NOMADIC VIRTUAL REALITY

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NOMADIC VIRTUAL REALITY:
Overcoming Challenges of Mobile Virtual Reality Head-Mounted Displays

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для мамы и папы

ABSTRACT

Technological advancements in the fields of optics, display technology and miniaturization have enabled high-quality virtual reality (VR) head-mounted displays (HMDs) to be used beyond research labs and become available as consumer products. In turn, this development enabled mobile VR HMDs, which are untethered and self-contained headsets, allowing users to immerse themselves wherever and whenever they wish. This creates a novel interaction scenario in which a user is immersed in a virtual environment using a mobile VR HMD inside an unknown context (e.g., watching a 360-degree video while commuting by public transport).

This thesis defines this novel interaction scenario as *nomadic VR* and systematically explores its upcoming challenges and opportunities. For this, the interaction scenario is embedded into a larger vision of ubiquitous mixed reality, using models and approaches from the field of context-aware computing which already explain a similar transformation and paradigm shift from stationary PCs to mobile computing (smartphones): The form factor changed dramatically, cursor-based input was replaced with multi-touch, sound and visual feedback was extended with vibration and the constant changing environment enabled a variety of location-based features and services. We[1] argue that a similar transformation will happen from stationary VR HMDs to mobile VR HMDs: the *input* will be adapted, novel *output* modalities will be added and the *context* of use will be incorporated into the virtual environment.

This dissertation consists of six case studies, each addressing one aspect of these challenges (*input*, *output* and *context*). To enable fast and precise *input* we present *FaceTouch*, a novel interaction concept leveraging the backside of the HMD as a touch-sensitive surface. *FaceTouch* allows the user to select virtual content inside the *nomadic VR* interaction scenario without the need for additional accessories or expansive gestures. To extend the *output* capabilities of mobile VR HMDs, we propose *GyroVR*, a set of HMD-attached flywheels, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation and generating the perception of inertia. *GyroVR* was

1 Despite this thesis being written only by me (Jan Gugenheimer) and only reflect my thoughts and ideas, throughout the rest of the thesis I will use the term 'we' to emphasize that all underlying projects were done in collaboration with my co-authors.

designed as a mobile and ungrounded feedback device fitting into the *nomadic VR* interaction scenario.

The *context* was divided into the *physical environment* and *human factors*. With *CarVR*, we explored how to enable the usage of VR HMDs inside of moving vehicles such as cars. The *CarVR* system senses and incorporates the additional motions arising inside of these dynamic *physical environments*, enabling an increment of enjoyment and reduction of simulator sickness compared to a stationary setup. The *SwiVRChair* system presents a motorized office chair, exploring how everyday objects inside a static *physical environment* can be incorporated into the *nomadic VR* interaction scenario to enhance the overall user experience. Since the *nomadic VR* interaction scenario often takes place inside of public environments, for the *human factor* context we focused on social scenarios in which people use VR HMDs when people without HMDs (non-HMD users) are in the vicinity. With the *ShareVR* system, we present a prototype which uses floor projection and mobile displays combined with positional tracking to visualize the virtual world to (non-HMD) users and enable an asymmetric interaction. In a follow-up case study, we adapted the *ShareVR* concept to fit into a mobile VR HMD. *FaceDisplay* is a modified VR HMD that consists of three touch-sensitive displays and a depth camera attached to the back of the HMD, allowing the non-HMD user to perceive and interact with the virtual world through touch or gestures.

We conclude this dissertation with three overarching findings that resulted not out of the individual research questions but emerged throughout the whole process of this thesis: (1) We argue that current HMDs are mainly optimized for the wearer and ignore the whole social context; future HMDs have to be designed to be able to include non-HMD users. (2) We show that the physical environment should not only be seen as a challenge, but can be leveraged to reduce problems such as simulator sickness and increase immersion. (3) We propose that similar to the very first smartphone, current HMDs should be seen as an unfinished device type. We argue for an engineering research approach that extends the current form factor through novel sensors and actuators.

ZUSAMMENFASSUNG

Technologische Fortschritte in den Bereichen Optik, Displaytechnologie und Miniaturisierung ermöglichten es, hochwertige Datenbrillen zur Simulation Virtueller Realitäten (VR) über die Forschungslabore hinaus einzusetzen und als Konsumgüter anzubieten. Diese Entwicklung ermöglichte auch die Entwicklung von mobilen VR-Datenbrillen, die einem Benutzer erlauben jederzeit und überall in eine virtuelle Welt einzutauchen. Dadurch entsteht ein neuartiges Interaktionsszenario, in dem ein Benutzer mit einer mobilen VR-Datenbrille in einem unbekannten Kontext interagiert (z.B. ein 360 Grad Video in einem Bus konsumieren)

Diese Arbeit definiert dieses neuartige Interaktionsszenario als *nomadic VR* und untersucht systematisch sich daraus entwickelnde Herausforderungen und Möglichkeiten. Dazu wird das Interaktionsszenario in eine größere Vision (*ubiquitous mixed reality*) eingebettet und Modelle und Ansätze aus dem Bereich des *context-aware computing* verwendet. Diese konnten bereits einen ähnlichen Paradigmenwechsel vom stationären PC zum Smartphone erklären: Der Formfaktor änderte sich dramatisch, die zeigerbasierte Eingabe wurde durch Multi-Touch ersetzt, Ton- und visuelles Feedback wurde durch Vibrationen erweitert und die sich ständig ändernde Umgebung ermöglichte eine Vielzahl von ortsbezogenen Funktionen und Diensten. Die These lautet, dass eine ähnliche Transformation von stationären VR Datenbrillen zu mobilen VR Datenbrillen stattfinden wird: Die *Eingabe* wird angepasst, neue *Ausgabe*-Modalitäten werden hinzugefügt und der *Kontext* der Nutzung wird in die virtuelle Umgebung integriert.

Diese Dissertation besteht aus sechs Fallstudien, die jeweils einen Aspekt dieser Herausforderungen behandeln (*Eingabe*, *Ausgabe* und *Kontext*). Um eine schnelle und präzise *Eingabe* zu ermöglichen, präsentieren wir *FaceTouch*, ein neuartiges Interaktionskonzept, das die Rückseite der Datenbrille als berührungsempfindliche Oberfläche nutzt. *FaceTouch* ermöglicht dem Benutzer, virtuelle Inhalte innerhalb des *nomadic VR* Interaktionsszenarios auszuwählen, ohne dass zusätzliches Zubehör oder ausfallende Gesten erforderlich sind. Um die *Ausgabe*-Fähigkeiten von mobilen VR-Datenbrillen zu erweitern, präsentieren wir *GyroVR*. Das Konzept erweitert VR-Datenbrillen um Schwungräder, die den gyroskopischen Effekt beim Ändern der Drehachse nutzen und es ermöglichen, eine Wahrnehmung von Trägheit

zu erzeugen. *GyroVR* wurde als mobiles und ungeerdetes Konzept entwickelt, damit man es im *nomadic VR* Interaktionsszenario einsetzen kann.

Der *Kontext* wurde unterteilt in die *physische Umgebung* und *menschliche Faktoren*. Mit *CarVR* haben wir untersucht, wie man VR-Datenbrillen in Fortbewegungsmitteln wie Autos einsetzen kann. Das *CarVR*-System erfasst und integriert die zusätzlichen Bewegungen, die innerhalb dieser dynamischen *physischen Umgebungen* entstehen, und fürt zu einer Steigerung der Freude und eine Verringerung der Simulatorkrankheit im Vergleich zu einem stationären System. Das *SwiVRChair*-System besteht aus einen motorisierten Bürostuhl, mit dessen Hilfe untersucht wurde, wie Alltagsgegenstände innerhalb einer statischen *physischen Umgebung* in das *nomadic VR*-Interaktionsszenario integriert werden können, um das allgemeine Benutzererlebnis zu verbessern. Da das *nomadic VR*-Interaktionsszenario oft innerhalb von öffentlichen Umgebungen eingebettet ist, haben wir uns auf den *menschlichen Faktor* in soziale Szenarien konzentriert, in denen Menschen VR-Datenbrillen verwendeten, während Menschen ohne Datenbrillen (Nicht-Datenbrillen-Nutzer) sich in der Umgebung aufhalten. Mit dem *ShareVR*-System präsentieren wir einen Prototyp mit Bodenprojektion und mobilen Displays in Kombination mit Positionsbestimmung, um die virtuelle Welt für Nicht-Datenbrillen-Nutzer zu visualisieren und eine asymmetrische Interaktion zu ermöglichen. In einer anschließenden Fallstudie haben wir das *ShareVR*-Konzept in eine mobile VR-Datenbrille integriert. *FaceDisplay* ist eine modifizierte VR-Datenbrille, das aus drei berührungsempfindlichen Displays und einer Tiefenkamera auf der Rückseite der Datenbrille besteht. Dies ermöglicht es den Nicht-Datenbrillen-Nutzern die virtuelle Welt wahrzunehmen und durch Berührung oder Gesten mit der virtuellen Welt zu interagieren.

Die Disssertation endet mit der Darstellung dreier übergreifenden Ergebnisse, die sich nicht aus den einzelnen Forschungsfragen ergeben haben, sondern während des gesamten Prozesses dieser Arbeit entstanden sind: (1) Wir argumentieren, dass aktuelle Datenbrillen hauptsächlich für den Träger optimiert sind und den gesamten sozialen Kontext ignorieren. Zukünftige Datenbrillen, sollten so konzipiert werden, dass sie auch Nicht-Datenbrillen-Nutzer einbeziehen können. (2) Wir zeigen, dass die physische Umgebung nicht nur als Herausforderung angesehen werden sollte, sondern auch genutzt werden kann, um Probleme wie die Simulatorkrankheit zu reduzieren. (3) Wir argumentieren, dass aktuelle Datenbrillen - ähnlich wie das allererste Smartphone - als unfertiger Gerätetyp angesehen werden sollten und plädieren für einen Forschungsansatz, der den aktuellen Formfaktor durch neuartige Sensoren und Aktoren erweitert.

PUBLICATIONS

Some ideas, figures and wordings of this cumulative dissertation have appeared previously in the following core publications.

[Core1] **Gugenheimer, Jan**, David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, **UIST '16**, pages 49–60, New York, NY, USA, 2016. ACM.

[Core2] **Gugenheimer, Jan**, Dennis Wolf, Eythor R. Eiriksson, Pattie Maes, and Enrico Rukzio. GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, **UIST '16**, pages 227–232, New York, NY, USA, 2016. ACM.

[Core3] **Gugenheimer, Jan**, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, **CHI '16**, pages 1996–2000, New York, NY, USA, 2016. ACM.

[Core4] Philipp Hock, Sebastian Benedikter, **Gugenheimer, Jan**, and Enrico Rukzio. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, **CHI '17**, pages 4034–4044, New York, NY, USA, 2017. ACM.

[Core5] **Gugenheimer, Jan**, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. ShareVR: Enabling Co-Located Experiences for Virtual Reality Between HMD and Non-HMD Users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, **CHI '17**, pages 4021–4033, New York, NY, USA, 2017. ACM.

[Core6] **Gugenheimer, Jan**, Evgeny Stemasov, Harpreet Sareen, and Enrico Rukzio. FaceDisplay: Towards Asymmetric Multi-User Interaction for Nomadic Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, **CHI '18**, pages 54:1–54:13, New York, NY, USA, 2018. ACM.

ALL PUBLICATIONS

During the duration of my PhD I was involved in more publications that also in parts influenced this dissertation:

[All1] **Gugenheimer, Jan**, Alexander De Luca, Hayato Hess, Stefan Karg, Dennis Wolf, and Enrico Rukzio. Colorsnakes: Using colored decoys to secure authentication in sensitive contexts. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, **MobileHCI '15**, pages 274–283. ACM, 2015.

[All2] **Gugenheimer, Jan**, Pascal Knierim, Christian Winkler, Julian Seifert, and Enrico Rukzio. Ubibeam: exploring the interaction space for home deployed projector-camera systems. In *Human-Computer Interaction*, **INTERACT '15**, pages 350–366. Springer, Cham, 2015.

[All3] Christian Winkler, **Gugenheimer, Jan**, Alexander De Luca, Gabriel Haas, Philipp Speidel, David Dobbelstein, and Enrico Rukzio. Glass unlock: Enhancing security of smartphone unlocking through leveraging a private near-eye display. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, **CHI '15**, pages 1407–1410. ACM, 2015.

[All4] **Gugenheimer, Jan**. Nomadic virtual reality: Exploring new interaction concepts for mobile virtual reality head-mounted displays. In *Adjunct proceedings of the 29th Annual Symposium on User Interface Software and Technology*, **UIST '16**, pages 9–12. ACM, 2016.

[All5] **Gugenheimer, Jan**, Frank Honold, Dennis Wolf, Felix Schüssel, Julian Seifert, Michael Weber, and Enrico Rukzio. How companion-technology can enhance a multi-screen television experience: a test bed for adaptive multimodal interaction in domestic environments. *KI-Künstliche Intelligenz*, 30(1):37–44, 2016.

[All6] **Gugenheimer, Jan**, Katrin Plaumann, Florian Schaub, Patrizia Di Campli San Vito, Saskia Duck, Melanie Rabus, and Enrico Rukzio. The impact of assistive technology on communication quality between deaf and hearing individuals. In *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing*, **CSCW '17**, pages 669–682. ACM, 2017.

[All7] **Gugenheimer, Jan**, Christian Winkler, Dennis Wolf, and Enrico Rukzio. Interaction with adaptive and ubiquitous user interfaces. In *Companion Technology*, pages 209–229. Springer, Cham, 2017.

[All8] Michael Rietzler, Florian Geiselhart, **Gugenheimer, Jan**, and Enrico Rukzio. Breaking the tracking: Enabling weight perception using perceivable tracking offsets. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, **CHI '18**, page 128. ACM, 2018.

[All9] Michael Rietzler, Teresa Hirzle, **Gugenheimer, Jan**, Julian Frommel, Thomas Dreja, and Enrico Rukzio. Vrspinning: Exploring the design space of a 1d rotation platform to increase the perception of self-motion in vr. In *Proceedings of the Conference on Designing Interactive Systems*, **DIS '18**. ACM, 2018.

[All10] Michael Rietzler, **Gugenheimer, Jan**, Teresa Hirzle, Martin Deubzer, Eike Langbehn, and Enrico Rukzio. Rethinking redirected walking: On the use of curvature gains beyond perceptual limitations and revisiting bending gains. In *Proceedings of the IEEE International Symposium for Mixed and Augmented Reality*, **ISMAR '18**. ACM, 2018.

[All11] Teresa Hirzle, **Gugenheimer, Jan**, Florian Geiselhart, Andreas Bulling, and Enrico Rukzio. A design space for gaze interaction on head-mounted displays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, **CHI '19**. ACM, 2019.

[All12] **Gugenheimer, Jan** , Christian Mai, Mark McGill, Julie Williamson, Frank Steinicke, and Ken Perlin. Challenges using head-mounted displays in shared and social spaces. In *Workshop at the 2019 CHI Conference on Human Factors in Computing Systems*, **CHI '19**. ACM, 2019.

