights the importance of flexible interactive projections, which can support interaction techniques on the device and on the projection surface according to task. This inspires a number of interaction techniques that create different personal and shared interactive display alignments to suit a range of different mobile projection situations. Future work will include determining what interaction techniques are best suited for such environments and how users can move content across from one display to another.

Choice of interaction technique

Another issue with mobile devices is that currently most applications make use of the touch screen to interact with various elements of the device while this is not always the most adapted input. It also generates issues such as occlusion of the display during the interaction phase; which prevents a smooth experience. More recent applications use the device's sensors such as the on-board accelerometer [Softonic 2013] or the camera in an augmented reality application [iTunes 2013]. Additional research could determine what interaction techniques are best for each embedded technology and how they can be combined. Meanwhile researchers should keep in mind that richer devices means richer choice of interaction techniques.

Foot interaction

Finally, this work lays some of the basis of using the foot to interact with personal projection. It shows how suited foot projection is for personal projection and this work has also sparked Teng Han's research work on kick gestures for general mobile devices [Han 2012]. While there have been recent developments in the field of foot interaction, there is more work to be done to understand what type of gestures can be accurately performed and to what extent foot interaction can be used. Some acceptability concerns are also being raised.

Relative alignments of displays in MMDEs

This chapter highlights the importance of the relative alignments of the displays and identifies that different placements are needed for different tasks and depending on the number of people using the device. If the displays are not suitably aligned, then this affects the interaction experience. Yet, at the same time, users expect to project at different locations depending on context. Steerability showed strong advantages towards offering on-the-spot reconfiguration to the device. Future work will look at better design for embedded mobile steerability such as using MEMS mirrors. It is expected that new interaction techniques combining digital and physical steering will be required to suit these emerging capabilities. Future research work could build a framework for handheld steerable mobile devices in the same spirit as Levas et al.'s architecture and framework for steerable interface systems [Levas 2003].

Projection space and location

Study 1: Projection-Device Orientation shows that different alignments between the screen and the projector are needed for different tasks; but also that the position of the projection space itself is critical. For example, users preferred projecting on a desk when projecting personal information to reduce the amount of people who could see the information, bringing the space to a more private setting. Future work should include identifying the type of contextual spaces that exist, private and public spaces for a start, considering that additional types of spaces may need to be included. It will also include researching where to project those spaces around the user. Researchers could identify projection zones around the user and define the ones best suited for each scenario. A framework of projection around the user could be established.

Moreover, it is anticipated that automated steerable projection will support future techniques such as detecting optimal projection spaces depending on external conditions (such as lighting or surrounding white spaces). Designers could also imagine automatic placement of the projection space depending thanks to the context aware mobile device. So in the same way a phone would sense whether to ring or not [Hinckley 2001]; a phone could sense where to display depending on context.

Single and multi-user usage

Finally, the device was tested for both single and multiple users (in pairs). In a single-user scenario, the input can easily be located on the physical device. However when multiple people are using the device, one person will more likely hold it while others may still want to interact with the projection. Interaction designers may therefore want to include more indirect inputs capabilities for multiple users. Besides, multiple users often mean multiple devices; in which case designers may want to combine the capabilities of the devices, such as proposing a larger projection area with two projectors or enhanced interaction capabilities between the devices if only one projector is available but multiple users want to send information from their own personal devices.

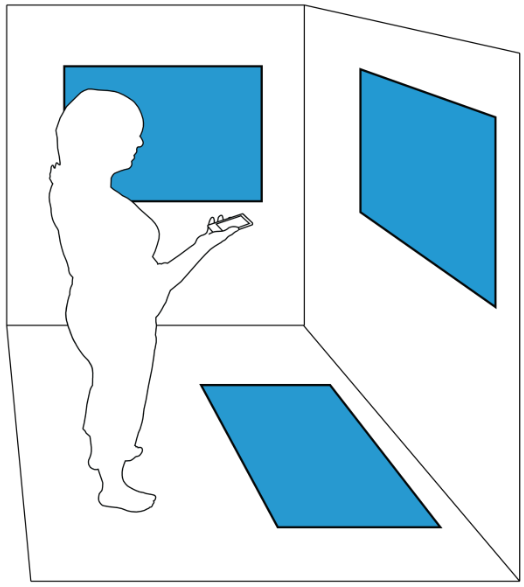
3.8.2 Discussion

In this chapter, the idea of steerable projection was proposed as a way to overcome alignment problems between projected displays and the mobile device's screen in a heterogeneous projection-screen MMDE. The research work focussed on problems linked to displaying information and interacting with the devices. This chapter proposed the first ever-designed steerable projection prototype. In an exploratory user study, it was established that participants preferred different projection angles for different tasks. Participants described their initial preferences in which screen and projection were oriented at different angles with respect to the device and screen.

Out of three possible angles between the screen and the projection beam, the overall preferred projection-screen angle was 30º, and not the 0º angle currently preferred in the manufacturing of projector phones. The chosen angle appeared to be dependant on the way the user holds the device, so that different people will prefer deferent angles. In a task involving moving while holding the device, the 0º angle was completely discarded as alternative steerable options are provided. This shows evidence that there is a correlation between the lack of use of existing projector phone configurations and continuous mobility. All of the participants preferred to change angle to accomplish various tasks and all agreed that they would use different angles depending on the context or the application that they were using.

Evidence showed that screen-based interaction techniques were not optimal for mobile projections, as users had to stop their action to touch the screen in a mobile situation. A number of interaction techniques based on the alignment or misalignment between the projection and the screen were then implemented. Initial experience with these techniques suggests that these interaction techniques need to adapt to different situations and exploit opportunities such as whether the mobile-projection unit and the embedded camera are aligned. Although hand-based touch interaction seems fairly easy and intuitive, it does not seem optimal for interactive surfaces created by wearable or handheld projectors. Foot tracking, however, seems to be a very promising interaction technique for steerable mobile projection. Both techniques, however, can be used as secretive gestures in the case where the projector and camera are misaligned.

Based on the findings from this chapter and those of Chapter 2, one can observe that there are sufficient research questions arising for single users in MMDEs, used as personal devices, to focus exclusively on single-user scenarios during this dissertation. The following chapter investigates relative alignments of the projection and the screen and explore whether issues linked to display alignments in the fixed MDE transfer to the Mobile MDE. In particular, a controlled user study observes visual separation effects in heterogeneous projection-screen MMDEs for three different alignments between the screen and the projector. The study also compares the handheld condition to when the device is rested on a flat surface.



Chapter 4
ALIGNMENT AND VISUAL SEPARATION EFFECTS IN MMDES

Chapter 3 highlights the significance of display alignments in Mobile Multi-Display Environments (MMDEs). Results from the user study show that different alignments are needed between the screen and the projector depending on task and context. The results also demonstrate that, in a mobile situation, participants did not use the orientation angle currently proposed by projection-screen devices' manufacturers. Instead, they all used a shorter separation angle and unanimously projected on the floor. Chapter 3 serves an exploratory role in the field of projection-screen MMDEs.

In this chapter[1], a controlled user study measures the effects of various alignments in such MMDEs. In particular, it identifies which zones around the user, out of the three main possible projection surfaces (in front of the user on the wall; on the floor and on the wall by the side of the user) are best suited to project in a projection-screen MMDEs. This work will also contribute to demonstrate the suitability of projection-screen MMDEs for synchronous use of the multiple displays.

[1] Part of the material in this chapter was published at UIST'11 [Cauchard 2011]

This chapter first presents some of the challenges encountered in the fixed MDEs literature and discusses how they translate to Mobile MDEs. Two major challenges – alignment and visual separation – that affect heterogeneous projection-screen MMDEs are then identified. A user study evaluates visual separation effects using an innovative experimental technique with eye tracking data. Empirical data proves that the displays need to be arranged in the same field of view to avoid extra cognitive load on users. It also demonstrates that mobility does not hinder the user experience and that users actually prefer handheld conditions to resting the device on a surface. The chapter concludes with a discussion on design implications.

4.1 INTRODUCTION

Figure 4.1 illustrates the example of projecting on the floor or the wall from a projection-enabled MMDE. As can be seen on the figure, the physical affordances of having multiple displays on one mobile device result in additional display real estate. The available display surface in a MMDE, especially when fitted with a mobile-projection unit is much higher than the available display surface usually available in traditional mobile devices. Besides, the displays can also be used for different purpose. Often the larger display – here the projection – allows sharing public information while private information can be kept on the device's screen for the owner's eyes only. The smaller display can also be principally used to support input feedback for the larger display space. Nonetheless, this dissertation is interested in understanding whether the multiple displays can be used synchronously.

Existing studies in MDEs illustrate various effects, such as visual separation effects, between the displays, propose guidelines towards positioning the displays, and suggest interaction techniques that mitigate these effects. In the mobile environment, however, MMDEs with heterogeneous displays are designed without reference to visual separation issues. It is therefore critical to establish whether concerns and opportunities raised in the existing fixed MDE research literature apply to the emerging category of Mobile MDEs.

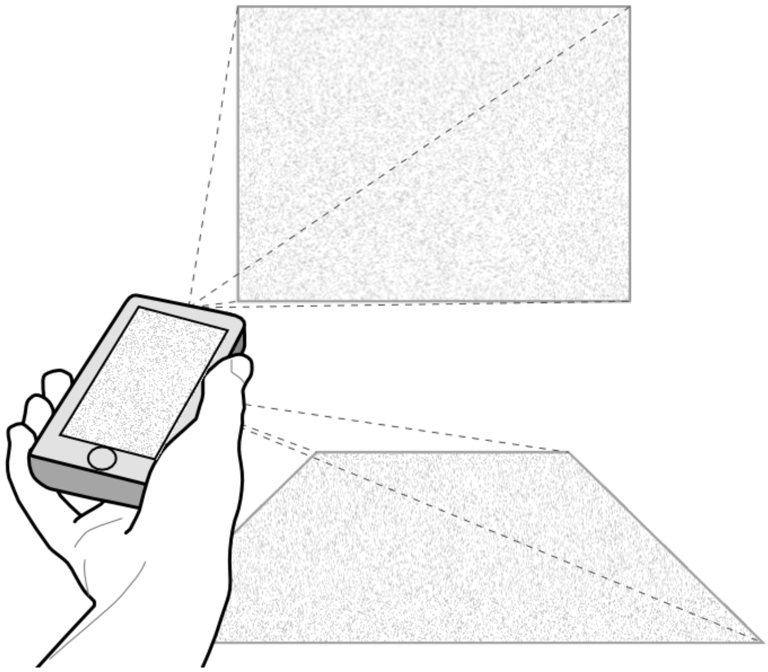


Figure 4.1: Example of a projection-screen device that projects either on the wall or on the floor. The MMDE presents increased display surface for the same form factor as a single-display device.

This chapter is organised as follow: The Background section (4.2) introduces challenges that occur when positioning displays in a MDE, presents how those challenges can be reflected in the MMDEs space, and identifies design factors for MMDEs (4.3). The user study (4.4) aims to ascertain visual separation effects for different relative placements of the screen and the projector in both static and handheld conditions. Visual separation effects are evaluated using an innovative experimental technique with eye tracking data.

The user study was run in conjunction with Markus Löchtefeld at the DFKI German Research Centre for Artificial Intelligence in Saarbrücken, Germany. I designed the user study including the study content and Markus Löchtefeld designed the software framework. We set up the experimental hardware together and took turns to run the experiment with the participants. Markus Löchtefeld verified the eye tracking data collected and I analysed the entire experimental data set.

Empirical results of the study show that MMDEs present a lot of flexibility in their design in terms of displays alignments as results did not show significant effect of position on the error rate and task completion time. Nonetheless, the eye tracking data shows that when the displays are in the same field of view, the cognitive load on the user is reduced and designers will therefore prefer this configuration for highly cognitively demanding tasks. Experimental results also show that mobility should be encouraged as it does not disturb the user experience and as users actually prefer handheld conditions. The chapter concludes with a discussion on design implications for MMDEs (4.5).

4.2 BACKGROUND

The existing MDE literature shows how such device ecologies are affected by the unavoidable visual separation effects caused by multiple displays [Tan 2003, Su 2005]. Simply defined, visual separation is the division of information across space in MDEs. Non-continuous presentation of information can be inefficient to interact with, if it is not handled properly [Hinckley 2004, Bi 2010]. Research in MDEs has shown that visual separation of content can affect performance [Mandryk 2005, Forlines 2006]. Tan and Czerwinski [Tan 2003] found a significant detrimental effect when dividing information across multiple displays at different depths for the same separation angle. Likewise, Su and Bailey [Su 2005] found that when positioning large displays through workspaces, the relative depth between displays can affect users' performance.

On one hand, direct control over the projection and the closeness of the display on a mobile device could mitigate the effects of visual separation on MMDEs. However, on the other hand, mobile devices can create conditions whereby their mobility accentuates static MDE problems. For example, projection-screen MMDEs have an inherent depth differential between the screen and the projection. Prior work in MDEs would suggest negative visual separation effects due to this depth gap. With a lack of understanding of how visual separation affects usability and performance, it is hard to identify appropriate designs and suitable interaction techniques or adapt these devices to specific applications.

Factors amplifying the effects of visual separation have been studied for a range of multi-display configurations including when displays are of different sizes, when placed at different distances from the user, if oriented at different relative angles and when separated by surrounding bezels or frames. Borrowing on principles derived from research in MDEs, the factors that could negatively affect visual separation in MMDEs are being mapped.

4.2.1 Size and Depth

Mandryk et al. [Mandryk 2005] show that users are faster at interacting between two identical and continuous monitors compared to using a secondary monitor of smaller size placed with a small gap to the primary screen. Pointer warping techniques such as Mouse Ether [Baudisch 2004] and frame memory pointer [Benko 2007b] propose cursor movement techniques that can help reduce the effects of visual separation across displays of different sizes in heterogeneous MDEs.

Early literature in ergonomics [Ankrum 1999] advises that documents and screen be kept at the same distance from the user for data-entry tasks that require rapid shifts between both elements, to reduce costs in switching views. Recently, Tan and Czerwinski [Tan 2003] show a detrimental effect due to visual separation when a screen and a projector are placed at different depths within the same visual field. These negative effects can be reduced with techniques such as the Perspective Cursor [Nacenta 2006], that remaps the ordinary mouse cursor in a complex heterogeneous MDE depending on the perspective of each user regardless of their position.

In MMDEs composed of multiple screens, the displays are traditionally chosen with same characteristics and dimensions, and are often positioned at the same distance from the user (e.g., where the device is being held). However, in projection-enabled mobile devices, the projection varies in size and distance depending on the proximity to the projection surface. This category of heterogeneous projection-screen MMDEs usually contains a small to medium sized personal screen and a larger projection area. Although the absolute size and distance can be configured by manipulating the device, the relative size and distance between the heterogeneous displays may cause visual separation effects due to angular or focal displacement.

4.2.2 Angular Separation / Field of view (FOV)

Tan and Czerwinski [Tan 2003] show greater visual separation effects of depth when the data is separated by a 55° angle (i.e., outside the useful FOV) compared to a 27° angle (i.e., inside the useful FOV). Su and Bailey [Su 2005] studied visual separation for multiple large displays and found negative effects when the secondary screen is situated on the same horizontal plane as the primary screen but at an angle of 70° relative to the user, at the periphery of their field of view. Their study also showed a negative effect when the second screen was completely behind the user (i.e., in a completely separate FOV); however, they found no effect when the secondary screen was oriented at an angle from the first screen and were both at the same distance from the user. Following their experiment, they presented guidelines on how to position two large displays relative to each other: the displays should be positioned on the same horizontal plane, at no more than a 45° subtended visual angle and should not be placed behind a user; in other words, both displays should stay within the user's FOV.

As seen in previous chapters, MMDEs are often designed with the displays in different fields of view. For example, some clamshell phones are equipped with both an internal and an external display, such as the Samsung Alias™ 2. With this configuration, the screens are on different sides of the device (i.e., in a different FOV) and cannot be used synchronously. Codex [Hinckley 2009] is a dual-screen device that works with a hinge between the screens and offers different functionalities for different rotational 'postures' of the screens, that can be in same or different FOV depending on context. Z-agon [Matsumoto 2006] is another example of MMDE with 6 screens fitted in a cubic arrangement. Held in the palm, it can be moved to explore content on the two or three faces in front of the user while other faces remain hidden at the back of the cube.

4.2.3 Bezels

This extends the discussion in 2.2.2 and 2.2.3. In MDEs, Tan and Czerwinski [Tan 2003] found no effects of visual separation due to bezels and physical distance between screens alone. Yang et al. [Yang 2010] found minimal visual separation effects between Lens-Mouse (a mouse with screen on top) and the monitor. Task performance in Yang et al.'s study [Yang 2010] degraded in their dual-monitor condition attributed to distance and not bezels. Contrarily, Bi et al. [Bi 2010] found that splitting symbols across two displays with a bezel in the middle was detrimental in a search task. Bi et al. [Bi 2010] also found that interacting with data was faster with no bezel compared to a tiled screen. Forlines et al. [Forlines 2006] show that for an individual user; having information split across multiple vertical screens is detrimental in terms of reaction time to accomplish a visual search task compared to a single vertical screen. Stitching [Hinckley 2004] is an interaction technique designed to reduce visual separation effects by using a pen interface to draw interaction lines across multiple displays.

Chen et al. [Chen 2008] present a dual-display e-book reader and shows advantages of using multiple screens for reading. For example, information can be separated on both screens through the bezel for multi-document reading. Moreover, the device supports interaction techniques that draw on real books, such as moving one screen towards the other to 'turn pages'. In addition, the screens can be detached and reassembled for different modes of use. Devices with dual screens separated by a bezel already exist, such as phones, laptops or even game consoles as the dual-screen Nintendo DSi™ [Nintendo 2011] or the dual-touch screen Toshiba Libretto laptop [Toshiba 2011].

4.2.4 MMDEs vs. MDEs

In all the above designs, Mobile MDEs have very different characteristics to fixed MDEs. Inherent size and depth gaps were identified, which create potential angular and focal separation in the case of projection-enabled mobile devices or individual displays placed in separate fields of view such as clamshell phones. Previous research in MDEs shows that multiple screens need to be placed within the same useful FOV of the user to avoid negative effects of visual separation [Su 2005] and also that specific interaction techniques need to be applied if the size of the displays differs. Yet, MMDE designs do not necessarily follow these guidelines because the studies presume a fixed position and orientation and no or limited control over changing display placement during the task. It is therefore critical to determine whether visual separation effects previously demonstrated in fixed MDEs translate to the mobile

MDE. This chapter explores the design space for MMDEs and determine if aligning displays within the same field of view can reduce the negative effects of visual separation in MMDEs.

4.3 Design Factors for Mobile MDEs

Section 2.3.1: Classification for MMDEs; shows how the displays can be positioned one compare to the other in a *single-device-multi-display* environment.

Depending on the design of the device, the displays are either relatively *fixed*: always at the same distance and angle from each other or *reconfigurable*: the distance and angle between the displays is context-dependent such as in Codex [Hinckley 2009]. Reconfigurable devices are especially interesting since they can adapt to different contexts by rearranging the displays with respect to one another (as with the steerable projection presented in *3.4: Prototype*). Experimentally, reconfigurable displays can be simplified to devices that offer a set of fixed configurations; visual separation effects can then be studied for fixed configurations only.

When the displays are close to each other or at a small angle, they are in the same Field Of View (FOV). However when the separation angle has a high value, the displays are in different FOVs. In MDEs, displays tend to be in the same FOV, which is not the case in current MMDEs. The following user study will determine whether placing the displays in different FOVs increase visual separation effects.

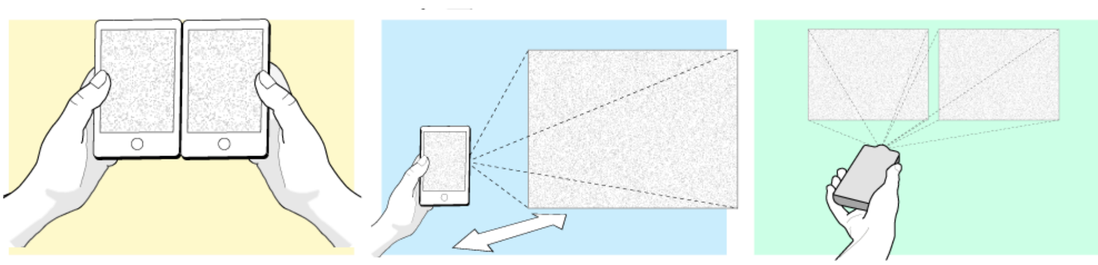


Figure 4.2: There are three types of displays MMDEs: Mutliple screens (Left), screens and projectors (Middle) or multiple projectors (Right).

Figure 4.2 shows that for any pair of displays in a MMDE, there are three cases: *two screens*; *a screen and a projector*; and *two projectors*.

In the *two screens* case, the screens are unlikely to be more than a few centimetres apart in order for the device to be handheld; the design is therefore similar to traditional screens in MDEs separated by a bezel. The visual separation effects are then likely to be similar to the effects of bezels in MDEs. However, bezels do not affect visual separation as long as information is not cut across the bezel [Bi 2010] and appropriate interaction techniques are implemented [Hinckley 2004]. It was therefore decided not to explore visual separation effects for this configuration.

In the case of *a screen and a projector*, the displays have by default heterogeneous characteristics such as different size, resolution, and depth separation. The literature on MDEs shows that depth can be an important factor when managing visual separation effects. Moreover, the position of the projector lens on the device itself will determine if both displays will be in the same field of view or not. It can be expected that visual separation effects will be at their strongest in this type of environment, hence the decision to run the user study with a projector enhanced mobile device.

The *two projectors* case is similar in characteristics to traditional large displays MDEs, such as two projection spaces that will display either on the same, on an orthogonal or on opposite planes, characteristics that have already been explored in the MDE literature. Yet, dual-projectors mobile devices present some interesting features such as the ability to display at different depths depending on the surrounding environment, as when displaying on an uneven wall. Nonetheless, in most multi-projector cases, the projections will either be separated in distance (depth), in plane or in size of projection. It can be argued that those issues are similar to the ones encountered by "a screen and a projector" case and that any experimental results obtained for the former configuration would apply to this category too.

4.4 STUDY

The purpose of this study is to identify the effects of visual separation on heterogeneous projection-screen MMDEs when the multiple displays are in the same field of view and when they are not, as well as when the device is static – rested on a surface – or handheld. The study was run using a projection-screen prototype, as the display technologies embedded on the device – screen and projection – are by design of different sizes and displaying at different depths. The “projection-screen” case is studied, as it is expected that the lack of physical connection between displays will generate greater effects of visual separation.

The experimental setup includes the following aspects of mobility:

- Handling: Participants can handle the device as feels comfortable
- Portability: It implies that the size and distance of the projection will vary
- Unsteadiness: Jitter is not compensated as in a real-life scenario

However, participants do not have the freedom to move outside the experimentation room, in order to allow comparison between results in the *static* and the *handheld* settings.

4.4.1 Task

The task chosen for this experiment is a visual search task. Visual search is a typical task for analysing visual separation [Forlines 2006]. Tan et al. [Tan 2003] use different types of task including text comparison as it is “representative of tasks in which the user must cross reference and compare content displayed in multiple locations” (p.4). Chen and Chien [Chen 2007] use a pattern matching task where participants had to find a Chinese character amongst a grid of 10x10 characters in order to understand the effects of visual performance on small screens. The experiment presents an image over a text comparison task, since the laser projector’s resolution could affect reading accuracy. The task chosen is similar to Chen and Chien’s task and consisted of matching a pattern on the screen (Figure 4.3 Top) with a sparse version of the same pattern positioned inside a projected 3x3 grid of competing matches (Figure 4.3 Bottom). This makes use of the different display sizes, showing the initial pattern only and a keypad on the small display and the 9-pattern grid on the larger projected display. The sparse versions are randomly created by deleting half of the items from the initial pattern and replacing them with blank cases. The competing patterns in the grid are other sparse versions of the initial pattern for which five items are permuted in order to look similar but not match the initial pattern.

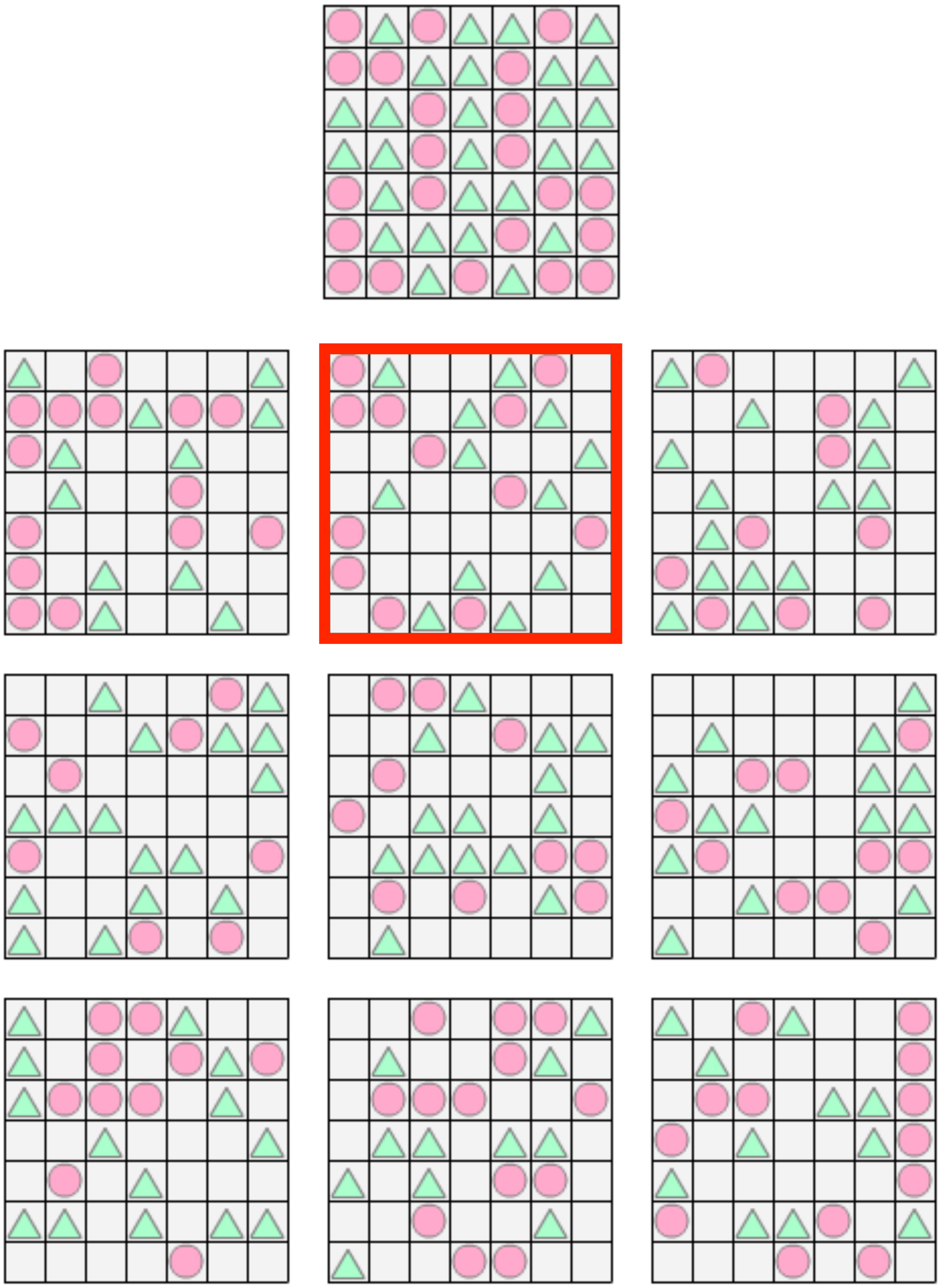


Figure 4.3: Visual Search task used in the user study. Participants need to match the pattern displayed on the prototype's screen (Top) with the corresponding pattern out of nine patterns organised in a 3x3 grid on the projected display (Bottom). The red square represents the matching sparse version of the pattern shown at the (Top).

In a pilot study, 4 participants were presented with two types of patterns: a matrix filled with letters ‘P’ and ‘B’ (Figure 4.4) and the matrix presented above filled with coloured shapes: circles and triangles (Figure 4.3).

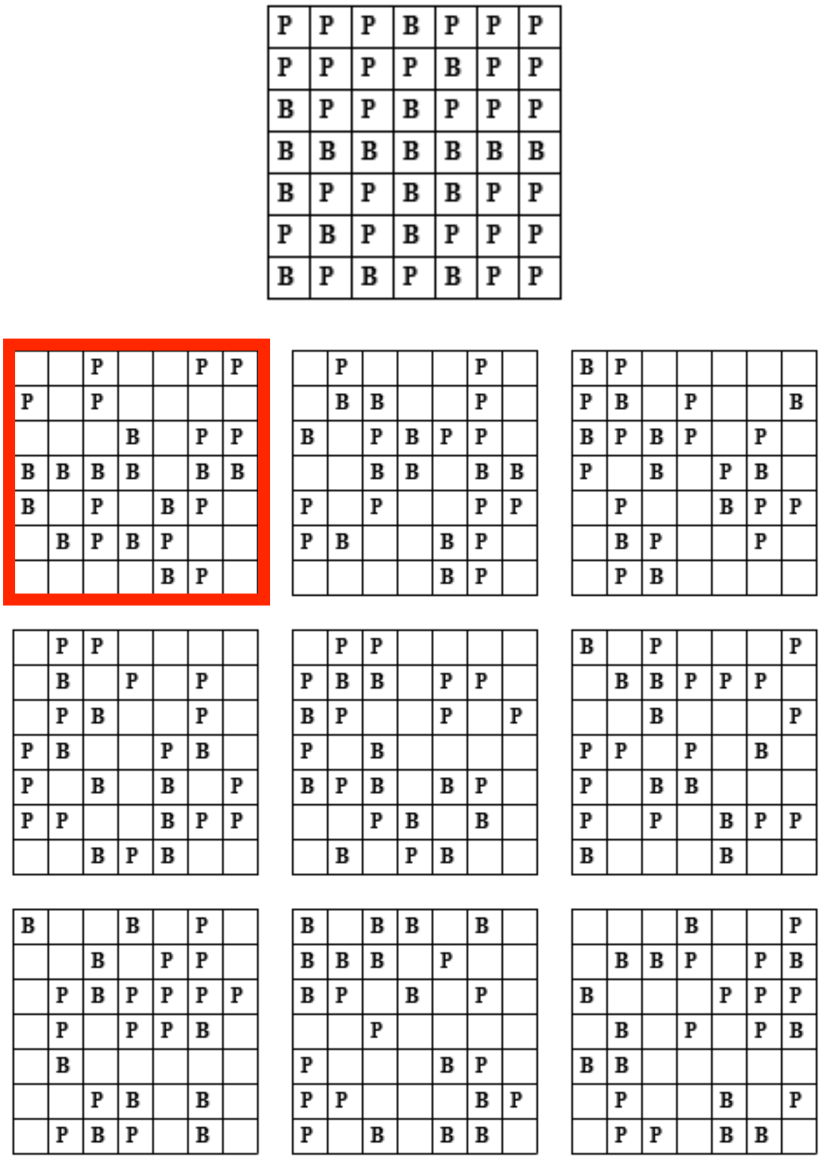


Figure 4.4: Example of the B and P pattern tried as visual search task in the pilot study. As for Figure 4.3, the matrix at the (Top) is displayed on the prototype’s screen and the participant had to identify the matching pattern in the 3x3 grid displayed on the projection (Bottom). The red square represents the matching sparse version.

The letter-based task was very long to perform and extremely tiring for the user while results obtained were similar to the shape-based task. It was then decided to run the study using the shape-based task.

The participant would select a matching pattern on the projection by pressing the corresponding number on the numeric keypad on the screen below the initial pattern. Depending on the answer, the participant could receive positive audio-feedback and continue to the next trial or receive negative audio-feedback and would have to repeat the same trial until the correct matching pattern was found.

4.4.2 Experimental Design

Apparatus

The study prototype is designed using a Google Nexus One with touch screen combined to a Microvision ShowWX laser mobile projector (Figure 4.5). The study makes use of a portable eye tracker since these systems have already been used to measure visual search tasks [Kern 2010]. The experimental room was darkened to optimize the projector viewing conditions.

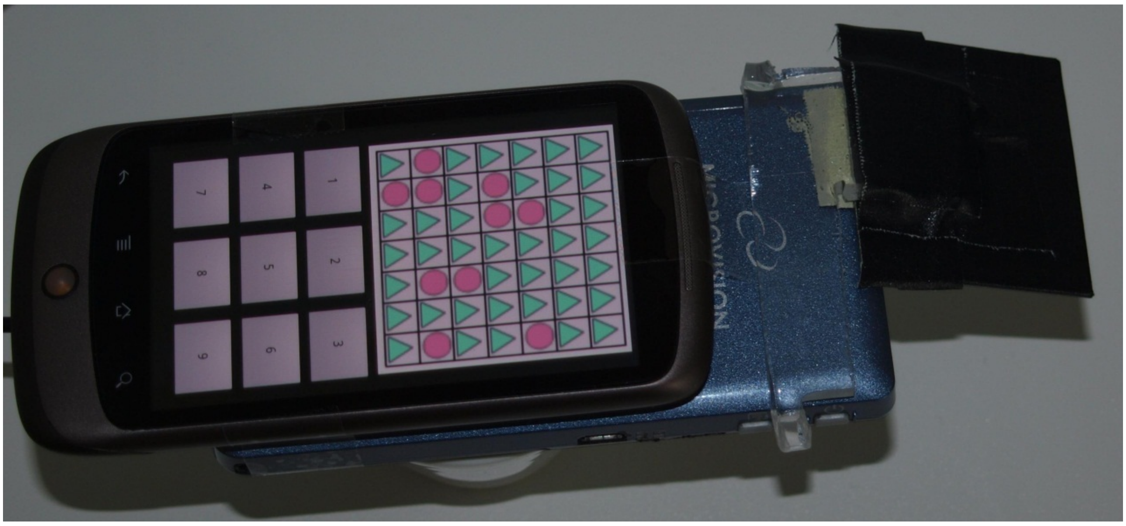


Figure 4.5: Projection-screen prototype used for the user study and fitted with the mirror corresponding to the Floor projection scenario. A Google Nexus One phone was used combined to a Microvision ShowWX laser mobile projector.

Independent variables

The independent variables were:

- *Position of the projection relative to the screen*: in the same field of view (Floor), in different fields of view separated by one angular plane (Front) or by two angular planes (Side)
- *Mobility:* whether the device is fixed on a tripod (*static* setting) or handheld by the user (*handheld* setting).

4.4.3 Conditions

Position of the projection relative to the screen

The projection spaces relative to the screen are described on Figure 4.6: The Front projection corresponds to the alignment of the phone and the projector. A mirror is placed at the top of the projector lens and oriented at 60° downwards for the Floor condition, as shown in Figure 4.5, and 40° sideways for the Side condition. In order to reduce the keystone effect introduced by the mirror, the projected resolution was smaller than the projector's maximum resolution.

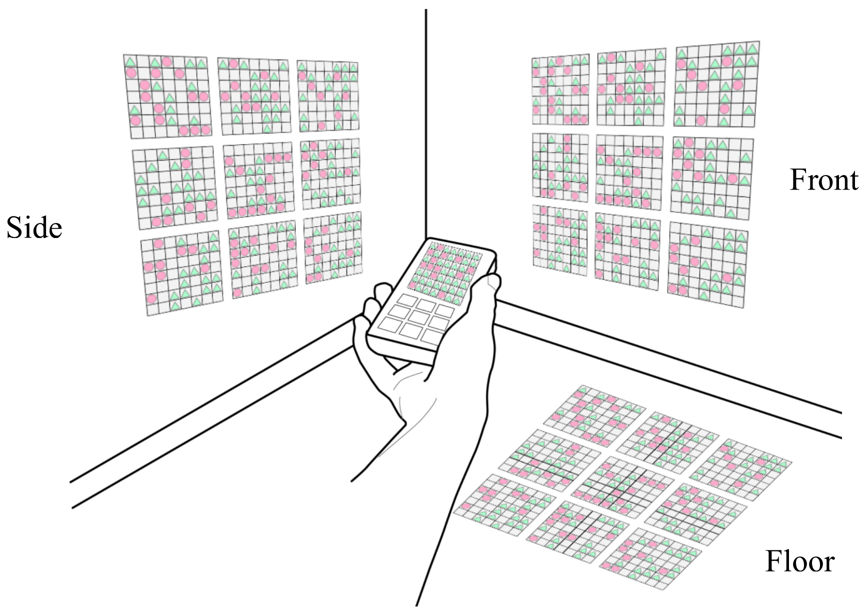


Figure 4.6: Example of the pattern on the screen and the grid of sparse patterns on the projection. For each trial, the grid is displayed in one setting only in the three positions used in the static setting: Front, Floor, and Side.

Mobility

In terms of mobility, the device was either rested on a tripod (*static* setting) or held by the user (*handheld* setting).

In the static setting, the assembly phone-projector is placed on top of a tripod and the participant stands on footsteps marked by the tripod. The position of each projection space (on the floor, front, and side walls) was predefined in order to set a constant position and aspect ratio of the projection for all participants. It was ensured that all three projection spaces were the same distance from the prototype (110cm) and would therefore remain at a constant size (middle of the projected grid fixed at 60cm wide).

In the handheld setting, the user is holding the device and can use any projection surface at any distance or size with which they are comfortable. The user was free to move around the room with the device. The distance to the wall and the size of the projection would then vary depending on user's movements. Users were not given any restriction on how they would hold the device. Nonetheless, given the physical constraints, the side projection would for example always remain on the side of the user. Observation showed that most participants held the device in the non-dominant hand and touched the screen with their dominant hand, while other users held the device in both hands and used their thumbs to touch the screen. None held the device with their dominant hand.

4.4.4 Eye Tracking Procedure

The context switches were measured using a mobile eye tracker: Tobii® Glasses (Figure 4.7) that recorded eye movements at 30 Hz. This eye tracker is non-intrusive as it is low weight (75 grams glasses) and fully mobile so participants could roam freely. Some infrared (IR) markers were positioned around the various display spaces (in the *static* setting) to allow automatic data mapping and help repositioning the projected image at the same place for each participant. The eye tracker records both a video of the scene and where the user is looking at in the scene.

Figure 4.7: ©Tobii[1] Glasses mobile eye tracker

4.4.5 Hypothesis

Based on the literature review and preliminary exploration of the issues, it was expected that display configurations – relative positions of displays within the same or in different fields-of-views – and whether the device is being held – mobility – would significantly affect performance and produce visual separation effects.

It was presumed that visual separation effects would be less important when the screen and the projection are in the same field of view – floor setting – than when the projection is in a different field of view than the screen – front and side settings –. It was also expected that participants would compensate visual separation effects when holding the device since they could reconfigure the display areas by themselves.

4.4.6 Procedure

Twelve volunteers (five men) aged between 24 and 35 years old (μ=28.6) were recruited within the University of Saarbrücken and were compensated 20€ for their participation. All participants were familiar with touch screen technology and had normal colour vision. A within-subjects design was used where position and mobility

[1] http://www.tobii.com

were counterbalanced across participants. The task was explained to each participant individually. To start a trial, the participant pressed the "Start" button whenever they felt ready. There were eight trials for each experimental condition. Participants were also told that they should say aloud if they pressed the wrong button in order to identify false negatives. After the experiment, users filled out a NASA TLX satisfaction survey.

In summary the experimental design was:

2 mobility factors x 3 positions x 8 trials x 12 participants = 576 data points.

4.4.7 Measures

Figure 4.8: Snapshots from the eye tracker's video. The red dots correspond to the tracing of the participant's right eye movement. Left: User looking for the matching pattern on the projection. Right: User looking at the initial pattern on the phone's screen.