> *Showing gratitude is one of the simplest yet most powerful things humans can do for each other.*
>
> — **Randy Pausch**

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CONTENTS

LIST OF FIGURES

ACRONYMS

HCI Human-Computer Interaction

MR mixed reality

HMD head-mounted display

VR virtual reality

AR augmented reality

UCD User-Centered Design

SAR spatial augmented reality

PRO-CAM projector-camera system

CAVE Cave Automatic Virtual Environment

EMS electrical muscle stimulation

BCI brain-computer interface

IMU inertial measurement unit

OBD on-board diagnostics

Part I

THESIS

1 INTRODUCTION

> *The screen is a window through which one sees a virtual world. The challenge is to make that world look real, act real, sound real, feel real.*
>
> **— Ivan Sutherland**

With the distribution of the Internet and constant access through personal devices such as smartphones, we are currently living inside two realities: a physical one and a digital one. Current consumer devices such as smartphones and laptops offer quick and easy access to the digital world but still enforce a strict separation between physical and digital. The currently dominant paradigm of interacting with digital content consists of using these devices as a window into the digital realm. However, alternative approaches such as mixed reality (MR) and augmented reality (AR) are arising and aim to merge these two realities into a more fluid and interwoven perception of these two worlds.

Paul Milgram and Fumio Kishino gave a definition of MR by presenting the reality-virtuality continuum, which spans between the two extrema of a fully real environment (physical world) and a fully virtual environment (virtual reality (VR)) [148]. Everything in between is defined as MR, which in turn makes AR a subset of MR[1]. Since both terms (AR and VR) lack one formal definition, we will present one common definition which is used throughout this thesis and set both concepts in relationship to one another.

> *"Virtual Reality is an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment."* (Merriam-Webster Dictionary [1])

The main difference for defining AR is that the environment is not fully artificial but AR superimposes artificial content over the real environment. Azuma defines AR as:

1 Following this definition, VR is technically not part of MR. However, since currently the term MR is used interchangeable with different concepts [216], we will clarify that throughout this thesis we will use MR as an umbrella term spanning the whole reality-virtuality continuum.

> *"In Contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space [...]"* (Ronald T. Azuma [10])

One of the goals for AR and VR technology is to enable an experience for users in which they can not distinguish if the experience was real or virtual. One formulation of this vision was written down in 1965 by Ivan Sutherland in his visionary paper *The Ultimate Display* [227]. In this work Sutherland describes the *Ultimate Display* as

> *"[...] a room in which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal."*

In 1968 Sutherland wrote a consecutive paper presenting his first attempt of building such an *Ultimate Display* in the form of the first head-mounted display (HMD) [228] (see Fig. 1.1). The system was later called *Sword of Damocles* since it had to be mounted on the ceiling and was hanging over the user's head. Today, we consider this to be one of the first AR HMDs. Both projects nicely show how both, AR and VR technology are closely related to each other and should not be perceived as competing but rather as coalesce technologies.

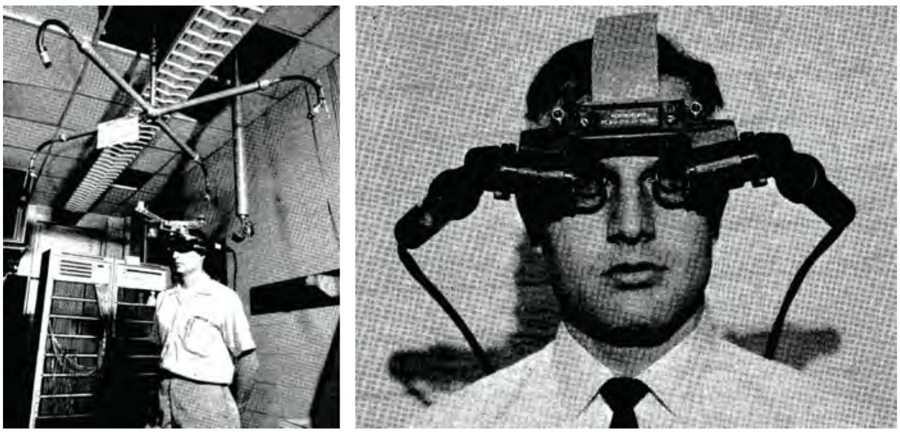


Figure 1.1: (left) The *Sword of Damocles* system mounted on the ceiling and consisting of two (right) miniature cathode ray tubes [228]

These VR and AR systems are currently mainly realized through HMDs, which core parts are a stereoscopic display, a set of positioning/-tracking sensors and a computing unit packed inside a glasses form factor. These core features could already be found in Sutherland's HMD and were further built into HMDs in the early 1990s. The technology presumably failed to reach a broad consumer adoption since it was not fully mature yet [207] (e.g., cost, resolution, refresh rate). However, all of these core technologies (display, tracking, computing) had significant improvements over the last years and resulted in a level of fidelity that is ready for consumer adoption (e.g., Microsoft HoloLens [146], Oculus Rift CV1 [57], HTC Vive [91], Magic Leap One[119]). Throughout the rest of this thesis we will focus on VR HMDs in particular and present a new interaction scenario, *nomadic VR* that was enabled through the technological progress.

1.1 THE SECOND RISE OF VIRTUAL REALITY

The current progress of VR HMDs is considered to be the second wave of virtual reality and started with the Oculus Rift DK1 in 2013 [207]. In contrast to prior HMDs the Oculus Rift DK1 was considered a high fidelity VR HMD for only $300 [2]. The founder Palmer Lucky stated in an interview that his "secret" was [207]:

> *"[...] the thing stopping people from making good VR and solving these problems was not technical. Someone could have built the Rift in mid-to-late 2007 for a few thousand dollars, and they could have built it in mid-2008 for about £500. It's just nobody was paying attention to that."* (Palmer Lucky)

The second version (Oculus Rift DK2) was released in 2014 and already sold 100.000 units by 2015 [2]. Around the same time HTC and Sony presented their VR HMDs: the HTC VIVE [91] and the Sony Playstation VR [215]. At the date of submission of this thesis, these three Companies are considered the main drivers behind stationary consumer VR HMDs [47].

1.2 A NEW DIRECTION: MOBILE AND NOMADIC

A new aspect of this second wave of VR was the device type of mobile VR HMDs [47]. These devices allow the user to carry the technology around and interact with it outside of the known and familiar environment. They can be categorized in *phone based* and *standalone* mobile VR HMDs.

Phone Based: These devices leverage a smartphone as the display and computing unit. They often come with a case for the phone and a pair of lenses. Good examples of these devices are the Samsung Gear VR [198] and Google Cardboard [68]. One of their big disadvantages is the effort of transforming one phone into the device.

Standalone: The most recent development are standalone device types: self-contained, mobile VR HMDs in a small form factor coming with an integrated display, lenses and a computing unit. The currently most prominent example is the Oculus Go [161] and Oculus Quest[162].

Both these device types enable a new interaction scenario that we will define as *nomadic VR*:

> *Nomadic Virtual Reality is a stationary interaction scenario in which a user is immersing oneself in a virtual environment using a mobile VR HMD inside an unknown context (e.g., public or social setting). Example: Watching a 360-degree video while commuting by public transport.*

This definition is based on Kleinrock's definition of nomadic computing [109]. Kleinrock defines the laptop to be a nomadic device, since the user can not interact with it on the go but has to sit down and interact. Another term for this could be portable computing. Mobile VR HMDs have a similar interaction paradigm, the user has to choose a location and then immerse himself. This interaction scenario enables a new form of experiencing virtual reality since HMDs can now be used outside of the living room or research laboratory.

The vision of always carrying a VR HMD around might initially sound not very appealing. However, *nomadic VR* does not stand for itself but is part of the greater vision of ubiquitous mixed reality HMDs. Instead of carrying special equipment, users will wear either simple glasses or even contact lenses that are capable to operate on the full reality-virtuality continuum[2], allowing to either augment the physical environment around them or switch to a fully immersed mode and enable the *nomadic VR* interaction scenario. This fully immersed mode can be imagined inside a variety of application scenarios such as receiving a full 360-degree image from a friend, exploring a remote environment or simply playing an immersive game.

1.3 PROBLEM STATEMENT OF NOMADIC VR

This new interaction scenario comes with a new set of challenges. The technology matured so much that these challenges are not mainly technical but starting to arise on the intersection between machine and human and how this new technology can be integrated into the

2 This idea of technology (AR and VR) merging into one device is nothing fully formulated and can't be credited to one piece of work, but exists as a possible idea inside the Human-Computer Interaction (HCI) community [216].

daily lives of social beings. This is why the field of HCI is increasingly focusing on exploring these new and upcoming challenges for mobile and nomadic virtual reality [All12]. We defined the *nomadic VR* interaction scenario based on context-aware computing [204, 206], seeing an interaction between user and machine as an interplay of three factors (see Fig. 1.2):

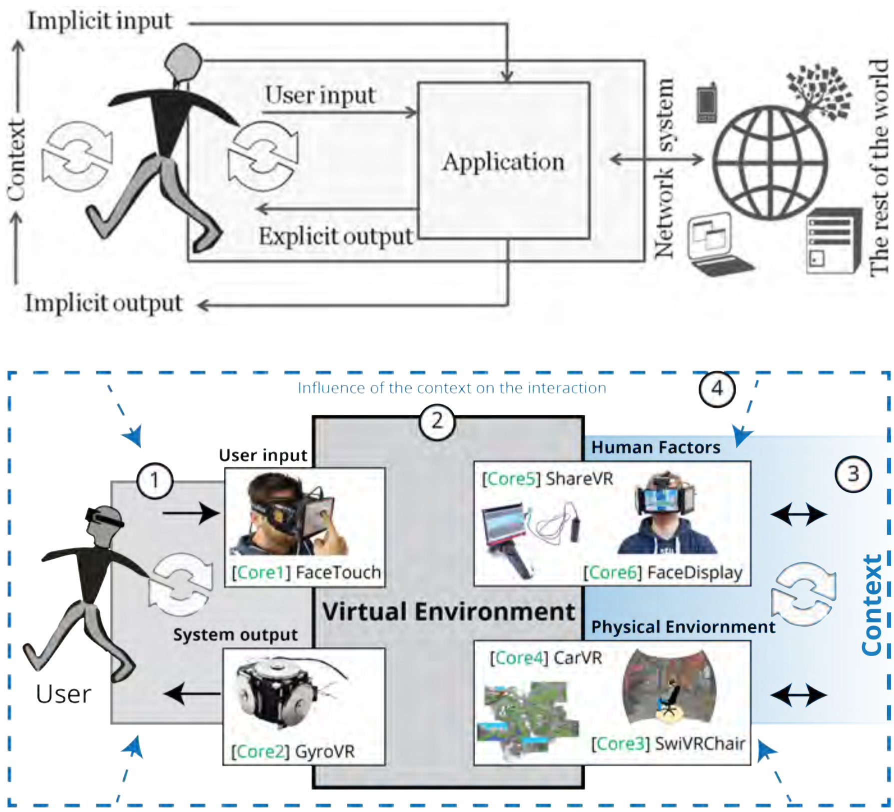


Figure 1.2: (top) A visualization of the implicit Human-Computer Interaction model (iHCI) [204] breaking down interaction into *input*, *output* and its influence through *context* [203] (bottom) An adaption of this iHCI model to the *nomadic VR* interaction scenario. The context (b.4) is hereby enclosing and impacting the virtual environment (b.2) and the explicit interaction cycle (b.1). Furthermore, the subdivision of context of Schmidt. [206] into *human factors* and *physical environment* is added to the model (b.3) to visualize its impact and relationship to the virtual environment (b.2).

- **Input:** The user has to input information and manipulate the virtual environment in any form. The nomadic scenario brings here new challenges since the environment is not known a priori and therefore can not be instrumented with any form of devices (e.g., external tracking).
- **Output:** After the user manipulated any form of information the system generates a form of feedback to acknowledge the input. This feedback can either be visual but often involves

different modalities (e.g., haptic, sound) to enhance the experience. Similar to the input, one big challenge is the form factor and unknown environment which forces the feedback to to be integrated into the device itself.

- **Context:** All this interaction (input and output) happens inside a certain context. Based on the definition of Schmidt et al., this context can be divided into two parts (*Human Factors* and *Physical Environment*) [206]. The context itself impacts both prior factors (input and output) and its changing nature is going to be one of the big future challenges of *nomadic VR*.
  – *Human Factors:* The human factors relate to information about the user (e.g., emotional state), the social environment (e.g., co-located user) and the user's task.
  – *Physical Environment:* The physical environment considers the location (e.g., absolute position), infrastructure (e.g., surrounding resources) and physical conditions (e.g., noise, light).

Looking back in history, this set of particular challenges also had to be overcome in the transition from stationary computing to mobile computing. The input paradigm changed from a mouse to touch, the feedback modalities were extended by using vibration and the ever changing context was woven into the interaction through location based services. This thesis argues that a similar transformation will happen with VR HMDs when they are going to leave the stationary lab environment and started to be adopted and used on a daily basis.

1.4 SCOPE AND METHOD

The scope of this thesis is to define and understand the *nomadic VR* interaction scenario from an HCI perspective and propose first solutions for the three challenges (*input*, *output* and *context*). Since HCI is a widely interdisciplinary field it applies methods from Psychology, Computer Science, Design and Engineering. The overarching framework used for this thesis can be loosely defined as a mix of User-Centered Design (UCD) [159, 50] and Design Thinking [54]. UCD is an iterative process defined in ISO 13407, consisting of four distinct phases that aim to put the user first and optimize for usability. Design thinking on the other hand shares several similarities but is less formally defined and can be better applied for ill-defined problems and often results in innovative solutions [28].

The thesis consists of six case studies within the scope of the *nomadic VR* interaction scenario. The following steps show the individual process which was applied for each of the case studies conducted within this thesis:

- **Define and Understand the Problem:** Similar to the first phase of UCD, this phase consists of understanding the user, his needs and the context of use. The insides in this phase arise partially from a thorough literature review and partially through applying qualitative methods from psychology (e.g., interviews, focus groups, surveys).
- **Ideation:** In the ideation phase, a set of creativity techniques (e.g., Brainstorming) from Design Thinking are applied to generate large amount of unconstrained ideas how to solve the prior identified problem. These ideas are later refined to a smaller set of possible approaches.
- **Concept and Implementation:** During the concept and implementation phase the unconstrained ideas are further refined and first prototypes are build in soft- and hardware. At the end of this phase at least one running prototype (often with several variations) exist which can be further used inside a user study.
- **Evaluation:** In the evaluation phase, users are exposed to the system and formal user studies (qualitative and quantitative) are conducted to assess if and how good the prototype is able to address the problem. The collected data is then analyzed using the appropriate statistical tests.

1.5 CONTRIBUTIONS

The general contribution of this work is the definition and systematic exploration of the *nomadic VR* interaction scenario (see Fig 1.2). In particular, six case studies were conducted that each explore one of the individual challenges (input, output and context). Based on the classification of HCI contributions by Wobbrock, each of the six case studies provide an *Empirical*, *Artifact* and *Theoretical* contribution [247]. The results of these case studies are further used to give implications of how to design VR HMDs that are more tailored towards the *nomadic VR* interaction scenario [Core1, Core2, Core3, Core5, Core4, Core6].

(1) Input: To address the input challenge we propose *FaceTouch* (see Fig. 1.3 a), a modified VR HMD that leverages the backside of the HMD as a touch-sensitive surface. *FaceTouch* fits nicely into the *nomadic VR* interaction scenario since it is integrated into the HMD and does not

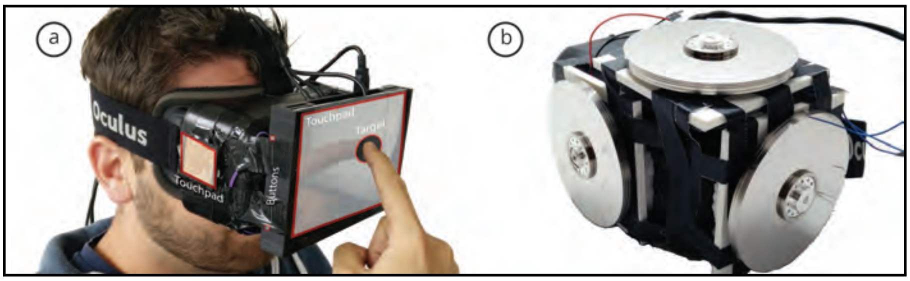


Figure 1.3: (a) A user interacting with FaceTouch, a multi-touch surface mounted on the back of aVR HMD [Core1]. (b) A first prototype implementation of GyroVR consisting of attached flywheels on each rotational axis of an Oculus Rift DK2 [Core2].

force to user to carry additional accessories [Core1].

(2) Output: To enable a novel form of feedback modality for mobile VR HMDs, we propose *GyroVR* (see Fig. 1.3 b), head worn flywheels designed to render kinesthetic forces such as inertia. To fit the *nomadic VR* interaction scenario *GyroVR* was implemented using an ungrounded approach, meaning that it does not need to counterbalance the output force which would need an instrumentation of the environment [Core2].

(3) Context (Human Factor): For the human factor context, we focused particular on the scenario where people used VR HMDs when people without HMDs (Non-HMD users) were around. In a first case study we build a system that aims to solve these problems in a stationary setup. *ShareVR* is a prototype using floor projection and mobile displays combined with positional tracking to visualize the virtual world to (non-HMD) users (Fig. 1.4 a). To present a solution suitable for the *nomadic VR* interaction scenario we build upon and adapted the *ShareVR* concept to work without an instrumentation of the en-

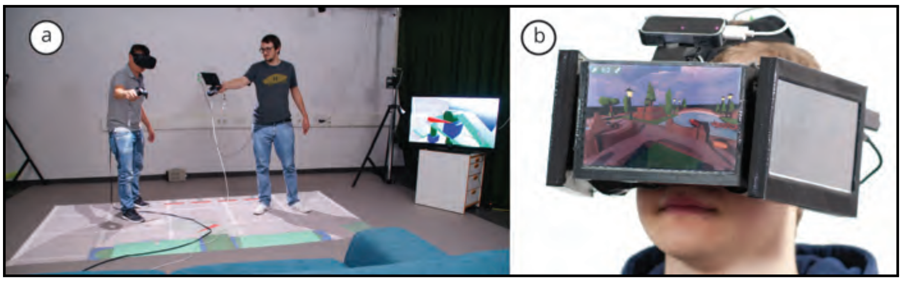


Figure 1.4: (a) Two user having an asymmetric interaction (HMD and non-HMD) with the ShareVR system using a tracked display and a floor projection to visualize the virtual world for the non-HMD user [Core5]. (b) A user wearing the FaceDisplay prototype, a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back [Core6].

Figure 1.5: (a) A user sitting in the front passenger seat and interacting with the CarVR system which maps the physical rotation of the car into the virtual environment [Core4]. (b) The physical prototype of the SwiVRChair system, consisting of a modified office chair with a motor and a clutch, enabling to nudge a users orientation inside the virtual environment [Core3]

vironment. *FaceDisplay* is a modified VR HMD that consists of three touch sensitive displays and a depth camera attached to the back and sides of the HMD (Fig. 1.4). This allows the Non-HMD user to to perceive and interact with the virtual world through touch or gestures. [Core5, Core6] .

(4) Context (Physical Environment): We explored the physical environment context from two perspectives (stationary and dynamic environments). In a first case study we explored how VR HMDs can be used inside a dynamic environment; a car. VR HMDs can currently not be used inside of moving vehicles since the car's rotation impacts the rotational sensor of the HMD. To counter this, we present a solution that uses an additional sensor inside the car and subtracts the rotation of the vehicle. The second case study focused on a stationary scenario and went out to explore how an everyday object such as a swivel chair can be leveraged to increase the experience of virtual reality. To enable this, we modified a regular swivel chair using a 24V DC motor, a rotary sensor and an electromagnetic clutch. The result of both case studies shows how the environment can not only be seen as a challenge but can also be leveraged to increase the experience of the virtual environment [Core4, Core3].

1.6 THESIS STRUCTURE

The rest of the thesis is structured as follows.

Chapter 2

starts by presenting the Milgram-Weiser continuum, integrating the contributions of this thesis and additionally categorizing prior art along the three challenges *input*, *output* and *context*.

Chapter 3
gives a formal definition of the *nomadic VR* interaction scenario. Afterwards the arising challenges of this scenario are presented and formulated into research questions.

Chapter 4
presents the found results of the six case studies and aims to answer the prior established research questions. Consecutively, the findings are used to deduct implications for the future design of VR HMDs.

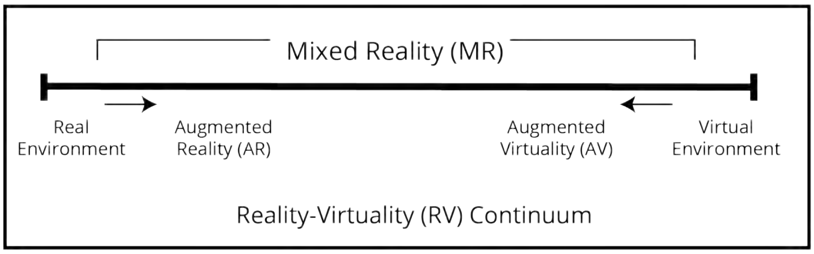
Chapter 5
summarizes the thesis with a conclusion and provides an outlook into future research directions of mobile and social virtual reality.

2 RELATED WORK

> *Machines that fit the human environment, instead of forcing humans to enter theirs, will make using a computer as refreshing as taking a walk in the woods.*
>
> — **Mark Weiser**

To be able to position this work within the broader field of mixed reality (augmented and virtual reality) research we will use the Milgram-Weiser continuum first presented by Newman et al. [155]. This continuum spans the field of mixed reality using the taxonomy presented by Milgram et al. [148] (*reality-virtuality continuum*) and mixes it with the vision of Mark Weiser's ubiquitous computing [240]. The result is a two dimensional plane consisting of technology types resulting in a vision we call *ubiquitous mixed reality*. This chapter starts with discussing both of these works individually and then further shows how two perpendicular axis can be deducted from each of them and formed into the Milgram-Weiser continuum. Consecutively, we present and formulate the vision of *ubiquitous mixed reality* and discuss prior art from the fields of input for mixed reality HMDs, haptic feedback for mixed reality HMDs and context-aware mixed reality HMDs.

Paul Milgram's Reality-Virtuality Continuum
Milgram et al. presented a taxonomy of mixed reality visual displays that were arranged along an axis of "virtuality" (see Fig. 2.1 top) [148, 149]. In the original work, the authors proposed three factors (extent of world knowledge, reproduction fidelity and extent of presence metaphor) that essentially distinct the individual types of mixed reality displays. However, the most known and common categorization is along the "virtuality" axis which has itself four discrete points (*real environment*, *augmented reality*, *augmented virtuality* and *virtual environment*). The axis is spanned between the two extreme cases of a fully *real environment* on the furthest left and a fully *virtual environment* at the furthest right. By definition the two extreme points are either solely virtual or solely real. Starting from the *real environment* and gradually introducing virtual objects results into *augmented reality*. The majority of the presented world here is still real, but has some form of virtual information added. Starting from the *virtual environment* and gradually introducing real objects results into *augmented virtuality*. The majority of the presented world is virtual but parts can be real



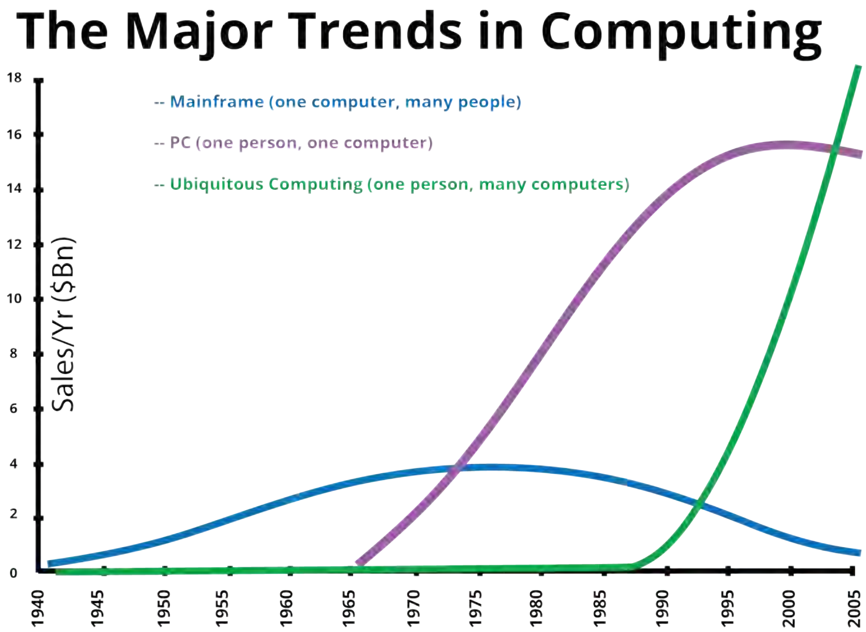


Figure 2.1: (top) Milgram's Reality-Virtuality Continuum, spanning from a real environment to virtual environment and positioning mixed reality is the collective term for every point in between [148, 149]. (bottom) A redrawn graph based on Mark Weiser's categorization of the three waves/major trends in computing [240].

or are based on aspects of the real world (e.g., shape of the physical environment). This axis of *virtuality* is going to be the x-axis for the Milgram-Weiser continuum.

Mark Weiser's Ubiquitous Computing:
In his work "The Computer of the 21st Century" [240], Mark Weiser presents a vision of how computing technology will at one point blend into our daily lives and disappear into the background. He draws parallels to literacy and how reading and writing, probably the first form of information technology ("literacy technology"), became such an integral part of our life that we stopped consciously thinking about the fact that we read but focus on the content. He argues that something similar will happen with computing technology and coins this future vision ubiquitous computing, where computing technologies

will disappear and "weave themselves into the fabric of everyday life" [240]. As a visualization of this progress, Mark Weiser presented the three waves/major trends of computing (Fig. 2.1 bottom[1]). He additionally distinguishes the individual waves with their interaction scenario (one computer, many people; one person, one computer; one person, many computers). Mainframe computers are only available at one dedicated location in the world and are operated by many people (one computer, many people). Personal computers become more accessible and therefore available for users at their homes but still restrict the context of usage (one computer, one user). Mobile computing is one step towards ubiquitous computing in which the context of usage changes but still follows the personal computing interaction scenario (one computer, one user). Ubiquitous computing envisions a complex and interwoven ecosystem of computing devices which enable access to digital information at anytime and everywhere in the world (many computer, one user). Using the same metaphor and interaction scenario, we can start arranging VR technology similarly: A Cave Automatic Virtual Environment (CAVE) is available at one location in the world used by multiple people. A stationary VR HMD makes VR more accessible and available for people to use at home. Mobile VR HMDs, starting to change the context of usage but currently still follow a similar interaction paradigm (one computer, one user). Ubiquitous mixed reality HMDs would work inside of an interwoven ecosystem of computing devices which communicate additional information of the context to the HMD. This axis of *ubiquity* is going to be the y-axis for the Milgram-Weiser continuum.

2.1 THE MILGRAM-WEISER CONTINUUM

The Milgram-Weiser continuum mixes these two prior deducted axis (virtuality and ubiquity) to maps out the progress of mixed reality in light of it becoming a ubiquitous every day technology (Fig. 2.2). This device perspective is only one possible perspective onto the Milgram-Weiser continuum and does neither claim completeness nor to be the only interpretation of the intersection. However, it is used in this thesis to be able to visualize the current position of the *nomadic VR* interaction scenario between stationary HMDs and mobile HMDs.

This specific definition and usage of the Milgram-Weiser continuum to position technology types and its interaction scenarios deviates

1 The original graph was presented by Mark Weiser and hosted on his xerox parc website that is not available anymore. This recreation is based on a figure still often used in papers such as [4]

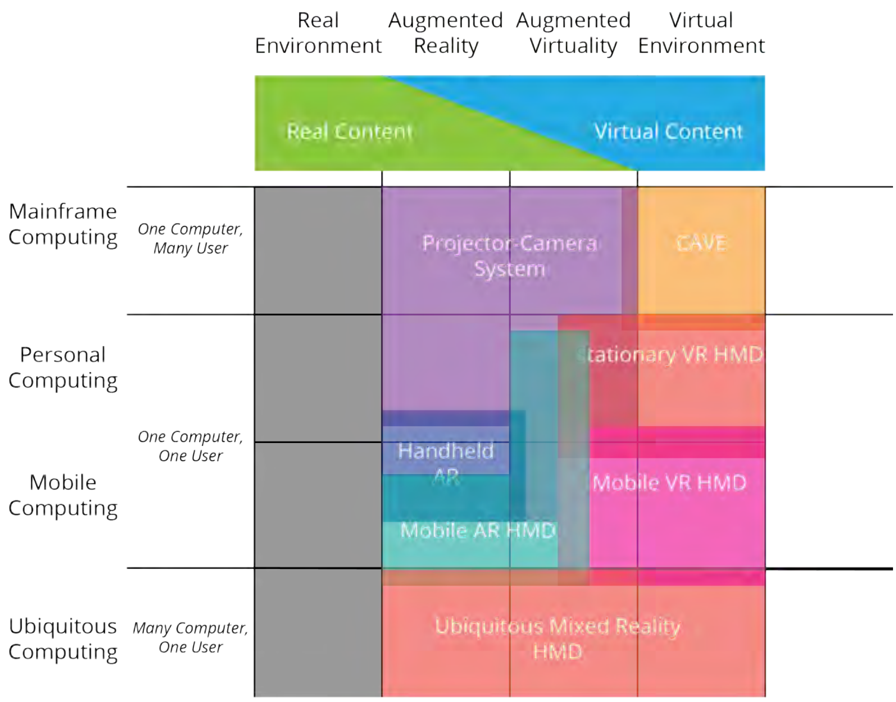


Figure 2.2: A technological (x-axis: reality-virtuality, y-axis: ubiquity) perspective onto the the Milgram-Weiser continuum [155]. This perspective allows to position specific devices types of mixed reality based on their interaction scenario and its degree of ubiquity (e.g., AR HMDs such as the HoloLens [146] enable a mobile interaction scenario and are capable of representing augmented reality/virtuality content, while CAVE [46] systems are stationary devices able to create a fully immersive virtual experience)

from the originally proposed version of Newman et al. [155]. The goal of this new perspective onto the Milgram-Weiser continuum is to use this as an approach of visualizing the progress of one type of technology (here mixed reality) towards it becoming ubiquitous. The overall result, is not a new vision but rather a subset of Mark Weiser's vision of ubiquitous computing. Mark Weiser's vision was that computing technology will disappear and weave itself into the fabric of our lives and mixed reality is only a subset of computing technology. Adding this one axis based on one specific type of computing technology also allows us to more clearly understand the sub-vision of ubiquitous computing for this one particular technology. A similar graph could be constructed with different types of technologies such as brain-computer interfaces (BCIs). One can imagine a gradient of BCI technology from intrusive to non-intrusive along the x-axis and the gradient of ubiquity along the y-axis. This would likewise create a form to categorize BCI work based on its progress towards one higher vision of ubiquitous brain-computer interfaces.