Number of context switches between the screen and the projected display. Previous studies on visual separation do not measure the number of context switches. However the problems induced by context switches are quantified in mobile projector phone studies [Hang 2008] as well as in some MDE studies [Benko 2005, Dickie 2006]. This is measured by the portable eye tracker. The number of context switches is computed by the eye tracking software in the *static* condition using the IR markers and is then manually verified through analysis of the eye tracker video. In the handheld setting, the switches are manually counted at the video analysis stage (Figure 4.8) since the position of the projection space is not constrained in this setting.

- *Completion time* and *number of errors* in performing each trial, including the number of false positives: These are typical measures in visual separation studies [Tan 2003, Su 2005, Forlines 2006] and allow comparing participants' efficiency for different experimental settings. The completion time is timed between the start of the task to its successful completion.
- *Position preferred* - NASA TLX: This test assesses subjective information on a 7-point Likert scale for mental, physical, and temporal demand; performance; effort and frustration. The traditional subjective workload questionnaire was combined with personalised questions aimed at gathering user preference data.

4.4.8 Results

A repeated measures ANOVA test was used for the number of context switches, completion time, and number of error; while a univariate ANOVA test was used for the NASA-TLX results analysis with subject as a random factor.

- *Number of context switches*: A main effect was found for position ($F_{(2,94)}$=62.817, $p< .001$), pairwise post-hoc comparison showed significant differences between the positions: Front and Floor ($p< .001$), and Side and Floor ($p< .001$) and no significant differences between *Handheld* and *Static* conditions ($F_{(1,95)}$=1.034, $p> .05$). The mean for Front and Side were respectively 20.49 and 19.62 context switches compared to 31.41 for the Floor condition, and are presented on the chart on Figure 4.9.

- *Number of errors*: No significant difference was found in error-rates for the different positions ($F_{(2,94)}$=1.049, $p> .05$) and for mobility ($F_{(1,95)}$=1.143, $p>.05$). The average error rate across all conditions was 8.9%.

- *Task completion time*: The findings showed no significant difference in trial completion time for position ($F_{(2,94)}$=0.390, $p>.05$) and for mobility ($F_{(1,95)}$=0.057, $p>.05$). Figure 4.10 shows the average trial completion times across all conditions.

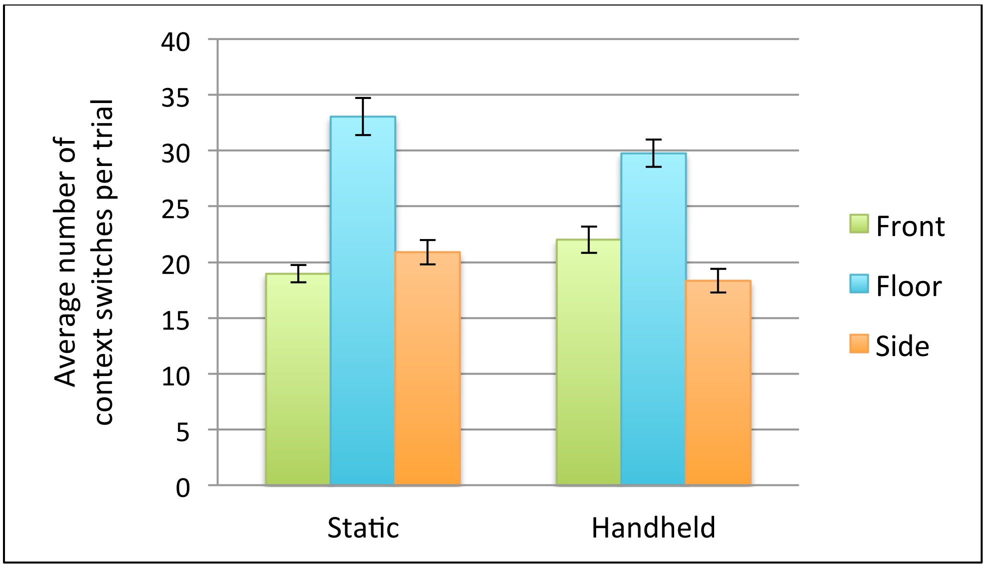


Figure 4.9: Average number of context switches per trial for each condition: Front, Floor, and Side in the *Static* and *Handheld* settings.

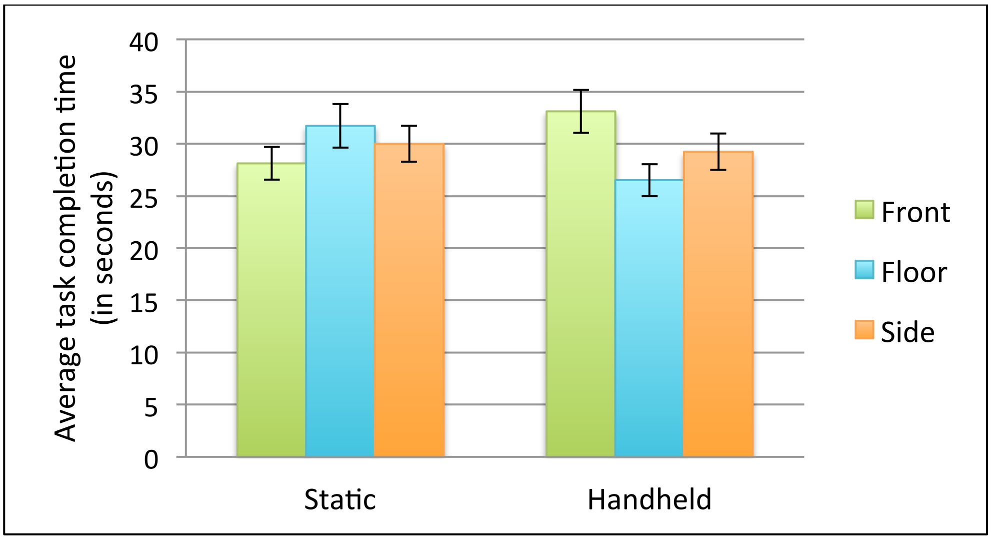


Figure 4.10: Average task completion time for each condition: Front, Floor, and Side in the *Static* and *Handheld* settings.

- *NASA TLX*: A significant difference was found in temporal demand only ("How hurried or rushed was the pace of the task?") for position ($F_{(2,22)}=4.086$, $p=0.031$). Floor is perceived as faster than Front and both are perceived as faster than Side (means for temporal demand for Floor is 3.67, Front is 3.83 and Side is 4.33 on a 7-point Likert scale). No significant effect was found for all other variables.

- *Position preferred.* In the *static* setting, 75% of participants chose the Front position with the remaining participants preferring the Floor. In the *handheld* setting, half of the participants preferred the Floor, 42% the Front and 8% the Side. When asked what their favourite position was overall, 75% favoured a mobile position compared to a static one (Figure 4.11).

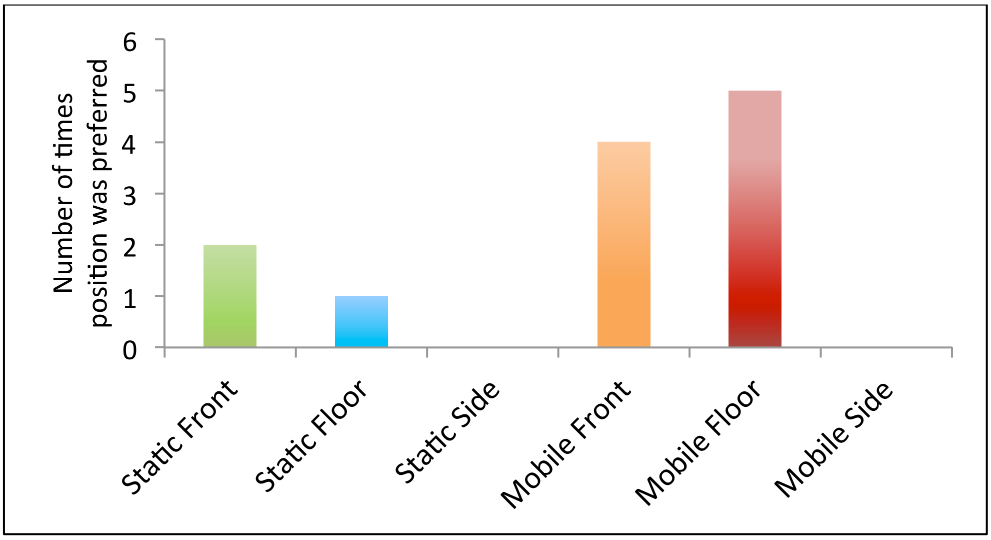


Figure 4.11: Overall preferred position for the user study for each participant. 75% of the participants preferred a mobile condition overall.

4.5 Discussion

In this section, the above results are discussed on the four following themes: A. Viability of Mobile MDEs, B. Dual-display configurations, C. Substantiation of mobile uses and D. Design implications

A. Visual separation does not impair the viability of MMDEs

The results of the study show that visual separation effects did not prevent users from carrying out the task, which is reflected through the low error rate of only 8.9% over all tasks and conditions. This result is valid for both the *static* and the *handheld* conditions.

During the experiment, participants had no difficulties using a mobile dual-display device even with very heterogeneous displays in terms of size, resolution, and depth of the displays. To perform this task on a single-display mobile device, it would not have been possible to display all items on the grid at once and participants would have had to keep changing the images on the screen until they found the correct pattern. In a case where tasks are divided across displays, heterogeneous projection-screen MMDEs should outperform today's single-display devices. Moreover, the tasks can make use of the different displays' characteristics, such as the experiment uses the device's screen to display a single pattern and a keypad and the large projection to display the larger nine-pattern grid. I conclude that:

The multiple displays of the heterogeneous MMDEs can be used synchronously.

B. Displays should ideally be in the same field of view.

The eye tracker recorded significantly more eye context switches in the floor condition: over 30% more than in the other positions; whereas no significance was found in completion time and error rate across the three positions. No statistical differences were found for each independent variable between the *static* and *handheld* settings. This important result would have been overlooked should a traditional task performance measures only had been used.

Our task was complex enough that participants could not simply memorise the whole pattern and find the matching pattern on the projection. The results show that the number of eye context switches does not affect task performance and that there are more context switches when both displays are in the same field of view. This suggests context switches are cheaper to perform when both displays are in the same field of view (Floor setting). In this condition, switching context requires a simple eye movement and little or no head and neck movements, unlike the Side and Front conditions where participants reported discomfort. One participant said about the Side setting: "It was very uncomfortable to constantly turn my head during the experiment". The higher number of context switches in the Floor condition can be due to the fact that context switches are to be considered as epistemic [Kirsh 1994], using the active memory to store the position of the geometric shapes in the pattern. Instead of having to remember the positions in the pattern, users could externalise their thought processes by switching context more often. This could also explain why this setting appeared as being faster paced to the participants.

As default, displays in projection-screen MMDEs should be aligned in the same field of view (Figure 4.12).

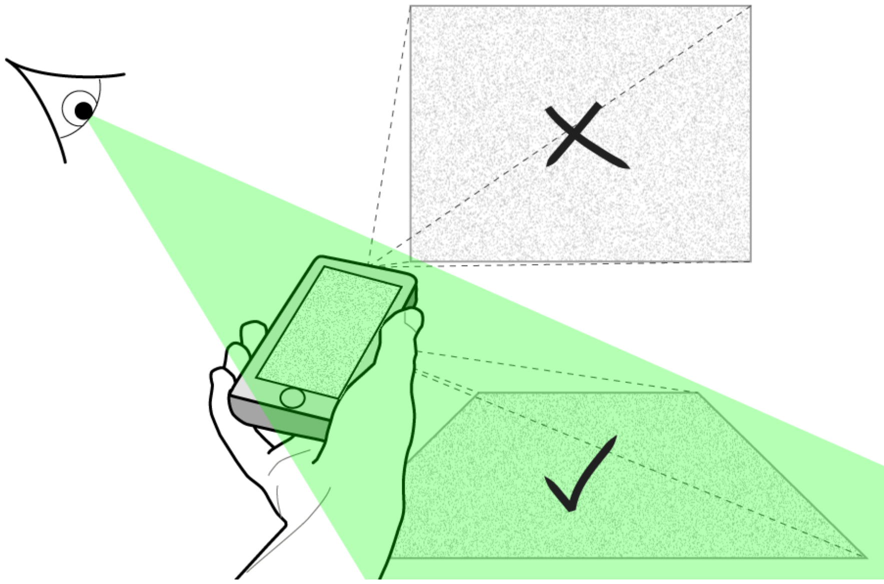


Figure 4.12: Design recommendation: The study shows that for a visual search task, it is better suited to have both displays aligned in the same field of view.

C. Mobility factors do not exacerbate visual separation.

Since no significant difference was found between mobile and static setting in terms of error rate, task completion time or context switches, the following mobility factors: handling, portability, projection size and unsteadiness, are believed to have no particular effect on visual separation.

Participants' wrist and hand movements in the mobile setting did not help compensate the effects of visual separation. A possible reason could be that they were already compensating for the jitter of the projection resulting from the participants holding the device in their hands. Since no participant mentioned jitter as a problem during the experiment and in the post-study questionnaire, it is believed that users instinctively compensated for any mobility-induced jitter effects. The experiment showed no more visual separation effects between mobile and static settings, even though the projection space and display size were varying; and since participants showed a strong preference for the mobile setting, the investigation of mobile scenarios is justified.

Factors such as handling, portability, and unsteadiness do not exacerbate visual separation. Although fully mobile conditions were not explicitly tested, it is anticipated that those results are transferable to such environments.

D. Design implications

The following sections present some design implications for future MDEs that emerge from the discussion in terms of type of displays, display physical arrangements, flexibility of design and mobility.

Type of displays for MMDEs

Our experiment demonstrates that Mobile MDEs are viable, which includes heterogeneous dual-display solutions. Although dual-display solutions for mobile devices are technically possible, they are currently under-exploited by manufacturers. This user study demonstrates that these solutions should be envisaged more often since visual separation effects do not present issues for carrying out activities where tasks are distributed across displays, such as in the experiment. This is also valid for activities wherein the user chooses which display to use depending on application and context needs. Those scenarios of use are consistent with most common uses of MDEs as described by [Grudin 2001].

Additionally, most existing dual-display mobile devices are designed with multiple displays of similar types, whereas heterogeneous displays offer more potential, such as the ability to choose where to display depending on the context without generating negative visual separation effects. While current usage of heterogeneous dual-display mobile devices is often limited to one display at a time, designers are encouraged to consider exploiting both displays synchronously. This would also allow more flexibility in the choice of interaction technique; such as in Chen's e-book reader [Chen 2008].

Physical arrangements of displays

Our experiment shows that having both displays in the same field of view is paramount for applications that make use of both displays. There is evidence that users can reduce the amount of information they have to *remember* and can instead use active memory to *recall* information by switching gaze between displays more frequently. This is particularly important for applications that suffer from heavily cluttered displays, such as map applications. This pattern of increased context switches to alleviate cognitive load is equally important when one display is also used to facilitate input to the other display. For instance, in the case of a projection-screen device, a touch screen can be used to manipulate content in the projected space. In this situation, the displays must be arranged within the same field of view. When both displays are in the same field of view, one display can be partially occluding the second display. This case is especially likely to occur in MMDEs where there is a depth gap between displays as in projection-enabled devices.

Besides, arranging displays in the same field of view is not trivial in a mobile environment where external factors influence how the user holds the device and on which surfaces content can be displayed. These external factors range from luminosity and glare to the available projection surfaces, the number of users who are viewing the content, and the type of information being displayed. The usage of a steerable projection could overcome these environmental issues, as proposed by Pinhanez [Pinhanez 2003a] for static and discussed in Chapter 3 for mobile projection. Moreover, steerable projection can reduce visual separation effects in MMDEs by automatically reconfiguring the alignment of the displays according to the current context of the device.

Flexibility of design

Prior research conducted in MDE suggests that displays arranged on different planes or separated by more than 45° angle result in lower task performance and provide negative visual separation effects [Su 2005]. However, in this study, no significant task performance differences were found, whether in time completion or error rate, across the different settings. These results show that guidelines for MDEs are not directly applicable to MMDEs. One explanation could be that MMDEs use a comparably small display that is close to the user, compared to MDEs. This shows that although it is preferable for the user to have both displays in the same field of view, there is more flexibility in the alignment of displays in MMDEs than in MDEs.

This is especially the case for applications that do not require epistemic actions from the user, and for which the need for rapid context switching is not crucial. For those applications, manufacturers have more freedom to position the mobile-projection unit wherever it best suits the device ecology. This could result in smaller devices since the mobile-projection unit could be placed where it fits best without generating visual separation effects on performance. In this case, a wide range of interaction techniques can be supported for which displays do not need to be aligned, such as foot interaction on the floor Chapter 3 or even shadows on the projection [Cowan 2011] for any other projection setting.

Floor Projection

The experimental results also illustrates that projecting on the floor is a promising option. When the projection-screen device is held horizontally, the user can have both displays in the same field of view by projecting on the floor. This is especially helpful for street navigation applications where users can follow directional arrows on the floor instead of reading a map on a small screen. Moreover, unlike a wall, the floor is a surface that is constantly available for projection.

However, projecting on the floor is not straightforward and involves careful technical considerations. As is the case for any projection surface, the floor can be uneven, as on a cobbled street for instance. There is also the issue of the user paying attention to the projected display only while being inattentive to their surroundings. This can be very dangerous especially when walking around, so it is crucial to design a system that will retain users' awareness to hazards.

The choice of interaction technique will partially depend on the position of the floor projection with respect to the user. Projecting close to the user allows foot interaction or even a full body interaction; projecting further away from the users' body will require indirect input such as through buttons or sensors on the projecting mobile device. The position of the projection can also be adapted to the user's pace. For example, if the person is walking, the projection could be further away from their body [Ota 2010] and move closer when the user stops walking to allow for direct interaction.

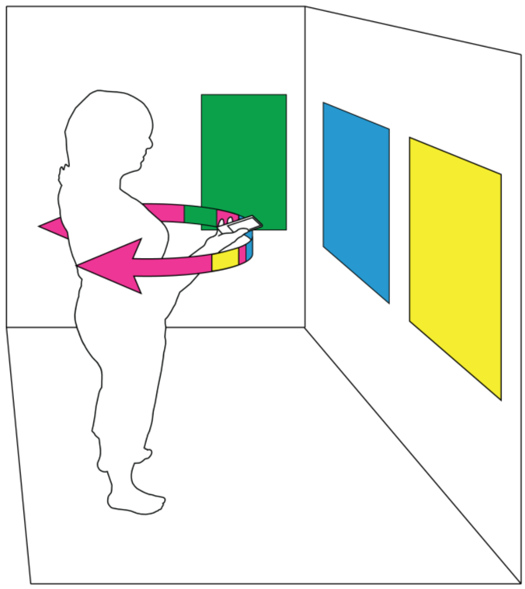
Mobility

In the study, empirical data shows no more visual separation effects when the device is handheld than when the device is fixed on a tripod. Most MMDEs are built for scenarios of use in which the device is rested on a surface. The study shows that various factors of mobility are worth investigating, such as when the user is walking while holding the device; or stopping by to obtain contextual information about the area they are walking by; or when using a QR-code on a poster for example. Many contextual applications could benefit from true mobility and new interaction paradigms could be envisaged, such as the use of haptic while on the move.

4.6 CONCLUSION

This chapter presented design factors that can affect experience in MMDEs. Visual separation effects were investigated for MMDEs and compared to the current literature in MDEs. Through an innovative eye tracking methodology, different angular separations of a projection and a screen were compared: two displays of different sizes and resolutions, positioned at different distances from the user. It was determined that although task performance was not affected by the displays being in the same or in different fields of view, the number of eye context switches was over 30% higher in the condition where both displays were in the same field of view. Mobility was tested as a dependent variable in the experiment and empirical study results helped conclude that mobility did not increase visual separation effects in MMDEs. The chapter finally presents design implications in terms of types of displays used in MMDEs, physical arrangements of the displays, flexibility of design of MMDEs, and mobility.

The following chapter investigates whether users can access various workspaces on their mobile devices by moving the MMDE around their body, making use of spatio-kinaesthetic cues. To investigate this interaction technique, three prototypes were developed and evaluated across two user studies. In the first study, a novel spatially aware interaction technique is compared to existing techniques to switch workspaces using a screen-only prototype. In the second study, the three spatially aware prototypes are compared against one another. Results show that spatially aware interaction techniques significantly improve workspaces switching in mobile environments.



Chapter 5
SECONDARY DISPLAYS IN MMDES: THE CASE OF VIRTUAL WORKSPACES

Chapter 4 explores how visual separation affects Mobile Multi-Display Environments (MMDEs). In particular, it investigated how different alignments between the phone and the projection in a projection-screen MMDE affect user experience. In this research, three interaction zones around the user were investigated: on the wall in front of the user, on their side, and on the floor; which corresponded to the displays being aligned or separated by one or two angular planes. Quantitative study results proved the viability of heterogeneous projection-screen MMDEs and helped produce guidelines towards keeping the position of the screen and of the projection in the same field of view. This work also identified flexibility in the alignment of the display spaces in projection-screen MMDEs.

This chapter[1] builds upon the research from the previous chapter to determine whether the physical space around the user can be used to interact with a heterogeneous projection-screen MMDE when the displays are aligned. It first introduces the concept of virtual workspaces and present the background literature specific to spatially aware

[1] Part of the material in this chapter was published at MobileHCI’12 [Cauchard 2012b]

interfaces. Three prototypes of spatially aware virtual workspaces were developed and evaluated in two user studies. The first study compares a screen-only prototype with existing interaction techniques for switching workspaces in mobile devices. Results prove that spatially aware virtual workspaces were faster to use and less prone to errors when performing the task. The second study evaluates and compares the three prototypes. It is shown that adding a mobile projector to the existing screen-only prototype improves the capabilities of the interaction technique. This chapter is concluded with design considerations for spatially aware mobile virtual workspaces.

5.1 INTRODUCTION

Previous work has been done using spatial awareness, memory, and kinaesthetic cues to interact with digital content [Tan 2002, Yee 2003, Li 2009]. This dissertation research interest lies in using the space around the user's body to use the device and to project on different spaces around the user. A spatial interaction technique is then proposed, combined to multiple projection spaces as a way to investigate if it is feasible to use spatial awareness as a way to interact with a heterogeneous projection-screen MMDE. This spatial UI is tested across three phone-based prototypes: *mSpaces (mobile Spaces)*, *pSpaces (projected Spaces)*, and *m+pSpaces (mobile+projected Spaces)*. The implemented UI allow simple and fast access to multiple interaction spaces around the user, drawing on their spatial memory and awareness.

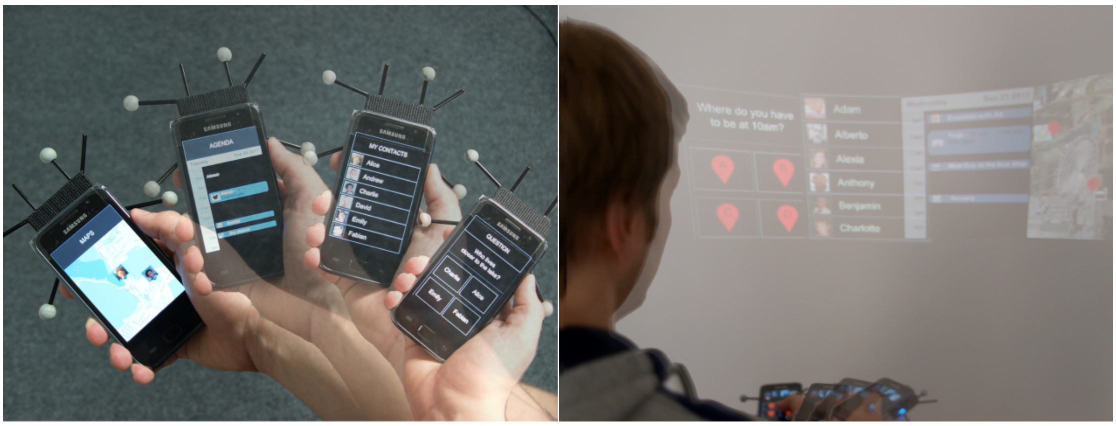


Figure 5.1: Pictures of two spatially aware mobile virtual workspaces. Four images are superposed to show the different views seen by the user when moving the prototype. Left: The user can change the workspace currently displayed on the screen by moving the device around their body. Right: Similarly, the user can access the various workspaces via the projection by moving the device around their body.

With *mSpaces*, the user accesses the different spaces by moving the phone to different physical locations (Figure 5.1 Left) and *pSpaces* gives access to multiple virtual spaces by pointing the mobile projector to various physical locations (Figure 5.1 Right). This interface makes full use of the user's spatial awareness. Finally, *m+pSpaces* uses both the screen and mobile projector.

To test the spatially aware interaction technique, virtual workspaces were implemented for mobile devices, which virtual locations are linked to real physical locations relative to the user. The concept is further detailed in the related background section along with literature on virtual workspaces and spatially aware interactions (5.2). Two experiments compare *mSpaces* (5.3.2) to the current use of multiple concurrent applications on a mobile phone and to *p*- and *m+pSpaces* (5.4.2). The first study (5.3) looks at the single-display only condition to avoid extra cognitive burden on the participants and to first verify the usability of the spatial interaction. The second study (5.4) investigates the heterogeneous projection-screen MMDE using the same spatial user experience but adding the projection capability. This chapter concludes with design considerations for spatially aware mobile virtual workspaces (5.4.6 & 5.5). This work was done is collaboration with the DFKI research centre in Saarbrücken, Germany. I designed the user study including the study content and Markus Löchtefeld coded the software framework and ran the study. I analysed the entire experimental data set using data provided from the experimental software, photo and video recordings.

The contributions of this chapter are:

- Findings that suggest that spatially aware virtual workspaces provide easier and faster switches between applications in the mobile context.
- Three spatially aware prototypes of mobile virtual workspaces, two of which include the use of mobile projection spaces that capitalizes on the emerging trend of augmenting mobile phones with projection capability.
- Mobile projection improves the capabilities of spatially aware mobile virtual workspaces.
- The contribution of using mobile workspaces is extended and the design of *m*- and *pSpaces* is completed, by proposing a set of design considerations to create, manipulate, and manage these techniques.

5.2 Background

This section presents some specific background literature on virtual workspaces and spatially aware interaction techniques.

5.2.1 Virtual Workspaces

The use of multiple workspaces is common in desktop computing and integrated into most Operating Systems (OS). Known as *workspaces* on Linux, *spaces* in Mac OS or *virtual desktop* in Windows OS, they allow users to de-clutter their principal workspace and mitigate physical display size limitations by adding virtual display real estate. For mobile platforms, the concept of virtual display space is quite different; it is often used to store icons but rarely to switch between tasks or activities that have already been started. Users instead go back to the main menu and select an icon to access the corresponding application. Since the use of multiple virtual workspaces was initially recommended as a technique to alleviate some of the mental workload in limited display real estate [Card 1986], it seems natural to use this concept for mobile phone technologies.

Current desktop environments represent virtual workspaces using thumbnails spatially arranged in a line or grid. In mobile environments, since the devices themselves have intrinsic spatial properties, these spatial properties can be used instead of a graphical representation. This will give users a more tangible and direct interaction with virtual workspaces that does not exist in fixed desktop computing thus expanding the capabilities of current systems.

The concept of virtual workspaces as it exists in desktop computing can be translated to the mobile environment. Yet, this is not a straightforward process and the results obtained would be suboptimal if careful consideration was not given to the design, as the two categories of devices have very different characteristics and capabilities.

Desktop virtual workspaces

Virtual workspaces are first introduced by Card and Henderson [Card 1986, Henderson 1986], who proposed *Rooms*, a system for managing multiple virtual workspaces as a way to cope with limited display real estate by expanding it into virtual workspaces. Multiple workspaces lower the cognitive overhead created by trying to switch tasks and move windows across a limited physical display real estate. One of the authors' arguments for virtual workspaces is that they help overcome the limitations of small screen size, which is a highly relevant issue for today's mobile technologies.

Ringel [Ringel 2003] proposes a "taxonomy of organization strategies" for users of multiple virtual workspaces. Five organization strategies emerged from a field study. Participants would consistently use the different workspaces to either: divide tasks, divide subtasks, change context between personal and professional usage, use multiple OS, and classify applications. They also show that virtual workspaces have different uses to multiple displays. It is therefore likely that adding an auxiliary display to a mobile environment would not replace the need for multiple workspaces. Finally, users with smaller displays used "more virtual desktops, on average," [Ringel 2003]. This proves that multiple workspaces will be well suited to mobile environments that traditionally afford smaller displays.

Mobile virtual workspaces

The terms *mobile devices* is used to refer to handheld devices such as mobile phones and tablets. In this section, laptops are not considered as part of this category since they are traditionally rested on a flat surface and not handheld. Fitzmaurice [Fitzmaurice 1993] presented the Chameleon system in 1993, offering spatially aware interactions with the environment using a palmtop computer. Despite, the concept of virtual workspaces as it exists in fixed desktop environments is seldom implemented in mobile devices and many mobile phones only offer the possibility of displaying static menu icons on one or more virtual desktops. Moreover, while some mobile phones have the capability to display multiple applications at once, they do not exploit advantages offered by virtual workspaces, as they exist in the fixed environment. Adapting multiple virtual workspaces to mobile devices will extend the current range of possibilities offered, such as providing users with a task-partitioning tool.

While the concept of multiple virtual workspaces can be translated to the mobile domain, the interaction techniques need to be adapted. This is particularly evident since display sizes and interaction techniques are inherently disparate between fixed and mobile environments.

Representation of virtual workspaces

In the desktop environment, multiple workspaces are often displayed as a group of thumbnails, each representative of one workspace. They are traditionally organized as a line of thumbnails – such as when pressing ALT+TAB in Windows OS or CMD+TAB in MacOS – or as a 2x2 grid when four workspaces are being shown. In early systems, thumbnails were referenced to using numbers. They are now often presented as a thumbnail of the actual workspace with its applications positioned as in the workspace itself.

In existing mobile environments, the main screen can sometimes be extended to display additional static information such as extra application icons. These application launcher spaces can be represented as a line of dots in the main menu where one dot is highlighted, indicating the workspace in view. Some phones now propose solutions close to the multiple workspaces concept in desktop computing, as the Nokia N900 where multiple applications can be running in additional virtual space. Yet, there is no point of reference to what the user is currently viewing with respect to the virtual space.

In all instances presented above, there is a spatial relationship between the workspaces: one can be represented next to the other, above or below.

5.2.2 Spatial Awareness

The use of spatial awareness to represent and provide users with an understanding of virtual workspaces is to be expected since using spatial memory has proven to be effective for tasks such as the document management technique Data Mountain [Robertson 1998]. Additionally, Tan et al. [Tan 2002] show that using kinaesthetic cues increases spatial recall. Li et al. build on this theory and propose Virtual Shelves [Li 2009], allowing users to orient a mobile phone to trigger shortcuts. They show that the user can "accurately point to 7 regions on the Θ plane and 4 on the Φ plane". A more recent study by Gustafson et al. [Gustafson 2011] shows that one can interact with mobile devices by transferring the spatial memory of the interaction technique to the palm of their hand.

Earlier, Yee presented Peephole [Yee 2003], an interaction technique for a spatially aware display that "provides a window on a larger virtual workspace". They mention that this window could be used to display several applications on the same workspace where users could draw connections between applications. In *mSpaces*, this concept is brought further by mapping the location of each distinct virtual workspace to a physical location, relative to the user. The user can access each workspace by orienting the mobile device in the direction of the workspace, hereby receiving permanent visual feedback to which workspace they are looking at. This technique utilizes the intrinsic properties of a context-aware mobile device, the user's spatial memory, as well as kinaesthetic cues that will ostensibly alleviate some of the user's mental workload.

Besides, Cao and Balakrishnan [Cao 2006] explore using a mobile projector to access multiple items on a single virtual space. This doctoral research work goes further by accessing multiple virtual spaces at different physical locations with constant visual feedback. In *m-* and *pSpaces*, each virtual space is linked to a location relative to the user, who points at the physical location to display the associated virtual space.

In order to determine how virtual workspaces can be displayed in the mobile environment, a user study comparing various implementations was conducted.

5.3 User Study 1: Mobile Virtual Workspaces

This study aims to find out the type of interface is suited to implement virtual workspaces in a fully mobile environment. While there are many ways to implement mobile virtual workspaces, this study compares the current use of mobile phones to two probable implementations.

In order to keep the current display paradigm used in mobile phones, each workspace contains one application only. The screen would quickly become cluttered if more than one application were displayed at a time on such a small display. Ringel indicates an average number of four virtual workspaces used in desktop computing [Ringel 2003]; the prototypes were then implemented with four virtual workspaces and applications.

5.3.1 Apparatus

The three conditions for the experiment are *no virtual workspace*, which corresponds to the current use of mobile phones; *workspace switcher*, which provides a representation of the workspaces; and *mSpaces*, which distributes the workspaces across space. All conditions have been implemented on the same mobile phone, a Samsung Galaxy S running Android 2.3 OS.

5.3.2 Conditions

No virtual workspace

This condition reflects the current usage of mobile phones. To switch applications, the user returns to the main menu by performing a short click on the home button at the bottom of the screen (Figure 5.2 Left). There, they click on the icon corresponding to the application they want to open. This operation must be performed every time the user wants to switch application. This technique is a typical interaction technique for browsing through applications in mobile phones. The menu displayed consists of a 2x2 grid of icons, each one representing an application (Figure 5.2 Right).

Workspace switcher

This condition simulates the current metaphors for switching workspaces in the desktop environment. The *workspace switcher* is a graphical representation of the available workspaces, consisting of a bar of icons that appears at the bottom of the screen superimposing and partially hiding the current visible workspace (Figure 5.3). Each icon represents a workspace as in the *no virtual workspace*'s condition menu. The user performs a long click (500 ms.) on the home button to access the *workspace switcher*, as they would typically do for switching context on mobile phones when the functionality is available.

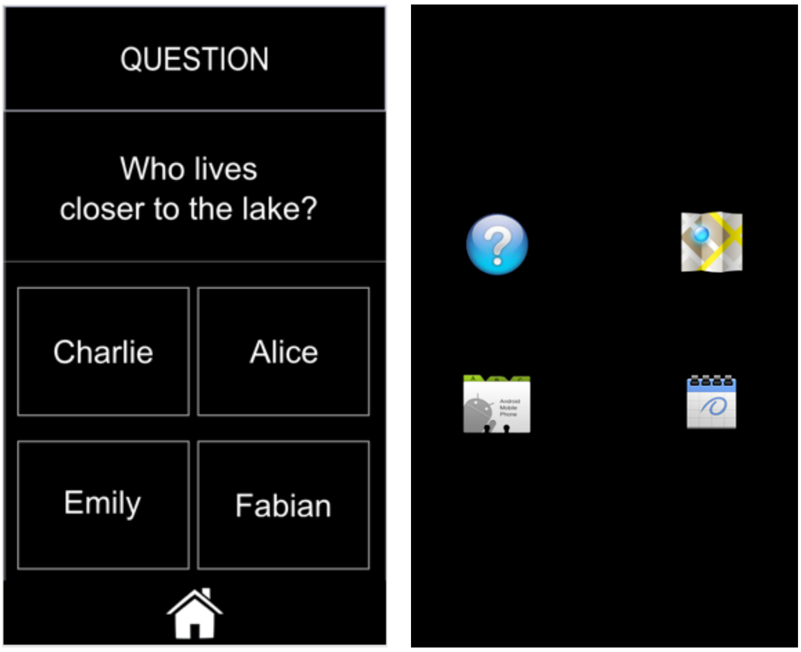


Figure 5.2: Two screenshots of the *No Virtual Workspace* condition: Left: Home button represented by a house icon available underneath the question. Right: A menu of icons representing available applications appears when a short click is performed on the home button.

Figure 5.3: Screenshot of the *Workspace Switcher* interface. A bar of icons representing the workspaces appears at the bottom of the screen when the user performs a long click on the home button.

mSpaces

The third condition, *mSpaces*, is a prototype that allows the user to choose which virtual workspace they want to display by moving to its physical space. The technique is in the same idiom as the interaction techniques presented in Imaginary Interfaces [Gustafson 2010], Virtual Shelves [Li 2009] and Peephole [Yee 2003]. In *mSpaces* however, kinaesthetic cues are attached to the workspace switches. The user accesses the distinct workspaces with permanent visual feedback; without having to press any button; just by moving the device to a new physical location. *mSpaces* is a spatially-aware device, in which 6 degrees of freedom tracking is realized using a NaturalPoint OptiTrack motion-capture system through IR-reflecting markers attached to the prototype (Figure 5.4). Workspace are separated from one another on the horizontal axis by a 30° angle as is advised in the literature [Li 2009]. In the experiment, the workspaces are positioned on a single vertical level but the prototype would in addition support having workspaces at multiple heights.

The position of the workspaces was fixed for the experiments and participants had a chance to become familiar with the system prior to the experiment.

Figure 5.4: Superposed pictures of the *mSpaces* prototype, a spatially aware mobile device. Different workspaces appear depending on the device's position around the user.

5.3.3 Tasks

To evaluate how virtual workspaces need to be designed for mobile devices, participants were asked to answer questions for which they needed to look up information using familiar mobile applications. Spatial search tasks were proposed, where participants needed to access multiple virtual workspaces to find the right answer. Since the tasks are spatial, the applications do not require any user interaction, aside from navigating between workspaces and using the touch screen to answer the question. The applications visible to the users are pre-designed screenshots of applications that may contain some clues to answer the trial question. The user can retrieve the clues by perusing the screenshots using the workspace switching technique. This task is representative of a task where a user consults their calendar to give a date or location to a person on the phone or next to them. This task is not designed for "on-the-move" scenario but instead a scenario where the user would stop for a short moment to consult some data on their phone as this is current practice.

For the four workspaces available, four applications are proposed: question (Figure 5.5 a), contact list (Figure 5.5 b), calendar (Figure 5.5 c) and map (Figure 5.5 d).

These applications correspond to everyday tasks commonly undertaken on mobile phones. Four types of tasks were presented to generate different sets of workspace switches. Type 1 respectively involves looking at the contact list and the map; type 2 at the map and the calendar; type 3 at the contact list and the calendar; and type 4 involves all workspaces and is therefore harder than other types.

The aim of each task is to answer the trial question. The participant does not know the type of the task; and for each trial, all four workspaces are available even if they do not all provide clues to answering the question. Once the answer is found, the participant gets back to the initial question workspace to validate their choice by touching an answer out of four choices on the touch screen (Figure 5.5 a).