2.1.1 Categorization Criteria and Axis

In the following we will more clearly define how we are going to position the technology types and their interaction scenarios along the individual axis and what criteria were used.

Virtuality: The x-axis represents the degree of virtuality the technology offers. The axis spans between the two extreme cases of a fully *real environment* on the furthest left and a fully *virtual environment* at the furthest right. These two extreme cases are by definition either completely real or completely virtual. We will define completely virtual as being a fully computer generated virtual environment completely independent of the physical space around it (similar to the definition of virtual reality given in chapter 1). A completely real environment consists only of objects that are present in the physical space without any addition of virtual/digital information. Since technically, all devices are capable of presenting the real environment by merely removing them or turning them off, this column will not be fully formulated but only kept in the model for the sake of completeness.

This definition of the two extremes allows us to deduce the gradient in between. Starting from the most right (fully virtual environment) and gradually adding information from the real/physical environment results in *augmented virtuality*. Based on this definition a three degrees of freedom VR HMD such as the Samsung Gear VR [198] is considered a virtual reality device close to the most right extreme. However, a six degrees of freedom VR HMD (e.g., HTC Vive [91]) that allows the user to walk through a physical space would be already one step closer towards an augmented virtuality device, since it needs to add information about the physical environment to allow the user to move and keep him save without bumping into things. Even if the information added into the experience is not visual, it is still something dependent on the physical space around the user. It is important to realize that this definition is independent of the device type and also includes gaming experiences on PCs or mobile phones as a virtual reality environment and would categorize it on the most right (fully virtual) of the axis. Since the focus of this thesis is on immersive virtual reality, these types of experiences will not be discussed.

Starting from the most left (real environment) and gradually introducing virtual information leads to *augmented reality*. This definition is again independent from the actual device type used to introduce the visual augmentation. A smartphone using depth sensors to understand the physical space and superimposing information onto objects inside this space would be on the same level as an AR HMD such as the Microsoft HoloLens. The main factor for the gradient is how much of the information one perceives comes from the physical space and how much is virtually added.

Ubiquity: The y-axis represents the level of ubiquity of a technology and its corresponding interaction scenario. Similar to the virtuality axis, we will use the two extreme points to deduct two additional logical steps inwards. The axis spans between the two extreme points of mainframe computing and ubiquitous computing. The extreme point on the top represents mainframe computing and its interaction paradigm of custom tailored solutions, having one dedicated location on earth where this specific interaction scenario is possible (many people, one computer). A good example of this type of research are CAVE systems, that build a dedicated setup for VR experiences at one specific location, often times running on special high end rendering clusters. The next discrete step towards ubiquitous computing is personal computing and its interaction scenario of being able to have technology in every household. Current VR HMDs such as the HTC Vive and Oculus Rift CV1 give a nice example of a device type from personal computing. The next step on the scale is mobile computing and the interaction scenario of carrying the computing device at any time to allow for easier access to information. The interaction scenario of mobile computing falls somewhere in between personal computing (one computer, one user) and ubiquitous computing (many computer, one user). Despite having access to many computers (e.g., smartphone, smartwatch), our main form of interaction is still going through one multi-purpose device (smartphone). A traditional example for a mobile computing device would be smartphones that can be used for augmented reality [154]. However, also AR HMDs such as the Google Glass [67] or Microsoft HoloLens [146] fit into this category. Handheld devices are positioned as less ubiquitous than HMDs due to their access time compared to HMDs, which allow for a constant augmentation of the world without having to pull out a device and start a certain application [141]. The final step is ubiquitous computing and its vision of calm and interconnected devices, allowing for constant access to digital information.

Device Types for Mixed Reality: Drawing these two axis as presented, creates the *Milgram-Weiser Continuum*, a two dimensional plane allowing us to categorize, position and differentiate device types for mixed reality (see Fig. 2.2). One of the benefits of this perspective is that it nicely illustrates the expected merge of both technologies AR and VR into one device type capable of effortlessly moving on the full spectrum of the reality-virtuality continuum. This combination of a technological vision paper alongside the full spectrum of one specific technology (here mixed reality visual displays) allows to explore the impact of each step of the vision (e.g., mainframe to personal computing) onto the technology itself (e.g., CAVES to HMDs). This application of Mark Weiser's vision onto this new visual paradigm of mixed reality displays, resulted in the vision of ubiquitous mixed reality that is presented in more detail in the next section.

In the following we will present and discuss the resulting device types and their interaction scenario:

- *Projector-Camera System*: The device type of projector-camera systems (PRO-CAMs) consist of a camera system to acquire world knowledge and a projector to visually augment this world. These devices were mostly used within the research field of spatial augmented reality (SAR). PRO-CAMs span over the whole spectrum between augmented reality and augmented virtuality. Some of the early works were created running on heavy machines and having the traditional "one computer, many user" paradigm in mind [178]. However, technical advantages in projector systems enabled also devices that were mobile [246, 81] and portable [All2] even reaching into the mobile/personal computing interaction paradigm (one computer, one user).
- *CAVE*: A CAVE is a fully immersive physical space augmented either through multiple projectors or large displays. Traditionally, CAVEs were realized using heavy computing power and follow the "one computer, many users" paradigm [46]. Before the technical advancements of HMDs, CAVEs were the most immersive form of virtual reality and the main device form for research. But even today, CAVEs enable an easier form of multi-user interaction research than HMD setups [99, 116].
- *Handheld AR*: The distribution of smartphones enabled every user to have constant access to a camera, display and computing device. This form factor allowed for early exploration of the mobile augmented reality interaction scenario [190, 191]. While early systems relied on custom made hardware [190], later research focused around leveraging the individual sensors and possibilities of smartphones to augment the world [154]. The wide distribution of smartphones allowed to have larger scale in-the-wild studies [158, 166] and first commercial products leveraging AR capabilities (e.g., Pokemo GO [157], INGRES [156]).
- *Mobile AR HMD*: In contrast to smartphones, mobile AR HMDs stand for a new interaction paradigm. Access to information does not need to be explicitly triggered anymore and does have less access time [141] compared to handheld AR. Wearing an

AR HMD enables a more fluid interaction scenario compared to the smartphone AR scenario where the user has to actively decide to access any form of visual augmentation and then go through the process of getting the device ready and starting the application. That is why mobile AR HMDs are positioned further to ubiquitous computing compared to phone based AR. While not fully successful yet, some products such as the Google Glass [67] and the Magic Leap One [119] had a commercial attempt in distributing this new computing platform to the broader consumer base.

- *Stationary VR HMD*: Stationary HMDs that are tethered to a computing unit and only allow the user to roam inside a limited space are mainly researched in the field of VR. In the early 90s, stationary VR HMDs where used as the main medium to research virtual reality. After the failed first attempt of commercializing this technology in the 90s, the current second attempt shows more promise in distributing the technology throughout households [47]. The interaction scenario for stationary VR HMDs is similar to traditional computing, having a dedicated device at home (e.g., Oculus Rift [57]) that grants temporally access to virtual information.
- *Mobile VR HMD*: The research direction around mobile VR HMDs, only started with the second rise of virtual reality around the 2010s. A main enabling technology were phone based mobile VR HMDs such as the Google Cardboard [68], Samsung GearVR [198] and Google Daydream [66]. These devices allowed any user to access a highly immersive virtual world outside of their living room just through the combination of a smartphone, some lenses and a plastic casing. The interaction scenario for mobile VR HMDs can be divided into a stationary scenario and a walking scenario. This thesis will focus on the stationary scenario and call it *nomadic VR* inspired by the term of nomadic computing by Leonard Kleinrock [109]. Chapter 3 will define this interaction scenario in more detail.
- *Ubiquitous Mixed Reality*: The vision of ubiquitous mixed reality revolves around being able to fluidly access and switch between states on the reality-virtuality continuum. The technology itself disappears into the background and the user only makes decisions on the task level (e.g., need for a visualization of a medical procedure) and not on the technology level (e.g., use AR or VR to solve the task). The device type capable of enabling such a vision is probably going to be a mix of all the technology used prior. One can imagine a hybrid between AR and VR HMDs allowing for a smoothing transition between the different levels of virtuality.

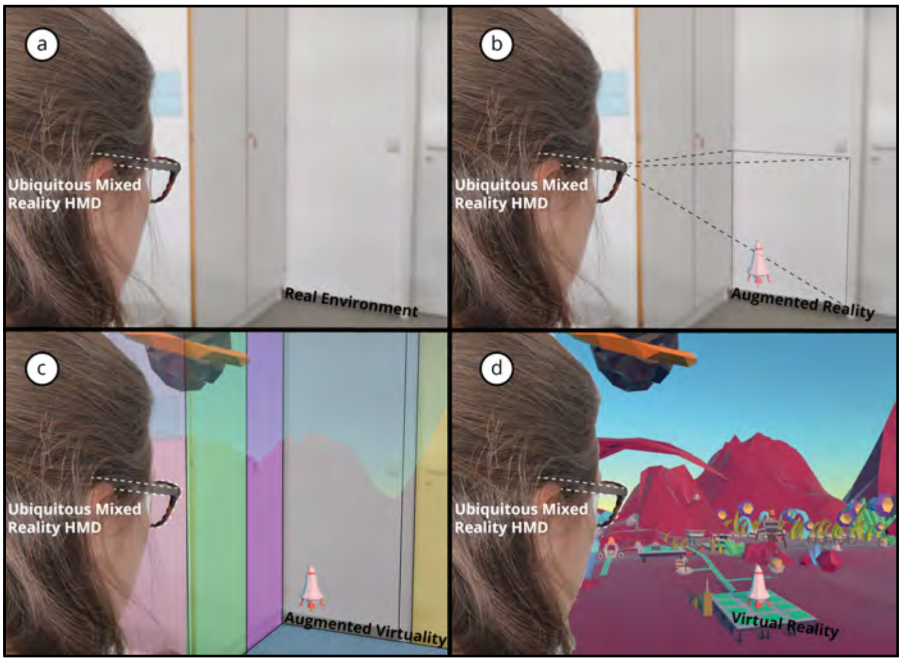


Figure 2.3: An envisioned ubiquitous mixed reality HMD capable of effortlessly transition along the reality-virtuality continuum and able to extend the (a) real environment using (b) augmented reality, (c) augmented virtuality and (d) virtual reality.

2.1.2 The Vision of Ubiquitous Mixed Reality

Mark Weiser himself positioned his vision of ubiquitous computing against the vision of virtual reality by saying they are on opposite sides of a spectrum. Where ubiquitous computing aims to blend technology into our everyday life, virtual reality aims to "make a world inside a computer".

> *"Although it may have its purpose in allowing people to explore realms otherwise inaccessible – the insides of cells, the surfaces of distant planets, the information web of complex databases – virtual reality is only a map, not a territory. It excludes desks, offices, other people not wearing goggles and body suits, weather, grass, trees, walks, chance encounters and in general the infinite richness of the universe. Virtual reality focuses an enormous apparatus on simulating the world rather than on invisibly enhancing the world that already exists"* (Mark Weiser)

The vision of ubiquitous mixed reality[2] follows this critique of Mark Weiser and treats VR only as one extreme point of the spectrum of mixed reality and envisions a world where AR and VR are not any

2 The term ubiquitous mixed reality was prior briefly used by Park et al. [171]. The work presented context as one challenge when combining internet of things and mixed reality without formally defining this term or putting it into perspective.

discrete states but something constantly present. Ubiquitous mixed reality allows users to not have to consciously decide to use augmented or virtual reality but focus on a certain action that implicitly demands the usage of AR or VR. This usage will not be for the sake of using any of the technology but for the sake of the actual task. Both technologies currently exist in a state where we have to actively decide to use them and think more about the technology than the task.

Imagine a future where a doctor is preparing for an upcoming surgery using constantly present mixed reality technology. For the sake of simplicity we will call the technology *mubi* but not further detail what type of mixed reality technology is used since the focus is not on the device type but on the interaction scenario (possible devices were presented by Billinghurst et al. [15] and by the artist Matsuda [143]). To get an initial overview of the procedure the doctor decides to look at prior operations and uses *mubi* to immerse himself into different surgery rooms exploring failed surgeries and successfully ones. Since the current physical environment is irrelevant to the task, *mubi* presents these prior surgeries in a mode we would call today virtual reality. In a second step the doctor decides to practice the necessary motions to perform the surgery on a medical dummy. The system now only partially augments virtual information onto a dummy, showing where to start the first cut (something we would call today augmented reality). This medical dummy is equipped with computing technology that allows him to constantly communicate his state (e.g., location of the cut, pressure of the cut) to the doctor's HMD. While the doctor continues working with the system, it will fluently switch between more augmentation and less augmentation. If necessary the doctor will be fully immersed and in the next moment only receive a subtle augmentation of the next step.

This future of ubiquitous mixed reality would be the logical conclusion of how mixed reality technology gets fluently integrated into our daily lives. Similar to how Mark Weiser argued that at one point computer technology will be such an integral part of our lives that they will blend with the environment and we will forget that we actual interact with computers but only focus on our task in mind. The vision of ubiquitous mixed reality follows the same reasoning and argues that virtual and augmented reality will at one point merge into one type of mixed reality technology being capable of the full spectrum of Milgram's reality-virtuality continuum. The technology will further blend more into our daily lives so that we will forget that we are actually using any specific technology (AR or VR) but accept all of the augmentations as a true and real experiences and a real part of our live. When the doctor from the prior example is later asked about how he prepared for the surgery, his reply will be by participating in several successful and failed prior surgeries and by operating several times himself. There will be no focus on real or virtual reality but only on the underlying task. This example also highlights how the interaction scenario of *nomadic VR* will still be relevant, since it is going to occur when a user will fully immerse oneself.

2.2 RESEARCH FIELDS OF MIXED REALITY HMDS

The rest of this chapter will present an overview of related work from the research fields of virtual and augmented reality HMDs [256, 107, 123]. Since the focus of this thesis is on the *nomadic VR* interaction scenario with the main challenges being *input*, *output* and *context*, the following presented work will be from within the fields of (1) input for mixed reality HMDs, (2) haptic feedback for mixed reality HMDs, (3) context-aware mixed reality HMDs.