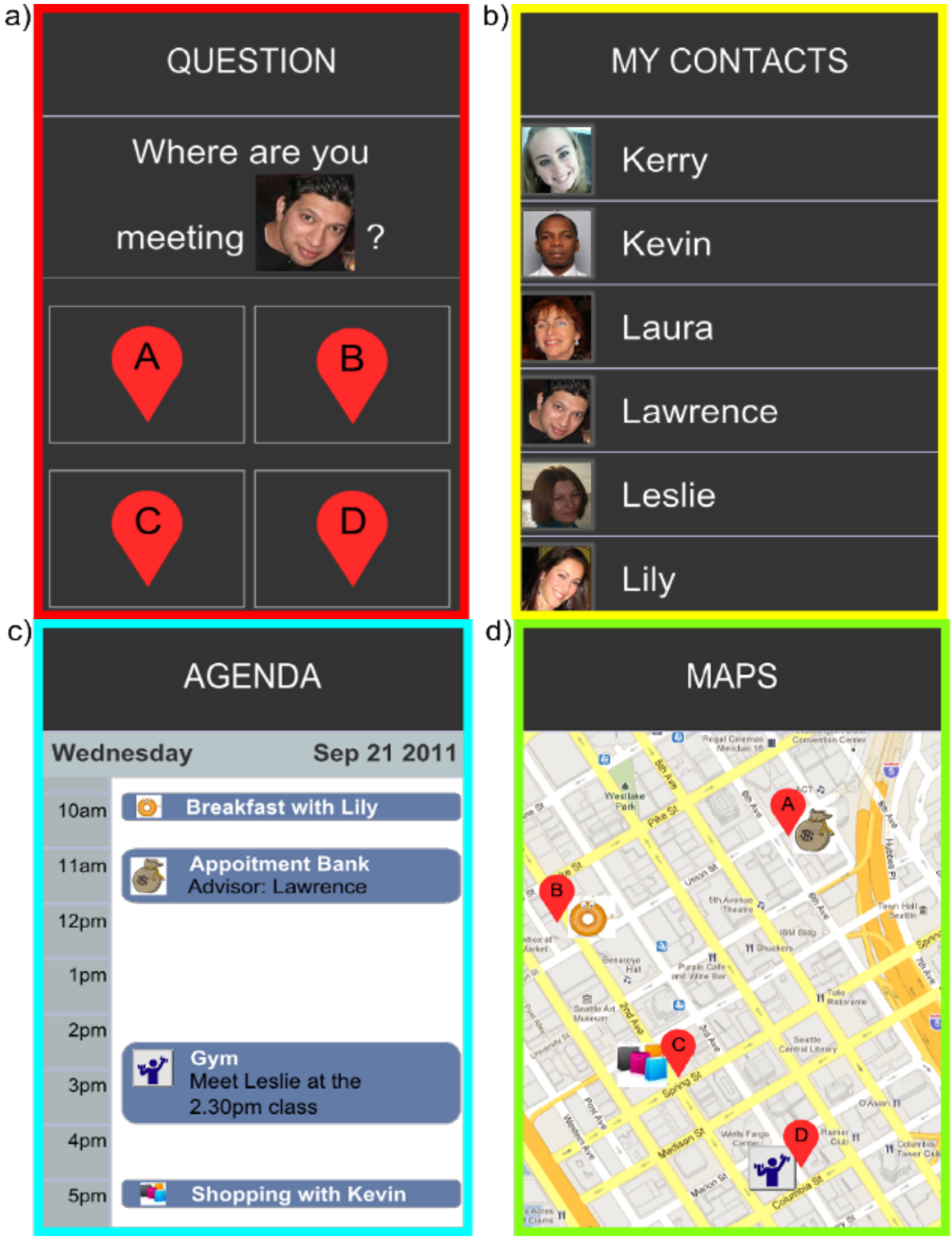


Figure 5.5: Screenshots of a type-4 task trial – To answer Question (a), the participant needs to match the picture with the person's name on the Contact list (b) and use the Calendar (c) to identify what activity they will be doing with this person. The next step is to use the Map (d) to locate the activity. Once the participant has navigated through all workspaces, they can answer the Question.

5.3.4 Procedure

Twelve volunteers (four female) aged between 23 and 44 ($\mu = 29.5$) were recruited from the DFKI research centre. All were right-handed, familiar with smartphones and touch screen technologies. A within-subjects experimental design was used where each participant had to answer all questions and the type of virtual workspace was counterbalanced across participants. The task was explained individually to participants who could try out each condition with a randomly chosen task in their own time. When the participant felt ready, they pressed the "Start" button to start the experiment and again before each trial. At the end of the experiment, users filled out a NASA TLX survey. Each session lasted between 45 and 60 minutes.

The independent variables were the *type of virtual workspaces*: No virtual workspace (Nv), workspace switcher (Ws), *mSpaces* (mSp); and the *type of task*: type 1 to 4 (t1 to t4). There were six questions of four different types per condition (i.e., type of workspace), which corresponds to twenty-four questions for each condition and seventy-two trials overall per participant.

The experiment had:

12 participants x 3 virtual workspaces x 4 tasks types x 6 trials for 864 data points.

5.3.5 Measures

The experimental software recorded trial completion time (MT) and error rate (ER) as dependent variables. MT is the total time taken to complete the task and is defined as the time taken for the user to perform a trial. The counter begins when the user presses "Start" and stops when the user clicks on one of the response buttons. If the user did not select the right answer, an error was registered and the user was allowed to progress to the next trial, no feedback was given to the user. Participants were asked to complete the NASA TLX questionnaire after the session. This allows assessing on a 7-point Likert scale subjective information for mental, physical, and temporal demand; performance; effort and frustration. In addition to the NASA TLX, participants were asked to rank the techniques and comment on their personal preferences.

5.3.6 Results

A univariate ANOVA with Tamhane post-hoc pairwise (unequal variance) comparisons was used for the following analyses.

Error rate

There were 59 errors out of 864 trials. With 8 incorrect trials, participants made fewest errors with *mSp* (mSpaces) followed by 21 incorrect trials for *Nv (No virtual workspaces)* and 30 for *Ws (Workspace switcher)* (Figure 5.6).

All 59 trials with incorrect responses were removed from further analysis.

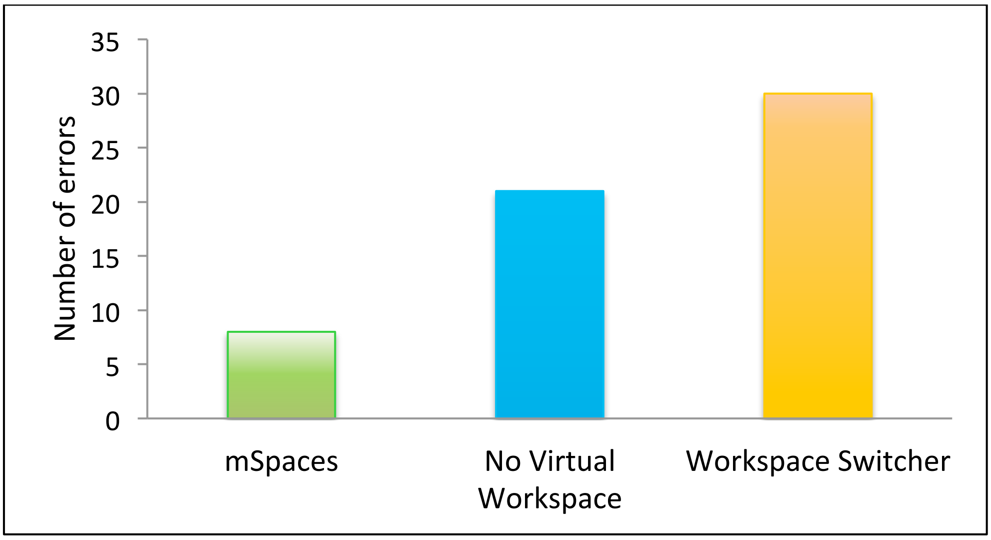


Figure 5.6: Number of errors for each technique in the mobile virtual workspace user study.

Completion time (MT)

The average trial completion time over all tasks and techniques was 16.6 seconds with standard deviation of 4.1 seconds. There was a significant effect of technique on trial completion time ($F_{(2,22)} = 10.85$, $p < .01$); *mSpaces* was significantly faster than the other two techniques followed by *No virtual workspace* (Nv) and *Workspace switcher* (Ws). No significant difference was found between Nv and Ws. There was a significant effect of task type on MT ($F_{(3,33)} = 19.6$, $p < .01$). Figure 5.7 shows the average trial completion time (MT) with standard error-bars for each technique and task type.

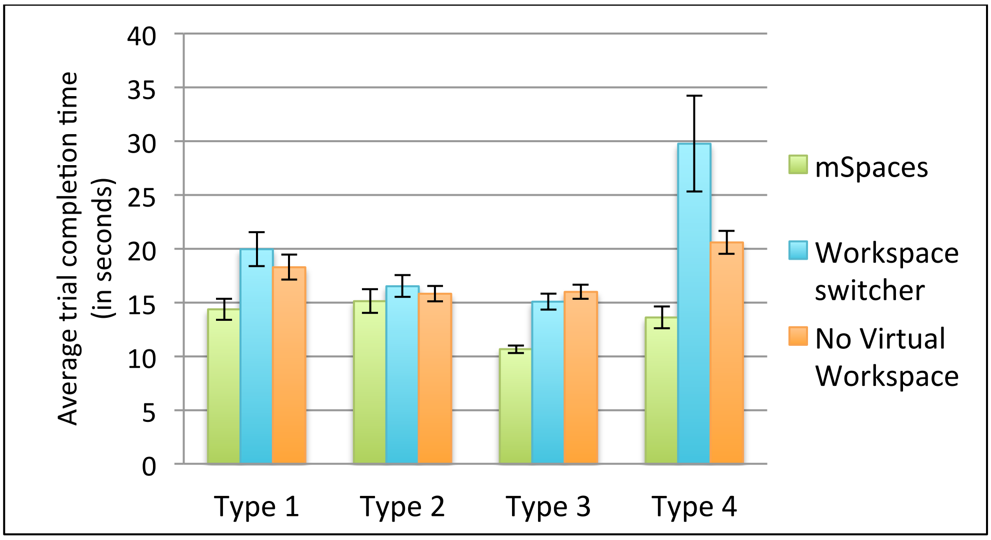


Figure 5.7: Average trial completion time for each technique across the four task types.

Subjective evaluation

The NASA TLX questions were analysed separately using non-parametric tests (k-related samples with Freidman Test Type) (Table 5.1). A significant difference was found for the following pairs: Mental Demand: (Ws,mSp), Performance: (mSp,Ws) and Effort: (mSp,Ws) & (mSp,Nv). All other combinations did not reveal significant differences.” Low performance value shows that users felt they performed well. Users felt *mSpaces* required the least mental demand and effort.

Factor	$\chi^2(12)$	P	mSp	Nv	Ws
Physical Demand	4.919	>0.05	1.96	1.62	2.42
Mental Demand	6.645	<0.05	1.54	2.08	2.38
Temporal Demand	0.261	>0.05	1.96	2.08	1.96
Performance	7.0	<0.05	1.67	1.92	2.42
Effort	11.862	<0.05	1.42	2.08	2.50
Frustration	2.606	>0.05	1.75	1.96	2.29

Table 5.1: Results of NASA TLX questionnaire

In overall ranking of techniques, 8 out of 12 participants preferred *mSpaces* to the other two conditions (Figure 5.8).

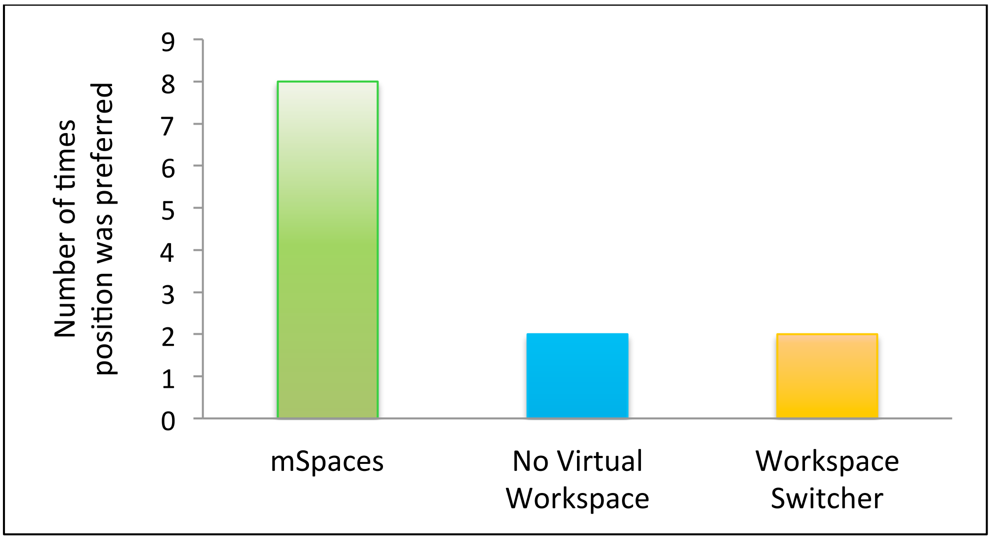


Figure 5.8: Participants subjective preferences of the different techniques.

5.3.7 Discussion

Virtual workspaces in mobile devices

Participants felt that the traditional use of a phone, as in the *no virtual workspace* condition, although it "was already common" and well understood, was "annoying to always start in the menu". The experiment shows that the use of virtual workspaces to complete tasks requiring serial switching through different applications can be significantly faster and less prone to errors than the traditional use of mobile phones. This is the case when comparing *mSpaces* to the *no virtual workspace* condition.

In the *workspace switcher* condition, the results were very similar to the ones of the *no virtual workspace* condition and slightly better for type 3 tasks and worse for type 4. This provides evidence that, although virtual workspaces can foster significant improvement over current use of mobile phones, they need to be carefully designed to realize their potential fully.

Spatial memory to position virtual workspaces

The results show that *mSpaces* improves decision-making accuracy. Additionally, the NASA TLX questionnaire shows that participants felt that they were less frustrated and required less effort to use *mSpaces*. This implies that virtual workspaces can therefore be managed on mobile phones using spatially aware techniques. With *mSpaces*, people use kinaesthetic cues and spatial memory to understand the positions of the various workspaces intuitively. In addition to being more efficient than the other conditions, *mSpaces* was preferred by 67% of the participants who enjoyed the opportunity to "build a spatial knowledge of the location of apps in space" and were able to "arrange [their] apps around [them]". They found *mSpaces* "faster", "easy to use", "quick and advanced", "very intuitive" and one mentioned that they "could browse everything pretty fast and easily look something up again".

Our implementation of *mSpaces* is built for displaying virtual workspaces, nonetheless the strong results and very positive feedback obtained from the study lead us to believe that the use of spatial awareness and memory to interact with mobile technology is very promising in spite of being under-exploited. It could be used not only to navigate through workspaces (*mSpaces*), menus [Gustafson 2010] and shortcuts [Li 2009], but also to manage interruptions in mobile technology.

Memory aids

The results show that using spatial memory only, participants can locate the different workspaces and navigate between them. Participants noted, "After a short learning phase it was easy and comfortable to switch between apps" and "Navigational help on the display would be useful". This suggests that *mSpaces* requires some memory aid. This will also be suitable as a reminder of the workspaces locations when users have not used *mSpaces* in some time. One way to provide a memory aid would be to display a map with the phone's current position compared to the overall position of all workspaces. A *workspace viewer* was therefore implemented and user study 2 will investigate if this functionality would improve usability.

Home button curse

In this experiment, it was noticed that imposing an extra click to request the workspace switch is time consuming and frustrating. Participants commented that the "long press was irritating" and that the *no virtual workspace* condition required a "ridiculous amount of clicking". Users should indeed be able to access a different workspace without having to first return to a main menu. One way would be to use a button dedicated to workspace navigation, which could display all workspaces available and allow navigation between them. This notion of a dedicated workspace button is described in more detail in the design considerations section. *mSpaces* obviously does not suffer from the "Home button curse" as the device is simply moved in order to switch to another workspace, neatly avoiding the issue. The current use of mobile phones with a home button to return to a main menu may then not be optimal, especially for tasks requiring several workspaces or application switches.

One-handed interaction technique

Participants were not instructed on how the phone should be held. They could hold it as they felt comfortable and all held it naturally, as they would with their own mobile phone. Nonetheless, the observer noticed that for *mSpaces*, 75% of the participants held the device in their dominant hand only and interacted with the dominant thumb, leaving their second hand completely free. Only two held the phone in their dominant hand while interacting with the other hand. Finally one person used both hands after the first three trials as they "[feared] to drop the phone when moving it too fast". For the two other conditions: *workspace switcher* and *no virtual workspace*, seven out of twelve participants used both hands to hold the prototype. This is despite both techniques being implemented on the same prototype as *mSpaces*.

Number of workspaces

For a task with a higher number of switches such as type 4 tasks, there was a significant difference in time completion across the techniques. *mSpaces* was more efficient and less error prone than the other two conditions. The number of workspaces may well therefore influence which technique is most appropriate. With the number of applications being simultaneously used on mobile phones growing, *mSpaces* seems better suited than other techniques that would clutter the screen with extra icons, switches or scroll bars. Yet, *mSpaces* scalability will need to be determined in future work. According to [Ringel 2003], some users prefer partitioning information on their screens by using external displays rather than virtual workspaces. This work goes beyond this statement by proposing improved use of *mSpaces* by adding an external display (mobile projector) on the phone and fitting it with the *mSpaces* approach.

5.4 User Study 2: Extending mSpaces

User study 2 tests if spatially aware virtual workspaces can be exploited in a heterogeneous projection-screen MMDE. An additional display was then included to the *mSpaces* prototype, as well as a workspace viewer. Since mobile projectors are common additional displays used for today's mobile phones, *pSpaces* is proposed as a projected version of *mSpaces*. *pSpaces* has the added advantage of displaying the workspaces externally from the device via the projection beam, which may improve the speed and accuracy of users when performing a task. This study also compares both solutions to a hybrid version: *m+pSpaces* where the main workspace is displayed on the screen while other workspaces are being projected one at a time depending on the position of the projection, as in *pSpaces*. For both *pSpaces* and *m+pSpaces* prototypes, the user points the projector at the physical space to display the virtual workspace corresponding to the location.

5.4.1 Apparatus

All prototypes used a Samsung Galaxy S and Microvision ShowWX+ mobile projector (depth: 14 millimetres – weight: 122 grams) (Figure 5.9). To guarantee the comparability of results the *mSpaces* prototype used in this experiment uses the same hardware as *pSpaces* and *m+pSpaces* with the projector switched off.

Figure 5.9: Photography of the physical prototype used in the second user study. The prototype is composed of a Samsung Galaxy S and a Microvision ShowWX+ mobile projector equipped with IR-reflecting markers. In the first user study, the projector is removed.

5.4.2 Conditions

pSpaces

pSpaces was implemented with a mobile projector connected to a phone where the user can point at the virtual workspace to display it. The mobile projector is fixed to the phone and the participant moves the projection-screen prototype to different locations to display different content. The motion-capture system used is the same as for the *mSpaces* prototype described in the first user study. The computer determines which workspace to display depending on the prototype's position (Figure 5.10).

All workspaces are accessible and displayed via the projection. In *pSpaces*, a spatial representation of the virtual workspaces, *workspace viewer* (Figure 5.11), is displayed on the screen. Workspaces are represented by a thumbnail and not an icon, as in current mobile phones displays; allowing users to benefit from both their visual and spatial memory [Lewis 2004].

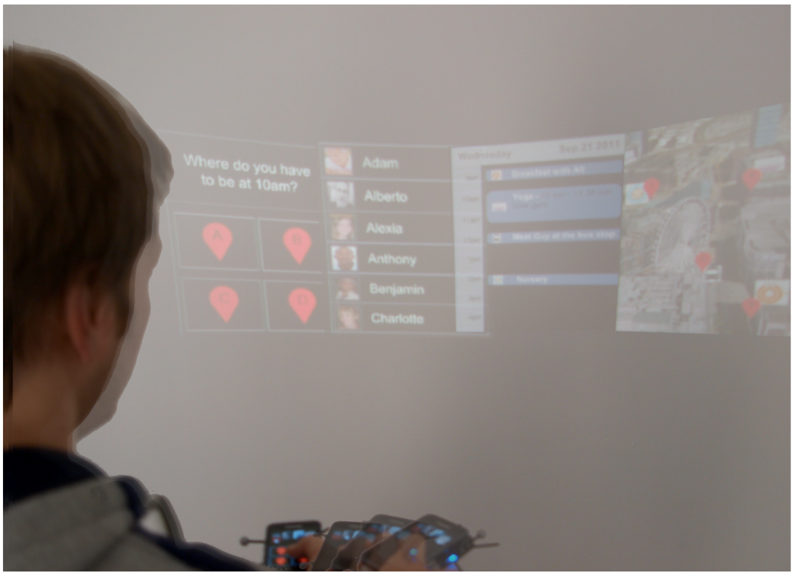


Figure 5.10: Superposed photographs of pSpaces in use with four workspaces. The user can access the workspaces by moving the device to different locations around the body.

The *workspace viewer* provides constant information on users' location in the environment compared to other workspaces. This answers some of the concerns addressed by participants in user study 1 where some felt that they could not remember the exact physical location of workspaces: "you first had to discover and "save" [remember] the positions of the apps". In order for participants to complete the task and not to introduce a new interaction technique, participants used the touch screen to answer the question as for *mSpaces*. Participants needed to return to the question workspace for the answer buttons to appear on the screen below the *workspace viewer*.

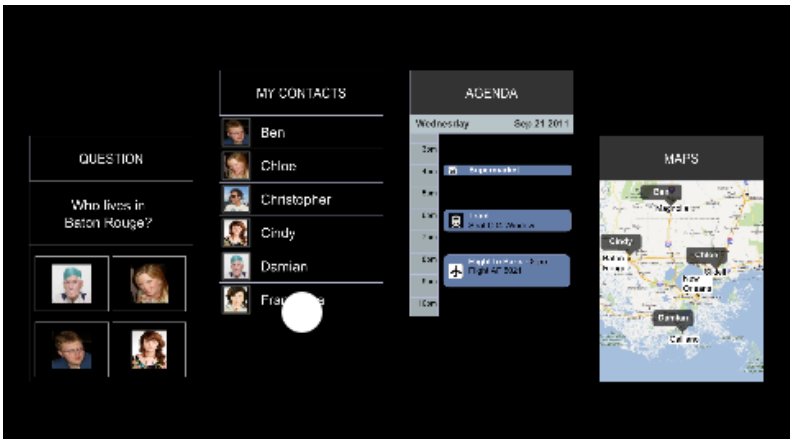


Figure 5.11: Screenshot of the *Workspace Viewer*: Each workspace is represented in an icon with the spatial representation of the icons matching the physical layout of the workspaces. The workspace viewer is positioned on the top part of the phone's screen. The device's current location is represented by a white dot.

m+pSpaces

This condition is a hybrid version of *mSpaces* and *pSpaces* where the main workspace in use (Question – Figure 5.5 (a)) is displayed on the screen while all other workspaces are accessible by projecting towards their physical locations (as for *pSpaces*). As the only input needed from the user is on the question workspace, the latter is defined as main workspace, constantly displayed on the screen and therefore not projected. Since the screen will display the main workspace, the *workspace viewer* will not be displayed or made available. Some interaction techniques that can be used to define what workspace to display on the device's screen are discussed in the design considerations section.

5.4.3 Procedures

The tasks used for this experiment are the same as for the previous experiment. Twelve new participants (three female) were recruited for this study, aged between 23 and 45 (μ = 31.3), all but one right-handed and all but two smartphone owners. While all participants were familiar with touch screens, only two had used a mobile projector prior to the study.

A within-subjects experimental design was employed where all participants had to answer all questions and prototypes were counterbalanced across participants. The tasks were explained individually to each participant who could try out the prototypes with a randomly chosen task in their own time. When they felt ready, they pressed a "Start" button to begin the experiment and again to initiate each trial. After the experiment, users filled out a NASA TLX survey.

The independent variables were the *virtual workspaces prototype*: *mSpaces* (m), *m+pSpaces* (m+p) and *pSpaces* (p) and the *type of task*: type 1 to 4 (t1 to t4).

There were 6 questions of 4 types per prototype corresponding to 24 questions for each prototype and 72 trials overall per participant. In summary the experimental design was:

12 participants x 3 virtual workspace prototypes x 4 types of tasks x 6 trials
= 864 data points.

5.4.4 Measures

The experimental software recorded trial completion time (MT) and error rate (ER). In addition, the number of switches between workspaces (SW) was recorded as dependent variable. SW corresponds to the number of times (switches) the user stops on a workspace during a trial. This data is measured to ensure that visual separation effects (discussed in Chapter 4) in the *m+p* and *pSpaces* conditions do not hinder the results. A switch is recorded each time the user spends at least 300 consecutive milliseconds on a workspace. There is no maximum number of switches as users can change workspaces as many times as they want until they find the answer to the question. Since *m+pSpaces* has one workspace displayed on the screen, SW is recorded as the actual number of switches per task minus the minimum number of switches required to perform this type of task with a given prototype. The same qualitative data as for user study 1 was gathered.

5.4.5 Results

A univariate ANOVA with Tamhane post-hoc pairwise (unequal variance) comparisons was used for the following analyses.

Error rate

There were a total of 43 errors out of 864 trials (Figure 5.12). With 9 incorrect trials, participants made fewest errors with the *pSpaces* technique followed by 16 incorrect trials for *mSpaces* and 18 for *m+pSpaces*. The 43 trials with incorrect responses were removed from further analysis.

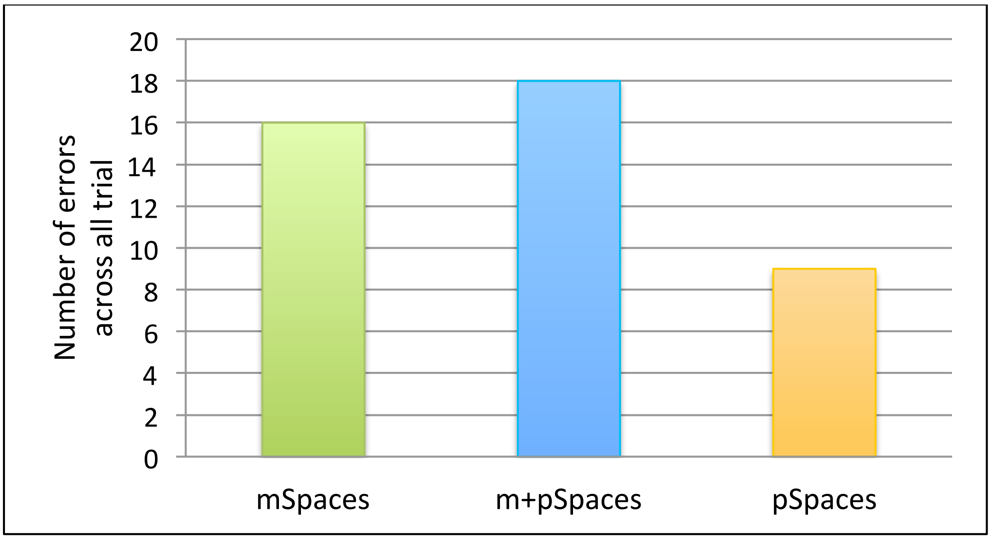


Figure 5.12: Overall number of errors for each workspace prototype in user study 2. Participants made fewer mistakes with *pSpaces*.

Completion time (MT)

The average trial completion time overall was 14.4 seconds with standard deviation of 2.6 seconds (Figure 5.13). There was a significant effect of type of task on trial completion time ($F_{(3,33)}$=17.09, p< .001). Yet, no significant effect of workspace prototype was found.

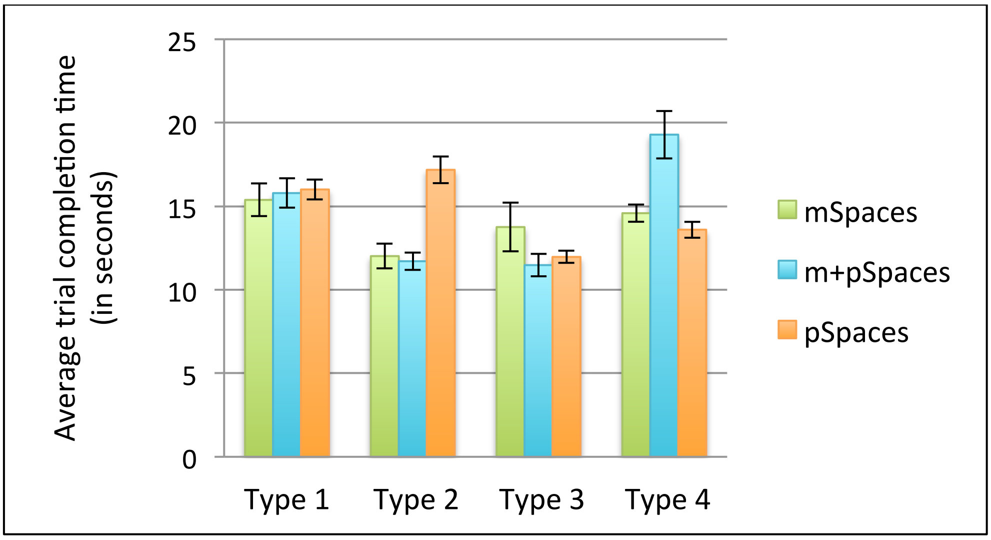


Figure 5.13: Average trial completion time for each prototype and task type in user study 2.

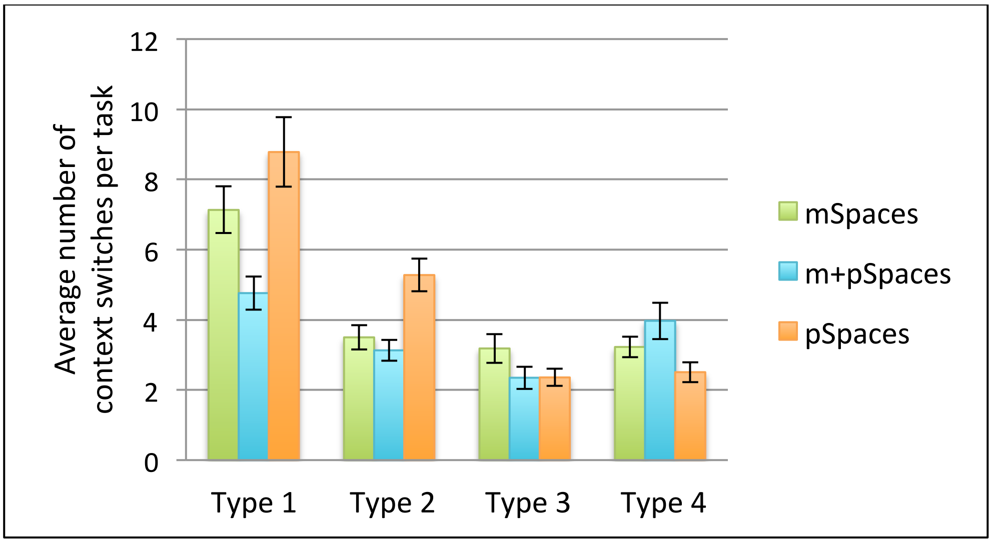


Figure 5.14: Average number of switches – as measured by the mobile eye tracker – between workspaces for each technique of the three techniques and the four task types in user study 2.

Switches between workspaces (SW)

The average number of switches overall was 4.2 with standard deviation of 0.2. There was a significant effect of prototype used on number of switches ($F_{(2,22)}$=5.83, p< .05). *mSpaces* (m) and *m+pSpaces* (m+p) resulted in significantly less switches than *pSpaces* (p) (Figure 5.14). There was also a significant effect of type of task on trial number of switches ($F_{(3,33)}$ = 67.9, p< .001).

Subjective evaluation

The NASA TLX questions were analysed separately using non-parametric tests (k-related samples with Freidman Test Type). No statistical difference was found between the different prototypes on any of the NASA TLX factors. In terms of preferences, eight out of twelve participants preferred *m+pSpaces*, two *mSpaces* and one *pSpaces* (Figure 5.15).

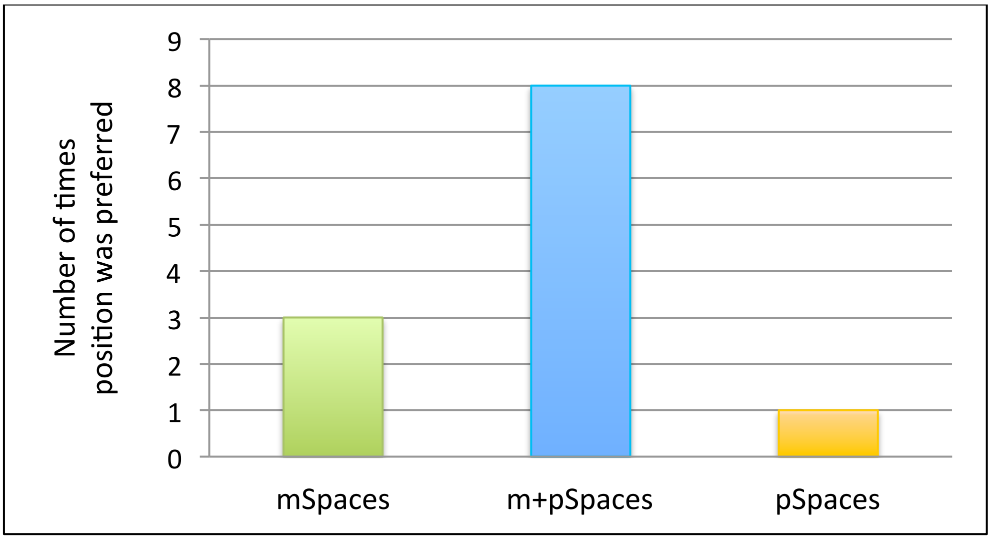


Figure 5.15: Overall preferred prototype for User Study 2 for each participant. The *m+pSpaces* prototype was clearly preferred by the participants. Overall 75% of the participants preferred a multi-display prototype to a single-display one.

5.4.6 Discussion

Spatially aware virtual workspaces

In this experiment, no significant difference was found in the overall task completion time over the three spatially aware virtual workspaces prototypes. In the first study, for the same tasks, using spatially aware workspaces was found significantly faster than current usages of mobile devices. In conclusion, while using spatial awareness greatly improves current usages, the way in which the spatially aware system is designed does not seem to influence the system's pace. This further reinforces the first user study findings that virtual workspaces need to be designed with considerations to users' spatial awareness.

Memory aids

During the first study where *mSpaces* is compared to current usage of mobile phones, users have reported needing time to learn the position of the workspaces and mentioned: "navigational help on the display would be useful". It was therefore decided to provide users with a workspace viewer in the *pSpaces* condition since all workspaces were projected and the prototype's screen could then be used for displaying the workspace viewer. The idea was to provide users with a constant reference to their position in the environment. This technique also relates well to current existing techniques for switching workspaces in the desktop environment. Surprisingly, when users were asked if they found the workspace viewer helpful and if they used it, the ten out of twelve participants who answered, unanimously replyed not using it nor finding it useful. The reasons they provided were that "it was quite easy to spot the projections" and "easy to remember the positions". They mentioned they "concentrated on the projection", "knew the arrangement already from the task [they] did before" and "that the other screens were sufficient".

This suggests that with *pSpaces*, users are able to remember the position of the workspaces without needing any workspace viewer. Projection onto the external space has rich spatial cues that, when combined with the kinesthetic cues of moving the device, help users remember the location of the workspace. Additionally, no participant mentioned struggling with finding the position of the workspaces across all conditions, contrary to the first study. Furthermore, in the second study, contrary to the first, all conditions expect users to remember the physical locations of the workspaces so it is possible that the nature of the task condition people to remember the workspaces locations better than in the first study. This leads us to think that when there is no reference to other types of interaction; people feel comfortable and lose their apprehension towards using such interfaces.

Workspaces switches

The number of workspace switches is significantly higher for *pSpaces* than for both *mSpaces* and *m+pSpaces* while there is no significant difference in the average time needed to perform the trials; which shows that users switched between workspaces in a faster way using *pSpaces*. At the same time, the NASA TLX shows that participants did not find *pSpaces* more mentally or physically demanding or even more frustrating than the other two prototypes. Since participants had no issue finding the position of the workspaces, it can be concluded that participants chose, whether consciously or not, to switch more often betwen workspaces in the *pSpaces* condition. This is also very likely to be the reason why users made considerably less errors in performing the task with *pSpaces*. This higher number of switches seems to indicate that *pSpaces* provide an easy avenue to externalize users' thoughts as discussed in Chapter 4.

One-handed vs. two-handed interaction

In this experiment, only two participants held the prototypes in their dominant hand, while all others always held the prototypes with both hands. It was hoped that the projector would be small and light enough not to affect the interaction technique. Unfortunately, the device was bigger and heavier than in the first study and that affected the interaction. Since this *mSpaces* prototype was held in both hands instead of one for the first study prototype, there is a potential for *pSpaces* and *m+pSpaces* to be one-handed techniques too, provided a smaller embodiment of mobile projection technology inside phones.

Projected virtual workspaces

In terms of performance, *pSpaces* appears to be the best technique as users answered more accurately for the same completion time and swap workspaces more often, probably as a way to externalize their thoughts. Nonetheless, *m+pSpaces* was preferred by 75% of the participants and for performances similar to *mSpaces*. Participants preferred *mSpaces* as "it [is] useful to have the task visible all the time while working on it" and as it was "interesting to have one workspace always in sight". Some participants also liked "having the screens in [a] big size on the wall and at the same time to have the question at hand" and finally one mentioned "it somehow "divided" the task and space".

In summary, whether due to performances (*pSpaces*) or user preferences (*m+pSpaces*), external projection improves the capabilities of spatially aware virtual workspaces.

5.5 Design Considerations

The two user studies presented in this chapter show that virtual workspaces have the potential to improve the usability of mobile environments. This section proposes some design considerations for both *m-* and *pSpaces*.

There are different aspects to take into consideration when designing virtual workspaces. The workspace needs to be created and an application needs to be allocated to this particular workspace. The virtual workspace also has some attributes such as size and position that need to be defined. This set of design considerations is presented below.

Creating & positioning new workspaces

There are two strategies for creating workspaces in the space around the user. The first consists of creating an empty workspace and moving applications inside it in separate actions. The second consists in directly positioning an application and creating the workspace at the same time. The latter strategy is the most efficient when there is only one application per workspace. It is advised that there should not be more than one application per workspace to keep the current mobile device interaction paradigm, and also because of the small amount of screen real estate available for mobile phones.

A a specific button – software or hardware – could be introduced to trigger and control the workspaces management. This will preserve the one-handedness of the interaction technique while keeping it intuitive for the user. The interaction can be "hold and release" based where the user holds the button, moves the device to a physical location and releases the button to complete the operation. This technique allows a direct allocation of the application in view to the newly created workspace.

Another solution is to implement a drag-and-drop approach similar to Boring et al. [Boring 2010]. For *pSpaces*, an application launcher could be displayed on the mobile screen for the selected application to open up on the actual external projection at the current pointing direction of the device. The workspace position can then be directly controlled by pointing or moving the device to the physical location corresponding to where the workspace will be residing.

Workspaces dimension

While in *mSpaces* the workspace size is limited to the size of the mobile device's screen, as discussed in the previous section, in *pSpaces* the corners and size of the workspaces could directly be defined by manipulating the projection area in the environment through an appropriate gesture via the device itself. Designers could envisage having a virtual workspace larger than the size of the device's screen in *mSpaces*, similarly to the concept of Peephole displays [Yee 2003], but this would require a set-up stage via the touch screen or some movement recognition technique and incur additional interaction controls to scroll through the virtual workspace.

Moving applications across workspaces

When moving applications across workspaces, designers need to differentiate between *m-* and *pSpaces*. *mSpaces* proposes a similar approach to the way applications are already organized on a smartphone application launcher space while *pSpaces* can take advantage of the mobile device screen to "drag" an application and "drop" it on an arbitrary workspace after having "pointed" at it. A special "drag" gesture (such as quickly tilting towards the user, as in Boring's Tilt interface [Boring 2009]) could be used to copy the actual projected workspace to the screen in *m+pSpaces*, so the user can provide touch input to an application.

Repositioning workspaces

The thumbnails representing workspaces or applications can be rearranged on the *workspaces viewer* on the mobile device's screen to rearrange the actual physical location of workspaces. The spatial alignment of the thumbnails and their sizes on the screen will directly translate into the spatial alignment and actual sizes of the workspaces surrounding the user in an appropriate manner – such as by inserting at least 30 degree separation angles between workspaces. The rearrangement of thumbnails on the screen will then lead to the corresponding spatial realignment of the workspaces themselves. In the case of *m+pSpaces*, the same technique is used for ad-hoc selection and modification of which workspace is to be displayed on the screen and respectively the projection.

Finding virtual workspaces

In this configuration, users get shortly accustomed to their current workspaces' spatial configuration and so do not need a memory aid. Yet, this will be useful when people move workspaces around or create new ones, disturbing the established spatial arrangement. This will also benefit users with high numbers of workspaces or who haven't used the system in a long time. An overview of the arrangement of the workspaces on the device screen is needed as well as a finding function which allows rapid access to a workspace. A graphical representation of virtual workspaces could be used, similar to Nacenta's work on MDEs with a graphic representation of all available displays [Nacenta 2009]. Finding a particular workspace could be done by displaying arrows on the screen pointing to the direction of the workspace's location. Haptic feedback could be used to indicate the position of a workspace, which would allow users to simply wave the device until they receive the haptic feedback (similar to Sweep-Shake [Robinson 2009]).

Favourite configuration

Storing favourite configurations would allow for the configuration of different arrangements based on context as Böhmer [Boehmer 2010] proposes for icons. In fact, when the phone is used in different contexts – e.g. personal or professional – or when used by more than one person, different favorite configurations may exist. For multi-users, it is equivalent to starting one's own session on a shared computer.

Applications & tasks awareness

To be used for more effective task management, designers can provide awareness that a task in another virtual workspace requires a user's attention by adding some visual feedback. A coloured bar could be displayed on the side of the display (reflective of the position of the other workspace) and for example changing its colour [Matthews 2006] to indicate the status of the task. Another possibility is to use a halo technique [Baudisch 2003b] or an off-screen visualization pointing triangle [Ens 2011]; and haptic feedback could also be used. For example, a light vibration would indicate an alert on a workspace which is currently not visible associated to a stronger vibration when the user hovers over the workspace in question – as described in the 'Creating & Positioning New Workspaces' paragraph above.

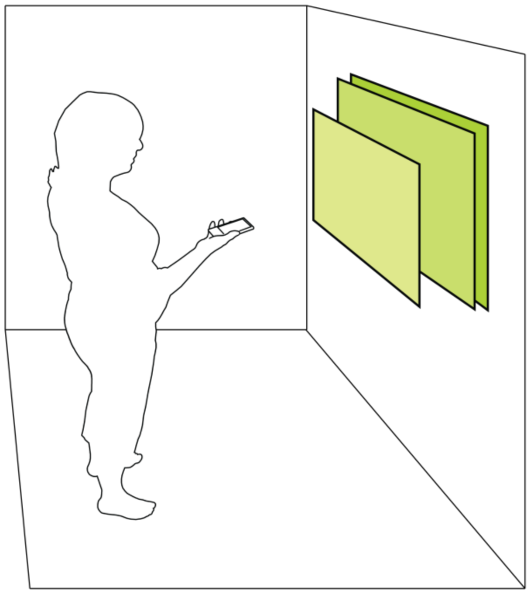
Deleting a virtual workspace

A gesture, such as drawing a cross while pointing at the workspace could be used to delete it. Alternatively, a specific button could indicate deletion of the workspace. This may require a confirmation click or movement. If the deletion is not linked to the deletion of the application on the workspace, then the confirmation is not compulsary as the effects of a mistake will only be minimal.

5.6 SUMMARY

This chapter has investigated the use of virtual workspaces in mobile environments. It first considered existing techniques for workspace management in the fixed desktop environment, with the view to translate and adapt them to mobile settings. It was demonstrated that extra spatial awareness, that is possible in the mobile context, vastly enhances users' performance. A first prototype was implemented, *mSpaces*, which corresponds to a spatially aware prototype for virtual workspaces that allows workspace switching by moving the prototype to various physical locations, while providing users with rich spatio-kinaesthetic cues. To determine if using external projection spaces further enhances users' performance, two additional prototypes were designed *m+p* and *pSpaces.* In a final user study, the three techniques are compared to show that projection enhances users' abilities to switch between workspaces, potentially encouraging designers to use such methods. This chapter concludes with design considerations to create, manipulate, and manage virtual workspaces in the spatially aware mobile environment.

The following chapter takes the concept of using spatial awareness for mobile interaction further, by using the projection not only around the user but also in the depth separating the user from the projection surface. Instead of using an increasing amount physical space to display additional information around the user, one could use a specific location, and layer information (such as workspaces) in depth. In the following section, the feasibility of using depth in the mobile projected environment is demonstrated. A mathematical model of perceived depth is proposed and two user experiments that validate the model are described. They help understand both the promises and limitations of having such capability embedded in a MMDE.



Chapter 6
DEPTH AND STEREOSCOPIC 3D FOR MOBILE PROJECTORS

Chapter 5 investigates the use of the physical space around the user to display information. One of the main outcomes of this work is that it proved that using the additional spatial awareness that exists in the mobile environment vastly enhances users' performance when switching workspaces or applications. Moreover, users enjoyed making use of the rich spatio-kinaesthetic cues and some reported appreciating not having to move their head or gaze to visualize information.

This chapter proposes that the space available between the user and the projection surface: in depth, can be used to project multiple layers of information. Using depth would allow using the unique spatial relationship between the user, the device, and the environment to display and interact with content. The findings of Chapter 5 on the use of spatio-kinaesthetic cues to interact with Mobile Multi-Display Environments (MMDEs) could then be applied to the aforementioned spatial relationships.

This chapter first presents background literature on using depth in the mobile environment, and on how people perceive depth. A mathematical model of perceived depth is then put forward; it was specifically developed for mobile stereoscopic 3D devices based on the existing models of perceived depth in fixed environments. A first user study validates the model in a fixed setting, with distances matching the ones used in handheld mobile environments. The results from the experiment prove the validity of the mathematical model and show that users perceived depth as predicted by the model with over 95% accuracy. The second user study adds a mobility component to the system by varying the distances between the user, the projector, and the projection surface. The study verifies if the changes in depth are actually perceivable in a handheld mobile scenario. Results show that scenarios where the distance between the projector and the user remains constant result in significantly higher accuracy. The chapter concludes with design considerations for further developing systems that can layer information in depth and avenue for future work.

6.1 INTRODUCTION

Acquiring the ability to use projection depth would offer considerable advantages in mobile projection systems. First, users would not be constrained by the amount of projection surface available to project on in the environment. Instead, they would use any projection surface; and layer information in depth in the physical gap between them and the physical space, as shown in Figure 6.1.

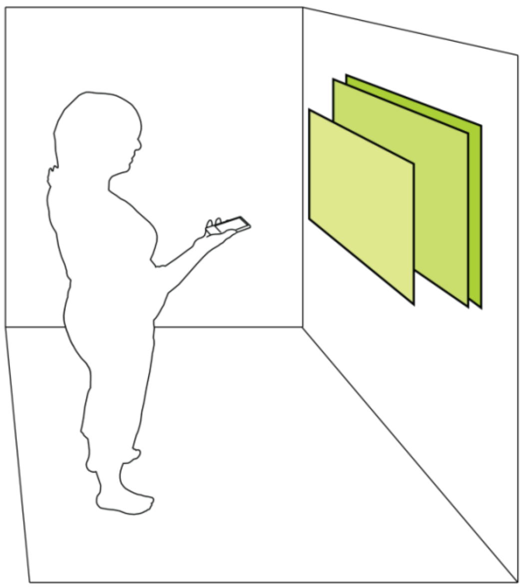


Figure 6.1: A person projecting information on the wall in front of them and using several projection layers in the depth between them and the wall.

This would therefore increase the available display space – virtually – while still using the same amount of projection surface – physically –. Additionally, this would not require additional display hardware since only one stereoscopic mobile projector would suffice to layer information in depth. Another significant advantage of using depth, and more specifically in MMDEs, is that the multiple displays can be kept in the same field of view, as per recommendations in Chapter 4; while at the same time using multiple depth planes to project on; therefore still providing additional display real estate thanks to the projection.

Additionally, in the same way that the space around the user is being used in Chapter 5, researchers could exploit the physical space in front of the user to project different workspaces. Users could therefore use this physical space to interact with the projected content and potentially with content available on other displays in the MMDE too. In terms of usage scenario, different depth levels could correspond to different privacy levels; this could furthermore be emphasized by the projection size that gets smaller when the projector gets closer to the projection surface. Privacy zones, based on proxemics research, could then be created. Finally, the distance to the projection could be mapped onto zooming levels when studying a map or a complex image.

As 3D displays are becoming increasingly popular and available in both mobile screens and projectors, these scenarios are getting closer to us and will become a reality in the near future. However, at this time, the research community does not have an understanding of how depth is actually being perceived by users in handheld mobile projection systems, and what factors potentially influence this perception.

This chapter is therefore focussing on understanding how depth is perceived in the mobile projected environment and what factors affects this perception. The work presented corresponds to the research work conducted during my internship at Microsoft Research Asia (MSRA) in Beijing, working with Dr. Xiang Cao. This chapter starts by describing related literature on depth perception and 3D in mobile devices (6.2). It then proposes a novel geometric model for perceived depth for mobile stereoscopic projection based on the existing model of perceived depth for fixed stereoscopic projected environments (6.3). Two controlled user studies were conducted to validate the model in conditions consistent with typical mobile projection scenarios. Xuyong Yang ran the first experiment (6.4) under Dr. Xiang Cao's supervision at MSRA. I participated in the implementation of the software tool and the design of the experiment. Xuyong Yang built the final software based on my original code, ran the study and sent me all experimental software data as well as photographs of the study and set-up. All of the data evaluation, statistical analysis and conclusions presented in this section are my own work. In this first experiment, all the distances are fixed (but consistent with mobile scenario) in order to gather very precise data on how depth is actually perceived by participants. The geometrical model is experimentally verified and resulted in over 95% accuracy compared to the predicted model. Some design considerations are identified; and, for example, it can be inferred from the results that 3D perception is significantly better when the projector is handheld compared to body-mounted.

The second experiment was conducted at the University of Bristol, UK. In the second user study (6.5), the device is handheld allowing testing the effectiveness of the model in real-world conditions. A mobility condition was added to verify if the changes in depth would be perceivable in a close-to-real world setting where the distances between the projector, the user, and the projection surface present small variations. Empirical data show that adding mobility presents some new challenges towards depth perception and factors affecting the perception are discussed. Results also demonstrate that when the distance between the projector and the user remains constant, the trials presented significantly higher accuracy rate. The chapter finally concludes with design guidelines (6.6.1) and future work opportunities (6.6.2).

6.2 Background

This section presents the more specific background in interacting using depth, 3D in mobile projection and depth perception.

6.2.1 Interaction using depth

This section covers the relevant background literature on how depth has been used to interact with digital content. Two types of depth are considered, *Virtual depth* as the simulation of a 3D environment and layout in a physical 2D world, and *Physical depth* as the depth used with physical cues in a true 3D environment.

Virtual depth

Using depth to layer information has already been exploited in the desktop environment as in Data Mountain (Figure 6.2 Left) [Robertson 1998], a document management system that emulates a 3D spatial layout to position files; using users' spatial memory to manage documents. Robertson et al. propose the Task Gallery [Robertson 2000] as a window manager, building on findings from Data Mountain on using users' spatial cognition and memory for them to interact with their desktop. Patterson takes the concept further and introduces "active 3D interfaces" (Figure 6.2 Right) that use depth and motion to present data to the user [Patterson 2007].

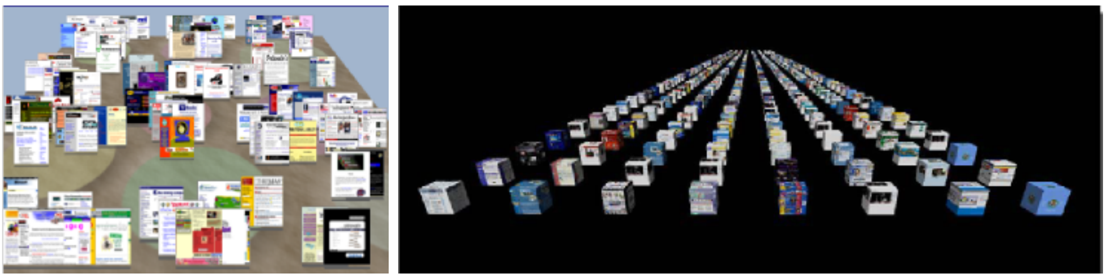


Figure 6.2: Left: Snapshot of Data Mountain [Robertson 1998], a 3D spatial visualisation system that uses virtual depth for document management. Right: Snapshot of the flow component part of the "active 3D interfaces" concept [Patterson 2007] that consists in using both depth and motion to present data to the user.

Physical depth

In the case of physical depth, a physical movement can be mapped to the interaction with the system. Subramanian et al. [Subramanian 2006] present the concept of exploiting the space between the user and the tabletop to interact with multiple layers of visual content. The visual content however always remains at the same level on the tabletop. Spindler et al. [Spindler 2012] then propose to use the space between the user and the tabletop to display multiple contents on a magic lens. This space is divided in "discrete parallel layers stacked upon each other" p.1 [Spindler 2012]. They determine a maximum number of layers depending on the task and a minimal layer thickness that varies for horizontal and vertical interaction. The work presented in this chapter is similar although the interaction would be in the z-axis instead of the x and y Cartesian axes in Spindler et al.'s work.

6.2.2 3D in Mobile Projection Devices

In the Background chapter, section *2.1.3:* Mobile Projectors*:* Interaction Techniques, it is presented that mobile projector interaction has attracted interest of many researchers. More specifically, Molyneaux et al. explored interacting with projected pseudo-3D objects using a mobile projector, based on a 3D reconstruction of the physical environment [Molyneaux 2012]. MotionBeam [Willis 2010] changes the perspective of projected character based on the mobile projector's 3D orientation. In both works, regular 2D projectors are being used to emulate a 3D impression.

Moreover, following the maturing of miniaturized projection technologies; mobile projectors capable of projecting stereoscopic 3D content also start to emerge, promising an entirely new interaction space. Miller and Laviola [Miller 2010] present a mobile stereoscopic projector prototype for simple interactions with a projected 3D virtual world. Although relatively preliminary, these works suggest the rich potential of 3D handheld mobile projector interaction.

6.2.3 Objects Perception in Depth

Since Wheatstone described binocular vision and created the stereoscope in the early nineteenth century [Wheatstone 1838]; researchers have kept imagining new techniques and devices capable of showing images while recreating the depth perception that occurs when looking at a natural scene. Wheatstone demonstrated that humans perceive depth based on a variety of visual cues, the most prominent of which is binocular disparity (also known as stereopsis). It is the fact that the same object appears at slightly different horizontal positions for the two eyes. Based on this principle, stereoscopic 3D displays show the virtual object at a different horizontal screen location for each eye, creating the perception that the object is at a different depth than the screen itself.

Special glasses are usually used to allow each eye to see the respective view, although glasses-free solutions exist too. Stereoscopic 3D displays are not perfect because other depth cues which are not replicated – such as accommodation (i.e., change of eye focal length) – may cause discomfort, confusion, or failure if they significantly conflict with stereopsis [Jones 2001].

Many researchers studied depth perception on stereoscopic displays, such as [Swan 2007]; including stereo projectors [Benko 2012] and volumetric displays [Grossman 2006]. In particular, Holliman [Holliman 2006] presents a mathematical model for the perceived depth of a virtual object displayed on a stereoscopic display screen which is adapted in the following section to create a new model of perceived depth for mobile stereoscopic projectors.

6.3 Geometric Model of Perceived Depth

This section presents an adapted geometric model of perceived depth for mobile 3D stereoscopic projection.

6.3.1 Depth Perception Model for a Stereoscopic Display

Many have studied the geometric model for perceived depth, such as [Von Helmholtz 1924, Valyus 1966, Jones 2004]. [Holliman 2006] and [Sun 2012] describe an equation based on previous research that defines the user's perceived depth of digital stereoscopic images. Holliman's model takes into account the screen disparity d – physical displacement of the object on the screen between the two views –, the viewing distance z – distance from the user's eyes to the screen –, as well as the user's eye separation e – distance between the two eyes –. This model does not take into account the depth compression [Jones 2001] which is overlooked in this work too in order to consider the main factors affecting perceived depth only.

Figure 6.3 geometrically illustrates Holliman's model [Holliman 2006], which is intuitively based on intersecting the lines of sight from both eyes to their respective views of the object on the screen (illustrated as a single point here). The model considers both cases: $d > 0$ – left eye view is displayed on the left – where the object is perceived to be further than the screen itself ("behind the screen"); and $d < 0$ – left eye view is displayed on the right – where the object is perceived to be nearer than the screen ("in front of the screen").

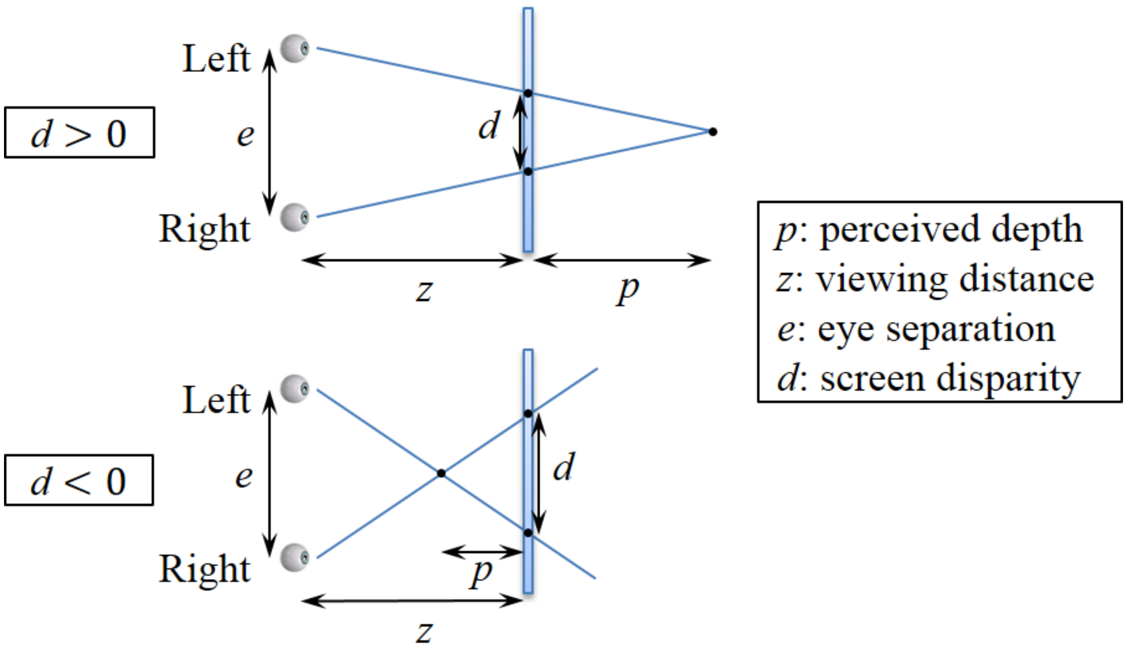


Figure 6.3: Geometrical model for perceived depth for a planar stereoscopic display as illustrated by [Holliman 2006]. Top: The illustration corresponds to a positive disparity (i.e., the displayed object appears "behind the screen"). Bottom: The illustration corresponds to a negative disparity (i.e., the displayed object appears "in front of the screen").

Holliman defines the perceived depth p as the unsigned distance between the screen and the perceived position of the virtual object, and derived:

$$p = \begin{cases} \dfrac{z}{\left(\dfrac{e}{|d|}\right) - 1} & when \quad d > 0 \\ \dfrac{z}{\left(\dfrac{e}{|d|}\right) + 1} & when \quad d < 0 \end{cases} \qquad \text{(VI.1)} \qquad \text{[Holliman 2006]}$$

Understandably, when $d = 0$, the object is perceived at the same depth of the screen, that is $p = 0$.

6.3.2 Differences Between Fixed and Mobile Stereoscopic Projected Environments

While one may expect to operate a stereoscopic mobile projector in the same way as a traditional fixed 3D projector, there are new variables that appear in handheld environments that can potentially change the perception of stereoscopic images. For instance, in a traditional 3D environment, the projector is positioned at a strategic position either in front or behind the projection surface (front or rear projection) to obtain the best image depending on the projection size and distance to the projector. Therefore, in a traditional fixed stereoscopic projection environment, the distance between the projector and the display is fixed and the only variable component is the position of the user in the projector-surface space. In a handheld environment however, the relative distances between the screen, the projector, and the user can all change at any given time, affecting the user's perceived depth as on Figure 6.4.

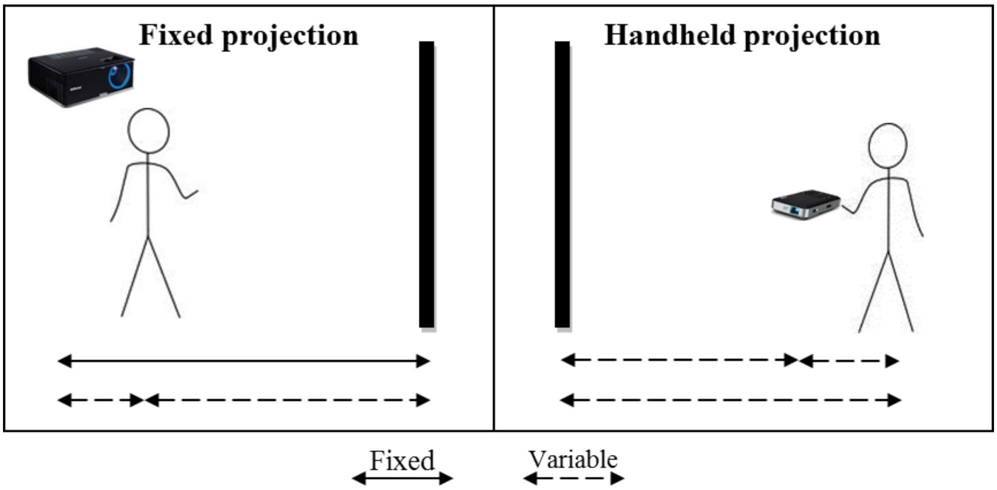


Figure 6.4: Comparison of the fixed and variable distances in both fixed and handheld mobile projected environments.

Equation (VI.1) shows that the main factors affecting perceived depth apart from the viewing distance are the eye separation and screen disparity; both values can be controlled in software when setting up the virtual environment. In the handheld mobile environment however, the viewing distance (*User-to-Surface* distance) is not fixed and other characteristics will become variable such as the relative distances between the user, the projector, and the projection surface. A new geometric model of perceived depth that can take into account the new varying distances is then required.

6.3.3 Depth Perception Model for a Mobile Stereoscopic Projector

Built upon Holliman's model [Holliman 2006], a new model of perceived depth for mobile stereoscopic projectors is derived. Here it is assumed that the viewing direction and projecting direction are parallel to each other while both are perpendicular to the planar projection surface. All distance metrics in the model are defined along this direction. This assumption should be approximately satisfied in most handheld mobile projection scenarios where the user consciously tries to project and view undistorted imagery. If the condition is not satisfied, additional measures can be taken to compensate for perspective distortion similar to those in [Cao 2006, Molyneaux 2012].

The projector's throw ratio is defined as the distance measured from its optical centre to screen (D_{PS}), divided by the width of the image that it will project (w). In a static stereo display setup, the rendering software alone controls the screen disparity d. However, with a mobile projector, d is also dependent on the *Projection-to-Surface* distance ("throw"), which can change even during mobile interactions.

The screen disparity is characterized as:

$$d = \frac{D_{PS} d_s}{wR} \tag{VI.2}$$

where:

- D_{PS}: (*Projector-to-Surface* distance) is the projection distance measured from the projector's optical centre to the projection surface. It is always positive.
- d_s is the software disparity controlled by the rendering software, defined as the object's displacement (in pixels) between the pair of stereo images. It has the same sign as d.
- w is the projector's horizontal resolution (width) in pixels.
- R is the projector's throw ratio (throw divided by projected image frame width).

Both w and R are constant for a specific projector (or at least for a specific resolution).

Furthermore, considering the handheld mobile projector interaction scenario: the user freely walks around to approach various surfaces for projection, moves the projector closer or farther from themselves through hand and arm movement and sees projected objects floating in their own surrounding. These suggest that this perception model should adopt a user-centric metric both for its input parameters and for the resulting perceived depth, which will prove more intuitive and convenient for the user and the system.

The new geometrical model can then be illustrated as follow:

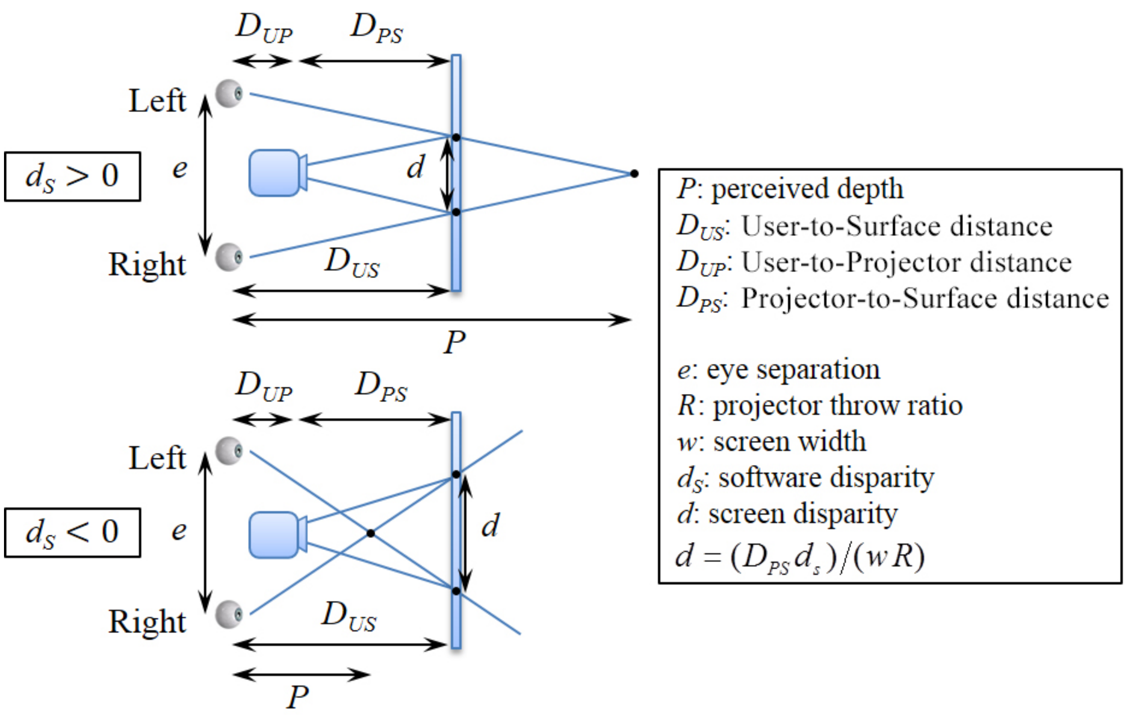


Figure 6.5: Geometrical model for perceived depth with a mobile stereoscopic projector. The model is based on the geometrical model for perceived depth in fixed scenarios illustrated in Figure 6.3. Note that the perceived depth *P* is now the distance between the viewer's eyes and the displayed object, allowing for a user-centric metric. Top: The illustration corresponds to a positive disparity. Bottom: The illustration corresponds to a negative disparity.

Based on the above, I refine the model's variables and propose the geometrical model using a user-centric perceived depth in Figure 6.5.

- D_{US} (*User-to-Surface* distance – previously z in Equation (VI.1)) is the viewing distance from the user's eyes to the projection surface. It is directly controlled by the user when walking towards or away from the surface. It is always positive.
- D_{UP} (*User-to-Projector* distance) is the distance from the user's eyes to the projector's optical centre. It is directly controlled by the user when moving the projector – hand/arm movement towards or away from their body. It usually remains positive in handheld scenarios as the projector is typically held in front of the user; but it could become negative when the projector is mounted on the user's shoulder as in [Harrison 2011].

- D_{PS} (*Projector-to-Surface* distance), is the projection distance with $D_{PS} = D_{US} - D_{UP}$. It is therefore indirectly controlled by the user, by the combination of walking and hand/arm movement.
- P is the perceived depth, defined as the distance from the user's eyes to the projected object's perceived position. It corresponds to the perceived depth from the user's perspective and not from the display's perspective, allowing for user centric design and interaction. It is always positive.
$$\begin{cases} P = D_{US} + p \quad when \quad d > 0 \\ P = D_{US} - p \quad when \quad d < 0 \end{cases}$$

After inserting P and replacing z by D_{US} into Equation (VI.1):

	$P = D_{US} + \frac{D_{US}}{\frac{e}{d} - 1}$	(VI.3)
Since: $d = \frac{D_{PS}d_s}{wR}$	$P = D_{US} + \frac{D_{US}}{\left(\frac{e}{\frac{D_{PS}d_s}{wR}} - 1\right)}$	(VI.4)
	$P = D_{US} \times \left(1 + \frac{1}{\frac{e}{\frac{D_{PS}d_s}{wR}} - 1}\right)$	(VI.5)

Equations (VI.5) can be simplified as:

$$P = \frac{eD_{US}}{e - \frac{D_{PS}d_s}{wR}} \qquad \text{(VI.6)}$$

Equation VI.6: Mathematical model of perceived depth for mobile stereoscopic projectors derived from the existing model for fixed stereoscopic environments.

Where:

- d_s is controlled by the rendering software
- D_{US} and D_{PS} describe the spatial relationship between the user, the projector, and the surface

- e, w and R are constants respectively specific to the user or the projector.

Note that $D_{US} = D_{UP} + D_{PS}$; therefore, in interactive scenarios the system can conveniently sense any two of the three parameters to predict the current depth perceived by the user. Also, note that the two conditions in Equation (VI.1) conveniently unified to the same equation through the derivation.

This model is based purely on stereopsis and does not account for other depth cues, such as accommodation; as it is the case for Holliman's model. Nonetheless, it is expected that it will be a good first-order prediction useful for interaction purposes.

6.4 User study 1: 3D perception with fixed distances

Two controlled user experiments were conducted to validate the model in conditions consistent with typical mobile projection scenarios. In the first experiment, all the distances are fixed in order to gather very precise data and verify the precision of the model. In the second experiment, a handheld condition is included to verify the effectiveness of the model in a close-to-real world condition.

6.4.1 Apparatus

The hardware consists of a 3D-ready mobile projector, Vivitek Qumi Q2 pocket projector (162×32×102mm) for a weight of 490g (Figure 6.6 Right). The 3D is visualised thanks to a pair of NVIDIA 3D vision wireless active shutter glasses (Figure 6.6 Left). The projector is mounted on a movable platform and projects onto a movable flat projection screen. It has a throw ratio (R) of 1.87, and projects with a resolution of 800×600 (so width $w = 800$) at 120Hz in synchronisation with the shutter glasses, alternating between left and right eye views, so that the participant sees a stereo image pair at 60Hz.

The participant indicates perceived depth of the projected stimulus via a metal rod (40cm long and 0.8cm thick) mounted vertically on a movable pedestal on the experiment table. Using a retractable pole connected to the pedestal, the participant can freely move the depth marker (the vertical rod) along the projecting direction to cover the entire experiment space. The position of the depth marker is measured at the nearest millimetre. To ease the participant's judgment, the projection screen and the pedestal are placed in a way so as to minimize the horizontal distance between the projected stimulus and the depth marker. A vertically adjustable metal bar hangs above the participant's chair, so they can touch their forehead against it to maintain a fixed viewing position. The lighting in the experiment room is dimmed to reduce interference from the surrounding, yet bright enough to clearly see the depth marker. This set-up is illustrated on Figure 6.7.

Figure 6.6: Pictures of the hardware used to display 3D images in the mobile environment. Left: NVidia 3D vision glasses with IR emitter. Right: Qumi Q2 Pocket 3D-ready projector [Vivitek 2011]

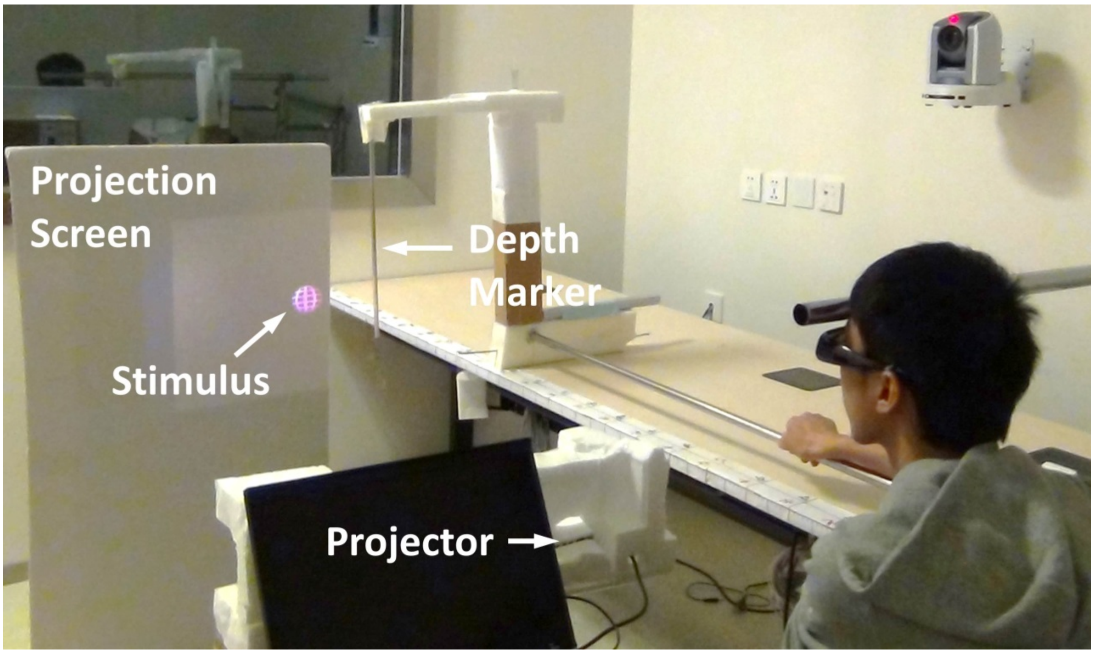


Figure 6.7: Picture of the User Study 1 experimental setup. The participant moves the metal rod on their right-hand side to align the depth marker with the viewed 3D image. (Lighting is not dimmed for illustration purposes only).

6.4.2 Task and Stimuli

The experiment task consists in the participant indicating the perceived depth of the projected stimulus in each trial. The stimulus is rendered as a wireframe 3D sphere. A sphere was chosen over other shapes to minimize the perspective depth cue, yet still provide the impression of a 3D object. The angular size of the sphere is normalized to be always 4.58° in visual angle regardless of *User-to-Surface* and *User-to-Projector* distances to remove the depth cue from apparent size.

The participant moves the depth marker to match their perceived depth P of the stimulus, and the experimenter measures P as the distance from the participant's eyes to the depth marker using a ruler on the experiment table. To prevent the participant from "racing through" the task, the stimulus is presented for 20 seconds with a voice countdown; the measurement is then taken at the end of the 20 seconds. If the participant feels they need more time, an additional 20-second period is granted. When the participant cannot fuse the two views into one object, the trial is considered a failure.

6.4.3 Procedure

Ten volunteers, aged 20-26 (μ = 23 years old), were recruited from Microsoft Research Asia. Participants were screened to ensure that they all had normal or corrected-to-normal vision, normal stereo vision and were able to perceive depth clearly through the display hardware. A within-participant experimental design was used.

The independent variables were:

- *User-to-Projector Distance* D_{UP} : $-22cm, 0cm, 22cm, 44cm, 66cm$
- *User-to-Surface Distance* D_{US}: $26cm, 66cm, 106cm, 146cm$

The choice of values is related to the handheld mobile projection scenario where the user directly – and somewhat independently – controls the distance between themselves and the projection surface D_{US} (when walking or moving the projection screen) and the distance between them and the projector D_{UP} (by holding the projector and moving the hand and arm).

The variables ranges are based on the dimensions of typical indoor environments (for D_{US}) and typical arm's reach (for D_{UP}: also including -22cm to capture the shoulder-mounted scenario where the projector may be behind the user's eyes. The combination of these two variables determines the *Projector-to-Surface* distance D_{PS} as $D_{PS} = D_{US} - D_{UP}$.

The valid D_{US} and D_{UP} combinations are identified in Table 6.1. Not all combinations can be valid to ensure that the user is always in front of the screen and not right by the screen where they would not perceive depth.

User-to-Projector D_{UP} (cm)	-22				0			22			44		66	
User-to-Surface D_{US} (cm)	26	66	106	146	66	106	146	66	106	146	106	146	106	146

Table 6.1: Valid combinations of *User-to-Projector* and *User-to-Surface* distance used for the experiment. Indeed, the projector cannot be placed after the screen.

For each valid combination, the participants conducted 8 trials with different **desired stimulus depth**, which is termed $\boldsymbol{P_d}$. The P_d values are chosen in a semi-random manner to cover a typical range for interactive applications; empirically determined to be from 15cm to 225cm. To do this, the software starts from eight "seed" values (22cm, 50cm, 78cm, 106cm, 134cm, 162cm, 190cm and 218cm) and offsets each of them by a small Gaussian noise (mean = 0, σ = 7cm). This results in a set of values that sample the entire variable range in a nearly uniform way, yet also provide a more continuous coverage compared to using predetermined discrete levels. Further, this also prevents the participant from guessing the "correct answer" of the trial.

For each trial, the software disparity is back-calculated using the model to render the desired P_d based on the current D_{US} and D_{UP} setting, and the participant's eye separation e measured before the experiment.

The experiment therefore had:

10 participants x 14 valid combinations x 8 trials = 1120 data points

The presentation order of the trial settings is randomized for each participant. The participant conducts practice trials before the experiment starts until they feel fully comfortable. The experiment lasted about 80 minutes for each participant. Participants were free to take breaks in between trials.

6.4.4 Results

Failure rate

The failure rate f is defined as the ratio of trials in which the participant cannot fuse the two views. A Pearson's chi-square test conducted for f on each independent variable: *User-to-Surface* distance D_{US} and *User-to-Projector* distance D_{UP}.

Viewing distance

User-to-Surface distance D_{US} is found to have statistically significant effects on the failure rate f with $(\chi^2 = 111.62,\ df = 3, p < .001)$. It is observed that $D_{US} = 26cm$ results in significantly higher failure rate compared to the other conditions (Figure 6.8).

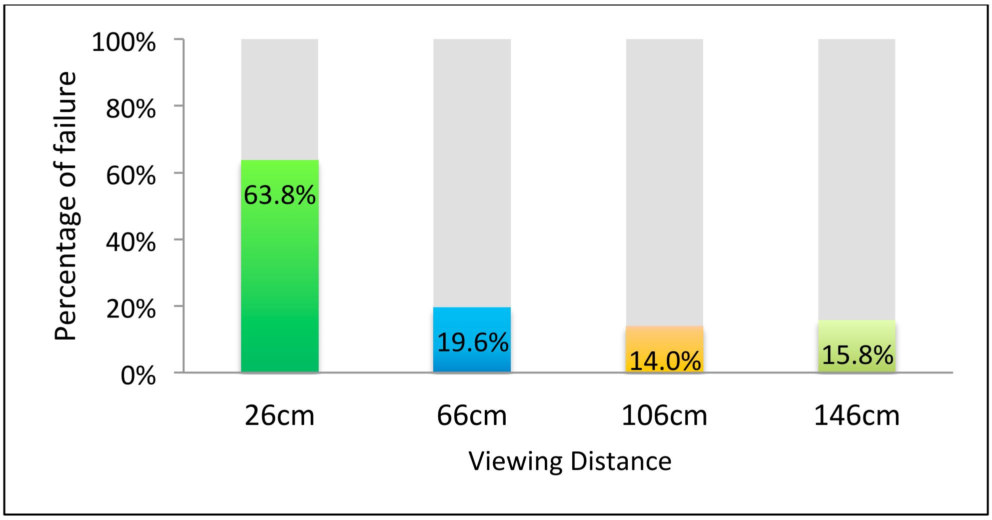


Figure 6.8: Ratio of trials where participants cannot fuse the two views (left and right images) to create a 3D image. The failure rate *f* is expressed in percentage of trials for each *User-to-Surface* distance.