2.2.1 Input for Mixed Reality HMDs

Over time, researchers proposed different types of taxonomies and classifications of interaction techniques for augmented and virtual reality [6, 183, 21, 123]. While Bowman et al. [21] used a classification based on subtasks (e.g., indication of object, confirmation of selection and feedback), Poupyrev et al. [183] proposed a multi-level classification based on interaction metaphors (e.g., egocentric interaction vs exocentric interaction). A more recent classifications was proposed by Lee et al. [123] which categorize interaction methods into *touchless input*, *touch input* and *handheld devices*. However, all of the prior classifications distinguish strongly between virtual and augmented reality despite having strong commonalities in terms of interaction metaphors. In the following we will use a mix of these classifications to discuss prior work and mainly distinguish between three dimensional interaction (3DUI, e.g., free hand gestures) and two dimensional (2DUI, e.g., touch input on a screen). Similar to Bowman et al. we argue against using *handheld devices* as a separate class, since "input devices are just the physical tool used to implement various interaction techniques" [24]. Since the focus is on 3DUI and 2DUI input approaches, we will not in depth discuss work from the fields of gaze input [All11][170, 11, 175] or voice input [147, 19] which are often used as an additional modality but often not as the only modality for interaction [19].

In contrast to the two dimensional interaction paradigm of traditional desktop systems (e.g., mouse and keyboard), interaction for systems that are on the mixed-reality continuum are often from within the field of 3D User interfaces [24]. Bowman et al. defined 3D UIs as a "user interface that involves a 3D interaction". A 3D interaction was further defined as a "human-computer interaction in which the user's tasks are performed directly in a 3D spatial context." [25]. This definition emphasizes the spatial nature of the interaction necessary for a mixed-reality systems and nicely distinguishes the interaction from traditional 2D interfaces such as a mouse. 2D input devices traditionally followed the WIMP (Windows, Icons, Menus, Pointers) paradigm and relied on these components to enable a user interface. 3D UIs on the other hand are often considered "post-WIMP" or "Natural User Interfaces" since the interfaces do not have to contain of WIMPs and forgo interaction metaphors which are often necessary in 2D UIs (e.g., moving the mouse horizontally manipulates an indirect cursors on a vertical display) [22].

Interaction techniques from the field of virtual reality (positioned more towards the virtual part of the reality-virtuality continuum) can be classified into exocentric and egocentric interaction metaphors [183]. Egocentric interaction lets the user interact from a first-person perspective while exocentric interaction (also known as "God's eye viewpoint") allows the user to manipulate the virtual environment from an external perspective. Examples for exocentric interaction are world-in-minature [220] and world scaling techniques [60]. Egocentric interaction can further be divided into a virtual hand metaphor or a ray casting metaphor [181, 6]. The virtual hand metaphor is applied by tracking the user's hand and creating a visual representation of it, allowing the user to interact with content within arm's reach [136, 129]. To allow users to interact with a distant object using the virtual hand metaphor, researchers proposed concepts such as GoGo [182] or HOMER [23] which apply non-linear scaling of the hand position and allow the user to reach virtually further then they physically could. Virtual pointer metaphors are based around casting a ray into the virtual scene to allow for user interaction [151]. A variety of techniques were presented that determine the rays orientation but are mostly focused around tracking the users hand similar to the virtual hand metaphor. The orientation of the ray can further be controlled by the users hand position and wrist orientation or as a ray cast from the user's viewpoint through the hand [177]. Further approaches are based around integrating both hands [152] or eye tracking [231, 175] to further control the ray.

When starting to move towards the reality side of the reality-virtuality continuum we can find interaction techniques that are used on AR HMDs but are grounded in similar principles and approaches as presented for virtual reality. Kytö et al. presented with Pinpointing a ray casting interaction where the ray is also corrected through eye gaze data [118]. This approach can be categorized as an egocentric ray casting interaction. Researchers also adopted egocentric virtual hand metaphors such as GoGO and HOMER to AR HMDs to allow for bare-hand interaction in locations out of reach of the user [76, 100]. Chae et al. presented an exocentric interaction concept for AR HMDs, where the users can warp and scale down a virtual representation of the physical environment, enabling him to easier interact (e.g., place a virtual object) with physical environments out of reach [31]. However, the further we go towards the reality side the more of the physical environment is visible for the user. This allows for using physical objects in the environment as a tangible interaction devices [95] and is an interaction technique that is widely used in the field of AR [256, 107, 103]. One of the first systems to introduce this concept was VOMAR by Kato et al. [103]. The system consisted of a physical paddle that allowed users to select and arrange virtual furniture in an AR living room. Irawati et al. later on presented an extension of the VOMAR system that included speech as an additional input modality [94]. Often used tangible objects are maps and books, since they allow to augment an already known interaction with more digital information [73, 69]. Reitmayr et al. presented such a system that augmented a static map with dynamic digital visualizations (e.g., flowing rivers) [188].

All prior presented input techniques for mixed reality HMDs can mostly be classified as three dimensional/spatial interaction. However, a big portion of work in the field interaction techniques for mixed reality, focuses around using known and already accepted 2D input modalities (e.g., touch) to enable input on HMDs [123]. The main contributions of these papers are often input metaphors or hardware prototypes that allow for a new type of input. Similar to [123] we will distinguish between on-device and on-body touch interaction.

On-device input is often times realized through some form of touch sensitive surface on the HMD. A frequently used location for this touch surface in consumer oriented HMD is the temple (e.g., Google Glass [67], Samsung Gear VR [198]). Researchers proposed several techniques [71, 254] that could leverage this one dimensional touch frame to input text by adapting interaction metaphors such as unistroke [65]. A slightly different approach called MRTouch was presented by Xiao et al., where the touch surface was not on the HMD itself but rather enabled through sensors available to the HMD [250]. MRTouch leveraged the depth cameras on the HMD to allow for sensing touch on any surface in front of the user. A big portion of work presents some form of wearable devices such as rings [105, 252, 7, 164] or wristbands [78, 189] that can function as an external input device for HMDs. Similarly to MRTouch, LightRing [105] and MagicFinger [252] are both modified rings, enabling the user to conduct touch input on any flat surface. Nenya on the other hand, is a modified ring that can sense its rotation and enable the user make subtle and unobtrusive interactions [7]. A similar goal was pursued by NailIO, a modified nail sticker that is capable of sensing touch on the fingernail and allow for simple one handed input gestures [102]. Besides allowing for touch input, Ogata et al. presented iRing which is also capable of reconstructing the posture of the finger using an infrared reflection sensor, allowing for additional input using finger gestures [164]. Kim et al. extended this approach by sensing not only one finger, but the whole hand using an infrared sensor illuminating individual points on the users finger and using these points inside a kinematic model to reconstruct the posture of the whole hand [106]. Jun Rekimoto presented a similar modified wristband, but instead of using infrared sensor he applied capacitive sensing to reconstruct individual gestures the user does with the arm wearing the device [189].

On-body input on the other hand aims to enable input capabilities on the users body (e.g., touch [83]) and leverage human abilities such as proprioception (locating the position of our arm in space in relationship to our body) [133] and body landmarks (e.g., knuckles on the hand) [75, 239]. Harrison et al. provided an in-depth exploration of what parts and locations of the body participants prefered to use as input locations [82]. Participants reported the hands [74, 81, 83, 235, 236, 238, 92] and forearms [8, 128, 163] to be the most ideal locations for such an interaction. However, researchers also explored locations on the human body that were initially not considered by users such as the face [208] and the ear [130]. The overall advantage of using on-body interaction compared to on-device interaction is that no additional accessory has to be added to the interaction (e.g., ring, wristband). An additional advantage of 2D interaction is that when conducted in a public space the user does not have to make wide and open gestures but can have a more subtle and unobtrusive form of input. That is why this type of input (2D on-body input) seems preferable for a *nomadic VR* interaction and was explored inside the FaceTouch case study [Core1].

2.2.2 Haptic Feedback for Mixed Reality HMDs

Research within the field of mixed reality often focuses mainly on the visual and auditory sense [107, 256]. However, researchers argue that the next step to increase the level of immersion (and by that the overall experience) of the user is to include some form of haptic feedback [85, 253, 148]. Haptic feedback is hereby often divided into two sub-areas: *cutaneous/tactile* feedback and *kinesthetic* feedback. While cutaneous feedback is perceived through receptors embedded in the human skin (e.g., touching a rough surface), kinesthetic feedback is mainly perceived through muscles, tendons and joints (e.g., feeling weight)

[80, 70]. While this classification is often used to structure research within the field of haptics, both types of feedback are desirable and are difficult to position along the Milgram-Weiser continuum (both cutaneous and kinesthetic feedback should be present in nomadic and stationary VR). Therefore, we divide the research similar to [255] into *haptic feedback devices* and *device free haptic feedback*.

Haptic feedback devices are computer controlled devices that can simulate both types of feedback (cutaneous and kinesthetic) through any form of artifact interacting with the users. These artefacts can be further divided into wearables, handheld and grounded/external systems. We will exclude grounded systems form this overview such as the Phantom [142] or Hiro [55], due to their demand of being grounded and thereby not feasible for the *nomadic VR* scenario. Wearable haptic systems are mostly being realized through gloves [237] or finger tip sleeves [168, 140]. The wearable and mobile form factor of these devices make them usable inside a *nomadic VR* scenario. One of the earliest gloves was presented by Iwata. et al in 1992 [96]. The system was realized by a string attached to the users index finger which was controlled via a motor to enable kinesthetic feedback by restricting the grasping motion. Thereafter, many similar exoskeleton gloves were developed such as the CyberGlove [131], MR glove [18] and dexmo [72]. These exoskeleton approaches are mostly grounded at the back of the users hand and are capable of providing kinesthetic feedback through breaks or motors. Alternatively, researchers presented palm-based [20, 53] and digit-based glove systems [117, 43] that instead of wrapping around the users hand are connecting individual fingers or fingers and the palm [237]. Finger tip sleeves are mostly focusing on cutaneous feedback to the mechanoreceptors on the users finger tip. These wearable system are able to simulate haptic feedback through indentation [61, 214], skin stretching [233, 150] or vibration [37]. A more recent approach for wearable feedback in mixed reality is the usage of electrical muscle stimulation (EMS) which is capable to create kinesthetic feedback by actuating the users muscles [134, 132, 135]. Most of the here presented systems should conceptually work fine within the *nomadic VR* scenario due to the wearable form factor. However, they are often dedicated devices (e.g., gloves, finger sleeves, EMS pads) that are mainly used to generate feedback. Since current commercial HMDs are often operated via a tracked controller, researchers started to explore the integration of haptic feedback inside of handheld controllers. A big variety of these devices were presented that can simulate cutaneous and kinesthetic feedback such as weight [255], surface texture [13, 241] or a combination of multiple cutaneous and kinesthetic stimuli [44, 221].

A more recent development is the integration of the same concepts that are used in handheld and worn devices into the HMD itself. Sand et al.

presented an array of ultrasonic actuators on the backside of the HMD to create cutaneous feedback on the users hands when conducting gestures [199]. Rietzler et al. presented a modified HMD that can generate short wind bursts around the users head [194]. FacePush modified the straps of the HMD with motors to allow the whole HMD to apply force on the users face to simulate impact (e.g., peeing punched) [33]. Kon et al. used a similar approach of modifying the straps of an HMD to apply pressure precise enough on the users head to trigger the hanger reflex[3] [114]. An often used modification is the cushion between the HMD and the users face. Researchers explored here a variety of stimuli such as EMS [115], temperature [174, 36, 35], suction [101] and a combination of multiple stimuli [249, 79, 173, 248]. This integration into the HMD is a promising direction for the *nomadic VR* scenario since it is an ungrounded feedback working in mobile scenarios and additionally frees the user from carrying extra accessories.

Device free haptic feedback can be divided into passive haptics [86] and pseudo haptics [121]. Both approaches can simulate some form of feedback or the perception of feedback without using additional computer controlled artifacts. Passive haptics leverage physical objects as a surrogate to match the shape, texture and/or weight of a virtual object and was pioneered by Hinckley et al. [86]. Passive haptics is often used for AR applications [107, 256] to substitute the haptic experience of virtual objects with physical objects inside the users environment [85]. A similar approach was also researched in the field of VR by Simeone et al. [212]. However, VR system also have the advantage that the user can not see their physical hands and can therefore be slightly redirected [122] during the interaction to reuse the same physical object to represent multiple virtual objects [9, 40]. Pseudo haptics on the other hand is an approach that leverages vision and haptic illusions [122] to distort haptic perception [121]. A majority of the early presented approaches in the field rely on the concept of visual dominance [180], where the visual sense dominates the haptic perception when the senses are fused [186]. Researchers were able to apply these approaches in VR to simulate stiffness [120], weight [All8][51, 193] and shape [195] of an object. More recently, researchers starting to apply these concepts to the field of AR and were able to manipulate the perception of softness [185] and stiffness [184]. Both device free approaches (passive haptics and pseudo haptics) can be integrated into the *nomadic VR* interaction scenario but have a limited range of haptic sensation capable to create. Therefore, these approaches should be seen as an addition to haptic devices.

3 The hanger reflex is a phenomenon in which the users head can be rotated unintentionally when the right pressure distribution is applied to the head

2.2.3 Context Sensitive Mixed Reality HMDs

One of the major challenges of using HMDs outside of the laboratory is to make them work within the new context they are used in [98, 108, 222, 124, 125, 141, 165, 127]. One of the first approaches to explore the combination of context-aware VR HMDs was presented in 2005 by Jang et al. with the concept of ubiquitous virtual reality (U-VR) [98, 108]. The concept of U-VR was further refined by Lee et al. and defined along three key dimensions (context, reality and activity). These have to be taken into consideration to be able to design VR HMDs experiences working outside of a lab environment [125]. Lee et al. used the reality-virtuality continuum as the axis for the reality component [148] and divided context simply into static/dynamic and activity into personal/social. This definition of U-VR takes a similar approach to this thesis but uses a simpler understanding of the context of interaction (but also emphasizes social interaction as a crucial component). Similar approaches that focus on the context of use were presented in the field of AR [141, 165, 84, 202, 127]. Liberati et al. presented the potential symbiotic effects of combining AR and ubiquitous computing but make a clear distinguishment towards VR. In contrast, this thesis aims to combine all these three seemingly distinguished technologies AR, VR and ubiquitous computing within the umbrella of the Milgram-Weiser continuum. Similar to Schmidt et al. we will split the following related work for context into *human factors* (social environment, user, task) and *physical environment* (conditions, infrastructure, location). As this proposed split of the feature space is only one possible example and has to be further adopted to the particular use-case [204], we will only focus on the relevant features inside the two main categories (*human factors* and *physical environment*).

The two dominantly explored context features in the fields of HMD and *human factors* are the social environment and the user state. For the social environment, researchers explored different forms of co-located collaboration for HMD users in symmetric (HMD to HMD user) [17, 176, 201, 230, 16] and asymmetric (HMD to non-HMD user) [29, 218, 12, 93] scenarios. The Studierstube [201, 230] and "Shared Space" [16] are good examples of AR systems that allow co-located people to interact as long as both wear an AR HMD. These symmetric scenarios were mainly explored in productive and collaborative environments [176]. Early asymmetric systems (e.g., HMD and tablet [48]) also often focus on creating visualization and interaction approaches [218] that would benefit a certain productive task (e.g., creating architecture). Stafford et al. presented something called "god-like interaction" where a non-HMD user could point at a location on a tablet and the HMD user would get a visualization of a virtual finger inside his AR HMD [218]. A similar metaphor was used by Ibayashi for VR HMDs, where multiple non-HMD user could sit around a tabletop and help an HMD user to explore a virtual home [93]. Researchers explored a variety of potential visualizations (e.g., projection [59], desktop [89]) and explored collaboration between AR and VR HMDs [42].

All these systems present a possible solution on how non-HMD and HMD user inside the *social environment* can be included when collaborating on a productive task. However, due to the current distribution but lack of social acceptance [110, 112, 111] of HMDs, more recent research started to apply these approaches to more informal and spontaneous ad-hoc interaction scenarios [45, 213, 197, 196]. Researchers presented HMD prototypes that are designed to enable asymmetric interaction by presenting the virtual world to the non-HMD user [179, 138, 32]. Researchers additionally started to identify and focus on specific asymmetric scenarios that are happening during daily VR HMD usage, such as communicating the boundaries of the virtual space [251], how to approach an immersed HMD user [63] and how do people feel wearing a VR HMD in social and public environments [139, 137]. The goal is mainly to enable the non-HMD user to be able to engage [63] and interact with the HMD user and vice versa to break isolation and exclusion [All4, All12] [Core6, Core5]. Cheng et al. in particular explored how non-HMD users can be integrated and leveraged to generate haptic feedback for the immersed HMD user [38, 39, 41].

Due to the proximity of the HMD to the users face, researchers started to explore additional sensors (e.g., eye tracker [All11][232], single electrodes [14], BCI [211, 210, 58, 5]) that can easily be integrated into an HMD and give additional insights in the current user state (e.g., cognitive demand, attention and facial expression [229, 126]). These systems can be seen as a new form of collecting additional context information about the user state. Overall, all these projects show the potential of how future HMDs could become able to detect and adapt to the *human factors* of the context of usage.

The currently mostly considered and integrated features of the *physical environment* are the condition (e.g., acceleration [244, 144, 169, 77]) and the infrastructure (e.g., structure and shape of the available space [225, 209, 217]). Since the availability of VR HMDs increased, researcher started to explore a variety of non-stationary scenarios where VR HMDs can be used (e.g., driving car [144, 169, 77], airplane [244]). Alongside McGill et al.'s work [144], the *CarVR* system presented in this thesis [Core4] is considered to be the first to research the challenges of using of a mobile VR HMD inside a driving car. The car integration can be divided into research that focuses on enabling the use of VR HMDs inside the car[144, 169, 77] and research that aims to leverage the resulting kinesthetic forces to create more immersive driving simulators [64]. Besides the condition, researchers started to integrate aspects of the infrastructure such as the size and shape of the current physical environment. This allows for passive haptics [212, 209] or be able to align physical and virtual objects [62, 160] in augmented reality applications. Another field of research of VR HMDs that can be used to integrate the infrastructural context is redirected walking [187]. Since the physical space in which VR HMDs are used is not identical with the virtual world, the immersed HMD user is redirected while walking back into the physical space using perceptional illusions [224, 219, 223]. This technique allows to explore a significantly higher virtual environment, while constantly walking inside a constraint physical space [All10].

While a variety of work can already be classified in the field of context aware HMDs, the focus of most of the projects is not in detecting different contexts but more on picking one specific scenario (e.g., non-HMD people in the environment, driving car) and then propose a solution that could potentially resolve the issues inside this context. Future work on HMDs is expected to start to integrate a variety of contexts and also start to explore how these context can be automatically detected and integrated smoothly into the user experience.

3 NOMADIC VIRTUAL REALITY

> *Don't worry about what anybody else is going to do. The best way to predict the future is to invent it.*
>
> — **Alan Kay**

One important aspect of the transition from personal computing to mobile computing was that the context in which the interaction took place started to change drastically between interactions [204]. During the era of personal computing a software designer could be quite sure that the user interacting with his software is going to be seated in front of some kind of stationary display. Mobile computing changed this drastically by being now able to access computing devices in any physical and social context. As a result researchers adapted their understanding and definition of context [200, 49, 206, 204] and extended the interaction paradigm (context-aware computing) to something more implicit [203, 206].

The mobile computing interaction scenario can be conceptually broken down into two states: moving and stationary. Both states have to assume an unknown and changing environment but differ mainly by the mobility of the user. The moving interaction scenario represents a state where the user is moving through the physical environment and during this movement interacts with the technology (e.g., navigation on the phone, phone call). The stationary interaction scenario represents the state in which a user chooses a location, positions himself and then interacts with the technology without leaving the chosen location (e.g., writing a mail on a laptop). This stationary interaction scenario can be deducted from Leonard Kleinrock's work on nomadic computing and is the foundation for nomadic virtual reality. In his original work, Kleinrock presented a distinguishment between mobile computing and nomadic computing. He considered a smartphone to be a mobile device since it can be used in a mobile fashion. A laptop on the other hand is a nomadic device, since the user has to select a location and initiate the interaction stationary.

Nomadic VR can now be defined by combining nomadic computing [109] and nomadic interaction [All4][245] with display devices within the Milgram-Weiser continuum (see Figure 3.1). This distinction between the two states can not only be done for the mobile computing

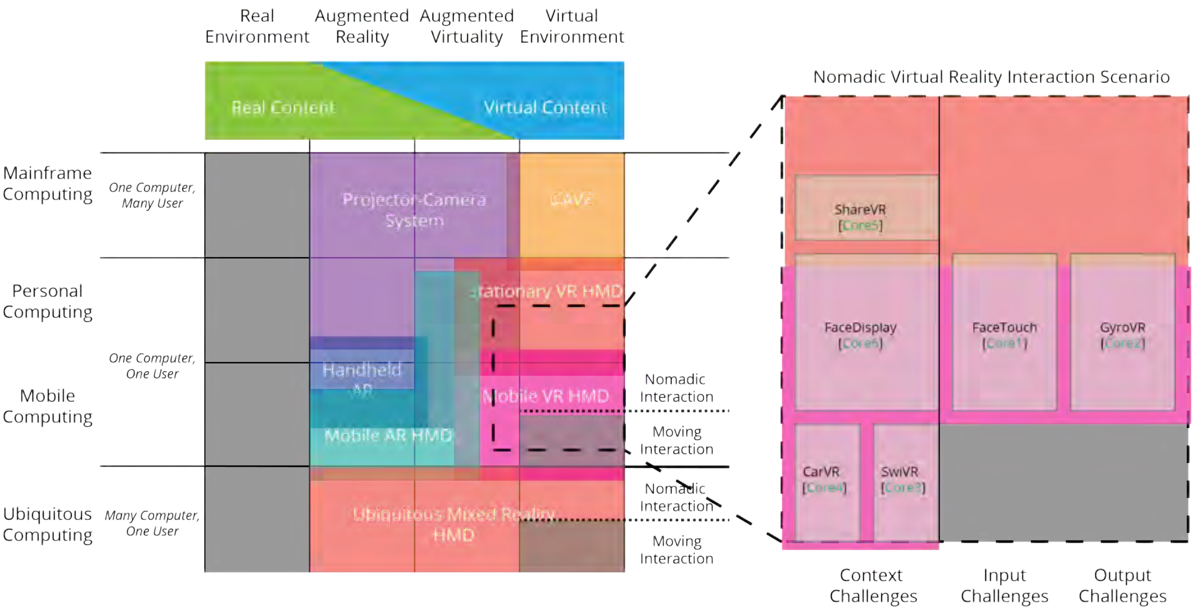


Figure 3.1: Visualizing the conceptual split of mobile computing and ubiquitous computing into nomadic interaction and moving interaction. This conceptual cut allows to position nomadic VR inside the Milgram-Weiser continuum and show its applicability to ubiquitous mixed reality as one interaction scenario (being fully immersed).

but theoretically also for the ubiquitous computing row, since its simply a conceptual division of the interaction scenarios. Its important to notice, that the resulting division in top and bottom half, has no locational meaning in relation to the Milgram-Weiser continuum (e.g., nomadic interaction is not more towards personal computing than ubiquitous computing).

3.1 THE NOMADIC VR INTERACTION SCENARIO

The transition from personal computing to mobile computing was initially aimed to be designed in a transparent way. This meant to offer the user constant functionality without noticing the impact of the context (e.g., having constant access to internet without noticing a change of network towers) [204]. This perspective got changed when Bill Schilit introduced and defined the concept of context-aware computing [200].

> *"Such context-aware software adapts according to the location of use, the collection of nearby people, hosts, and accessible devices, as well as to changes to such things over time. A system with*

these capabilities can examine the computing environment and react to changes to the environment." (Bill Schilit)

This concept of context-aware computing got further formulated by researchers, focusing on a broader definition of context [3, 52, 49, 206] a new interaction paradigm [203, 205, 97] and an overall updated understanding of context-aware computing [172, 34, 204]. In his work on implicit human-computer interaction Schmidt combines the field of HCI with context-aware computing by breaking down interaction between man and machine into three basic components: (1) the input a user can perform, (2) the output a machine can give and (3) the context in which both occurs. Traditional HCI focuses on the first two but context-aware computing uses the third part (context) to influence how both input and output are realized. Schmidt modeled this impact through context as implicit Human-Computer Interaction [203]. The interaction scenario of *nomadic VR* is going to be defined using the same basic components (see Figure 3.2).

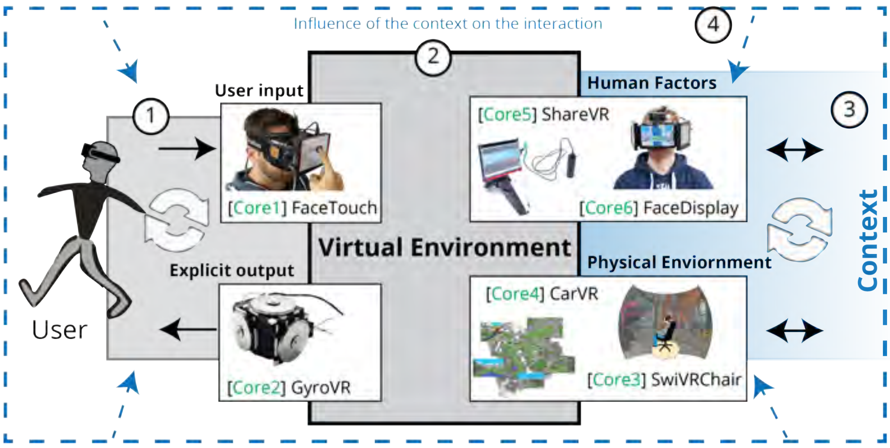


Figure 3.2: The interaction model used in this thesis to visualize the interplay between input, output and context for nomadic virtual reality. The context (4) is hereby enclosing and impacting the virtual environment (2) and the explicit interaction cycle (1). Furthermore, the subdivision of context of Schmidt. [206] into *human factors* and *physical environment* is added to the model (3) to visualize its impact and relationship to the virtual environment (2).

The application scenario for *nomadic VR* is that a user decides to have a fully immersive experience whilst being inside a mobile context. The user then chooses a location to immersive himself and has a semi-stationary experience. During the experience users remain mostly seated. Inside the current landscape of technology and applications this may seem like an unlikely scenario. However, upcoming applications in combination with further progress of technology will create demand for full immersion (e.g., receiving a 360-degree image from a loved one). These applications by themselves will not justify a dedicated *nomadic VR* HMD but will function within the broader vision of ubiquitous mixed reality and this new types of HMDs, capable of both full immersion and partial augmentation.

3.2 INPUT CHALLENGE

Within the interaction scenario of *nomadic VR* (see Figure 3.2), input can be seen as the engagement in selection and/or manipulation of virtual content by the human through any type of device/modality (e.g., physical controller, touch, speech). During the era of mainframe computing and personal computing, input devices and modalities where mainly focused around an indirect input device such as the mouse and had "severe shortcomings when it comes to matching the physical characteristic of their operators" [30]. The transition to mobile computing gave rise to a new device type (mobile phone/smartphone) and its main input paradigm changed from indirect 2D input to direct 2D touch input whilst steadily becoming more multi-modal [234].

As described in chapter 2, HMDs can be viewed as a display device for a new computing paradigm often referred to as spatial computing or mixed reality. As described in the vision of ubiquitous mixed reality, real and virtual objects are expected to occupy the same physical space around the user. The spatial nature and grounding within our physical environment of this computing paradigm resulted in 3D user interfaces and 3D interaction to be the main form of input for VR [21, 24] and AR [256, 107] technology. These 3D interactions are on the one hand beneficial to concepts such as immersion but on the other hand suffer from problems such as fatigue, lack of constraints and lack of precision [22, 24].

The application scenario for *nomadic VR* is that the user is within a mobile context (e.g., commuting home from work) and decides to immerse himself (e.g., experience 360 video content sent by a family member). The input challenge for *nomadic VR* comes with a set of specific requirements for the explicit input technique. Firstly, the input has to be fast and precise and work without additional accessories to free the user from carrying extra devices. Additionally, the input should work within a public/social context where people might be co-locating the environment. Therefore, open and expansive gestures such as often used within traditional 3D UI design might not be appropriate since the user is reaching out into an unknown space that might be occupied by someone in the surrounding. Prior research additionally showed that users dislike performing mid-air gestures in public spaces [104, 26].

Research Question 1: *How to enable fast and precise input for mobile VR HMDs without additional accessories within a nomadic VR interaction scenario ?*

3.2.1 FaceTouch

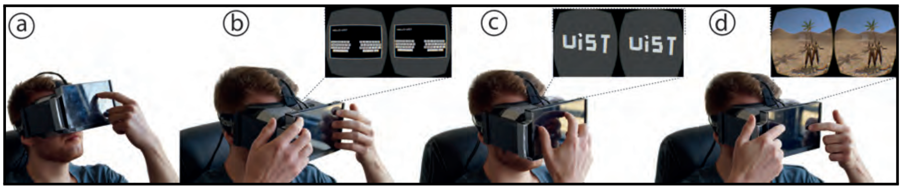


Figure 3.3: (a) A user interacting with FaceTouch, a multi-touch surface mounted on the back of a VR HMD. FaceTouch allows for precise interactions which can be used to implement applications such as text entry (b) or 3D modeling (c). Leveraging the sense of proprioception a user is able to blindly interact with control elements such as used in a gamepad to control a shooter game (d) [Core1].

To allow for this type of input in a *nomadic VR* interaction scenario, we presented *FaceTouch*. *FaceTouch* is a novel interaction concept for mobile VR HMDs that leverages the backside as a touch-sensitive surface. Using *FaceTouch*, the user can point at and select virtual content inside their field-of-view by touching the corresponding location at the backside of the HMD, utilizing their sense of proprioception. This allows for rich interaction (e.g., touch gestures) in *nomadic VR* scenarios without having to carry additional accessories (e.g., a gamepad). To study the precision of such a system, we built a prototype of *FaceTouch* and conducted two user studies. In the first study we measured the precision of *FaceTouch* in a display-fixed target selection task, using three different selection techniques. Our findings showed a low error rate of .2%, indicating the viability for everyday usage. To asses the impact of different mounting positions on the user performance we conducted a second study. We compared three mounting positions of the touchpad (face, hand and side) showing that mounting the touchpad at the back of the HMD resulted in a significantly lower error rate, lower selection time and higher usability. Finally, we present interaction techniques and three example applications that explore the *FaceTouch* design space [Core1].

The contributions of *FaceTouch* are:

- The concept, design and implementation of *FaceTouch*, an interaction technique for mobile VR HMDs allowing for fast and precise interaction inside the *nomadic VR* interaction scenario.

- Insights from two user studies, showing the feasibility of *FaceTouch* for display-fixed user interfaces (n=18) and comparing three different mounting positions of the touchpad (n=18).
- Implementation of three example applications (gaming controls, text input, and 3D content manipulation) to show and explore the possible design space enabled through *FaceTouch*.