User-to-Projector distance

The *User-to-Projector* distance D_{UP} was found to have statistically significant effect on failure rate f with ($\chi^2 = 19.88$, $df = 4$, $p = .001$). $D_{UP} = -22cm$ results in significantly higher failure rate than other conditions (Figure 6.9).

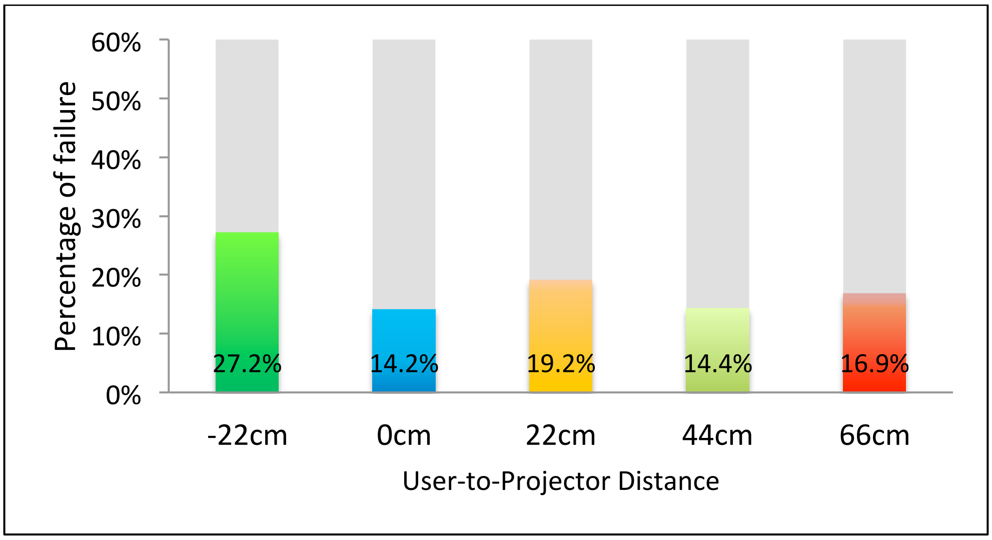


Figure 6.9: Ratio of trials where participants cannot fuse the two views (left and right image) to create a 3D image. The failure rate *f* is expressed in percentage of all trials for each *User-to-Projector* distance.

All trials for which the images could not be merged (failed trials) were then removed from further analysis.

Linear regression

To validate the model, a linear regression was performed between *Desired Stimulus Depth* P_d and measured Perceived Depth P without constant term so that:

$$P = kP_d$$

This yielded a tight fit: $(k = 0.955,\ R^2 = 0.989)$. This results in:

$$\boldsymbol{P = 0.955\ P_d}$$

Desired stimulus depth significantly predicted perceived depth ($b = -0.995$, $t(902) = 285.32,\ p < .001$). Desired stimulus depth also explained a significantly large proportion of variance in perceived depth ($R^2 = 0.989$, $F_{(1,902)} = 81407.04$, $p < .001$). The regression is plotted on (Figure 6.10).

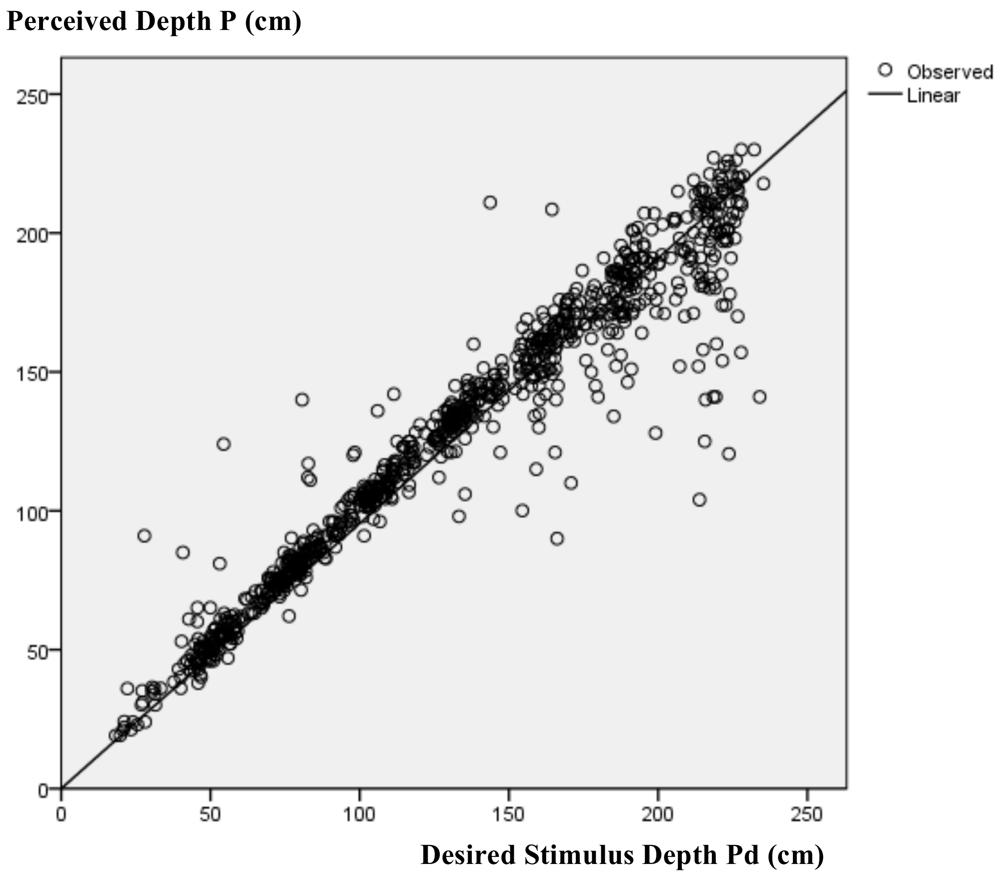


Figure 6.10: The model predicts a linear equation between the Desired Stimulus Depth (P_d) and the Perceived Depth (P) such that $P = 0.995\ P_d$. The black line on the image represents the linear model while the dots represent the actual measurements.

Table 6.2 presents the linear regression of Perceived depth using the *User-to-Projector* distance and the *User-to-Surface* distance as predictors to the model. Model 1 takes only *User-to-Projector* distance as predictor while Model 2 use both distances as parameters.

For Model 1 ($R^2 = 0.1,\ F_{(1,901)} = 10.30,\ p = .001$). This means that the *User-to-Projector distance* accounts for 10% of the variations in the Perceived depth.

For Model 2 ($R^2 = 0.32,\ F_{(1,900)} = 21.53,\ p < .001$). This means that adding the *User-to-Surface* to the *User-to-Projector distance* predictor helps the model predict 32% of the Perceived depth.

While significant, the *User-to-Projector* and *User-to-Surface* distances are less efficient to predict the *Perceived depth* than the *Desired Stimulus Depth* that on its own accounts for 99% of the variations.

	b	SE B	β	p
Step 1				
Constant	114.71 (105.70,123.72)	4.59		p = .001
User-to-Projector distance	0.15 (0.06, 0.23)	0.05	0.11	p = .001
Step 2				
Constant	98.02 (88.65, 109.39)	5.79		p = .001
User-to-Projector distance	-0.026 (-0.14, 0.09)	0.06	-0.02	p = .65
User-to-Surface distance	0.30 (0.17, 0.43)	0.07	0.20	p = .001

Note. $R^2 = 0.01$ for Step 1; $\Delta R^2 = 0.02$ for Step 2 $(ps < .001)$

Table 6.2: Linear model of prediction of perceived depth, with 95% bias corrected and accelerated confidence intervals reported in parentheses.

Perception "error"

To further understand participants' depth perception performance, the magnitude of perception "error": E was considered in each trial. The choice to use relative error ratio instead of absolute error was based on the fact people's depth perception resolution tends to decrease in proportion to the depth value [Swan 2007]. E can be described as:

$$E = \frac{|P - P_d|}{P_d}$$

ANOVA tests were performed on the effects of the two independent variables: *User-to-Surface* distance D_{US} and *User-to-Projector* distance D_{UP}.

Viewing distance

A main effect was found for *User-to-Surface* distance on the perception error magnitude E: $\left(F_{(3,899)} = 9.19,\ p < .001\right)$, pairwise post-hoc comparison Tukey HSD showed significant differences between 26 cm and all the other *User-to-Surface* distances with $(p < .001)$ for all pairs. No significant difference was found between the other *User-to-Surface* distances $(p > .05)$. Figure 6.11 shows the means of the magnitude of perception error for each *User-to-Surface* distance. The graph shows that the magnitude of perception error decreases monotonously as the distance increases.

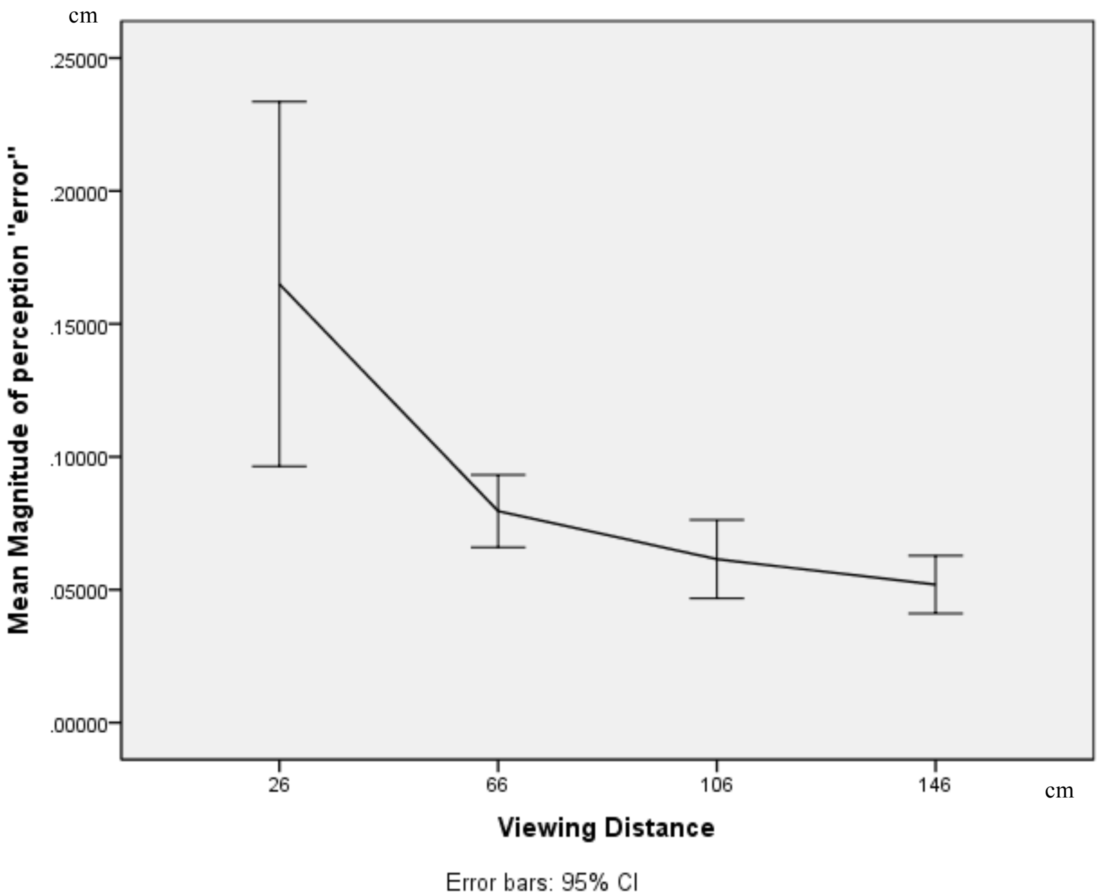


Figure 6.11: Chart of the mean of the magnitude of perception "error" for each *User-to-Surface* distance with error bars (95% CI). A significant effect of *User-to-Surface* distance on perception error $(p <. 001)$ was found.

User-to-Projector distance

A main effect for *User-to-Projector distance* on the perception error magnitude E: $\left(F_{(4,898)} = 3.55,\ p < .01\right)$ was found, pairwise post-hoc comparison Tukey HSD showed significant differences between -22 cm and 22 cm $(p < .05)$. No significant difference between the other *User-to-Projector* distances $(p > .05)$ was found. Figure

6.12 presents the means of the magnitude of perception error for each *User-to-Projector* distance. One can notice that the data on the graph can be separated into two groups: positive values of *User-to-Projector* distance where the magnitude of the error is lower than for the other group: negative and null values of the *User-to-Projector* distance.

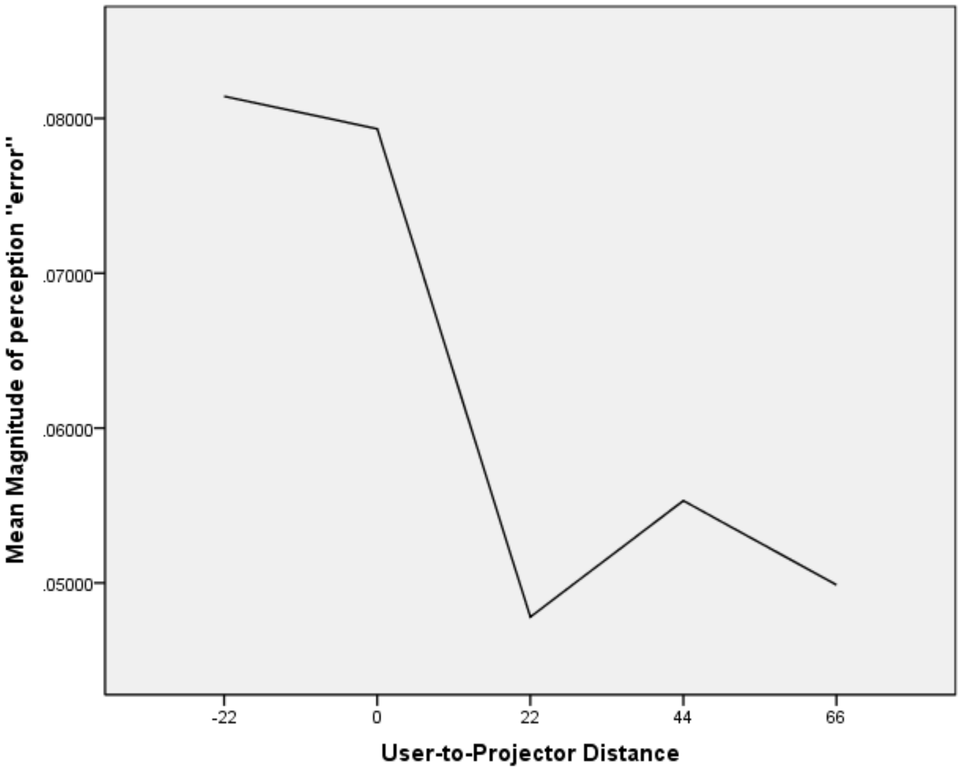


Figure 6.12: Chart of the mean magnitude of perception "error" for each *User-to-Projector* distance. A clear separation into two groups can be seen where positive values of *User-to-Projector* have lower magnitude of perception "errors" against negative and null values of *User-to-Projector* that have higher magnitude of perception errors.

6.4.5 Discussion

Validity of the model

The linear regression, which was performed between the stimulus depth P_d and the measured perceived depth P, illustrates that the model is an accurate prediction of the perceived depth, both in terms of correlation and in terms of absolute value with over 95% accuracy. This linear regression is illustrated in Figure 6.10.

Limitations of the model

Figure 6.10 suggests a slight tendency of positive bias in P at smaller P_d and negative bias at larger P_d. This is consistent with other depth perception studies such as [Swan 2007]; note that the setup is the inverse of the one presented in this chapter. They use a physical stimulus and a virtual marker; hence their negative bias translates to a positive bias in the presented setup, and vice versa.

Minimal comfort viewing distance

When the viewing distance (*User-to-Surface* distance) is minimal: 26cm, the failure rate – when users cannot fuse the two views – and the magnitude of perception error are both significantly higher compared to other conditions. This is likely due to the fact that 26cm is near the minimal comfortable viewing distance and suggests that in interaction scenarios, designers should avoid cases where the user is at such a close distance to the projection surface.

Higher viewing distance

The “error” rate E monotonously decreases as the distance between the user and the projection screen increases. This suggests that a longer viewing distance helps with depth perception accuracy. However, this may create some constraints when interacting with the handheld projected space, as when the user “touches” the projection. The reason that the distance couple (66cm|0cm) results in higher E is not clear to us and worth further investigation.

Handheld vs. body mounted

The “error” rate E and failure rate f are both significantly higher when the *User-to-Projector* distance is negative. This suggests that for 3D interactions using a mobile stereoscopic projector, the handheld configuration (*User-to-Projector* distance $D_{UP} > 0$) will be more suitable than shoulder or body mounted scenarios.

6.5 USER STUDY 2: 3D PERCEPTION IN THE HANDHELD CONDITION

The first study validates the mathematical model for perceived depth with handheld stereoscopic projectors in a static condition. According to the model, the perceived depth *P* changes as the relationship between the viewer, the projector, and the projection screen evolves. This means that depending on their own movements, users should perceive depth changes inherent to the physical properties of the setup. A second study was ran, which aims at identifying whether the inherent depth changes are perceivable when motion is introduced given the small distance changes that occur between the user, the projector, and the screen in a handheld configuration. This evaluation aims to determine: 1. if users perceive depth changes in the same way as predicted by the model; 2. the limitations of the model due to the limitation of the amplitude of movements available in a handheld mobile setting.

6.5.1 Methodology

The main methods developed to measure egocentric depth judgments are reported for See-through Augmented Reality by Swan et al. [Swan 2007]; they consist in: verbal report, perceptual matching, and open-loop action-based tasks. With verbal report [Gooding 1991], the observer verbally expresses their estimation of the distance between them and the stimuli (e.g. 3D object). This method has also been used to estimate object sizes and then compute the perceived depth. Perceptual matching consists in moving a virtual object until it perceptually matches the distance to a referent object. Swan et al. [Swan 2007] explain that perceptual matching is an example of action-based tasks; which involve the observer performing a physical action to indicate the perceived distance – as used in User Study 1 –. Open-loop action-based tasks are tasks for which the observer does not received visual feedback on their action. While there are many possible open-loop action-based tasks, one of the most common is blind walking. This involves for the observer to look at the stimuli for a few seconds and then to walk to this object blindfolded.

Any open-loop action-based tasks, such as blind walking or even a matching task, would demand from the user to perform extra movements in addition to the movements proposed in the Cases section, that are required to evaluate the geometric model. The verbal report method is preferred as to avoid extra movements that may prevent observers to concentrate on the perception aspect of the study fully, beyond the movements already required by the handheld mobile scenario. Moreover, since the study aims to identify changes in perceived depth and not the exact perceived depth of the virtual object, it does not require the precision that action-based tasks offer over verbal report. The study is therefore designed using the verbal report method.

6.5.2 Task

The task requires varying the relative distances between the participant, the projector, and the screen. The participant is asked to perform an action that will translate into a variation of the relative distances and to judge the displacement in perceived depth of a single 3D object. Since participants are performing movements, it is measured whether they accurately perceive the gross depth change without attempting to quantify the exact depth change. After performing the movement, the participant states whether the object moved *closer*, *farther away,* or *did not move* from their viewpoint.

This task is similar to tasks used to judge egocentric distance (i.e., distance from the observer's point of view to the 3D virtual object) and perceived depth in previous human depth perception studies [Wanger 1992, Grossman 2006]. Note that the participants were not required to perform any virtual object manipulations to ensure that the nature of the task would remain purely perceptual.

In order to define what distances will vary and how the user will perform the task, the following table of movements is put forward. Table 6.3 presents all the possible distance relationships between the user, the projector, and the projection surface. All cases are considered, whether the user holds the projector or decides to rest it down on a flat surface – this is consistent with a mobile scenario where a user would bring their personal device with them but leave it resting on a table while interacting with the content.

Case n#	Projector	User	Screen	D_{US}	D_{UP}	D_{PS}
1	Fixed	Fixed	Move	Variable	Static	Variable
2	Fixed	Move	Move	Static	Variable	Variable
3	Move	Move	Fixed	Variable	Static	Variable
4	Move	Fixed	Fixed	Static	Variable	Variable
5	Move	Fixed	Move	Variable	Variable	Static
6	Move	Move	Move	Static	Static	Static
7	Fixed	Fixed	Fixed	Static	Static	Static
8	Fixed	Move	Fixed	Variable	Variable	Static

Table 6.3: Cases of possible movements relationships between the user, the projector and the screen in a mobile 3D projection scenario. The table also shows the consequences on D_{US}, D_{UP} and D_{PS}. The greyed-out cases will not be investigated.

- **Case 1:** The user and projector are fixed while the projection surface is being moved. This situation occurs when the user moves the projection surface in front of the projector; the projection surface can be a piece of paper or even the user's hand.
- **Case 2:** The user and the projection surface move. The distance between the user and the projection surface remains constant while the distance between user and projector, and projector and screen change. This condition occurs when the user moves with the projection surface away or closer to the projector.
- **Case 3:** The user moves while holding the projector; the projection surface stays fixed. This is one of the most likely scenarios where the user moves towards or farther away from a wall for example while holding the projector.
- **Case 4:** The user moves the projector towards or farther away from the projection surface while remaining at the same position. This is also a very probable scenario as it corresponds to current use of mobile projectors.
- **Case 5:** The user would be moving the projector and the screen space at the same time while staying in the same position. This scenario is not plausible in a single-user scenario. It could however happen with multiple users if one was holding the projection surface and another the projector. This is a complex

scenario for multiple-users, which goes beyond the scope of this study. It will therefore not be considered in this user study.

- **Case 6:** The projector and the projection surface would move at the same time, keeping the distance between them constant. As for case 5, this scenario is only plausible in a multi-user context and even then, keeping the distance constant would be a challenge. For this reason, case 6 will not be included in the study.
- **Cases 7 and 8**: The projector and the projection surface are both fixed. These two cases match a fixed projection set-up. They will therefore not be studied here in order to focus on the mobile environment only.

Out of those eight cases, only the four relevant ones (Cases 1 to 4) will be investigated.

6.5.3 Experimental Design

Apparatus

The prototype used for this experiment is the same as for User Study 1 and is described in details in section 6.4.1. It is composed of a Qumi Q2 projector weighing 617 grams and the participant wears NVidia 3D vision glasses in order to see the object in 3D. For this study, the eye separation is assumed to be 6.25 cm. Positions are marked on the floor to determine where the participant should stand at the beginning of each trial.

Stimulus

The stimulus used for this study is a red cube presented at a 45° rotation angle in x and y axes and projected on a dark background (Figure 6.13). A cube was chosen instead of the sphere used in the previous study to provide users with additional depth cues, as they will be less able to focus on the 3D image while moving. Previous work shows that using a cube instead of a sphere should not affect depth perception [Rolland 1997].

Figure 6.13: Red cube stimuli used in User Study 2 displayed in front of a participant holding the projector in their hands.

When the relative distances between user, screen, and projector change, the perceived depth changes too. Additionally, the size of the projection gets bigger (resp. smaller) when the projector moves farther away (resp. closer) from the projection screen. As we want to observe whether users perceive those inherent depth changes, the size of the object is deliberately not fixed or controlled. This scenario remains consistent with users' expectations of handheld projected displays.

Conditions

The experiment is a [4x2x6] within-subject design with repeated measures and pairwise comparisons with three factors: *User-Screen-Projector Movements* (Cases 1 to 4), *Direction* (forward or backward) and *Depth level* (six levels: three in front and three behind the screen).

The independent variables are explained in more details below:

User-Screen-Projector movements

In this study, the depth level is fixed for each trial and the change in Perceived depth only occurs as a result from the changes in the distances between the user, the screen, and the projector. The four cases presented in the previous section (6.5.2) are tested.

- Case 1: *The screen moves*. The user stands by the projector that is rested on a table and manually moves the projection screen, a light white cardboard, from in front of the projector to their full arm's length.
- Case 2: *The user and the screen move*. The projector is sat on a table and the user moves while holding the projection screen.
- Case 3: *The user and the projector move*. The screen stays fixed.
- Case 4: *The projector moves*. Participants stay at a fixed distance to the projection screen and move the projector towards the wall, or bring it back towards themself.

Exact distances are not measured since they may vary from participant to participant and, as the aim of the study is verify how the user perceives the stimulus is moving in depth compared to the initial position.

Direction

For each Case from 1 to 4, the movement of the observer, projector, and projection screen can be either forward or backward. In Figure 6.14, the user moves forward from point A to point B. In order to avoid the user to guess which direction the object is moving, direction is added to the independent variables. The variables are randomized within the different user-screen-projector displacements variables.

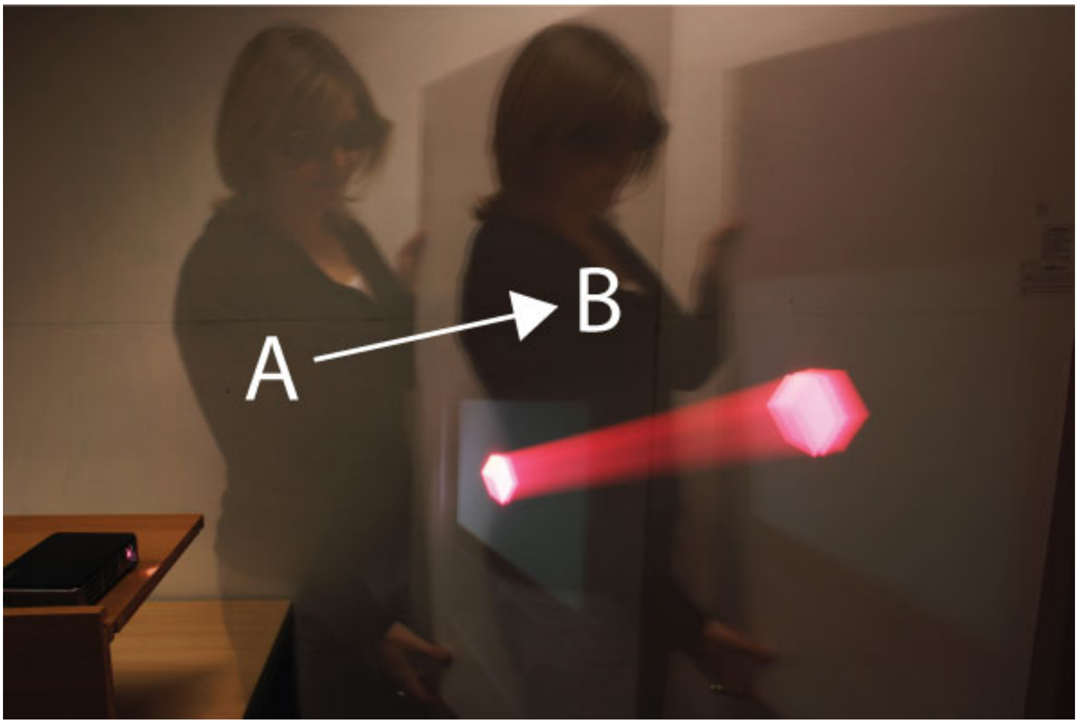


Figure 6.14: User-Screen-Projection movement case 2: The user moves with the screen from point A to point B while the projector is fixed, rested on a table.

Level of depth: distance from stimuli to projection surface

The disparity factor is modified in order to project the object at different depths from the projection surface. This should have an impact on the magnitude of the perception of changing depth as per the mathematical model of perceived depth for mobile stereoscopic projection. Three distance factors from the projection screen are proposed, with values either positive: in front, or negative: behind the projection surface.

Expected Results

Given the model of perceived depth, the results expected are presented in Table 6.4.

Case n#	Object	Backward	Forward
1	In front of screen	Closer	Farther away
1	Behind the screen	Closer	Farther away
2	In front of screen	Farther away	Closer
2	Behind the screen	Closer	Farther away
3	In front of screen	Closer	Farther away
3	Behind the screen	Closer	Farther away
4	In front of screen	Farther away	Closer
4	Behind the screen	Closer	Farther away

Table 6.4: Object perceived depth changes relative to the participant according to the model

Hypothesis

This user study presents three hypotheses:

> H1: *Participants should see the object moving in the direction predicted by the model.*
>
> It is expected that since participants could perceive the object at the accurate depth in User Study 1, they will be able to see the changes in depth in the direction predicted by the model
>
> H2: *In some cases, the perceived depth changes may not be perceptible.*
>
> Because of the limitation in amplitude of available movements in the handheld environment, it is expected that some depth changes will be too small to be perceivable.
>
> H3: *The stimuli position in depth affects the accuracy of the depth change perception.*

It is expected that the chosen depth levels will affect results, as objects behind the screen may always feel further away in depth from the projection surface for example.

Procedure

Eighteen volunteers participants were recruited (nine females), aged from 20 to 68 years old (μ = 31.3 years old). All participants had self-reported normal or corrected-to-normal vision, no case of colour blindness, and normal stereo vision. The participants were volunteers and received no compensation.

Each participant first read the instructions explaining the aim of the experiment before being shown the apparatus. Participants then received explanations and demonstration on the four cases they had to perform. They were then asked to position themselves according to the first case. The observer would then display the first stimuli on the screen. For each trial, participants needed to move according to the case and use say aloud how they perceived the stimulus was moving compare to them. There is no time limit to the trial, but the user is only allowed to perform the movement once before having to report on the perceived movement. The first two trials of each session are discarded from the data analysis since most participants needed those trials to fully understand the task. The participants were allowed to take breaks in between trials and each session lasted around one hour.

A randomized Latin-square design was used for the levels of depth and; for each level of depth, the order of the user-screen-projector movement and the direction are also randomized. Each level of depth is selected three times in order to get three data sets for each displacement and direction while limiting any learning effect. A given level of depth cannot be selected twice in a row.

Each condition is repeated three times so each user goes through 4 cases x 2 directions x 3 trials = 24 trials per depth level, so 144 trials in total for 6 depth levels.

The experiment is:

4 cases x 2 directions x 6 depth levels x 3 trials x 18 participants = 2592 data points

For each trial, the experimenter recorded the *change in perceived depth* observed by the participant using a think-aloud protocol. There were three possibilities:

1. Closer: The object was perceived as moving towards the participant
2. Farther: The object was perceived as moving farther away from the participant
3. No movement: The object did not seem to be moving in distance to the user

Measures

The failure rate is measured as the rate of trials for which users do not see the object moving. Accuracy is measured by comparing the user's perceived depth change with the model's prediction.

6.5.4 Results

Failure rate

f is d the ratio of trials in which the participant did not see the object moving. The study did not account for cases where participants could not merge the two views. This is due to the fact that participants could always organize the relationship between the screen, the projector and themselves to merge the two images before the beginning of each trial. A Pearson's chi-square test was conducted for f on each independent variable: *User-Screen-Projector Movements*, *Direction* and *Level of Depth*.

User-Screen-Projector Movements

User-Screen-Projector movements, presented as Cases 1 to 4, have be found statistically significant effects on the failure rate f with $(\chi^2 = 8.83, df = 3,\ p < .05)$. Cases 1 and 4 results in lower failure rate compared to Cases 2 and 3 (Figure 6.15).

Direction

No statistically significant effect of Direction on the failure rate f was found with $(\chi^2 = 0.65,\ df = 1,\ p > .05)$.

Level of Depth

Level of Depth has been found to have statistically significant effect on the failure rate f with $(\chi^2 = 13.91,\ df = 5,\ p < .05)$. When the object is positioned in front of the screen and not close to the screen or behind it, the failure rate is significantly lower (Figure 6.16).

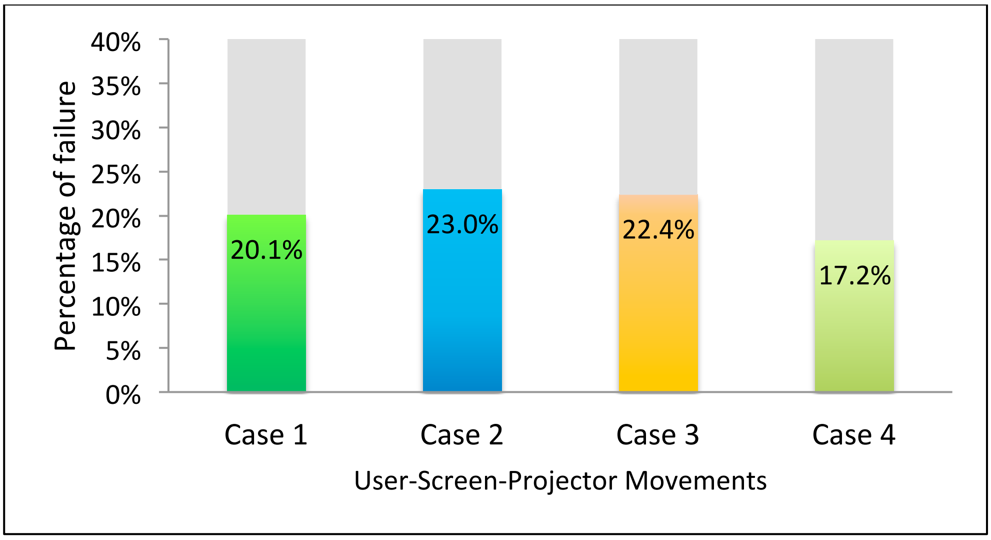


Figure 6.15: Ratio of trials where participant cannot see the stimuli moving in depth. The failure rate *f* is expressed in percentage of trials for each User-Screen-Projector movement.

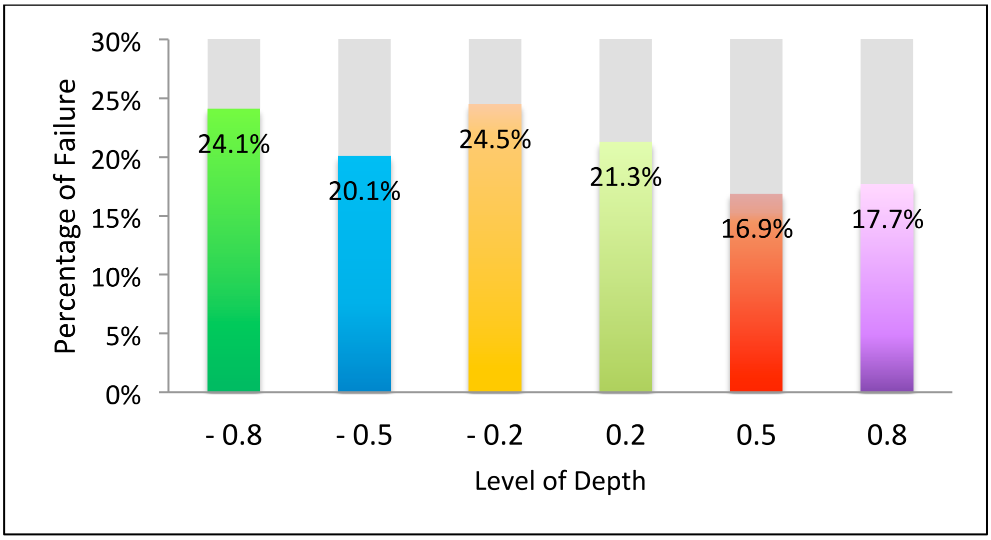


Figure 6.16: Ratio of trials where participant did not perceive the stimuli's movement. The failure rate *f* expressed in percentage of all trials for level of depth.

20.7% of the overall trials result in a failed trial, trials for which the participants could not see the stimuli moving. Those trials were removed from further analysis.

Accuracy

The accuracy is defined as the percentage of trials for which the participants saw the object moving in the direction predicted by the mathematical model.

User-Screen-Projector Movements

User-Screen-Projector Movements, presented as Cases 1 to 4 have been found to have statistically significant effects on Accuracy with ($\chi^2 = 10.47,\ df = 3,\ p < .05$). Figure 6.17 shows that Cases 2 and 4 do not perform as well as Cases 1 and 3. Note that the results show an overall accuracy of 52.3%.

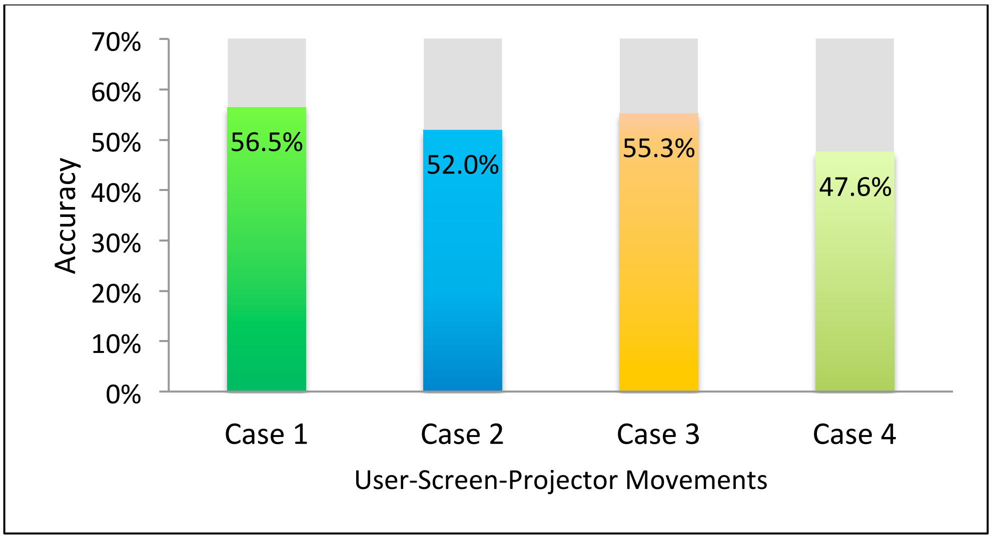


Figure 6.17: Ratio of trials where participant perceived the image moving in the same direction as predicted by the model of perceived depth for mobile stereoscopic projection. The accuracy is expressed in percentage of trials for each User-Screen-Projector movement.

Direction

No statistically significant effect of Direction on Accuracy was found with ($\chi^2 = 0.23,\ df = 1,\ p > .05$).

Level of Depth

Level of Depth was found to have statistically significant effect on Accuracy with ($\chi^2 = 14.31,\ df = 5,\ p < .05$). It can be observed that -0.2 and -0.5 perform better than the other depth levels and that 0.8 level gives worse accuracy (Figure 6.18).

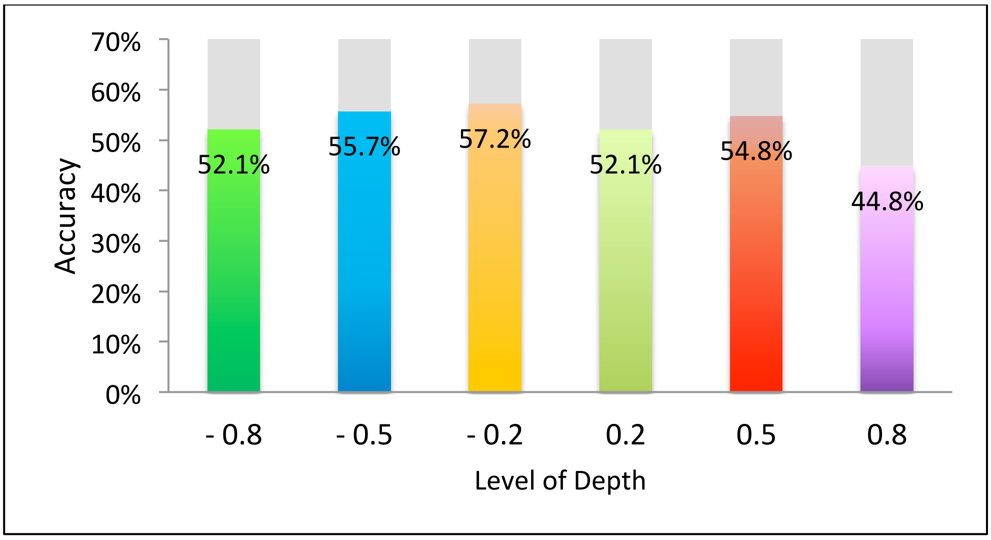


Figure 6.18: Ratio of trials where participant perceived the image moving in the same direction as predicted by the model of perceived depth for mobile stereoscopic projection. The accuracy is expressed in percentage of trials for each *Level of Depth*.