3.3 OUTPUT CHALLENGE

Within the interaction scenario of *nomadic VR* (see Figure 3.2), output can be seen as the feedback of the system to the user in any type and combination of modalities. Traditionally, output in computing systems was mainly done through the visual channel and started out as a command line interface. One of the first computing systems that solely relied on a graphical user interface was Sketchpad, presented by Ivan Sutherland in 1963 [226]. Over time additional modalities addressing different senses besides vision were added (e.g., audio).

Compared to the input channel (from indirect input to direct touch input) the output channel did not experience such a strong transformation from the personal to the mobile computing era. Displays got overall smaller and higher in resolution and overall quality, but at their core they still functioned on the same level as in Sketchpad 1963. Information is synthesized and presented on a flat 2D plane. The vision of ubiquitous mixed reality and spatial computing comes with a transformation of the fixed 2D plane to a stereoscopic representation of virtual information to the human eye through an HMD.

One of the big challenges with HMDs is how to incorporate additional haptic feedback that matches the visual perception of this novel stereoscopic representation [85, 148, 253]. Haptic feedback can be conceptually divided into kinesthetic feedback and tactile feedback. Kinesthetic feedback is mainly perceived through tendons and muscles and leverages the sense of proprioception (the ability to blindly locate the position and orientation of limbs towards each other and our body). Tactile feedback is perceived through mechanoreceptors in our skin [70, 80]. Tactile feedback is often generated through devices that have some form of contact to our skin (e.g., vibration feedback on mobile phones). Kinesthetic feedback on the other hand is often generated through mechanical systems that have to be grounded to counteract the force they generate.

We can assume a similar application scenario as presented for the input case. A user is commuting home from work and decides to experience any form of immersive application (e.g., playing a flight game). This immersive application uses currently mainly video and audio as an output channel. To enhance the overall experience in terms of immersion and enjoyment researchers explored how to add tactile feedback (e.g., to feel the wind on the skin when flying) and kinesthetic feedback (e.g., to experience the impeding movements due to wind resistance) to HMDs [192]. However, due to the nomadic interaction scenario its not possible to add any form of grounded kinesthetic feedback generating any form of impedance.

Research Question2: *How to enable kinesthetic feedback for mobile VR HMDs without the need for physical grounding within the nomadic VR interaction scenario ?*

3.3.1 GyroVR

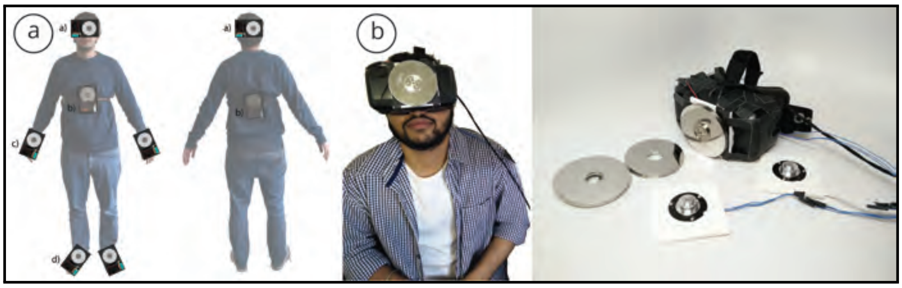


Figure 3.4: (a) The different mounting positions on the human body which were explored with the mobile implementation of GyroVR. (b) A user wearing a VR HMD with GyroVR attached and a prototype implementation of GyroVR attaching flywheels on the front of an Oculus Rift DK2 [Core2].

To generate kinesthetic feedback on HMDs inside a *nomadic VR* scenario we presented *GyroVR*. *GyroVR* is based around head worn flywheels designed to render inertia in Virtual Reality (VR). Motions such as flying, diving or floating in outer space generate kinesthetic forces onto our body which impede movement and are currently not represented in VR. We simulate those kinesthetic forces by attaching flywheels to the users head, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. *GyroVR* is an ungrounded, wireless and self contained device allowing the user to freely move inside the virtual environment. The generic shape allows to attach it to different positions on the users body (Fig. 3.4 a). We evaluated the impact of *GyroVR* onto different mounting positions on the head (back and front) in terms of immersion, enjoyment and simulator sickness. Our results show, that attaching *GyroVR* onto the users head (front of the HMD) resulted in the highest level of immersion and enjoyment and therefore can be built into future VR HMDs, enabling kinesthetic forces in VR [Core2].

The contributions of *GyroVR* are:

- The concept, design and implementation of *GyroVR*, an ungrounded kinesthetic feedback device for mobile VR HMDs inside the *nomadic VR* interaction scenario.
- Exploration and demonstration of the design space through three example applications, each presenting a different mapping between virtual environment and generated forces.
- Insights from first explorations and a user study (n=12) on the impact of kinesthetic forces by head worn flywheels attached to different locations in terms of immersion, enjoyment and simulator sickness.

3.4 CONTEXT CHALLENGE

An early perspective on context was highly location based, where context was mainly considered as the physical location in which an interaction takes place [206]. Personal computers were mostly setup and used inside of offices or factory floors and this locational context did not change much over the duration of usage [204]. With the progress of mobile computing, this context started to change more dramatically between interactions and researcher started to extend the definition of context beyond merely the physical location of the interaction [3, 52, 49, 206].

Anind Dey gave a broader definition of context where he included any information that could characterize the situation [49].

> *"Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application themselves."* (Anind Dey)

Keith Mitchell [153] and Albrecht Schmidt [206] proposed a hierarchical structure of the context and further proposed a possible division into the physical environment and human factors. This two level categorization of context can then in a next step be further divided into three categories each. This more holistic definition and categorization of context showed how the perspective onto context-aware computing changed. Initially, context was treated as something that should be unnoticeable inside the application (same experience everywhere). This perspective changed more towards leveraging the context as an implicit form of interaction [203, 205, 97].

For the scope of this thesis, a similar division into *physical environment* and *human factors* was applied and two case studies were conducted within each type of context. However, the focus was mainly on exploring how to handle context and not on how to detect the context.

Physical Environment The physical environment can be further divided into conditions, infrastructure and location. The physical conditions describe aspects such as noise, light or pressure. The infrastructure describes aspects such as surrounding resources and the location describes aspects such as the absolution position or relative position.

The application scenario that was presented earlier (commute in public transport and immerse during the ride) presents a good example scenario where the context changed compared to stationary HMDs and presents a challenge for the usage. Using a VR HMD inside a moving vehicle creates the problem that the rotational sensor of the HMD can not distinguish between rotations of the vehicle and rotations of the user. Additionally, perceived motion through the vehicle can create a mismatch with the visual stimulus and lead to simulator sickness [144].

Research Question 3: *How to enable the usage of mobile VR HMDs inside of moving vehicles (e.g., car) and avoid simulator sickness ?*

3.4.1 CarVR

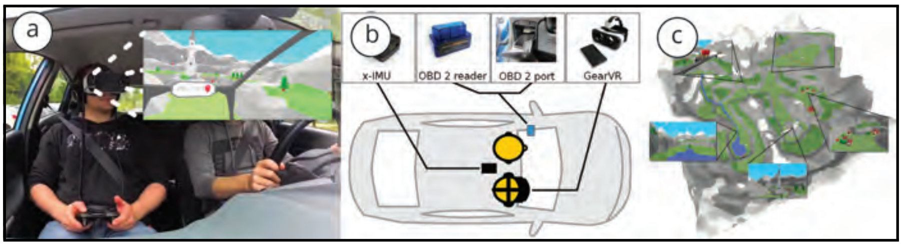


Figure 3.5: (a) A user interacting with CarVR on the front passenger seat playing a game while the car is moving. (b) Schematic overview of the technical setup used to implement CarVR. (c) The modeled scene used for the study. The five small images show the view from the ego perspective but without the cockpit [Core4].

The earlier presented example of commuting and experiencing VR is currently not possible, since the car's rotation affects the HMD's sensors and simulator sickness occurs when the visual and vestibular system are stimulated with incongruent information [113]. In this case study we present *CarVR*, a solution to enable VR inside moving vehicles by subtracting the car's rotation and mapping vehicular movements with the visual information. Creating this mapping, allows the user to feel the correct kinesthetic forces that arise during the VR experience. We compared *CarVR* in a user study (n=21) in a driving and standing condition, showing that the alignment of forces lead to a significant increase of enjoyment and immersion, while reducing simulator sickness. We further explore the design space of in-car VR entertainment applications and derive design guidelines and considerations for practitioners [Core4].

The contributions of *CarVR* are:

- The concept, design and implementation of *CarVR*, a modified mobile VR HMD to enable VR inside moving vehicles.
- Insights from a user study (n=21), showing significantly higher levels of enjoyment and engagement while having reduced simulator sickness using *CarVR* compared to a stationary baseline
- Exploration of the design space of in-car VR entertainment applications and providing a set of design considerations for practitioners.

The second case study within the physical context focuses on the infrastructure. The infrastructural aspect of the context explains the surrounding resources available. In a typical application scenario of *nomadic VR*, the user interacts in a seated position. Since the virtual environment fully surrounds the user (360-degree), swivel chairs are a preferred seating accommodation due to their ability of rotating 360-degrees effortlessly. In the following work, we explored how to leverage and integrate these potential infrastructural aspects into the virtual experience.

Research Question 4: *How to incorporate resources inside the physical environment to enhance the experience inside the virtual environment ?*

3.4.2 SwiVRChair

In this case study, we present the integration of a modified swivel chair into the virtual experience of a VR HMD user. *SwiVRChair* is a motorized swivel chair to nudge users' orientation in 360-degree storytelling scenarios. Since rotating a scene in virtual reality (VR) leads to simulator sickness, storytellers currently have no way of controlling users' attention. *SwiVRChair* allows creators of 360-degree VR movie content to leverage infrastructure in the physical enviornment and be able to rotate or block users' movement to either show certain content or prevent users from seeing something. To enable this functionality, we modified a regular swivel chair using a 24V DC motor and an electromagnetic clutch. We developed two demo scenarios using both mechanisms (rotate and block) for the Samsung GearVR and

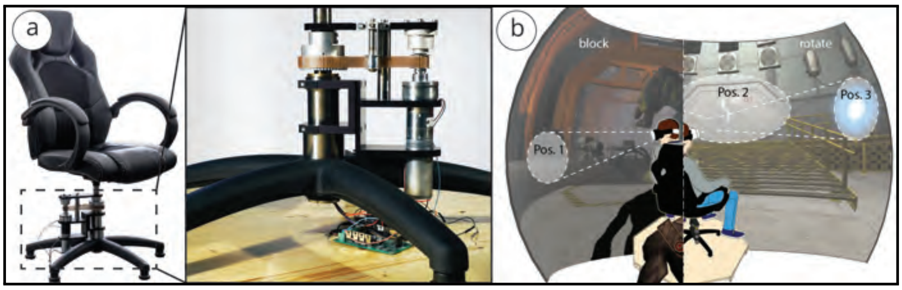


Figure 3.6: (a) The physical prototype of the *SwiVRChair* consisting of a motor and clutch attached to the chair shaft. (b) The virtual scene used in the study, showing two interaction concepts block and rotate. Block: The user is turned away from the monster (Pos.1) and only sees its shadow in front of them. The user can either accept this or fight the blockage using his feet to turn the chair. Rotate: The user is guided through the scene and certain content such as the purpose of the door (Pos.2) is explained in more detail. In case the user gets bored, he can start turning away from the current content [Core3].

conducted a user study (n=16) evaluating the presence, enjoyment and simulator sickness for participants using *SwiVRChair* compared to self control. Users rated the experience using *SwiVRChair* to be significantly more immersive and enjoyable whilst having a decrease in simulator sickness [Core3].

The contributions of *SwiVRChair* are:

- The concept and implementation of *SwiVRChair*, a motorized swivel chair to nudge users' orientation in 360-degree
- Findings of our user study (n=16), showing a significant increase of enjoyment and presence while reduced simulator sickness compared to a conventional swivel chair.

Human Factors The human factors can also be further divided into user, social environment and task. The information on the user consists of aspects such as emotional state or physiological data. The social environment consists of information on co-location of others, social interactions and group dynamics, whereas the task carries information about the nature of the activity (e.g., spontaneous) the engaged tasks and the general goals [206, 204].

The close proximity of an HMD to the users facial area enables a new variety of approaches and sensors to collect additional information about the user. More recent research in the field of AR and VR HMDs started to explore how to attach sensors on the contact surface between face and HMD to get access to physiological data [14]. Upcoming HMDs are also expected to come equipped with eye-tracking technology to allow for interaction but also collect additional physiological data [88]. In terms of the social environment, a wide range of work was conducted focusing on collaboration between co-located users in AR and VR, but with a strong focus on having access to the same technology [17, 16, 201, 230].

Assuming that every user in the social environment has access to a VR HMDs is currently unrealistic and should also not be necessary to be able to understand an interaction inside the *nomadic VR* interaction scenario. This results in a current scenario where VR HMDs are getting rarely used during social gatherings and more when the user is by himself [Core5]. To be able to let people without a VR HMD in the social environment understand and even participate in an interaction with a VR HMD user, some form of alternative representation and interaction concept has to be designed which leads to an asymmetry of experience.

We started out to explore this asymmetric interaction inside a stationary home scenario first. The following case study focuses around a living room entertainment system based on a VR HMD that aims to allow to include everyone inside the social environment in the experience.

Research Question 5: *How to allow people without a VR HMD, inside of the social environment of a VR HMD user, to understand and interact with the virtual world of the immersed user ?*

3.4.3 ShareVR

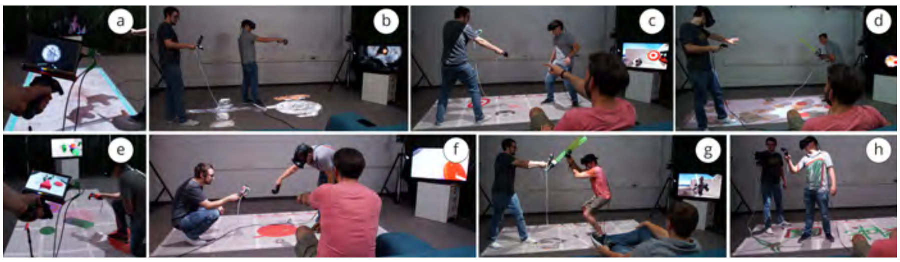


Figure 3.7: The ShareVR prototype, enabling co-located asymmetric interaction between users wearing an HMD and users without an HMD. ShareVR uses a tracked display (a, e) as a window into the virtual world and a floor projection to visualize the virtual environment to all Non-HMD users. It enables collaborative experiences such as exploring a dungeon together (b), drawing (h), sports (c) or solving puzzles (e, f) as well as competitive experiences such as "Statues" (d) or a sword fight (g). ShareVR facilitates a shared physical and virtual space, increasing the presence and enjoyment for both HMD and Non-HMD users [Core5].

In this case-study we proposed *ShareVR*, a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for the Non-HMD user, enabling them to interact with the HMD user and become part of the VR experience. We designed and implemented *ShareVR* based on the insights of an initial online survey (n=48) with early adopters of VR HMDs. We ran a user study (n=16) comparing *ShareVR* to a baseline condition showing how the interaction using *ShareVR* led to an increase of enjoyment, presence and social interaction. In a last step we implemented several experiences for *ShareVR*, exploring its design space and giving insights for designers of co-located asymmetric VR experiences [Core5].