6.5.5 Discussion

Hypothesis

When considering the initial hypotheses:

> H1: *Participants should see the object moving in the direction predicted by the model.*

The hypothesis is only partially verified. While results reveal significant differences in accuracy of perceived depth movement depending on *User-Screen-Projector* movements and on the chosen *Level of Depth*, the average accuracy is of only 52.3% overall. The accuracy rises above 55% for two cases: cases 1 and 3 and for two depth levels with the stimuli positioned behind the screen (-0.5 and -0.2).

> H2: *In some cases, the perceived depth changes may not be perceptible.*

This hypothesis is verified. Results show that over 20% of the overall trials result in the participant not being able to identify the change in depth. This is likely due to the small amplitude of movements that occur in the handheld scenario, which results in changes in depth so small that the viewer cannot see them. Additionally, some participants mentioned that sometimes "it feels like the cube is getting bigger, but [they didn't] see it moving [in depth]". Participants were most likely affected by the changes in size of the object that could be countering the depth movements; such as when the object would get bigger but at the same time move slightly further back.

> H3: *The stimuli position in depth affects the accuracy of the depth change perception.*

This hypothesis is verified, as there is a statistically significant effect of Level of Depth on the accuracy of the perceived depth change. There is also a significant effect of *Level of Depth* on the failure rate. This shows that when creating workspaces for mobile projection system, one should choose the position of the object in depth wisely. For instance, depth levels behind and close to the projection surface reveal lower success rate (i.e., more failed trials) while depth levels too far ahead of the screen reveals lower accuracy rate. A solution to this issue could be to choose a depth level that is fit and to keep the corresponding perceived depth constant throughout the experience.

From the results of User Study 2, additional conclusions are drawn on: Usage scenarios, Limitations of the model, and Factors influencing the perceived depth.

Useful interaction scenarios

Empirical results show that the accuracy rate is significantly better in Cases 1 and 3, when the *User-to-Projector* distance stays constant. This seems to indicate that designers should prefer usage scenario where the *User-to-Projector* distance remains constant. Interestingly enough Case 1 also results in significantly fewer failed trials. This seems to indicate that moving the projection surface provides the most useful interaction with 3D stereoscopic handheld projections.

Limitations of the model for depth changes

Participants did not detect the change of depth of the 3D object for 20.3% of all trials. Additionally, although significantly affected by the *User-Screen-Projector* movements, the accuracy across all trials is relatively low with 52.3% of success (47.5% ~ 56.5%).

It would appear that the inherent depth variations that occur in the handheld environment may not be sufficient for participants to perceive the changes in depth.

Moreover, some participants mentioned that sometimes “it feels like the cube is getting bigger, but [they didn’t] see it moving [in depth]”. Participants were most likely affected by the changes in size of the object that could be countering the depth movements. This would for example happen when the object would get bigger while moving slightly further back, therefore creating a visual contradiction.

Factors potentially influencing perceived depth changes.

Since users could see the object at the correct depth in the first user study, this section attempts to identify the factors that prevented users from accurately identifying the object movement in depth.

Walking

Results show significantly fewer failed trials in Cases 1 and 4, when only the projector or the screen is being moved. In both cases, the participant moves their arm but does not change their own position in the environment. In Cases 2 and 3, the participant walks, which may add some extra cognitive load affecting the perception of depth changes. This factor needs to be investigated further as this would potentially preclude users from being fully mobile while interacting with 3D projected content from a mobile device.

Viewing direction

The model assumes that the viewing direction and the projecting direction would be parallel to each other. It was expected that this condition would be approximately satisfied in the handheld scenario, as users would try to project and view an undistorted image. In the user study, participants would easily adjust their viewing direction by moving the projector. However, this was more difficult to achieve when moving the screen, while the projector was rested on a table. We noticed that participants tended to look down to view the object (as in Figure 6.14).

There are technical solutions to counterbalancing those effects, such as: compensating for the perspective distortion or using a steerable projector (Chapter 3) to adjust the beam depending on the user and screen positions. Nonetheless, Case 1 results in low failure rate and high accuracy, which seems to mediate the intensity of the viewing direction's effects.

Projected object size

The object size was not fixed in order to later on exploit natural projection size variations depending on the relative movements between the user, the projector, and the projection surface. The objective was to evaluate the model while limiting software modifications, relying on the physical properties of the projection only. This meant that during the experiment, the object would change size and depth depending on the case, direction, and chosen depth level.

Figure 6.19 shows the cube size increases when the projection surface is moved away from the projector. During the study, some participants mentioned that it was difficult for them to determine the direction of the object as in some cases the object was getting bigger while moving slightly further back, therefore creating a visual contradiction. Keeping the object size fixed presents some advantages such that the user can be more focused on the depth movement but it also has some drawbacks. For instance, it requires additional tracking hardware to know the position of the screen and the projector; and it prevents the use of the natural changes in depth and size of the projection that could actually be exploited to manage interaction spaces.

Nevertheless, in the future, interaction designers could keep the displayed objects at a given size and modify the number of objects available on the workspace instead. For example, by moving the projection further away from the screen, the workspace size would increase but the objects' size would not change.

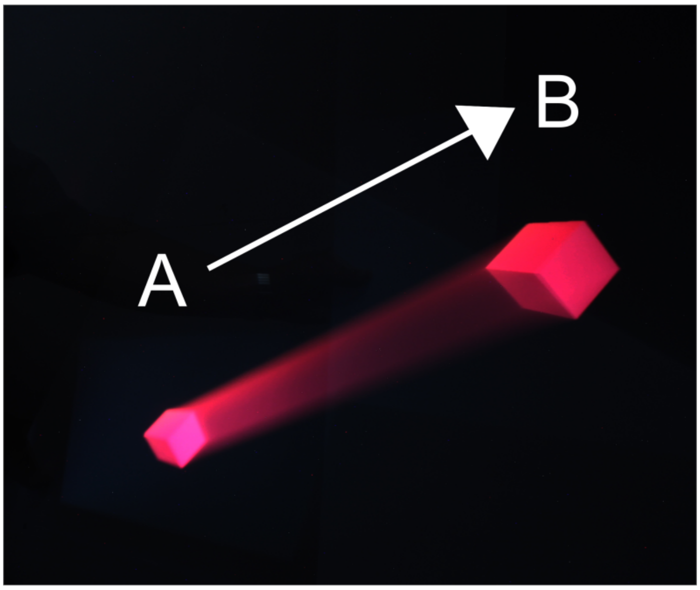


Figure 6.19: By moving the projection surface (screen) further away from the projector (direction A to B), the cube's depth perception is affected from the user's point of view. The cube also increases in size.

6.6 Conclusions And Future Work

6.6.1 Conclusions

By using depth with mobile projectors, users would gain a completely new area to display information. Not only would they secure this new projection area, they would actually have the ability to project in depth on any projection surface; therefore exponentially increasing available display spaces around them. Users would not be constrained by the available projection surfaces in their environments any longer. They would instead get levels of information layered in depth over a single projection space.

In MMDEs, and especially in heterogeneous devices, this would allow setting the screen and the projection to be in the same field of view as per recommendations from Chapter 4, while still projecting extra data in depth through the projection and without the need for extra display surface. Users would then access the different layers of data using spatial and kinaesthetic cues in the same way that they accessed workspaces in

Chapter 5. It was expected that the spatial aspect would increase performance in switching layers as that they did with the setup in Chapter 5.

However, at the starting point of this research, there was not enough comprehension to how depth is actually being perceived in the mobile environment to start developing interaction techniques and virtual workspaces. This chapter has then been focusing on understanding how depth is being perceived in the mobile environment. The research presents a mathematical tool and design guidelines to develop such interaction spaces.

Using depth to project content

In the chapter, a model of perceived depth for mobile projection was derived from the existing model of perception in the fixed environment. The new model takes into account the projector, the software disparity, and the spatial relationships between the viewer, the projector, and the projection surface. The model shows that when one or more of those spatial relationships changes, the perceived depth also changes; giving the impression to the viewer that the object is moving either closer or further away. The model is validated in the first user study where it provides accurate prediction of perceived depth with over 95% accuracy. The new model therefore enables a mobile stereoscopic projector to render 3D objects at specified depths from the user's perspective based on sensing its distance to the display surface and the projector. It therefore lays the basis for 3D mobile projector interactions, which should be further explored in the future.

User-Projector-Surface Relationship

In a mobile scenario, the spatial relationships between the user, the projector, and the projection surface can be set on the go and can change at any point in time and affect the way depth is actually being perceived.

User Study 1 shows that the distance between the projector and the user should be positive; with the projector placed in front of the user's eyes. This is confirmed in User Study 2 as Case 2 – the only situation where the projector is behind the user – presents significantly higher failure rate and lower accuracy. Therefore, body-mounted projection is not as suitable as handheld condition for 3D stereoscopic mobile scenario.

Higher viewing distances significantly provide better performance while the minimal comfort viewing distance (26cm) proves to be difficult for users to actually merge the two views and see a 3D image. It is therefore advised that the setup should always provide a minimum distance above 26cm and encourage higher viewing distances.

Finally, the second user study shows that cases where the distance between the user and the projector is fixed yield significantly better accuracy. The two corresponding scenarios are therefore encouraged: 1. The user moves with the projector to visualize content; rather then moving the projector on its own. 2. The user stays by the projector and moves the projection surface in front of the projection beam. This scenario can be a bit tricky to achieve as an arm's length is typically under a meter and that the minimal viewing distance is 26cm, which only leaves a small physical gap to project on.

Mobility and Model Limitations

The second user study includes a mobility condition to test whether participants could see the small changes in depth that occur in a fully mobile environment. Results show that for 20.3% of the trials users could not see the object moving. This can be both an advantage and a drawback. The drawback is that the natural depth changes cannot be directly exploited for users to perceive an object at a different location in space than before they moved. The advantage is that in spite of the movement, the object looked fixed, which means that the object could be "virtually" fixed in space while the user would move around it. This would also mitigate jitter effects in such environments.

Results also show that accuracy, although significantly different from a case to another, is quite low when mobility is involved. This could be affected by several factors such as the size of the object that is altered when the distance between the projector and the screen is altered; the fact that the user is walking; or even that their viewing direction is not parallel to the projection beam. Although more work is needed to identify those factors precisely, one could easily track the user's glasses and provide perspective correction to the projection. The appearance of the displayed object could be corrected so it would always appear at the same size from the user's viewpoint.

The next sections present directions for future work and a summary of the chapter.

6.6.2 Future work

Visualization layers

This chapter determined that stereoscopic depth could be used and properly recognized in the mobile environment. The initial concept is to take this work further and to display information layered in depth in the gap between the user and the projection surface. Future work could concentrate on determining how many depth zones or depth layers can be used, as Spindler's work with tabletops [Spindler 2012]. Future work will also include finding interaction techniques to configure the different levels of depth with mobile projectors and to access them; spatial interaction is a promising interaction scenario to access the different layers.

Privacy levels

Hall's proxemics research [Hall 1966] identified regions around a person that match the physical distance to social distance. Their work is now used by researchers to understand the interaction zones around mobile devices [Ballendat 2010] and is gaining increasing interests from researchers studying devices equipped with mobile projectors, which projections can reach zones beyond the user's personal space. When interacting with information layered in depth, researchers could identify privacy zones and distances from the projection surface and the user, which would determine the type of content being displayed.

Case of MMDEs

One very complex aspect of using the 3D stereoscopic projector embedded into a MMDE will be to understand how the eyes' convergence and accommodation between a 2D screen and a 3D projector will affect the experience. It was determined in Chapter 4 that visual separation effects were manageable in heterogeneous projection-screen MMDEs and that users could effectively use the displays synchronously. Future work should investigate how other types of heterogeneous displays can be used in parallel such as hybrid 2D and 3D displays. Additionally, interaction technique will need to reflect the complexity and particularity of the hybrid system.

Interaction techniques

There will be different aspect to the interaction, one will be the alignment of the displays in the MMDE, and the other will be interacting with the projection and the other display on the MMDE. In the future, one can envision smooth transition between interacting with a screen and a projector; while for now separate techniques are considered. When interacting with the projection, one will need to decide what content to display and then will need a suitable technique to interact with the 3D display. To decide which content should be projected, one can consider spatially aware techniques; such as the user walking towards a wall they are projecting on or walking away from it. The system could for example use infrared sensors or even depth camera, such as the Microsoft Kinect[1], to sense the position of the user or projector compare to the wall.

To interact with the content, users could use body gestures, shadowing techniques, virtual touch, and pointing or even use the screen to interact with the projection. Users could use the device has a magic window onto a real 3D environment; such as Konieczny's tablet to show slices of a 3D environment [Konieczny 2005]. This could be done when projecting on the floor and moving around the object for example. Haptic feedback could be envisioned so the user could feel what is happening in the projected environment. Future research will be conducted to understand the interaction challenges of such displays.

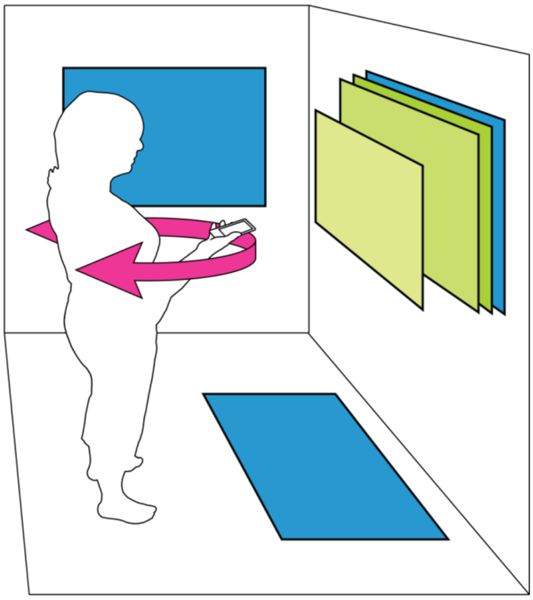
6.6.3 Summary

This chapter has investigated whether the depth gap between a mobile 3D stereoscopic projector and the projection surface can be used to display content. In particular, it was investigated how depth is actually perceived in the mobile projected environment. A mathematical model of perceived depth for 3D stereoscopic mobile projection was developed, taking into account the variable spatial relationships between the user, the projector, and the projection surface. Through a controlled user experiment, the model was validated in conditions consistent with mobile projector interaction scenarios. A second user study investigated four cases of movements between the user, the projector, and the projection surface; and investigated the effectiveness of the model in

[1] Kinect depth and motion sensing camera: http://www.xbox.com/en-GB/Kinect

a handheld scenario with a mobility factor. Results show that the physical gap between the projector and the screen can be used to visualise content. The chapter concludes by presenting some limiting factors; design guidelines, as well as avenues for future work.

The following section Chapter 7 concludes the work presented in this doctoral research. It first presents a summary of the work before answering the research questions posited in Chapter 1: Introduction. It then lists the contributions of this research, directions for future work and finally concludes this thesis.



Chapter 7
DISCUSSION AND CONCLUSIONS

The previous chapters covered: background work related to mobile projectors, fixed and Mobile Multi-Display Environments (Chapter 2), an exploration of MMDEs through various display alignments (Chapter 3), alignment and visual separation effects in MMDEs (Chapter 4), secondary displays in MMDEs, particularly the use of virtual workspaces (Chapter 5), and depth and stereoscopic 3D for mobile projectors (Chapter 6).

This chapter summarizes the research (7.1) and illustrates how the work conducted in this dissertation answers the four research questions posited in the introduction (7.2). Next, I discuss how the contributions validate the thesis statement, and present design considerations (7.3). The directions for future work that have emerged from this dissertation in the field of MMDEs are then discussed (7.4) before concluding this dissertation (7.5).

7.1 DISSERTATION SUMMARY

This doctoral research investigated the field of MMDEs. *Chapter 1: Introduction* defined this space, its scope, and the scope of the research. I first defined that this research would apply to single-user scenarios, as those devices are personal mobile devices. I then defined that this research would focus on studying the following interaction spaces around the user: in front of the user, on the sides, on the floor, and in the gap between the user and the projection surface. *Chapter 2: Background* then introduced the literature review of mobile projectors, fixed and Mobile MDEs. I presented similar systems, their applications, as well as visualization and interaction techniques for such environments. In this section, I defined a classification of MMDEs based on the number of devices that compose the environment, the type of displays, and the mobility factor.

Chapter 3: Exploration of MMDEs through Various Display Alignments presented my own approach and prototype design of a projection-screen MMDE. This prototype was used in an exploratory user study to understand the role of display alignments in a heterogeneous projection-screen MMDE design space. Results showed that different alignments between the screen and the projection beam are needed for different tasks but also that users would change alignment in the course of a task. The proposed steerable projection solution is a viable and efficient technical solution to giving this flexibility to MMDEs equipped with mobile projectors. It was also observed that out of the three proposed projection angles in the study (Chapter 3), participants did not prefer the 0º angle currently employed in the manufacturing of projector phones. Two interaction techniques for projection-screen MMDEs were implemented: one for when the projection beam and camera are aligned in the mobile device and one for when they are misaligned. The findings exposed that different interaction techniques are needed for different configurations and that a given interaction technique does not suit all alignments between the projection and the screen. For example, while "touch" on the projection is not adapted when projecting on the wall; it is well suited for a floor projection, by stepping on it.

Chapter 4: Alignment and Visual Separation Effects in MMDEs studies how visual separation effects that exist in MDEs affect the use of MMDEs for different display alignments. As per Chapter 3, those effects were investigated for a heterogeneous environment, composed of a screen and a projector, as those environments are the ones most likely to be affected by visual separation since the displays have different sizes, resolutions, and present content at different depths. In a study, participants were asked to perform a visual search task for three different alignments of the displays: positioned in the same field of view; separated by an angular plane; and separated by two angular planes. The study considered a fixed and a handheld condition and used an eye tracker to measure the number of eye switches between the displays. Results showed no statistically significant difference between the fixed and handheld condition for all independent variables, suggesting that mobility does not affect usability in MMDE. Results also presented no statistically significant difference across the three conditions in terms of task completion time and error rate. This indicates that visual separation effects are not as affected by angular separation in MMDEs than they are in MDEs, and so that MMDEs have a more flexible design in terms of display alignments. Finally, measurements exhibited 30% extra eye context switches in the aligned condition compare to when the displays are separated by one or two angular planes. I conclude that displays should by default, be aligned in the same field of view for synchronous use of the displays.

Chapter 5: Secondary Displays in MMDEs: The Case of Virtual Workspaces explored the spatiality around the user to find out how the physical spaces around the user can be used to interact with the MMDE. To explore this aspect, a set of spatially aware virtual workspace prototypes was developed. The prototypes featured a projection-screen MMDE that sensed its relative position compared to the user and chose what information to display based on the spatial information; therefore displaying various workspaces around the user. Two studies were carried out to test this concept. In order to better understand the use of space around the user and before adding extra cognitive burden on the user with the dual-display system; the first study used a screen-only prototype. The prototyped interface that accesses virtual workspaces with the mobile screen only (*mSpaces*) was compared to traditional workspace switching with mobile phones. Participants were asked to answer questions for which they needed to navigate across the various workspaces to find the right answer. Participants made fewer errors with *mSpaces* and the prototype was significantly faster in terms of trial completion time than the other two conditions. Overall, 67% of the participants preferred the *mSpaces* technique. Bolstered by those encouraging results, *pSpaces* is proposed as an enhancement of *mSpaces* with a mobile projector used as secondary display to the system, and based on the same interaction technique. I also put forward *m+pSpaces* a hybrid version of *m-* and *p-Spaces*. In the second user study, the three prototyped interfaces are compared and evidence showed that participants made fewer mistakes with *pSpaces* and performed significantly more context switches in *pSpaces* than in the other two conditions. I conclude that the projection improves the capabilities of the spatially aware virtual workspaces. Moreover, as results did not show significant effect of workspace type on trial completion time, I argue that while spatial interaction significantly improved user experience, the way in which the spatial aware system is designed does not seem to affect usability. I finally discuss design considerations when building virtual workspaces in MMDEs.

Chapter 6: Depth and Stereoscopic 3D for mobile projectors investigated using the space between the user and the projection surface to layer projected information. The motivation is that users could access more content in a smaller physical space while still interacting in a spatial manner with the system. Since mobile stereoscopic projection is a very novel topic, it is not well understood at that stage how users perceive it. I therefore defined a mathematical model of perception of mobile stereoscopic projection based on existing models in the fixed setting. The model is evaluated in a first user study that was run in a fixed condition where the experimental task was solely to determine at what depth they were seeing the stimuli. The study was highly successful in proving the validity of the model as the linear regression showed:

$$\textit{Measured Perceived Depth} = 0.955\ \textit{Desired Stimulus Depth}$$

Results showed significantly more perception error and failure in fusing the left and right views when the distance between the projection and the screen was near the minimum comfort viewing distance, suggesting using this distance as below the minimal distance for stereoscopic mobile projection. The second user study integrated the mobility factor and observed how well the model would perform in a close-to-real world scenario. Study participants were asked to vary the various distances between themselves, the mobile projector, and the projection surface. For each task, they had to evaluate if they saw the stimulus moving towards them, away from them or did not see any movement. The model predicts specific changes in the perceived depth depending on the user-projector-surface distance; yet, the small distances in a mobile environment may preclude the user from perceiving those changes. Results showed that for over 20% of the trials, users could not see the perceived depth changes, and that the overall accuracy is quite low with only 52.3% of successful trials. Yet, results show a significant effect of movement on accuracy and that the Cases for which the distance between the viewer and projector stays constant result in higher accuracy. It was also shown that the position of the stimuli in depth has significant effect on users. The chapter concludes with avenues for future work.

7.2 RESEARCH QUESTION

In the introduction, I presented four research questions to address the thesis statement. This section presents the answers to the research questions.

7.2.1 Research Question 1

> *Is synchronous use of the displays effective for mobile multi-display environments?*

This research question is addressed throughout Chapters 3, 4, and 5. Chapter 4 evaluated visual separation effects for different alignments between the displays in a heterogeneous projection-screen MMDE. Empirical data showed that participants could perform a cognitively *difficult* task that needed synchronous use of the displays with a low average error rate of 8.9% across all tasks and conditions. Moreover, no statistical difference was found in error rate and task completion time whether the device was fixed on a surface or handheld which seems to indicate that jitter is not an issue in single-user scenarios. This was actually *confirmed* in the study presented in Chapter 3 where users were asked to perform a reading task on the projected display while holding the device.

All users managed to perform the task and none complained of jitter effects. These indicate that in the context of the presented studies:

The multiple displays of a heterogeneous MMDE
can be used synchronously in both handheld and resting conditions.

Chapter 5 presented a spatially aware interaction technique to navigate through virtual workspaces based on kinaesthetic cues and spatial memory. The first prototype, *mSpaces*, composed of a screen only, was compared to traditional interaction techniques to switch workspaces in mobile devices. Results showed that users performed significantly better – less errors and significantly faster task completion time – using *mSpaces*. In a second user study, a mobile projector was fitted to the prototype, creating a MMDE: *pSpaces*, to interact with the spatially aware workspaces. A hybrid version, *m+pSpaces*, was also implemented where the main workspace was displayed on the screen while other workspaces were displayed on the projection. Empirical evidence showed that participants made fewer errors with *pSpaces* while there was no significant difference in the task completion time although people had to look at the two displays in both *pSpaces* and *m+pSpaces* conditions. Qualitative results also showed that 75% of the participants preferred a dual-display prototype to a single-display one. From those findings, I deduce that:

In a spatially aware environment, MMDEs are faster to use and result in
higher accuracy and are preferred over single-display environments.

While MMDEs are viable and usable environments, in Chapter 3, users prefer different alignments depending on task and context and in Chapter 4, the number of eye context switches significantly differed depending on display alignments. This aspect is discussed further in Research Question 2 where I pose that:

MMDEs have to propose flexible alignments between the displays.

Note that in the experiments conducted for this doctoral work, I mostly studied heterogeneous environments composed of screen and projection capabilities. Those environments present screen and projection displays with different resolutions, shapes and sizes; and even present content at different depth levels, and in some cases, on different angular planes. Given the complexity of such highly heterogeneous environment, I presume that this research is generalizable and applicable to homogeneous MMDEs. Note that these results also fit with current literature on multiple-display MMDEs presented in Chapter 2.

7.2.2 Research Question 2

> *How does the relative physical position between the multiple displays affect usability, and what are the optimal relative positions?*

This research question is addressed in chapters 3 and 4. First, when considering the literature in Chapter 2 on MDEs, previous research works show that the position between the various displays affect users and interaction techniques. The further apart the displays, the harder it is to, for example, drag content from a display to another [Nacenta 2008]. Research also show that bezels can affect the experience especially when information is divided across the bezel or for tunnelling [Bi 2010, Rashid 2012]. Moreover, it shows that when separating the displays, different phenomena can affect the user such as visual separation effect [Tan 2003]. Nevertheless, in a Mobile MDE, the physical properties of the device lead to smaller distances between the displays. Additionally, there is no bezel between a screen and a projection. It is therefore unclear whether users are affected by different positions of the displays, as is the case in MDEs.

In Chapter 3, three different alignments (Wall, Desk, and Floor) between the screen and the projector were evaluated using a steerable projection-screen prototype. In an exploratory study, participants preferred different alignments between the displays for different tasks. For example, in a task where users had to read an email from the projection, 57% preferred the *Desk* projection angle and the remaining 43% preferred the *Wall* angle. In another task where users were asked to follow directional arrows, the vast majority (71%) selected the Desk angle and the remainder (29%) chose the *Floor* angle. The experiment clearly illustrated that an alignment that was suitable for a task may not be suited at all for another task. For the task involving mobility, where there was no permanent wall space available to project on, all participants decided to project on the floor. Participants used different projection angles to project on the floor based on the way they hold the prototype. People holding the prototype flat, would prefer projecting the projection further away from their body while those holding it inclined would already project further away due to the projection angle. This indicates that the alignment should adapt to the person holding the device.

Chapter 4 presented a controlled study to verify if visual separation affects MMDEs. To do so, a user study was conducted for three different alignments of the projector and the screen in both handheld and fixed conditions. Results showed no significant differences for all independent variables between the mobile and fixed conditions. Yet, 9 out of 12 participants preferred a mobile condition overall. The empirical data revealed that users were able to use the displays simultaneously and with no significant difference in performance – completion time and error rate – across the different alignments. Besides, participants switched context 30% more in the condition where the displays are in the same field of view. As detailed in Chapter 4, the context switches can be considered as an epistemic action; which means that having the displays in the same field of view help users better externalize their thought process. The qualitative NASA TLX results expose that participants significantly perceived performing the task faster in the same field of view condition for an actually comparable task trial time. I conclude that it is better suited to have both displays aligned in the same field of view by default. Finally, in the mobile condition, some participants would project on the wall when the displays were aligned when it was initially expected that they would project on the floor. This suggests that the usability of the MMDE is affected as in Chapter 3's study by how the user holds the device.

Lastly, in Chapter 3, participants evoked being worried about privacy with the projected display. Some users mentioned that they would use the physical property of the device's projection to solve those privacy issues. As such, they would rather have a smaller projection on a horizontal surface if projecting personal data in a public environment. A list of factors affecting participants in the choice of the alignment between the displays was gathered:

These factors include:

- Number of people: that the user would want to show the projection to and total number of people in the vicinity of the user (in a public space for example);
- Users themselves: personal preferences and their hand's position when holding the device; current activity, such as standing or walking;
- Projection surfaces: availability, shape, colour and material;

- Lighting circumstances; and
- Application currently being used

I conclude that:

The relative position of the displays affects usability in a MMDE.

Yet, it does not appear to affect performance in a visual search task. I suggest aligning the displays in the same field of view as default alignment but argue that the device should present flexibility to re-align the displays depending on the user's context.

7.2.3 Research Question 3

How can the mobile-projection unit be used as a secondary display on a mobile device drawing on the concept of secondary display in fixed multi-display environments?

This research question was investigated through chapters 3, 4, and 5. There are multiple reasons why multiple displays are used in MDEs [Ringel 2003]. As users get additional display real estate, they choose to compartmentalize information on the peripheral view; show content to others on more adequate displays; and even manage different applications or computers at the same time. The displays often come on their own – such as computer monitors or fixed projectors – and can be connected to any computer. Some other displays, such as Microsoft Surface Table – renamed Pixel Sense [Microsoft 2012] –, come with processing power and do not need to be plugged into a computer. MDEs are then built by connecting displays together or by attaching computers together.

In the mobile environment however, as seen in Chapter 2, MMDEs can be composed of either multiple single-display devices or multiple displays on a single device. The affordances and interaction challenges differ from an environment to the other and this doctoral research focussed on the latter category. However the work done on mobile projection for multi-displays single-devices is applicable to single-display multi-devices environments as they are less constrained environments displays can be reconfigured just by moving the physical device itself.

In this research, I identified how the projection can be used as a secondary display to the screen. In Chapter 5, two prototypes *pSpaces* and *m+pSpaces* were developed, where the mobile projector was used in conjunction with the screen to navigate through spatially aware virtual workspaces. In the user study, participants made fewer errors with *pSpaces* than when using the screen only, *mSpaces*, and *m+pSpaces*. Additionally, for the same study, eight out of twelve participants preferred interacting with the *m+pSpaces* prototype which involved synchronous use of the displays with the main workspace always visible on the primary display (mobile screen) and the other workspaces available through the secondary display (mobile projection). I conclude that:

Mobile-projection units can be used as secondary displays in the mobile environment.

In Chapter 3, the exploratory study revealed privacy concerns when using the projected display. Some participants mentioned that they would not feel comfortable projecting personal information and would rather keep this type of information on screen. Designers therefore need to provide users with a way to choose what information to display or inform the system about the privacy level users feel comfortable with, especially since the mobile-projection unit is embedded in a personal mobile device. Users should therefore be provided with control over the data that is being projected to alleviate privacy concerns.

Additionally, in Chapter 4, participants all successfully performed a complex cognitive task using both displays together with an overall error rate of 8.9%. Furthermore, using the eye tracking measurements, I conclude that displays should be aligned in the same field of view to avoid extra cognitive load on the users. I argue that given a fit alignment between the displays:

Mobile projection goes beyond the secondary display scenario; and can be used synchronously with the screen or as the primary display to the MMDE.

Finally, Chapter 2 presented that projection-enabled MMDEs can be used in many ways and for many applications. They can be used as main displays, secondary displays, inputs [Schmidt 2012a], Peepholes [Kaufmann 2012], ambient displays [Reis 2011], to augment the world [Beardsley 2005]: for entertainment [Willis 2011a], to help workers [Raskar 2004] or learners [Löchtefeld 2011a], doctors and patients

[Ni 2011], soldiers [McFarlane 2009]; to tell stories [Åkerman 2011, Robinson 2012], to navigate [Wecker 2011] and even to augment mobile desktop environments [Aamoth 2010]. Moreover, Chapter 6 shows that, in the near future, researchers can imagine a projection not limited to the available projection surfaces but also allowing projecting in depth. Designers can now envision projection-units embedded into any type of devices providing embedded ambient displays that people can use whenever needed without physically holding a device. I conclude that:

Mobile-projection units can be embedded
into MMDEs to enhance user preferences for many types of applications.

7.2.4 Research Question 4

How can the space between the user and the projection surface *be enhanced with additional information?*

This research question was investigated in Chapter 6. The research motivation was to explore how the space between the user and the projection surface can be augmented. Therefore, when users wish to display extra information using spatio-kinaesthetic cues to interact with the MMDE (as in Chapter 4), they would not require additional available projection surfaces, and could instead use a single projection surface and interact in the gap between them and the wall. This aspect is particularly applicable in MMDEs containing projection capabilities, as the displays can be aligned as best suited for the task and context, and the user could then exploit the depth to get additional display space within the chosen display alignment. While a straightforward solution would consist in proposing an interaction technique consisting in moving towards the projection surface, I wanted to take the concept further and use the full extent of the space. Since this research coincided with the emergence on the market of portable stereoscopic 3D projectors, this research could then take full advantage of the mobility of the 3D projector to explore projecting information in the gap between the user and the projector.

This is pioneering work, and to the best of my knowledge, there was no prior research related to how portable stereoscopic 3D projections are perceived by users. The main difference in mobile, compared to fixed environments, is that the distance between the projector and the projection surface is not fixed. I started by defining a mathematical model of perceived depth in mobile stereoscopic 3D environments, derived from existing model of perceived depth in a fixed stereoscopic 3D environment [Holliman 2006]. This model is presented mathematically and illustrated geometrically in section 6.3: Geometric Model of Perceived Depth. The model is evaluated through a user study. After performing a linear regression between the expected perceived depth and the depth that was actually perceived, the model shows over 95% accuracy.

People can accurately perceive depth in a
mobile stereoscopic 3D projected environment.

Additional findings highlight that there are some limitations such that users cannot see the image in 3D (i.e., merge the right and left images) at a distance close to the minimal comfort viewing distance. Viewing distances are therefore advised to be at least 26 cm. Besides, the model shows that the perceived depth changes depending on the relationship between the user, the projector, and the projection surface. Therefore, when one of those distances changes, the projected object will appear at shorter or longer distance from the user. This natural depth change occurs without any software modification, it is solely based on the relative distances and the physical effects they induce. In a second study, it is investigated whether users can accurately recognize those depth changes for the small-scale distance variations that exist in the handheld mobile setting. It was expected that, as people can perceive the object at an accurate depth, they should equally understand those movement-induced changes; which would then allow researchers to exploit those movements and develop adapted interaction techniques for handheld mobile 3D stereoscopic projection. On the other hand, it was hypothesised that in some cases, the distance variations would be too small for the users to see the object move. Empirical evidence shows that for 20.7% of the overall trials, users cannot perceive any depth change. This failure rate is significantly lower when the user is not walking and only moving the projector or the projection screen. By interpreting the results, I deduce that:

Walking introduces a small, yet significant, negative impact
on depth movement perception.

For the successful trials, although the accuracy – i.e., trials for which the object perceived movement corresponds to the predicted movement – rate is somewhat low with only 52.3% of accurate trials, results show a significant effect of the stimulus depth level and of the case on accuracy. Results show that for situations where the distance between the user and the projector would stay steady, regardless of the projection surface, the accuracy was significantly higher. I propose that:

In mobile stereoscopic 3D environments, interaction designers should prefer scenarios where the distance between the user and the projector remains fixed.

When considering the data gathered in both user studies, it can be deducted that using depth in a mobile projected 3D environment is possible and that the depth at which users will see the virtual object can be accurately predicted thanks to the presented mathematical model. The empirical data highlights some challenges and limitations to using depth changes in scenario where the user is performing movements. In response to Research Question 4, I confirm that:

The physical space between the user and the projection surface is usable.

7.3 RESEARCH OBJECTIVES

At the beginning of this research work, I posited the following thesis statement:

Providing re-configurability of displays' relative placements in the heterogeneous MMDE and providing interaction using kinaesthetic cues and spatial memory, users can manage complex and highly cognitively charged tasks as well as complex information management across multiple displays.

This statement is addressed and verified in this dissertation. It is answered through the four research questions, as discussed, in the previous section, and through the four main contributions that are detailed below.

7.3.1 Contributions

This section presents the contributions made in this dissertation. There are four main contributions and additional secondary contributions. Those contributions help answer and validate the thesis statement.

Research contributions

1) A case study that demonstrates the viability of heterogeneous MMDEs for synchronous *use of the displays*

One of the major aspects of this dissertation was to identify that MMDEs are environments where displays can be used synchronously and enhance user experience compare to single-display environments. I intended to demonstrate that the displays in a MMDE are not just output technologies concatenated on a single device but that their synchronous use is key to improving small screen issues in mobile devices. The results show that additional screen real estate will help alleviate users' task load when working on a small screen device so that multiple displays actually enhance user experience and allow complex tasks to be carried out. MMDEs would then improve mobile computing in the same way that MDEs have enhanced desktop computing.

Heterogeneous projection-screen MMDEs present very specific and disparate inherent properties such as different display sizes, shapes, resolutions, display depths, and even a varying projection display size depending on the distance to the projection surface. Demonstrating synchronous use of the displays in such environments would also prove that synchronous use of the displays is also possible in less disparate environments, such as homogeneous MMDEs. Therefore, the work focused on proving the viability of heterogeneous MMDEs. As such, Chapter 4 presented a case study for heterogeneous projection-screen MMDEs with a highly cognitively loaded task where participants need to study both displays carefully. The overall success rate proves that the multiple displays in the heterogeneous projection-screen MMDEs can be used synchronously. Moreover, in Chapter 5, participants were presented with a task that could be achieved using a screen-only device or a screen-projector MMDE and for similar quantitative results, 75% of participants qualitatively preferred using the

MMDE. This shows that their experience was actually enhanced by having the projection in addition to the existing screen.

2) Design guidelines to design MMDEs in terms of display orientation and the use of virtual workspaces

Throughout the various chapters and projects, several heterogeneous projection-screen MMDEs are prototyped to explore how MMDEs should be designed in terms of the relative placement of the displays. While it is identified early on, in the research, that the 90° separation-angle between screens and projectors currently offered by manufacturers is not adapted to all situations; it was actually surprising in Chapter 3, to find out that in a mobile situation this angle would not be used at all by participants. Results showed that people preferred projecting on the floor in a mobile scenario. The choice of screen-projector separation angle for a floor projection depended on how the user held the device; for instance, a wider angle was preferred when the device was held flat, compared to a device held inclined. Finally, results prove that people adapt the projection-screen arrangement as a strategy to manage the level of privacy they feel comfortable with at a given time.

In Chapter 4, empirical evidence proves that separating the screen and projection in plane does not affect completion time and error rate in a complex visual search task. However, when the displays are in the same field of view, users can externalise their thoughts better and are less cognitively burdened than when the displays are separated in plane. I conclude that for cognitively demanding tasks and for extended use of both displays synchronously, displays should be positioned in the same field of view. Manufacturers should then provide flexibility and the option to reconfigure the display alignments depending on situation and context. Specific design guidelines are presented in the relevant chapters and summarized in the design considerations section.

Besides, in MDEs one strategy to overcome small display real estate is the use of workspaces containing one or multiple applications. Those virtual workspaces are also used to manage information across displays and facilitate multi-tasking. This concept was introduced for Mobile MDEs in Chapter 5, where it is presented that those workspaces can be accessed using the physical properties of the device itself as explained further in the third main contribution below.

3) A novel interaction scenario using kinaesthetic cues to interact with a MMDE and get additional content displayed around the user

While in a single-display mobile device, the interaction scenario usually consists of interacting with the content currently being displayed; interaction scenarios for MMDEs are, however, multifaceted. The user may have to decide what information will be displayed and on which display, how to switch information from one display to another and, as with single-display devices, interact with the content. In spite of the fact that the focus of this work was not to identify best interaction techniques, different interaction scenarios for MMDEs are presented throughout the dissertation. In particular, a novel interaction scenario is proposed in which the user can move the device around their body to change which workspace is currently being displayed on the screen and/or projection. Three spatially aware prototypes are designed in Chapter 5 to evaluate this novel interaction scenario. When comparing a spatially aware prototype to existing interaction techniques for single-display devices, the spatially aware prototype performs significantly better than existing techniques in a complex visual search task. Additionally, across the three prototypes, and for comparable performance, 75% of the participants preferred the multi-display to the single-display prototype. This scenario is therefore validated using kinaesthetic cues to interact with MMDEs.

4) A mathematical model of perceived depth for mobile 3D projection

Part of this research work consisted in understanding all the projection surfaces around the user that can be exploited in a projection-screen MMDE. Each piece of work that was presented explored a different space around the user. In Chapter 6, the limits were pushed back by projecting in the gap between the user and the projection surface. Projecting in this gap would potentially increase all projection surfaces into multiple layers of projection. In projection-screen MMDEs, this would be incredibly valuable as the screen and the projector could be positioned at a suitable separation angle while still having multiple virtual surfaces to project on for a single physical display surface.

Because of the lack of previous research work on the perception of depth in mobile stereoscopic 3D projected environments, the first step consisted in understanding how depth is actually perceived by users before taking the research further. I then defined a novel mathematical model of perceived depth in mobile 3D stereoscopic environments that is derived from existing models in the fixed environment. The mathematical model was validated through a quantitative user study where participants could recognize 3D objects at their expected depth with over 95% accuracy.

Secondary research contributions

In addition to the four main research contributions, this research work yielded additional contributions that are listed below.

- A definition of the term Mobile Multi-Display Environments (MMDEs) as well as its scope and a classification system;
- An exploration of the MMDE field;
- A series of designed MMDE solutions consisting of heterogeneous projection-screen MMDE prototypes;
- A set of interaction scenarios and some preliminary evaluations of interaction techniques;
- An exploration of floor projection;
- Empirical data gathered through user studies proving the viability of MMDEs for different conditions and use-cases;
- A set of design guidelines for designing MMDEs.

7.3.2 Design Considerations

Throughout this research, design guidelines were identified that will be useful for designers and researchers that work with MMDEs, as well as for manufacturers who build such environments. The design considerations are defined in the relevant chapters. This section presents a summary of the most important design guidelines.

- In projection-screen MMDEs, the displays need to be aligned in the same field of view when performing highly cognitively demanding tasks.
- MMDEs present flexible environments where visual separations effects do not prevent users from performing complex tasks even when the displays are positioned on different planes.
- Different display alignments are needed for different tasks and contexts.
- MMDEs should provide flexibility to re-arrange the displays.
- Since some interaction techniques are appropriate in some display configurations but not in others, MMDEs should provide adaptive interaction technique depending on the current display alignments.
- Holding the MMDE does not affect usability and is actually preferred by users when performing complex tasks using the displays synchronously.
- MMDEs are preferred to single MDEs when performing complex tasks.
- Interaction scenarios involving spatio-kinaesthetic cues are preferred when choosing what information to display.

7.4 FUTURE WORK

This section presents a discussion of some of the remaining research opportunities and avenues for future work that were revealed by this dissertation. In particular, it presents future work opportunities around three themes: the types of displays in MMDEs, interaction scenarios, and mobile devices composition.

7.4.1 Types of displays in MMDEs

In this dissertation, I demonstrated that MMDEs are useful environments, which allow users to perform complex tasks from a personal mobile device. In particular, this dissertation shows the validity of those environments by focusing on heterogeneous MMDEs that present strong disparity factors from one display to the other (projection-screen MMDEs). In this dissertation, I presented interaction scenarios and design guidelines that are specific to heterogeneous projection-screen MMDEs. While previous work had already focussed on interaction scenarios for homogeneous screen-screen MMDEs [Hinckley 2009], future work could specifically identify interaction scenarios and design guidelines for homogeneous projector-projector MMDEs. This is different from previous work on using multiple mobile projectors [Cao 2009], although building on Cao's findings, as the multiple projectors would be positioned on one device and the interaction challenges would therefore differ from the multiple device environment. In a projector-projector MMDE, the projections could be used as two separate display surfaces; they could also be used on the same surface, complementing one another in terms of content or even resolution, as Jaynes et al. work in fixed environments [Jaynes 2003]. I suspect that the homogeneous projector-projector MMDEs will need reconfigurability depending on task and context as for heterogeneous environments.

Future work could investigate heterogeneous MMDEs, composed of both 2D and 3D displays, as defined by Benko [Benko 2007a] in the fixed MDE. Those devices are a subset of MMDEs; they present the same general characteristics but present an extra separation in depth between the displays that may induce eye accommodation issues that need to be studied further. In the future, MMDEs may also include holographic projection [Buckley 2011] or shape-changing displays [Hemmert 2010] that will bring new visualisation characteristics and interaction challenges.

Finally, in the Background chapter, I define that a MMDE composed of any number of displays can be considered in terms of the relationship between any two displays individually. This doctoral work investigated, more particularly, the case of dual-display MMDE. Having additional displays could be useful to, for example, increase the display real estate or as an alternative to project on different locations without having to reconfigure the physical alignment between the displays. Future work could investigate to what extent having multiple displays can scale up and how interactions techniques would need to be adapted depending on the number of displays on the device.

7.4.2 Interaction scenarios

Throughout this dissertation, novel interaction techniques were prototyped and use to identify interaction scenarios suited to this exploration of the MMDE space. Nevertheless, since the focus of this work was not to determine the best suited interaction technique but instead to determine how those environments can be used in a suitable way, future work should identify appropriate interaction techniques in such environments.

In particular, future work could concentrate not only on interacting with the data on each display, which can be drawn from the current literature on interacting with mobile devices (either screen only or projection only); but more specifically on interacting with the displays simultaneously, such as how content can efficiently be moved from one display to another. While techniques exist in the fixed MDE, it is not clear whether they can be efficiently applied in the Mobile MDE where, for example, moving the device itself would affect all displays.

Moreover, when using one interaction metaphor for the screen and a different one for the projector, the user could become confused, and future work may lie in finding fluid interaction techniques that can be used across both display types. Similarly, it was discussed that the interaction technique should depend on the alignment between the displays. Techniques need to be developed to guide the user through the interaction when the interaction does not remain constant. Additionally, in the current work I have exploited visual modality only to interact with the MMDE. The transition could potentially be made smoother by using other modalities such as speech input to move content across. Using other modalities would allow keeping the device's screen from occlusion and users would not have to switch their attention away from the displays.

While this doctoral work has been focusing on exploring MMDEs as personal devices, there are equally interesting future scenarios, which involve multi-user collaboration in MMDEs. Supporting collaboration in a MMDE requires positioning displays in order to improve coordination and awareness, while potentially increasing visual separation effects. One direction of future research is to explore how visual separation issues affect collaboration and coordination between multiple users.

7.4.3 Mobile devices composition

In this doctoral work, the displays have primarily been used as outputs. In some situations, the touch screen was also used as input for both the screen and the projection. Recent work has proved that the projection too can be used as input [Schmidt 2012a], and not only as input to the projection but as input to other electronic devices. An interesting avenue for future work would be to investigate the use of MMDEs as input to surrounding devices and how the multiple displays can be used together to enhance the "remote-control" functionality. It is also worth investigating how the projection could be used as input to the screen in a MMDE.

Another interesting aspect to consider is that personal mobile devices incorporate an increasing array of input and output technologies. Each new capability introduces additional challenges to fit into the device ecology such that existing hardware and the corresponding interactive capabilities are not disrupted. Thanks to the recent miniaturization of all electronics and embedded technologies and sensors, mobile devices have appeared on the market equipped with a large array of components, such as: projector, camera, flashlight, accelerometer, and GPS. The situation used to be that having many components on one device would make the device bigger and cumbersome; but this is not the case anymore.

A major challenge is to understand how researchers and designers can provide appropriate user interactions and interfaces for each component when there are so many capabilities on the device with such different requirements. For example, in Chapter 3, using the camera to interact with the projection is only suited when the projector is strategically placed on the handheld. The placement of the mobile-projection unit in the device is then key to being able to interact using the camera, and even the screen. More generally, the relative placement of displays, cameras, sensors, and controls predetermine particular uses of the device by imposing how capabilities can be composed. Future work could therefore investigate the relative placements of inputs and outputs in mobile devices.

Device composition is another technique that researchers can use to deal with the above-described problem. By importing the concept of reconfigurable hardware [Plessl 2003, Garcia 2006] to the mobile platform, mobile devices could be composed of specific modules. So, one could attach the camera module to their personal device when going on holidays and feel they would not need this module the rest of the year. Therefore, instead of having all components at once, people could just "plug-in" components. Research obviously needs to be conducted on the technical aspects to achieve this and on the designs that would be suited for such interfaces.

7.5 VISION OF MMDES

As researchers and mobile users, we are currently experiencing new types of computing environments that are mobile, handheld, and extremely powerful. This is an incredible transition from the world of fixed desktop computing to a new world of portable and fully mobile computing. Some researchers even argue that mobile phones will become primary personal computing devices, replacing personal computers [Barton 2006]. Personal mobile devices now provide multiple displays to present an increasing level of information to the user at any time. However, mobile devices have not been designed as devices with high computing power that can help users achieve complex tasks. Similarly, interaction techniques and usage scenario do not take into account synchronous use of multiple displays, in the way that they are being used in fixed MDEs.

This dissertation presents an exploration of MMDEs and gives new perspectives on how those devices can be used. I demonstrate that mobile computing usage can be enhanced through MMDEs and that it is now possible to perform highly cognitively demanding tasks on small devices. This work identifies design guidelines that will enhance the functionalities of those devices and user experience. Besides, it was also determined that MMDEs open up new interaction and social challenges.

This work is the first evidence that MMDEs are as powerful in the mobile computing environment as MDEs are in the desktop environment. MMDEs have the potential to change mobile computing and become as widespread as MDEs, and even more so given the variety of mobile devices currently being manufactured. As users, we carry personal devices with us at all times and require an increasing amount of information to be available; as researchers, we expect MMDEs, and especially heterogeneous projection-screen MMDEs, to become fully ubiquitous.

APPENDIX

APPENDIX A: GLOSSARY

This is a glossary of the terms used in this dissertation:

Handheld projection

Handheld projection refers to a mobile projector that is being held by the user.

Heterogeneous displays

When a mobile device contains multiple displays of different technologies, the displays are heterogeneous. This is for example the case when referring to: a screen and a projector; a 2D screen and a 3D screen; a 2D projector and a 3D projector. These are sometimes referred as hybrid display environments in the literature.

Homogeneous displays

When a mobile device contains multiple displays of the same technology, those displays are homogeneous, creating an homogeneous MMDE.

Fixed projector

A fixed projector is a device that contains a projection unit as unique display and that is fixed in its environment. It is also known as a data projector.

Mobile Multi-Display Environment

A Mobile Multi-Display Environment (MMDE) is a mobile version of the MDE. It is defined as: *Any mobile computing environment containing more than one display.* It can be composed of multiple devices or be a single mobile device with multiple displays. A more complete definition of MMDEs can be found in section 2.3.1: Classification for MMDEs (page 47). In some in-text instances, MMDEs can be spelt: *Mobile MDEs*.

Mobile-projection unit

It refers to the chip that is embedded inside the mobile device to create a projection.

Mobile Projector

A mobile projector is a mobile device with a projection as unique display. Mobile projectors are also known as standalone, handheld, ubiquitous, portable or pico-projectors. In this dissertation, the term mobile projection is used to refer to the technology and not to the device itself.

Multi-Display Environment

Multi-Display Environments (MDEs) are computing environments consisting of more than one connected display [Hutchings 2004a, Benko 2007a]. MDEs are sometimes referred to as fixed MDEs in the dissertation to emphasize the difference between fixed and mobile environments.

Projection-enabled mobile device

Corresponds to a mobile device that contains at least one mobile-projection unit regardless of other displays. By derivation, *projection-enabled MMDEs* are MMDEs for which at least one of the displays is projected. A projection-screen device is a mobile device with a screen that is projection-enabled.

Projection-Screen Devices

This term refers to devices that contain both projection and screen display technologies. They are therefore heterogeneous MMDEs composed of both screen and projection capabilities.

Projection Space

This is the physical space around the user that is used for projecting. The projection can then use any projection surface within a given projection space.

Projection Surface

The projection surface is the physical item on which the projection is displayed. This can be a traditional projection screen or any physical surface the projection beam is directed onto.

Projector phones

Projector phones are an example of projection-enabled phones.

Single-Display Mobile Devices

Single-display mobile devices are mobile devices with only one display, either a screen or a projector.

APPENDIX B: PUBLICATIONS

Part of the work presented in this dissertation has been peer-reviewed. Below is a list of the peer-reviewed publications and workshops where this research work was presented:

- Cauchard J.R., Löchtefeld M., Krüger A., Fraser M. and Subramanian S. (2012) m+pSpaces: Virtual workspaces in the spatially aware mobile environment. In Proceedings of MobileHCI 2012: ACM Conference on Human-Computer Interaction with Mobile Devices and Services. ACM, New York, Y, USA.
- Cauchard J.R., Fraser M., Han T. and Subramanian S. (2012) Steerable projection: exploring alignment in interactive mobile displays. Personal and Ubiquitous Computing 16, pp. 27-37.
- Cauchard J.R., Löchtefeld M., Irani P., Schoening J., Krüger A., Fraser M. and Subramanian S. (2011) Visual separation in mobile multi-display environments. In Proceedings of 24th annual ACM symposium on User interface software and technology (UIST '11). ACM, New York, NY, USA, 451-460.
- Cauchard J.R. (2011) Mobile multi-display environments. In Proceedings of the 24th annual ACM symposium adjunct on User interface software and technology (UIST '11 Adjunct). ACM, New York, NY, USA, 39-42.
- Cauchard J.R., Fraser M. and Subramanian S. (2011) Designing mobile projectors to support interactivity. In CHI 2011: Mobile and Personal Projection workshop. Vancouver, Canada.
- Cauchard J.R., Fraser M., Alexander J. and Subramanian S. (2010) Offsetting Displays on Mobile Projector Phones. In Ubiprojection 2010, First International Workshop on Personal Projection at Pervasive 2010. Helsinki, Finland.

All related video figures are available on the DVD included on the back-cover of the dissertation.

REFERENCES

[Aamoth 2010] Aamoth, D. Mozilla Seabird Concept Phone: Dual Projectors, 3D Mouse. *Time Tech*, http://techland.time.com/2010/09/24/mozilla-seabird-concept-phone-dual-projectors-3d-mouse/. Accessed: 23/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HbIqkIoC)

[Acrossair 2009] Acrossair. Nearest Tube iPhone Application. http://www.acrossair.com/apps_nearesttube.htm. Accessed: 23/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HbJbqHb1)

[Åkerman 2011] Åkerman, P. and Puikkonen, A. Prochinima: using pico projector to tell situated stories. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*, ACM (2011), 337-346.

[Alexander 2012a] Alexander, J., Han, T., Judd, W., Irani, P. and Subramanian, S. Putting your best foot forward: investigating real-world mappings for foot-based gestures. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*, ACM (2012a), 1229-1238.

[Alexander 2012b] Alexander, J., Lucero, A. and Subramanian, S. Tilt displays: designing display surfaces with multi-axis tilting and actuation. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, ACM (2012b), 161-170.

[Alfaro 2011] Alfaro, S. and Bove, V. M. Surround vision --- a hand-held screen for accessing peripheral content around a main screen. In *Proceedings of the 4th* *international conference on Interactive Digital Storytelling*, Springer-Verlag (2011), 342-345.

[Amiri 2012] Amiri, K., Yang, S.-H., Kurdahi, F., Zarki, M. E. and Majumder, A. Collaborative video playback on a federation of tiled mobile projectors enabled by visual feedback. In *Proceedings of the 3rd Multimedia Systems Conference*, ACM (2012), 113-118.

[Ankrum 1999] Ankrum, D. R. Visual Ergonomics in the Office — Guidelines. Technical Report, (1999).

[Arning 2012] Arning, K., Ziefle, M., Li, M. and Kobbelt, L. Insights into user experiences and acceptance of mobile indoor navigation devices. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia (MUM '12)*, ACM (2012), 1-10.

[Ashdown 2005] Ashdown, M. and Sato, Y. Steerable Projector Calibration. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05) - Workshops* IEEE Computer Society (2005), 98.

[Augsten 2010] Augsten, T., Kaefer, K., Meusel, R., Fetzer, C., Kanitz, D., Stoff, T., Becker, T., Holz, C. and Baudisch, P. Multitoe: high-precision interaction with back-projected floors based on high-resolution multi-touch input. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 209-218.

[Ballagas 2006] Ballagas, R., Borchers, J., Rohs, M. and Sheridan, J. G. The smart phone: a ubiquitous input device. *Pervasive Computing, IEEE 5*.1 (2006), 70-77

[Ballendat 2010] Ballendat, T., Marquardt, N. and Greenberg, S. Proxemic interaction: designing for a proximity and orientation-aware environment. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*, ACM (2010), 121-130.

[Bandai 2010] Bandai. Tamagotchi. http://www.bandai.com/tamagotchi/. Accessed: 02/06/13.

[Barton 2006] Barton, J. J., Zhai, S. and Cousins, S. B. Mobile Phones Will Become The Primary Personal Computing Devices. In *Proceedings of the Seventh IEEE Workshop on Mobile Computing Systems & Applications*, IEEE Computer Society (2006), 3-9.

[Baudisch 2001] Baudisch, P., Good, N. and Stewart, P. Focus plus context screens: combining display technology with visualization techniques. In *Proceedings of the 14th annual ACM symposium on User interface software and technology*, ACM (2001), 31-40.

[Baudisch 2003a] Baudisch, P., Cutrell, E., Czerwinski, M., Robbins, D. C., Tandler, P., Bederson, B. B. and Zierlinger, A. Drag-and-Pop and Drag-and-Pick:

Techniques for Accessing Remote Screen Content on Touch- and Pen-Operated Systems. In *INTERACT*, M. Rauterberg, et al. Eds. IOS Press (2003a),

[Baudisch 2003b] Baudisch, P. and Rosenholtz, R. Halo: a technique for visualizing off-screen objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*, ACM (2003b), 481-488.

[Baudisch 2004] Baudisch, P., Cutrell, E., Hinckley, K. and Gruen, R. Mouse ether: accelerating the acquisition of targets across multi-monitor displays. In *CHIEA '04 Ext. Abs. on Human Factors in Computing Systems*, ACM (2004), 1379-1382.

[Baur 2012] Baur, D., Boring, S. and Feiner, S. Virtual projection: exploring optical projection as a metaphor for multi-device interaction. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems (CHI '12)*, ACM (2012), 1693-1702.

[Beardsley 2005] Beardsley, P., Baar, J. V., Raskar, R. and Forlines, C. Interaction Using a Handheld Projector. *IEEE Computer Graphics and Applications 25*2005), 39-43

[Benko 2005] Benko, H. and Feiner, S. Multi-monitor mouse. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems*, ACM (2005), 1208-1211.

[Benko 2007a]Benko, H. (2007a) User Interaction in Hybrid Multi-Display Environments. *PhD. dissertation*. Columbia University. pp.206.

[Benko 2007b] Benko, H. and Feiner, S. Pointer warping in heterogeneous multi-monitor environments. In *Proceedings of Graphics Interface 2007*, ACM (2007b), 111-117.

[Benko 2008] Benko, H. and Wilson, A. D. DepthTouch: Using Depth-Sensing Camera to Enable Freehand Interactions On and Above the Interactive Surface. In *IEEE Workshop on Tabletops and Interactive Surfaces '08* IEEE,(2008),

[Benko 2012] Benko, H., Jota, R. and Wilson, A. D. MirageTable: freehand interaction on a projected augmented reality tabletop. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2012), 199-208.

[Bi 2009] Bi, X. and Balakrishnan, R. Comparing usage of a large high-resolution display to single or dual desktop displays for daily work. In *Proceedings of the 27th international conference on Human factors in computing systems*, ACM (2009), 1005-1014.

[Bi 2010] Bi, X., Bae, S.-H. and Balakrishnan, R. Effects of interior bezels of tiled-monitor large displays on visual search, tunnel steering, and target selection. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI 2010*, ACM (2010), 65-74.

[Bier 1993] Bier, E. A., Stone, M. C., Pier, K., Buxton, W. and DeRose, T. D. Toolglass and magic lenses: the see-through interface. In *Proc. of the 20th annual conference on Computer graphics & interactive techniques*, ACM (1993), 73-80.

[Billinghurst 2002] Billinghurst, M., Kato, H., Kiyokawa, K., Belcher, D. and Poupyrev, I. Experiments with Face-To-Face Collaborative AR Interfaces. *Virtual Reality 6*.3 (2002), 107-121

[Blaskó 2005] Blaskó, G., Feiner, S. and Coriand, F. Exploring Interaction with a Simulated Wrist-Worn Projection Display. In *ISWC '05: Ninth IEEE International Symposium on Wearable Computers*, IEEE Computer Society (2005), 2-9.

[Boehmer 2010] Boehmer, M. and Bauer, G. Exploiting the icon arrangement on mobile devices as information source for context-awareness. In *Mobile HCI*, ACM (2010), 195-198.

[Booth 2002] Booth, K. S., Fisher, B. D., Lin, C. J. R. and Argue, R. The "mighty mouse" multi-screen collaboration tool. In *Proceedings of the 15th annual ACM symposium on User interface software and technology (UIST'02)* ACM, 209-212.

[Boring 2009] Boring, S., Jurmu, M. and Butz, A. Scroll, tilt or move it: using mobile phones to continuously control pointers on large public displays. In *OZCHI SIG: Design: Open 24/7*, ACM (2009), 161-168.

[Boring 2010] Boring, S., Baur, D., Butz, A., Gustafson, S. and Baudisch, P. Touch Projector: Mobile Interaction Through Video. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)* ACM (2010), 2287-2296.

[Bove 2003] Bove, V. M. and Sierra, W. P-125: Personal Projection, or How to Put a Large Screen in a Small Device. *SID Symposium Digest of Technical Papers 34*.1 (2003), 708-711

[Brown 2006] Brown, L. D. and Hua, H. Magic Lenses for augmented virtual environments. *Computer Graphics and Applications, IEEE 26*.4 (2006), 64-73

[Buckley 2011] Buckley, E. Holographic Laser Projection. *Journal of Display Technology 7*.3 (2011), 135-140

[Buxton 2004] Buxton, W. PROJECTION - VISION SYSTEMS: Towards a Human-Centric Taxonomy. May 25, 2004. http://www.billbuxton.com/projVis.pdf. Accessed: 25/05/2013.

[Cao 2006] Cao, X. and Balakrishnan, R. Interacting with dynamically defined information spaces using a handheld projector and a pen. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*, ACM (2006), 225-234.

[Cao 2007] Cao, X., Forlines, C. and Balakrishnan, R. Multi-user interaction using handheld projectors. In *Proceedings of the 20th annual ACM symposium on User interface software and technology (UIST 2007)*, ACM (2007), 43-52.

[Cao 2008] Cao, X., Massimi, M. and Balakrishnan, R. Flashlight jigsaw: an exploratory study of an ad-hoc multi-player game on public displays. In *ACM conference on Computer Supported Cooperative Work (CSCW '08)*, ACM (2008), 77-86.

[Cao 2009] Cao, X. (2009) Handheld projector interaction. *PhD. dissertation*. University of Toronto. pp.167.

[Card 1986] Card, S. K. and Austin Henderson, J. A multiple, virtual-workspace interface to support user task switching. *SIGCHI Bull. 17*.SI (1986), 53-59

[Cauchard 2010] Cauchard, J. R., Fraser, M. and Sriram, S. Offsetting Displays on Mobile Projector Phones. In *Ubiprojection 2010, Workshop on Personal Projection at Pervasive 2010*, (2010), 3.

[Cauchard 2011] Cauchard, J. R., Löchtefeld, M., Irani, P., Schöning, J., Krüger, A., Fraser, M. and Subramanian, S. Visual Separation in Mobile Multi-Display Environments. In *Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11)* ACM,(2011), 451-460.

[Cauchard 2012a] Cauchard, J. R., Fraser, M., Han, T. and Subramanian, S. Steerable projection: exploring alignment in interactive mobile displays. *Personal and Ubiquitous Computing 16*.1 (2012a), 27-37

[Cauchard 2012b] Cauchard, J. R., Löchtefeld, M., Fraser, M., Krüger, A. and Subramanian, S. m+pSpaces: virtual workspaces in the spatially-aware mobile environment. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*, ACM (2012b), 171-180.

[Cesar 2008] Cesar, P., Bulterman, D. C. and Jansen, A. J. Usages of the Secondary Screen in an Interactive Television Environment: Control, Enrich, Share, and Transfer Television Content. In *Proceedings of the 6th European conference on Changing Television Environments*, Springer-Verlag (2008), 168-177.

[Chan 2010] Chan, L.-W., Wu, H.-T., Kao, H.-S., Ko, J.-C., Lin, H.-R., Chen, M. Y., Hsu, J. and Hung, Y.-P. Enabling beyond-surface interactions for interactive surface with an invisible projection. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 263-272.

[Chen 2007] Chen, C.-H. and Chien, Y.-H. Effects of RSVP display design on visual performance in accomplishing dual tasks with small screens. *International Journal of Design 1*.1 (2007), 27-35

[Chen 2008] Chen, N., Guimbretière, F., Dixon, M., Lewis, C. and Agrawala, M. Navigation techniques for dual-display e-book readers. In *CHI'08*, ACM (2008), 1779-1788.

[Cheverst 2005] Cheverst, K., Dix, A., Fitton, D., Kray, C., Rouncefield, M., Sas, C., Saslis-Lagoudakis, G. and Sheridan, J. G. Exploring bluetooth based mobile phone interaction with the hermes photo display. In *7th international conference on Human computer interaction with mobile devices & services*, ACM (2005), 47-54.

[Cowan 2011] Cowan, L. G. and Li, K. A. ShadowPuppets: Supporting Collocated Interaction with Mobile Projector Phones Using Hand Shadows. . In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI 2011* ACM,(2011), 2707-2716.

[Cowan 2012] Cowan, L. G., Weibel, N., Griswold, W. G., Pina, L. R. and Hollan, J. D. Projector phone use: practices and social implications. *Personal Ubiquitous Comput. 16*.1 (2012), 53-63

[Cruz-Neira 1992] Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V. and Hart, J. C. The CAVE: audio visual experience automatic virtual environment. *Commun. ACM 35*.6 (1992), 64-72

[Czerwinski 2003] Czerwinski, M., Smith, G., Regan, T., Meyers, B., Robertson, G. and Starkweather, G. Toward characterizing the productivity benefits of very large displays. In *Proceedings of Interact'03* (2003), 9-16.

[Dachselt 2009] Dachselt, R. and Buchholz, R. Natural throw and tilt interaction between mobile phones and distant displays. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems*, ACM (2009), 3253-3258.

[Dao 2007] Dao, V. N., Hosoi, K. and Sugimoto, M. A semi-automatic realtime calibration technique for a handheld projector. In *Proceedings of the 2007 ACM symposium on Virtual reality software and technology*, ACM (2007), 43-46.

[Davies 2009] Davies, C. CES 2009: Samsung MBP200 & Anycall Show Pico-Projectors with TI DLP. *Slashgear*, Jan 10th, 2009. http://www.slashgear.com/ces-2009-samsung-mbp200-anycall-show-pico-projectors-with-ti-dlp-1029899/. Accessed: 06/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HAdJaZLN)

[Dearman 2008] Dearman, D. and Pierce, J. S. It's on my other computer!: computing with multiple devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2008), 767-776.

[Deller 2011] Deller, M. and Ebert, A. ModControl - mobile phones as a versatile interaction device for large screen applications. In *Proceedings of the 13th IFIP TC 13 international conference on Human-computer interaction - Volume Part II*, Springer-Verlag (2011), 289-296.

[Dickie 2006] Dickie, C., Hart, J., Vertegaal, R. and Eiser, A. LookPoint: an evaluation of eye input for hands-free switching of input devices between multiple computers. In *Proceedings of the 18th Australia conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments*, ACM (2006), 119-126.

[Dickson 2010] Dickson, F. Pico Projectors: One Reason Bigger Isn't Better. Technical Report IN1004722WH, In-Stat, (2010).

[Discovery Communications 2013] Discovery Communications, I. Discovery Kids Rocketship Projection Alarm Clock. http://press.discovery.com/us/discovery-commerce/programs/discovery-kids-rocketship-projection-alarm-clock/. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmtGzdVC)

[Dix 2010] Dix, A. and Sas, C. Mobile Personal Devices meet Situated Public Displays: Synergies and Opportunities. *International Journal of Ubiquitous Computing (IJUC) 1*.1 (2010), 11-28

[Do-Lenh 2009] Do-Lenh, S., Kaplan, F., Sharma, A. and Dillenbourg, P. Multi-finger interactions with papers on augmented tabletops. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, ACM (2009), 267-274.

[Ens 2011] Ens, B., Ahlström, D., Cockburn, A. and Irani, P. Characterizing User Performance with Assisted Direct Off-Screen Pointing. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)* ACM,(2011), 485-494.

[Facebook 2013] Facebook. http://facebook.com. Accessed: 25/05/13.

[Fitzmaurice 1993] Fitzmaurice, G. W. Situated information spaces and spatially aware palmtop computers. *Commun. ACM 36*.7 (1993), 39-49

[Forlines 2005] Forlines, C., Balakrishnan, R., Beardsley, P., Baar, J. v. and Raskar, R. Zoom-and-pick: facilitating visual zooming and precision pointing with interactive handheld projectors. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, ACM (2005), 73-82.

[Forlines 2006] Forlines, C., Shen, C., Wigdor, D. and Balakrishnan, R. Exploring the effects of group size and display configuration on visual search. In *Proceedings of the 2006 20th anniversary conference on Computer supported cooperative work (CSCW '06)*, ACM (2006), 11-20.

[Garcia 2006] Garcia, P., Compton, K., Schulte, M., Blem, E. and Fu, W. An overview of reconfigurable hardware in embedded systems. *EURASIP J. Embedded Syst. 2006*.1 (2006), 1-19

[Gauglitz 2012] Gauglitz, S., Lee, C., Turk, M. and Hoellerer, T. Integrating the physical environment into mobile remote collaboration. In *Proceedings of the 14th* *international conference on Human-computer interaction with mobile devices and services*, ACM (2012), 241-250.

[Gellersen 2009] Gellersen, H., Fischer, C., Guinard, D., Gostner, R., Kortuem, G., Kray, C., Rukzio, E. and Streng, S. Supporting device discovery and spontaneous interaction with spatial references. *Personal Ubiquitous Comput. 13*.4 (2009), 255-264

[Girouard 2012] Girouard, A., Tarun, A. and Vertegaal, R. DisplayStacks: interaction techniques for stacks of flexible thin-film displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2012), 2431-2440.

[Gooding 1991] Gooding, L., Miller, M. E., Moore, J. and Kim, S.-H. Effect of viewing distance and disparity on perceived depth. In J.O. Merritt and S.S. Fisher Eds. SPIE,(1991), 259-266.

[Gostner 2008] Gostner, R., Rukzio, E. and Gellersen, H. Usage of spatial information for selection of co-located devices. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services*, ACM (2008), 427-430.

[Greaves 2008] Greaves, A., Hang, A. and Rukzio, E. Picture browsing and map interaction using a projector phone. In *10th international conference on Human computer interaction with mobile devices and services*, ACM (2008), 527-530.

[Greaves 2009] Greaves, A. and Rukzio, E. View & share: supporting co-present viewing and sharing of media using personal projection. In *11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '09)*, ACM (2009), 1-4.

[Greenberg 1999] Greenberg, S., Boyle, M. and Laberge, J. PDAs and shared public displays: Making personal information public, and public information personal. *Personal and Ubiquitous Computing 3*.1 (1999), 54-64

[Grossman 2006] Grossman, T. and Balakrishnan, R. An evaluation of depth perception on volumetric displays. In *Proceedings of the working conference on Advanced visual interfaces*, ACM (2006), 193-200.

[Grudin 2001] Grudin, J. Partitioning digital worlds: focal and peripheral awareness in multiple monitor use. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'01)*, ACM (2001), 458-465.

[Gurevich 2012] Gurevich, P., Lanir, J., Cohen, B. and Stone, R. TeleAdvisor: a versatile augmented reality tool for remote assistance. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2012), 619-622.

[Gustafson 2010] Gustafson, S., Bierwirth, D. and Baudisch, P. Imaginary interfaces: spatial interaction with empty hands and without visual feedback. In

Proceedings of the 23nd annual ACM symposium on User interface software and technology (UIST '10), ACM (2010), 3-12.

[Gustafson 2011] Gustafson, S., Holz, C. and Baudisch, P. Imaginary Phone: Learning Imaginary Interfaces by Transferring Spatial Memory from a Familiar Device. In *Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11)* ACM,(2011), 283-292.

[Hall 1966] Hall, E. T. *The Hidden Dimension* (Vol. xii). Garden City [NY] : Doubleday, Anchor Books (1966).

[Hall 2007] Hall, K. Discovery Space Projection Alarm Clock wakes kids up to galactic sights. *Dvice*, 12/11/2007. http://www.dvice.com/archives/2007/11/discovery-space-projection-ala.php. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6Gmto2X0F)

[Han 2011] Han, T., Alexander, J., Karnik, A., Irani, P. and Subramanian, S. Kick: investigating the use of kick gestures for mobile interactions. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)*, ACM (2011), 29-32.

[Han 2012] Han, T. (2012) Kick Gestures for Mobile Interactions. *M. Sc. dissertation*. University of Bristol, UK. pp.103.

[Hang 2008] Hang, A., Rukzio, E. and Greaves, A. Projector phone: a study of using mobile phones with integrated projector for interaction with maps. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services (MobileHCI'08)*, ACM (2008), 207-216.

[Hardy 2008] Hardy, R. and Rukzio, E. Touch & interact: touch-based interaction of mobile phones with displays. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services (MobileHCI '08)*, ACM (2008), 245-254.

[Harish 2009] Harish, P. and Narayanan, P. J. A view-dependent, polyhedral 3D display. In *Proceedings of the 8th International Conference on Virtual Reality Continuum and its Applications in Industry (VRCAI '09)*, ACM (2009), 71-75.

[Harrison 2010] Harrison, C., Tan, D. and Morris, D. Skinput: appropriating the body as an input surface. In *CHI '10: 28th international conference on Human factors in computing systems* ACM,(2010), 453-462.

[Harrison 2011] Harrison, C., Benko, H. and Wilson, A. D. OmniTouch: wearable multitouch interaction everywhere. In *Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11)*, ACM (2011), 441-450.

[Harrison 2012] Harrison, C., Ramamurthy, S. and Hudson, S. E. On-body interaction: armed and dangerous. In *Proceedings of the Sixth International*

Conference on Tangible, Embedded and Embodied Interaction (TEI '12), ACM (2012), 69-76.

[Hartman 2002] Hartman, J. and Levas, T. Interacting with Steerable Projected Displays. In *Proceedings of the Fifth IEEE International Conference on Automatic Face and Gesture Recognition*, IEEE Computer Society (2002), 402-407.

[Hazas 2005] Hazas, M., Kray, C., Gellersen, H., Agbota, H., Kortuem, G. and Krohn, A. A relative positioning system for co-located mobile devices. In *Proceedings of the 3rd international conference on Mobile systems, applications, and services (MobiSys '05)*, ACM (2005), 177-190.

[Heider 2007] Heider, T. and Kirste, T. Usable multi-display environments: concept and evaluation. In *Proceedings of the 4th international conference on Universal access in human-computer interaction: ambient interaction*, Springer-Verlag (2007), 93-102.

[Helicopter Boyz 2010] Helicopter Boyz. Live performance at Yomiuri Land (2010), http://www.youtube.com/watch?v=P0tOOcgcHTE. Last visited: 25/05/2013.

[Hemmert 2010] Hemmert, F., Hamann, S., Löwe, M., Wohlauf, A. and Joost, G. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10)*, ACM (2010), 249-252.

[Henderson 1986] Henderson, D. A., Jr. and Card, S. K. Rooms: the use of multiple virtual workspaces to reduce space contention in a window-based graphical user interface. *ACM Trans. Graph. 5*.3 (1986), 211-243

[Hinckley 2001] Hinckley, K. and Horvitz, E. Toward more sensitive mobile phones. In *Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01)*, ACM (2001), 191-192.

[Hinckley 2004] Hinckley, K., Ramos, G., Guimbretière, F., Baudisch, P. and Smith, M. Stitching: pen gestures that span multiple displays. In *Proceedings of the working conference on Advanced visual interfaces (AVI '04)*, ACM (2004), 23-31.

[Hinckley 2009] Hinckley, K., Dixon, M., Sarin, R., Guimbretière, F. V. and Balakrishnan, R. Codex: a dual screen tablet computer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'09)*, ACM (2009), 1933-1942.

[Holliman 2006] Holliman, N. S. (2006). Three-Dimensional Display Systems. In *Handbook of Optoelectronics*, J.P. Dakin and R.G.W. Brown Eds. Taylor & Francis, New York and London, 1067-1100.

[Holmes 2012] Holmes, M. E., Josephson, S. and Carney, R. E. Visual attention to television programs with a second-screen application. In *Proceedings of the Symposium on Eye Tracking Research and Applications*, ACM (2012), 397-400.

[Honig 2013] Honig, Z. Sony Handycam PJ790V and PJ650V get brighter projectors with HDMI input, we go hands-on. *Engadget*, Jan 7th, 2013. http://www.engadget.com/2013/01/07/sony-handycam-pj790v-pj650v-hands-on/. Accessed: 06/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HAekx1MI)

[Hosoi 2007a] Hosoi, K., Dao, V. N., Mori, A. and Sugimoto, M. CoGAME: manipulation using a handheld projector. In *SIGGRAPH '07: ACM SIGGRAPH 2007 emerging technologies*, ACM (2007a), 2.

[Hosoi 2007b] Hosoi, K., Dao, V. N., Mori, A. and Sugimoto, M. VisiCon: a robot control interface for visualizing manipulation using a handheld projector. In *Proceedings of the international conference on Advances in computer entertainment technology*, ACM (2007b), 99-106.

[Huber 2012] Huber, J., Steimle, J., Liao, C., Liu, Q. and Mühlhäuser, M. LightBeam: interacting with augmented real-world objects in pico projections. In *Proceedings of the 11th International Conference on Mobile and Ubiquitous Multimedia*, ACM (2012), 1-10.

[Hutchings 2004a] Hutchings, D. R., Czerwinski, M., Meyers, B. and Stasko, J. Exploring the Use and Affordances of Multiple Display Environments. In *Workshop on Ubiquitous Display Environments at UbiComp'04*, (2004a), 6.

[Hutchings 2004b] Hutchings, D. R., Smith, G., Meyers, B., Czerwinski, M. and Robertson, G. Display space usage and window management operation comparisons between single monitor and multiple monitor users. In *Proceedings of the working conference on Advanced visual interfaces*, ACM (2004b), 32-39.

[Hutchings 2006] Hutchings, H. M. and Pierce, J. S. Understanding the whethers, hows, and whys of divisible interfaces. In *Proceedings of the working conference on Advanced visual interfaces*, ACM (2006), 274-277.

[Inami 2000] Inami, M., Kawakami, N., Sekiguchi, D., Yanagida, Y., Maeda, T. and Tachi, S. Visuo-Haptic Display Using Head-Mounted Projector. In *Proceedings of the IEEE Virtual Reality 2000 Conference*, IEEE Computer Society (2000), 233-240.

[iTunes 2013] iTunes. ARSoccer: Augmented Reality Soccer Game by Laan Labs. https://itunes.apple.com/us/app/arsoccer-augmented-reality/id381035151?mt=8. Accessed: 25/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GsHdx8vy)

[Jakobsen 2011] Jakobsen, M. R. and Hornbæk, K. Sizing up visualizations: effects of display size in focus+context, overview+detail, and zooming interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2011), 1451-1460.

[Jaynes 2003] Jaynes, C. and Ramakrishnan, D. Super-resolution composition in multi-projector displays. In *Proceedings IEEE International Workshop on Projector-Camera Systems (ProCams)* (2003),

[Johanson 2002] Johanson, B., Fox, A. and Winograd, T. The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms. *IEEE Pervasive Computing 1*.2 (2002), 67-74

[Jones 2001] Jones, G. R., Lee, D., Holliman, N. S. and Ezra, D. (2001). Controlling perceived depth in stereoscopic images. In *Stereoscopic displays and applications VIII*, A.J. Woods, et al. Eds. SPIE, Bellingham, WA, USA, 42-53.

[Jones 2004] Jones, G. R., Holliman, N. S. and Lee, D. Stereo images with comfortable perceived depth U.S. Patent: US6798406, (2004).

[Kajiwara 2011] Kajiwara, Y., Tajimi, K., Uemura, K., Sakata, N. and Nishida, S. ClippingLight: a method for easy snapshots with projection viewfinder and tilt-based zoom control. In *Proceedings of the 2nd Augmented Human International Conference (AH '11)*, ACM (2011), 1-8.

[Kane 2009] Kane, S. K., Avrahami, D., Wobbrock, J. O., Harrison, B., Rea, A. D., Philipose, M. and LaMarca, A. Bonfire: a nomadic system for hybrid laptop-tabletop interaction. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology*, ACM (2009), 129-138.

[Karitsuka 2003] Karitsuka, T. and Sato, K. A Wearable Mixed Reality with an On-Board Projector. In *Proceedings of the 2nd IEEE/ACM International Symposium on Mixed and Augmented Reality (ISMAR '03)*, IEEE Computer Society (2003), 321.

[Kaufmann 2011] Kaufmann, B. and Hitz, M. Eye-Shield: protecting bystanders from being blinded by mobile projectors. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, ACM (2011), 31-34.

[Kaufmann 2012] Kaufmann, B. and Hitz, M. X-large virtual workspaces for projector phones through peephole interaction. In *Proceedings of the 20th ACM international conference on Multimedia*, ACM (2012), 1279-1280.

[Kern 2010] Kern, D., Marshall, P. and Schmidt, A. Gazemarks: gaze-based visual placeholders to ease attention switching. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'10)*, ACM (2010), 2093-2102.

[Khalilbeigi 2011] Khalilbeigi, M., Lissermann, R., Mühlhäuser, M. and Steimle, J. Xpaaand: interaction techniques for rollable displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2011), 2729-2732.

[Khalilbeigi 2012] Khalilbeigi, M., Lissermann, R., Kleine, W. and Steimle, J. FoldMe: interacting with double-sided foldable displays. In *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*, ACM (2012), 33-40.

[Khan 2005] Khan, A., Matejka, J., Fitzmaurice, G. and Kurtenbach, G. Spotlight: directing users' attention on large displays. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, ACM (2005), 791-798.

[Kim 2010] Kim, S., Chung, J., Oh, A., Schmandt, C. and Kim, I.-J. iLight: information flashlight on objects using handheld projector. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*, ACM (2010), 3631-3636.

[Kirsh 1994] Kirsh, D. and Maglio, P. On Distinguishing Epistemic from Pragmatic Action. *Cognitive Science 18*.4 (1994), 513-549

[Kirstein 1998] Kirstein, C. and Mueller, H. Interaction with a Projection Screen Using a Camera-tracked Laser Pointer. In *Proceedings of the 1998 Conference on MultiMedia Modeling*, IEEE Computer Society (1998), 191.

[Kjeldsen 2002] Kjeldsen, R., Pinhanez, C. S., Pingali, G., Hartman, J., Levas, T. and Podlaseck, M. Interacting with Steerable Projected Displays. In *5th IEEE International Conference on Automatic Face and Gesture Recognition (FGR 2002)* IEEE Computer Society,(2002), 402-410.

[Klum 2012] Klum, S., Isenberg, P., Langner, R., Fekete, J.-D. and Dachselt, R. Stackables: combining tangibles for faceted browsing. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, ACM (2012), 241-248.

[Ko 2010] Ko, J.-C., Chan, L.-W. and Hung, Y.-P. Public issues on projected user interface. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*, ACM (2010), 2873-2882.

[Konieczny 2005] Konieczny, J., Shimizu, C., Meyer, G. and Colucci, D. A handheld flexible display system. In *Visualization, 2005. VIS 05.* IEEE,(2005), 591-597.

[Kortuem 2005] Kortuem, G., Kray, C. and Gellersen, H. Sensing and visualizing spatial relations of mobile devices. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, ACM (2005), 93-102.

[Kray 2009] Kray, C., Rohs, M., Hook, J. and Kratz, S. Bridging the gap between the Kodak and the Flickr generations: A novel interaction technique for collocated photo sharing. *International Journal of Human-Computer Studies 67*.12 (2009), 1060-1072

[Kray 2010] Kray, C., Nesbitt, D., Dawson, J. and Rohs, M. User-defined gestures for connecting mobile phones, public displays, and tabletops. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services*, ACM (2010), 239-248.

[Krum 2012] Krum, D. M., Suma, E. A. and Bolas, M. Augmented reality using personal projection and retroreflection. *Personal Ubiquitous Comput. 16*.1 (2012), 17-26

[Kurdyukova 2012] Kurdyukova, E., Redlin, M. and André, E. Studying user-defined iPad gestures for interaction in multi-display environment. In *Proceedings of the 2012 ACM international conference on Intelligent User Interfaces*, ACM (2012), 93-96.

[LaserFocusWorld 2003] LaserFocusWorld. Cell phone captures and projects images. In *Laser Focus World* PennWell Corporation (2003).

[Lee 2008a] Lee, H., Jeong, H., Lee, J., Yeom, K.-W., Shin, H.-J. and Park, J.-H. Select-and-point: a novel interface for multi-device connection and control based on simple hand gestures. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems*, ACM (2008a), 3357-3362.

[Lee 2009] Lee, H., Jeong, H., Lee, J., Yeom, K.-W. and Park, J.-H. Gesture-Based Interface for Connection and Control of Multi-device in a Tabletop Display Environment. In *Proceedings of the 13th International Conference on Human-Computer Interaction. Part II: Novel Interaction Methods and Techniques*, Springer-Verlag (2009), 216-225.

[Lee 2005] Lee, J. C., Hudson, S. E., Summet, J. W. and Dietz, P. H. Moveable interactive projected displays using projector based tracking. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, ACM (2005), 63-72.

[Lee 2008b] Lee, J. C., Hudson, S. E. and Tse, E. Foldable interactive displays. In *Proceedings of the 21st annual ACM symposium on User interface software and technology (UIST '08)*, ACM (2008b), 287-290.

[Leung 2011] Leung, M., Tomitsch, M. and Moere, A. V. Designing a personal visualization projection of online social identity. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, ACM (2011), 1843-1848.

[Leung 2009] Leung, M. C., Lee, K. K., Wong, K. H. and Chang, M. M. Y. A projector-based movable hand-held display system. In *Computer Vision and Pattern Recognition, 2009. CVPR 2009. IEEE Conference on* (2009), 1109-1114.

[Levas 2003] Levas, A., Pinhanez, C., Pingali, G., Kjeldsen, R., Podlaseck, M. and Sukaviriya, N. An Architecture and Framework for Steerable Interface Systems In *Fifth International Conference on Ubiquitous Computing* Springer-Verlag (2003), 333-348.

[Lewis 2004] Lewis, J. P., Rosenholtz, R., Fong, N. and Neumann, U. VisualIDs: automatic distinctive icons for desktop interfaces. In *ACM SIGGRAPH 2004 Papers*, ACM (2004), 416-423.

[Li 2009] Li, F. C. Y., Dearman, D. and Truong, K. N. Virtual shelves: interactions with orientation aware devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology (UIST)* ACM,(2009), 125-128.

[Li 2012] Li, Z., Wong, K.-H., Gong, Y. and Chang, M. M.-Y. A low-cost projector-based hand-held flexible display system. *Multimedia Tools Appl. 59*.1 (2012), 129-148

[Light Blue Optics 2010] Light Blue Optics. Light Touch Pico Projector. http://lightblueoptics.com/products/light-touch/. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmvBdS1h)

[Linder 2010] Linder, N. and Maes, P. LuminAR: portable robotic augmented reality interface design and prototype. In *Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 395-396.

[Löchtefeld 2009] Löchtefeld, M., Schoening, J., Rohs, M. and Krueger, A. Marauders light: replacing the wand with a mobile camera projector unit. In *Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia (MUM'09)*, ACM (2009), 1-4.

[Löchtefeld 2010] Löchtefeld, M., Gehring, S., Schöning, J. and Krüger, A. ShelfTorchlight: Augmenting a Shelf using a Camera Projector Unit. In *Workshop on personal projection (UBIPROJECTION 2010) at Pervasive*, (2010),

[Löchtefeld 2011a] Löchtefeld, M., Gehring, S., Jung, R. and Krueger, A. guitAR: supporting guitar learning through mobile projection. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, ACM (2011a), 1447-1452.

[Löchtefeld 2011b] Löchtefeld, M., Gehring, S., Jung, R. and Krueger, A. Using mobile projection to support guitar learning. In *Proceedings of the 11th international conference on Smart graphics*, Springer-Verlag (2011b), 103-114.

[Löchtefeld 2011c] Löchtefeld, M., Krüger, A. and Rohs, M. (2011c). Mobile Projection Interfaces for Augmented Reality Applications. In *Handbook of Augmented Reality*, B. Furht Ed. Springer New York, NY, USA, 177-197.

[Lopez-Gulliver 2009] Lopez-Gulliver, R., Yoshida, S., Yano, S. and Inoue, N. gCubik: real-time integral image rendering for a cubic 3D display. In *ACM SIGGRAPH 2009 Emerging Technologies*, ACM (2009), 1-1.

[Lucero 2013] Lucero, A., Jones, M., Jokela, T. and Robinson, S. Mobile collocated interactions: taking an offline break together. *interactions 20*.2 (2013), 26-32

[Lyons 2009a] Lyons, K., Pering, T., Rosario, B., Sud, S. and Want, R. Multi-display Composition: Supporting Display Sharing for Collocated Mobile Devices. In *Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part I*, Springer-Verlag (2009a), 758-771.

[Lyons 2009b] Lyons, K., Want, R., Munday, D., He, J., Sud, S., Rosario, B. and Pering, T. Context-aware composition. In *Proceedings of the 10th workshop on Mobile Computing Systems and Applications*, ACM (2009b), 1-6.

[Lyons 2012] Lyons, K., Nguyen, D., Ashbrook, D. and White, S. Facet: a multi-segment wrist worn system. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, ACM (2012), 123-130.

[Mandryk 2005] Mandryk, R. L., Rodgers, M. E. and Inkpen, K. M. Sticky widgets: pseudo-haptic widget enhancements for multi-monitor displays. In *CHI '05 Extended Abstracts on Human Factors in Computing Systems*, ACM (2005), 1621-1624.

[Manresa 2005] Manresa, C., Varona, J., Mas, R. and Perales, F. Hand tracking and gesture recognition for human-computer interaction. *Electronic Letters on Computer Vision and Image Analysis 5*.3 (2005), 96-104

[Markets and Markets 2010] Markets and Markets. Pico Projector By Application, Technology & Products Market (2010 - 2014) Technical Report, (2010).

[Marquardt 2012] Marquardt, N., Hinckley, K. and Greenberg, S. Cross-device interaction via micro-mobility and f-formations. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, ACM (2012), 13-22.

[Masoodian 2004] Masoodian, M., McKoy, S., Rogers, B. and Ware, D. DeepDocument: use of a multi-layered display to provide context awareness in text editing. In *Proceedings of the working conference on Advanced visual interfaces (AVI '04)*, ACM (2004), 235-239.

[Mathur 2011] Mathur, A., Ramachandran, D., Cutrell, E. and Balakrishnan, R. An exploratory study on the use of camera phones and pico projectors in rural India. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*, ACM (2011), 347-356.

[Matsuda 2012] Matsuda, D., Uemura, K., Sakata, N. and Nishida, S. Toe Input Using a Mobile Projector and Kinect Sensor. In *Wearable Computers (ISWC), 2012 16th International Symposium on* (2012), 48-51.

[Matsumoto 2006] Matsumoto, T., Horiguchi, D., Nakashima, S. and Okude, N. Z-agon: mobile multi-display browser cube. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems*, ACM (2006), 351-356.

[Matthews 2006] Matthews, T., Czerwinski, M., Robertson, G. and Tan, D. Clipping lists and change borders: improving multitasking efficiency with peripheral information design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'06)*, ACM (2006), 989-998.

[McCallum 2009] McCallum, D. C. and Irani, P. ARC-Pad: absolute+relative cursor positioning for large displays with a mobile touchscreen. In *Proceedings of the*

22nd annual ACM symposium on User interface software and technology, ACM (2009), 153-156.

[McFarlane 2009] McFarlane, D. C. and Wilder, S. M. Interactive dirt: increasing mobile work performance with a wearable projector-camera system. In *11th international conference on Ubiquitous computing*, ACM (2009), 205-214.

[Merrill 2007] Merrill, D., Kalanithi, J. and Maes, P. Siftables: towards sensor network user interfaces. In *TEI'07* ACM,(2007), 75-78.

[Microsoft 2012] Microsoft. PixelSense. http://www.microsoft.com/en-us/pixelsense/default.aspx. Accessed: 05/06/2013. (Archived by WebCite® at http://www.webcitation.org/6H9JM9Li2)

[Miller 2010] Miller, A. and LaViola, J. J. Towards a handheld stereo projector system for viewing and interacting in virtual worlds. In *IEEE Symposium on 3D User Interfaces (3DUI)* IEEE,(2010), 133-134.

[Mistry 2009a] Mistry, P. and Maes, P. SixthSense: a wearable gestural interface. In *ACM SIGGRAPH ASIA 2009 Sketches*, ACM (2009a), 1.

[Mistry 2009b] Mistry, P., Maes, P. and Chang, L. WUW - wear Ur world: a wearable gestural interface. In *27th international conference extended abstracts on Human factors in computing systems*, ACM (2009b), 4111-4116.

[Molyneaux 2009] Molyneaux, D. and Gellersen, H. Projected interfaces: enabling serendipitous interaction with smart tangible objects. In *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, ACM (2009), 385-392.

[Molyneaux 2012] Molyneaux, D., Izadi, S., Kim, D., Hilliges, O., Hodges, S., Cao, X., Butler, A. and Gellersen, H. Interactive environment-aware handheld projectors for pervasive computing spaces. In *Proceedings of the 10th international conference on Pervasive Computing*, Springer-Verlag (2012), 197-215.

[Montero 2010] Montero, C. S., Alexander, J., Marshall, M. and Subramanian, S. Would You Do That? - Understanding Social Acceptance of Gestural Interfaces". In *12th international conference on Human computer interaction with mobile devices and services (MobileHCI'10)* ACM,(2010), 275-278.

[Myers 1998] Myers, B. A., Stiel, H. and Gargiulo, R. Collaboration Using Multiple PDAs Connected to a PC. In *Proceedings CSCW'98: ACM Conference on Computer-Supported Cooperative Work*, (1998), pp. 285-294.

[Myers 2002] Myers, B. A. Mobile Devices for Control. In *Proceedings of the 4th International Symposium on Mobile Human-Computer Interaction*, Springer-Verlag (2002), 1-8.

[Nacenta 2006] Nacenta, M. A., Sallam, S., Champoux, B., Subramanian, S. and Gutwin, C. Perspective cursor: perspective-based interaction for multi-display environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'06)*, ACM (2006), 289-298.

[Nacenta 2007] Nacenta, M. A., Sakurai, S., Yamaguchi, T., Miki, Y., Itoh, Y., Kitamura, Y., Subramanian, S. and Gutwin, C. E-conic: a perspective-aware interface for multi-display environments. In *20th annual ACM symposium on User interface software and technology*, ACM (2007), 279-288.

[Nacenta 2008] Nacenta, M. A., Mandryk, R. L. and Gutwin, C. Targeting across displayless space. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2008), 777-786.

[Nacenta 2009] Nacenta, M. A., Gutwin, C., Aliakseyeu, D. and Subramanian, S. There and Back again: Cross-Display Object Movement in Multi-Display Environments. *Journal of HCI 24*.1 (2009), 170-229

[Nakamura 2005] Nakamura, S. Reversible display: novel interaction techniques for digital contents. In *Proceedings of the 4th decennial conference on Critical computing: between sense and sensibility*, ACM (2005), 113-116.

[Ng 2010] Ng, W. S. and Sharlin, E. Tweeting halo: clothing that tweets. In *Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 447-448.

[Ni 2011] Ni, T., Karlson, A. K. and Wigdor, D. AnatOnMe: facilitating doctor-patient communication using a projection-based handheld device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2011), 3333-3342.

[Nikon 2010] Nikon. Nikon Coolpix S1000pj. 2010. http://imaging.nikon.com/lineup/coolpix/s/s1000pj/ Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmvhPXpx)

[Nintendo 2011] Nintendo. Nintendo DSi. http://www.nintendo.com/ds/what-is;jsessionid=5E8EDF86383CB2516798EC50C704DAA4. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmvlF0y4)

[Olwal 2006] Olwal, A. LightSense: enabling spatially aware handheld interaction devices. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality*, IEEE Computer Society (2006), 119-122.

[Ota 2010] Ota, S., Takegawa, Y., Terada, T. and Tsukamoto, M. A Method for Wearable Projector Selection that Considers the Viewability of Projected Images. *Comput. Entertain. 8*.3 (2010), 1-16

[Oulasvirta 2007] Oulasvirta, A. and Sumari, L. Mobile kits and laptop trays: managing multiple devices in mobile information work. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2007), 1127-1136.

[Paek 2004] Paek, T., Agrawala, M., Basu, S., Drucker, S., Kristjansson, T., Logan, R., Toyama, K. and Wilson, A. Toward universal mobile interaction for shared displays. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*, ACM (2004), 266-269.

[Patterson 2007] Patterson, D. 3D SPACE: using depth and movement for selection tasks. In *Proceedings of the twelfth international conference on 3D web technology*, ACM (2007), 147-155.

[Pearson 2011] Pearson, J. and Buchanan, G. CloudBooks: an infrastructure for reading on multiple devices. In *Proceedings of the 15th international conference on Theory and practice of digital libraries: research and advanced technology for digital libraries*, Springer-Verlag (2011), 488-492.

[Pering 2005] Pering, T., Ballagas, R. and Want, R. Spontaneous marriages of mobile devices and interactive spaces. *Commun. ACM 48*.9 (2005), 53-59

[PhoneSuit 2013] PhoneSuit. Lightplay™ - Smart Pico Projector with Android. http://www.phonesuit.com/phonesuit-lightplay-android-mobile-video-projector. Accessed: 20/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HVxLPomK)

[PicoProjector-Info 2013] PicoProjector-Info. *R. Mertens*, http://www.picoprojector-info.com/. Accessed: 10/12/2013.

[Pierce 2008] Pierce, J. S. and Nichols, J. An infrastructure for extending applications' user experiences across multiple personal devices. In *Proceedings of the 21st annual ACM symposium on User interface software and technology*, ACM (2008), 101-110.

[Pingali 2003] Pingali, G., Pinhanez, C., Levas, A., Kjeldsen, R., Podlaseck, M., Chen, H. and Sukaviriya, N. Steerable Interfaces for Pervasive Computing Spaces. In *First IEEE International Conference on Pervasive Computing and Communications*, IEEE Computer Society (2003), 315-322.

[Pinhanez 2003a] Pinhanez, C., Kjeldsen, R., Levas, A., Pingali, G., Podlaseck, M. and Sukaviriya, N. Applications of steerable projector-camera systems. In *IEEE International Workshop on Projector-Camera Systems at ICCV 2003* IEEE Computer Society Press,(2003a), 8.

[Pinhanez 2003b] Pinhanez, C., Kjeldsen, R., Tang, L., Levas, A., Podlaseck, M., Sukaviriya, N. and Pingali, G. Creating touch-screens anywhere with interactive projected displays. In *Eleventh ACM international conference on Multimedia*, ACM (2003b), 460-461.

[Pinhanez 2001] Pinhanez, C. S. The Everywhere Displays Projector: A Device to Create Ubiquitous Graphical Interfaces. In *3rd international conference on Ubiquitous Computing*, Springer-Verlag (2001), 315-331.

[Plessl 2003] Plessl, C., Enzler, R., Walder, H., Beutel, J., Platzner, M., Thiele, L. and Tröster, G. The case for reconfigurable hardware in wearable computing. *Personal Ubiquitous Comput. 7*.5 (2003), 299-308

[Poupyrev 2006] Poupyrev, I., Newton-Dunn, H. and Bau, O. D20: interaction with multifaceted display devices. In *CHI '06 Extended Abstracts on Human Factors in Computing Systems*, ACM (2006), 1241-1246.

[Projector Central 2013] Projector Central. Projectors Specifications. http://www.projectorcentral.com/. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6Gmw0ecdU)

[Rapp 2010] Rapp, S. Spotlight Navigation: a pioneering user interface for mobile projection. In *Ubiprojection 2010, Workshop on Personal Projection at Pervasive 2010*, (2010), 4.

[Rashid 2012] Rashid, U., Nacenta, M. A. and Quigley, A. Factors influencing visual attention switch in multi-display user interfaces: a survey. In *Proceedings of the 2012 International Symposium on Pervasive Displays (PerDis '12)*, ACM (2012), 1-6.

[Raskar 1998] Raskar, R., Welch, G., Cutts, M., Lake, A., Stesin, L. and Fuchs, H. The office of the future: a unified approach to image-based modeling and spatially immersive displays. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, ACM (1998), 179-188.

[Raskar 1999] Raskar, R., Brown, M. S., Yang, R., Chen, W.-C., Welch, G., Towles, H., Seales, B. and Fuchs, H. Multi-projector displays using camera-based registration. In *Proceedings of the conference on Visualization '99: celebrating ten years*, IEEE Computer Society Press (1999), 161-168.

[Raskar 2001] Raskar, R., Welch, G., Low, K.-L. and Bandyopadhyay, D. Shader Lamps: Animating Real Objects With Image-Based Illumination. In *Proceedings of the 12th Eurographics Workshop on Rendering Techniques*, Springer-Verlag (2001), 89-102.

[Raskar 2003] Raskar, R., Baar, J. v., Beardsley, P., Willwacher, T., Rao, S. and Forlines, C. iLamps: geometrically aware and self-configuring projectors. In *ACM SIGGRAPH 2003 Papers*, ACM (2003), 809-818.

[Raskar 2004]Raskar, R., Beardsley, P., Baar, J. v., Wang, Y., Dietz, P., Lee, J., Leigh, D. and Willwacher, T. RFIG lamps: interacting with a self-describing world via photosensing wireless tags and projectors. In *ACM SIGGRAPH 2004 Papers*, ACM (2004), 406-415.

[Reho 2003] Reho, A. and Impi, J. Wearable projector and intelligent clothing. U.S. Patent: US 6,830,344 B2, (2003).

[Reis 2011] Reis, S. and Correia, N. An imaginary friend that connects with the user's emotions. In *Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology (ACE '11)*, ACM (2011), 1-8.

[Rekimoto 1997] Rekimoto, J. Pick-and-drop: a direct manipulation technique for multiple computer environments. In *Proceedings of the 10th annual ACM symposium on User interface software and technology*, ACM (1997), 31-39.

[Rekimoto 1998] Rekimoto, J. A multiple device approach for supporting whiteboard-based interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM Press/Addison-Wesley Publishing Co. (1998), 344-351.

[Rekimoto 1999] Rekimoto, J. and Saitoh, M. Augmented surfaces: a spatially continuous work space for hybrid computing environments. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, ACM (1999), 378-385.

[Ringel 2003] Ringel, M. When one isn't enough: an analysis of virtual desktop usage strategies and their implications for design. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*, ACM (2003), 762-763.

[Robertson 1998] Robertson, G., Czerwinski, M., Larson, K., Robbins, D. C., Thiel, D. and Dantzich, M. v. Data mountain: using spatial memory for document management. In *Proceedings of the 11th annual ACM symposium on User interface software and technology, UIST'98*, ACM (1998), 153-162.

[Robertson 2000] Robertson, G., Dantzich, M. v., Robbins, D., Czerwinski, M., Hinckley, K., Risden, K., Thiel, D. and Gorokhovsky, V. The Task Gallery: a 3D window manager. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, ACM (2000), 494-501.

[Robertson 1996] Robertson, S., Wharton, C., Ashworth, C. and Franzke, M. Dual device user interface design: PDAs and interactive television. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (1996), 79-86.

[Robinson 2009] Robinson, S., Eslambolchilar, P. and Jones, M. Sweep-Shake: Finding Digital Resources in Physical Environments. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '09)* ACM,(2009), 1-10.

[Robinson 2012] Robinson, S., Jones, M., Vartiainen, E. and Marsden, G. PicoTales: collaborative authoring of animated stories using handheld projectors. In *Proceedings of the ACM 2012 conference on Computer Supported Cooperative Work*, ACM (2012), 671-680.

[Roeber 2003] Roeber, H., Bacus, J. and Tomasi, C. Typing in thin air: the canesta projection keyboard - a new method of interaction with electronic devices. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems*, ACM (2003), 712-713.

[Rolland 1997] Rolland, J. P. and Arthur, K. Depth judgments in a see-through head-mounted display. In *Proceeding of SPIE 3058, AeroSense'97* (1997), 66-75.

[Rukzio 2010] Rukzio, E. and Holleis, P. Projector Phone Interactions: Design Space and Survey. In *Workshop on Coupled Display Visual Interfaces at AVI 2010*, (2010), 4.

[Rukzio 2012] Rukzio, E., Holleis, P. and Gellersen, H. Personal Projectors for Pervasive Computing. *IEEE Pervasive Computing 11*.2 (2012), 30-37

[S-Vision 2010] S-Vision. S-Vision mobile projector phone prototype. http://www.concept-phones.com/cool-concepts/svision-projector-phone-concept-aims-business-people/. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmcvEbFT)

[Savov 2011] Savov, V. Fujitsu LifeBook S761/C and P771/C replace optical drives with pico projectors, past with future. *Engadget*, Apr 22nd, 2011. http://www.engadget.com/2011/04/22/fujitsu-lifebook-s761-c-and-p711-c-replace-optical-drives-with-p/. Accessed: 06/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HAgGp0h1)

[Schmidt 2010] Schmidt, D., Chehimi, F., Rukzio, E. and Gellersen, H. PhoneTouch: a technique for direct phone interaction on surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 13-16.

[Schmidt 2012a] Schmidt, D., Molyneaux, D. and Cao, X. PICOntrol: using a handheld projector for direct control of physical devices through visible light. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, ACM (2012a), 379-388.

[Schmidt 2012b] Schmidt, D., Seifert, J., Rukzio, E. and Gellersen, H. A cross-device interaction style for mobiles and surfaces. In *Proceedings of the Designing Interactive Systems Conference*, ACM (2012b), 318-327.

[Schmitz 2010] Schmitz, A., Li, M., Schönefeld, V. and Kobbelt, L. Ad-Hoc Multi-Displays for Mobile Interactive Applications. In *Eurographics 2010: 31st annual conference of the European Association for Computer Graphics-Areas Papers* The Eurographics Association,(2010), 45-52.

[Schöning 2009] Schöning, J., Rohs, M., Kratz, S., Löchtefeld, M. and Krüger, A. Map torchlight: a mobile augmented reality camera projector unit. In *27th international conference extended abstracts on Human factors in computing systems*, ACM (2009), 3841-3846.

[Schwarz 2012] Schwarz, J., Klionsky, D., Harrison, C., Dietz, P. and Wilson, A. Phone as a pixel: enabling ad-hoc, large-scale displays using mobile devices. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*, ACM (2012), 2235-2238.

[Scott 2010] Scott, J., Dearman, D., Yatani, K. and Truong, K. N. Sensing foot gestures from the pocket. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 199-208.

[Shen 2007] Shen, G., Li, Y. and Zhang, Y. MobiUS: enable together-viewing video experience across two mobile devices. In *Proceedings of the 5th international conference on Mobile systems, applications and services*, ACM (2007), 30-42.

[Slay 2006] Slay, H. and Thomas, B. H. Evaluation of a universal interaction and control device for use within multiple heterogeneous display ubiquitous environments. In *Proceedings of the 7th Australasian User interface conference - Volume 50*, Australian Computer Society, Inc. (2006), 129-136.

[Smart Q 2013] Smart Q. The world's first tablet with a projector built-in. *Smartdevices*, Sept 24th, 2012. http://en.smartdevice.com.cn/News/201209/24-166.html. Accessed: 06/06/2013. (Archived by WebCite® at http://www.webcitation.org/6HAf39FNI)

[Softonic 2013] Softonic. Fastlane Street Racing iPhone application. http://fastlane-street-racing.en.softonic.com/iphone. Accessed: 25/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GsHEaP32)

[Song 2009] Song, H., Grossman, T., Fitzmaurice, G., Guimbretière, F., Khan, A., Attar, R. and Kurtenbach, G. PenLight: combining a mobile projector and a digital pen for dynamic visual overlay. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2009), 143-152.

[Song 2010] Song, H., Guimbretière, F., Grossman, T. and Fitzmaurice, G. MouseLight: bimanual interactions on digital paper using a pen and a spatially-aware mobile projector. In *28th international conference on Human factors in computing systems*, ACM (2010), 2451-2460.

[Sony 2011] Sony. Handycam PJ30VE Full HD Flash Memory camcorder. http://www.sony.co.uk/product/cam-high-definition-on-memory-stick/hdr-pj30ve. Accessed:

[Spindler 2012] Spindler, M., Martsch, M. and Dachselt, R. Going beyond the surface: studying multi-layer interaction above the tabletop. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems*, ACM (2012), 1277-1286.

[Stavness 2010] Stavness, I., Lam, B. and Fels, S. pCubee: a perspective-corrected handheld cubic display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM (2010), 1381-1390.

[Stern 2006] Stern, M., Yavid, D., Tan, C., Wittenberg, C., Nambudiri, N., Strat, A., Slutsky, M., Gonzalez, D., DiFazio, C., Smajek, R. and Baldwin, D. Laser projection display (LPD): a miniature, high resolution projection engine. In *Americas Display Engineering and Applications Conference (ADEAC)* (2006), 186-188.

[Su 2005] Su, R. and Bailey, B. P. Put Them Where? Towards Guidelines for Positioning Large Displays. In *Proc. of Graphics Interface '05* (2005), 337-349.

[Subramanian 2006] Subramanian, S., Aliakseyeu, D. and Lucero, A. Multi-layer interaction for digital tables. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*, ACM (2006), 269-272.

[Sugimoto 2005] Sugimoto, M., Miyahara, K., Inoue, H. and Tsunesada, Y. (2005). Hotaru : Intuitive Manipulation Techniques for Projected Displays of Mobile Devices. In *INTERACT 2005*, M. Costabile and F. Paternò Eds. Springer Berlin / Heidelberg, 57-68.

[Sugimoto 2009] Sugimoto, M., Ito, T., Nguyen, T. N. and Inagaki, S. GENTORO: a system for supporting children's storytelling using handheld projectors and a robot. In *Proceedings of the 8th International Conference on Interaction Design and Children*, ACM (2009), 214-217.

[Sun 2012] Sun, G. (2012) Perceived Depth Control in Stereoscopic Cinematography. *PhD. dissertation*. Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/3458/.

[Suzuki 2012] Suzuki, G. and Klemmer, S. TeleTorchlight: remote pointing and annotation using a mobile camera projector. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services companion*, ACM (2012), 35-40.

[Swan 2007] Swan, J. E., Jones, A., Kolstad, E., Livingston, M. A. and Smallman, H. S. Egocentric Depth Judgments in Optical, See-Through Augmented Reality. *Visualization and Computer Graphics, IEEE Transactions on 13*.3 (2007), 429-442

[Tajimi 2010] Tajimi, K., Uemura, K., Sakata, N. and Nishida, S. Stabilization Method for Floor Projection with a Hip-Mounted Projector. In *ICAT2010* (2010), 77-83.

[Tan 2002] Tan, D. S., Pausch, R., Stefanucci, J. K. and Proffitt, D. R. Kinesthetic cues aid spatial memory. In *CHI '02 Extended Abstracts on Human Factors in Computing Systems*, ACM (2002), 806-807.

[Tan 2003] Tan, D. S. and Czerwinski, M. Effects of Visual Separation and Physical Discontinuities when Distributing Information across Multiple Displays. In

International Conference on Human-Computer Interaction (INTERACT '03), IOS Press (2003), 252-255.

[Tomitsch 2012] Tomitsch, M., Mitchell, M. C. and Weng, H. Designing for mobile interaction with augmented objects. In *Proceedings of the 2012 International Symposium on Pervasive Displays (PerDis '12)*, ACM (2012), 1-6.

[Toshiba 2011] Toshiba. Libretto W100-106. http://www.toshiba.co.uk/discontinued-products/libretto-w100-106/. Accessed: 20/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmxKhE88)

[Tsang 1996] Tsang, P. W. M. and Tsang, W. H. Edge detection on object color. In *International Conference on Image Processing 1996* (1996), 1049-1052.

[Underkoffler 1999] Underkoffler, J., Ullmer, B. and Ishii, H. Emancipated pixels: real-world graphics in the luminous room. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, ACM Press/Addison-Wesley Publishing Co. (1999), 385-392.

[Valyus 1966] Valyus, N. A. *Stereoscopy* (Vol. trans. from Russian). The Focal Press (1966).

[Vivitek 2011] Vivitek. Qumi HD pocket projector. http://www.myqumi.com/. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmxllSEE)

[Von Helmholtz 1924] Von Helmholtz, H. *Treatise on physiological optics* (Vol. 3). J.P.C. Southall, Optical Society of America, New York (1924) pp. 318. Inital version from 1910 translated in English, Electronic edition (2001) University of Pennsylvania: http://poseidon.sunyopt.edu/BackusLab/Helmholtz/.

[Wanger 1992] Wanger, L. The effect of shadow quality on the perception of spatial relationships in computer generated imagery. In *Proceedings of the 1992 symposium on Interactive 3D graphics*, ACM (1992), 39-42.

[Want 2008] Want, R., Pering, T., Sud, S. and Rosario, B. Dynamic composable computing. In *Proceedings of the 9th workshop on Mobile computing systems and applications*, ACM (2008), 17-21.

[Wecker 2011] Wecker, A. J., Lanir, J., Kuflik, T. and Stock, O. Pathlight: supporting navigation of small groups in the museum context. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*, ACM (2011), 569-574.

[Wellner 1993] Wellner, P. Interacting with paper on the DigitalDesk. *Commun. ACM 36*.7 (1993), 87-96

[Wheatstone 1838] Wheatstone, C. Contributions to the Physiology of Vision.--Part the First. On Some Remarkable, and Hitherto Unobserved, Phenomena of Binocular

Vision. *Philosophical Transactions of the Royal Society of London 128*.ArticleType: research-article / Full publication date: 1838, (1838), 371-394. The Royal Society.

[Wigdor 2007]Wigdor, D., Forlines, C., Baudisch, P., Barnwell, J. and Shen, C. Lucid touch: a see-through mobile device. In *Proceedings of the 20th annual ACM symposium on User interface software and technology*, ACM (2007), 269-278.

[Willis 2010] Willis, K. D. D. and Poupyrev, I. MotionBeam: designing for movement with handheld projectors. In *CHI '10 Extended Abstracts on Human Factors in Computing Systems*, ACM (2010), 3253-3258.

[Willis 2011a] Willis, K. D. D. Character interaction with handheld projectors. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, ACM (2011a), 445-446.

[Willis 2011b] Willis, K. D. D., Poupyrev, I., Hudson, S. E. and Mahler, M. SideBySide: ad-hoc multi-user interaction with handheld projectors. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, ACM (2011b), 431-440.

[Willis 2013] Willis, K. D. D., Shiratori, T. and Mahler, M. HideOut: Mobile Projector Interaction with Tangible Objects and Surfaces. In *TEI '13: Proceedings of the Seventh International Conference on Tangible, Embedded and Embodied Interaction* ACM,(2013), 331-338.

[Wilson 2005] Wilson, A. D. PlayAnywhere: a compact interactive tabletop projection-vision system. In *Proceedings of the 18th annual ACM symposium on User interface software and technology*, ACM (2005), 83-92.

[Wilson 2006] Wilson, A. D. Robust computer vision-based detection of pinching for one and two-handed gesture input. In *UIST '06. 19th annual ACM symposium on User interface software and technology*, ACM (2006), 255-258.

[Wilson 2012a] Wilson, A. D., Benko, H., Izadi, S. and Hilliges, O. Steerable augmented reality with the beamatron. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, ACM (2012a), 413-422.

[Wilson 2012b] Wilson, M. L., Craggs, D., Robinson, S., Jones, M. and Brimble, K. Pico-ing into the future of mobile projection and contexts. *Personal Ubiquitous Comput. 16*.1 (2012b), 39-52

[Winkler 2011a] Winkler, C., Broscheit, M. and Rukzio, E. NaviBeam: Indoor Assistance and Navigation for Shopping Malls through Projector Phones. In *CHI 2011 Workshop on Mobile and Personal Projection* (2011a),

[Winkler 2011b] Winkler, C., Reinartz, C., Nowacka, D. and Rukzio, E. Interactive phone call: synchronous remote collaboration and projected interactive surfaces. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS'11)*, ACM (2011b), 61-70.

[Winkler 2012a] Winkler, C., Hutflesz, P., Holzmann, C. and Rukzio, E. Wall Play: a novel wall/floor interaction concept for mobile projected gaming. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services companion*, ACM (2012a), 119-124.

[Winkler 2012b] Winkler, C., Pfeuffer, K. and Rukzio, E. Investigating mid-air pointing interaction for projector phones. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*, ACM (2012b), 85-94.

[Wowwee 2010] Wowwee. Cinemin Swivel pico projector. http://www.wowwee.com/en/products/tech/projection/cinemin/swivel. Accessed: 21/05/2013. (Archived by WebCite® at http://www.webcitation.org/6GmyCc7nJ)

[Xiao 2011] Xiao, R., Nacenta, M. A., Mandryk, R. L., Cockburn, A. and Gutwin, C. Ubiquitous cursor: a comparison of direct and indirect pointing feedback in multi-display environments. In *Proceedings of Graphics Interface 2011*, Canadian Human-Computer Communications Society (2011), 135-142.

[Xu 2012] Xu, L., Fang, Y., Wang, K. and Li, J. Plug&Touch: a mobile interaction solution for large display via vision-based hand gesture detection. In *Proceedings of the 20th ACM international conference on Multimedia*, ACM (2012), 1177-1180.

[Yang 2010] Yang, X.-D., Mak, E., McCallum, D., Irani, P., Cao, X. and Izadi, S. LensMouse: augmenting the mouse with an interactive touch display. In *Proceedings of (CHI'10)*, ACM (2010), 2431-2440.

[Yatani 2005] Yatani, K., Tamura, K., Hiroki, K., Sugimoto, M. and Hashizume, H. Toss-it: intuitive information transfer techniques for mobile devices. In *CHI '05 Ext. Abs. on Human Factors in Computing Systems*, ACM, (2005), 1881-1884.

[Ye 2010] Ye, Z. and Khalid, H. Cobra: Flexible Displays for Mobile Gaming Scenarios. In *Ext. Abstracts CHI 2010*, ACM (2010), 4363-4368.

[Yee 2003] Yee, K.-P. Peephole displays: pen interaction on spatially aware handheld computers. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'03)*, ACM (2003), 1-8.

[Yoshida 2010] Yoshida, T., Hirobe, Y., Nii, H., Kawakami, N. and Tachi, S. Twinkle: Interacting with physical surfaces using handheld projector. In *Virtual Reality Conference (VR)* IEEE,(2010), 87-90.

[Zhao 2010] Zhao, J., Liu, H., Zhang, C. and Zhang, Z. MobileSurface: interaction in the air for mobile computing. In *Adjunct proceedings of the 23nd annual ACM symposium on User interface software and technology*, ACM (2010), 459-460.

[Zhao 2011] Zhao, Y., Xue, C., Cao, X. and Shi, Y. PicoPet: "Real World" digital pet on a handheld projector. In *Proceedings of the 24th annual ACM symposium adjunct on User interface software and technology (UIST Adjunct)*, ACM (2011), 1-2.