The contributions of *ShareVR* are:

- Concept, design and implementation of *ShareVR*, a proof-of-concept prototype based on user feedback (n=48), enabling people in the social environment without an HMD to become part of the virtual experience.
- Insights from a user study (n=16), showing the impact of *ShareVR* on enjoyment, presence and social interaction compared to a baseline (gamepad + television).
- Presenting three example applications to explore the design space of co-located asymmetric VR experiences and deduct a set of further guidelines for designers and practitioners.

After this stationary and domestic scenario was used in *ShareVR*, the next case study aimed to explore how a similar result can be achieved without the need to instrument the environment (e.g., projector, external tracker). This fits more the *nomadic VR* interaction scenario where a user moves to a public space (e.g., commute home from work in public transport). At the current state of technology, a user would completely isolate himself from other people and also start to act in an unpredictable manner, since it is not clear what the user perceives visually.

Research Question 6: *How to design a mobile VR HMD that allows non-HMD users to perceive the virtual environment and be able to interact with the HMD user ?*

3.4.4 FaceDisplay

This case study presents *FaceDisplay*, a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back. People in the surrounding can perceive the virtual world through the displays and interact with the HMD user via touch or gestures. To further explore the design space of *FaceDisplay*, we implemented three applications (FruitSlicer, SpaceFace and Conductor) each presenting

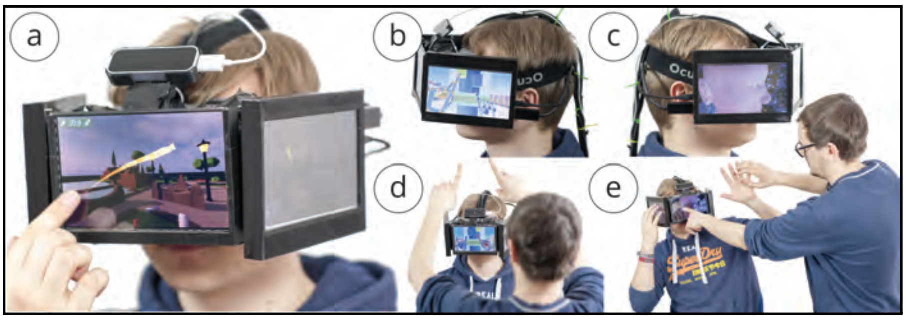


Figure 3.8: The FaceDisplay prototype, a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back (a-c). This allows people in the surrounding to perceive the virtual world through the displays and interact with the HMD user either through touch (e) or gestures (d) [Core6].

different sets of aspects of the asymmetric co-located interaction (e.g., gestures vs touch). We conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications and showing a high level of enjoyment and social interaction with and without an HMD. Based on the findings we derive design considerations for asymmetric co-located VR applications and argue that VR HMDs are currently designed having only the HMD user in mind but should also include Non-HMD Users [Core6].

The contributions of *FaceDisplay* are:

- The concept, design and implementation of *FaceDisplay*, a modified mobile VR HMD to include non-HMD users into the virtual experience inside a *nomadic VR* interaction scenario.
- Exploring two different interaction modalities (gesture and touch) through three example applications – each presenting multiple aspects of this novel design space.
- Insights from an exploratory evaluation (n=16), showing the implications of *FaceDisplay* on enjoyment, presence, social interaction and discomfort.

These six case studies built the foundation of this dissertation. They each focused on one particular challenge within the scope of *nomadic VR*. The following chapter will present and discuss the findings of each case study individually and consecutively derive three overall insights arising from this thesis.

4 FINDINGS AND IMPLICATIONS FOR VR HMDS

> *The most important thing about a technology is how it changes people.*
> — **Jaron Lanier**

This chapter divides the findings of this thesis into two parts. The first part focuses around answering the research questions proposed in the prior chapter and provides the findings of each individual case study done within the scope of this thesis. The second part presents three overarching findings that resulted not out of one specific research questions but emerged throughout the whole process of the thesis.

4.1 RESEARCH QUESTIONS

4.1.1 Input

Research Question 1: *How to enable fast and precise input for mobile VR HMDs without additional accessories within a nomadic VR interaction scenario ?*

To enable fast and precise input for mobile VR HMDs without the need for additional accessories, we proposed the *FaceTouch* system. *FaceTouch* leverages the backside of the HMD as a touch sensitive surface and should be treated as an additional interaction modality when more immersive spatial input is not desirable (e.g., unknown and public environments [104, 26]). We designed *FaceTouch* to fit into the demand of future *nomadic VR* applications such as quick access to pointing interaction for navigating menus and avoiding expansive gestures to protect the user from reaching into an unknown space. We explored the design space and validity of the approach by implementing three different selection modes (LandOn, LiftOff , PressOn [Core1]) and conducting two user studies (n=18) evaluating accuracy, efficiency and user satisfaction.

In a first user study, we have demonstrated the viability of *FaceTouch* for display-fixed UIs using LiftOff for precise interactions such as text entry and LandOn for fast interactions such as game controllers. We further revealed important insights into the design aspects of *FaceTouch* like the right distance to display content, impacts of various input methods (LandOn, LiftOff , PressOn [Core1]) and resulting overshooting behavior. Further, we provided optimal target sizes for implementing UIs for LandOn interaction. Our second user study compared the mounting position for the touchpad and their impact onto the performance of the interaction. We showed that mounting the touchpad on the face resulted in a significant lower error rate for LandOn (8% less than hand and 29% less than side) and LiftOff (2% less than hand and side) and the fastest interaction (LandOn .96 s and LiftOff 1.78 s) [Core1].

4.1.2 Output

Research Question2: *How to enable kinesthetic feedback for mobile VR HMDs without the need for physical grounding within the nomadic VR interaction scenario ?*

To demonstrate how kinesthetic feedback can be generated without the need for physical grounding, we presented the *GyroVR* system. *GyroVR* consists of a flywheel attached to the back of a VR HMD allowing to impede the motion of the user to simulate inertia. We presented the design and implementation of *GyroVR* and explored different mounting techniques and their perceived forces. In a preliminary user study (n=12) we were able to explore the impact different mounting positions have on immersion, enjoyment and simulator sickness. Overall, participants reported they enjoyed the concept despite a certain base level of simulator sickness. Even though the user study did not quantitatively show a clear benefit for immersion, engagement and enjoyment when using *GyroVR*, a possible trend does exist. This warrants further testing with a larger sample size to determine if the trend truly indicates significance. We additionally implemented and presented three example applications that further present the potential design space and different concepts of mapping the force inside of the virtual environment. Our results give a first understanding of the implications of attaching a flywheel to the back of a VR HMD to enable kinesthetic forces for mobile VR HMDs without the need for physical grounding [Core2].

4.1.3 Context

Research Question 3: *How to enable the usage of mobile VR HMDs inside of moving vehicles (e.g., car) and avoid simulator sickness ?*

To explore how mobile VR HMDs can be used and leveraged inside of a moving car, we presented the *CarVR* system. *CarVR* is a prototype consisting of a mobile VR HMD, an external inertial measurement unit (IMU) and an on-board diagnostics (OBD) reader. By collecting the rotational information of the car using the IMU and combining it with the acceleration from the OBD reader, we were able to align the virtual world with the physical forces and thereby resolving the conflict between visual and vestibular information. In a user study (n=21), we compared the *CarVR* inside a moving vehicle to the baseline condition of having no kinesthetic forces (standing vehicle). Our results showed that the perceived kinesthetic forces in the driving condition were able to significantly increase enjoyment and immersion while significantly reducing simulator sickness. We further presented a set of design considerations for designing in-car VR entertainment applications for designers and practitioners [Core4].

Research Question 4: *How to incorporate resources inside the physical environment to enhance the experience inside the virtual environment ?*

To demonstrate how common objects in the physical environment (e.g., office chair) can be embedded into the virtual world to enhance the experience, we presented *SwiVRChair*. *SwiVRChair* is a motorized office chair that is capable of rotating the user towards a certain direction and additionally block a users rotation. In this case study we showed that everyday objects can be incorporated through a slight modification with actuators (motor and clutch), sensors (AS5047D rotary sensor) and a careful design of the virtual environment around the included object. *SwiVRChair* was embedded into a story telling context, allowing to nudge a user's attention towards virtual content and thereby empowering the content creator to have control of the current view of the user. By using a physical rotation instead of a virtual rotation of the camera we were able to avoid simulator sickness. In a preliminary user study (n=16) we were able to show that using the *SwiVRChair* system compared to virtual rotation, participants experienced significantly higher immersion and enjoyment while having a reduction of simulator sickness (not statistically significant). Additionally, we found that it was important to keep some abilities (e.g., manual rotation) of the integrated object to not break the mental model of interaction (putting my feet on the ground and rotate) of the user.

The overall very low simulator sickness in both conditions of the *SwiVRChair* system was a surprising outcome. We partially explain this effect with the overall lower head movement of the participants using *SwiVRChair*. Participants were more "leaning back" and enjoying the experience and did not have the pressure of having to explore the whole environment to "not miss anything". While we offered the ability of always breaking free of the chair's movement, participants often did not see the need for it, since they got directed towards the relevant content. This case study showed how resources in the physical environment can be incorporated to enhance virtual experience of the user [Core3].

Research Question 5: *How to allow people without a VR HMD inside of the social environment of a VR HMD user to understand and interact with the virtual world of the immersed user ?*

To explore how people without a VR HMD (non-HMD user) can be integrated in a meaningful way into a VR experiences, we presented *ShareVR*. *ShareVR* is a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for non-HMD users and enable them to interact with the HMD user and become part of the VR experience. We designed and implemented *ShareVR* based on the feedback of early adopters (n=48) of VR technology. We implemented three experiences for *ShareVR* which each explore a different aspect of the novel design space. In a next step we conducted a user study (n=16) comparing *ShareVR* to a baseline condition (TV + gamepad) showing its advantage in terms of enjoyment, presence and social interaction. We found that the physical interaction with *ShareVR* not only increased the enjoyment for the non-HMD user but also for the HMD user. This shows that the integration of non-HMD users does not only help to include people in the virtual environment but also increases the overall experience of the HMD user. In a final step we conducted a short exploratory evaluation (n=6) which we used to help us explore the design space of *ShareVR* and give insights and guidelines for designers of co-located asymmetric VR experiences. [Core5].

Research Question 6: *How to design a mobile VR HMD that allows non-HMD users to perceive the virtual environment and be able to interact with the HMD user ?*

To explore an appropriate design for mobile VR HMDs that are capable of incorporating non-HMD users, we presented *FaceDisplay*. *FaceDisplay* is a mobile VR HMD prototype consisting of three touch sensitive displays and a depth camera attached to its back. *FaceDisplay* enables people in the surrounding to perceive the virtual world through the displays and interact with the HMD user via touch or gestures. We presented three applications (FruitSlicer, SpaceFace and Conductor), each focusing on one specific aspect of the asymmetric co-located interaction. We further conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications. Our results showed that *FaceDisplay* was able to let the Non-HMD User perceive and interact with the HMD User but resulted also in a high level of dominance and responsibility of the Non-HMD User over the HMD User [Core6].

4.2 IMPLICATIONS FOR HMDS

Besides the answers to the research questions and as one additional overall contribution of this thesis, three implications for the design of VR HMDs are presented. These insights were developed throughout the whole duration of the thesis and mainly arised through observation and exposure of users and as a direct conclusion of presented findings of this thesis.

4.2.1 Social Co-located Virtual Reality

At the time of writing, VR HMDs are mainly optimized for the wearer and ignore everyone else in the surrounding and result in little usage of the technology within social and public spaces [Core5]. As part of the *ShareVR* project, we conducted an online survey (n=48) with early adopters on the online forum Reddit. The survey focused in parts on the current coping mechanisms when one VR HMD is shared by multiple people. When asked about their social coping, respondents agreed (48%) to prefer traditional consoles over VR HMDs when friends are around and would invite friends over more often (52%) for gaming sessions if there would be a better way of playing together having one HMD. Furthermore, respondents agreed that they would not mind being a passive observer (58%) and can imagine having fun playing with another person with an HMD whilst not having an HMD themselves (71%) [Core5].

The main issue here is that HMDs are currently still being designed as if they will be used alone in a living room. Since HMDs are inherently visually exclusive (only the wearer can see the virtual world), the technology lacks the usage in social situations where multiple people are present. This highly impedes the adoption and distribution of the technology because users prefer to use VR when they are alone.

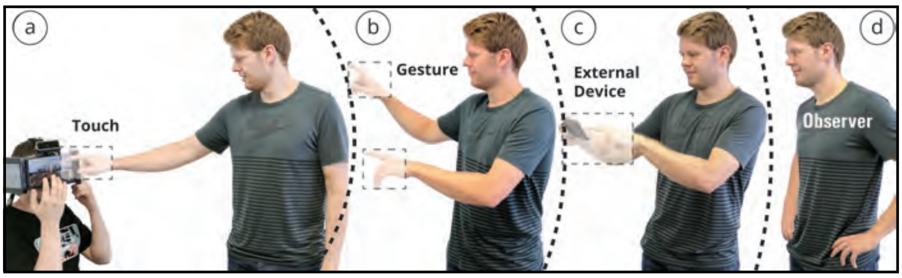


Figure 4.1: The interaction gradient for FaceDisplay. Starting from the most engaged (a) touch to (b) gesture, (c) external device and (d) observing [Core6].

One of the main arguments of this thesis is that VR HMDs can become more socially accepted and even socially engaging if the technology will start to consider its full social context of use. This change of the design perspective has to be done in hardware and software. On the one hand the hardware should support possibilities to visualize the virtual world to non-HMD users but also allow for some form of interaction of non-HMD users. On the other hand the experiences have to be designed in a form that non-HMD users can potentially become a part of the experience in either a passive (observer) or active form. This addresses both challenges that were identified in this thesis that currently impede VR HMD usage in social contexts, namely *exclusion* of the non-HMD user and *isolation* of the HMD user. This thesis presents two approaches on how to build an "inclusive" VR experiences for stationary [Core5] and mobile [Core6] VR HMDs. In this context we further presented an interaction gradient (see Figure 4.1) which covers several levels of engagement. This thesis proposes, that to battle *exclusion* of non-HMD users, VR HMDs have to provide at the minimum the ability to observe some abstraction of the virtual world in any form. To further battle *isolation* of the HMD user, the VR HMDs have to provide some form of interaction and manipulation of the virtual world by the non-HMD users. This allows the non-HMD user to interact with the HMD and even resulted in a significantly increased level of engagement for the HMD user when this interaction had a physical component (e.g., touching the HMD user, sharing the same physical space) [Core5]. Both projects (*ShareVR* and *FaceDisplay*), further showed how the asymmetry of the interaction can be leveraged inside the design of the experience to result in highly different but highly enjoyable experiences that exploit the individual strength of each role. Even if one could make the argument that in a future everyone is going to wear HMDs, there still will be a division between immersed and non-immersed users. Not everyone will be part of my virtual experience but still stand next to me observing my actions in some form. My world and my actions have to be presented to the non-immersed user in some form or another to be able to avoid these pitfalls of *exclusion* and *isolation*. To explore this future research direction and start a community within the field of HCI, a workshop was organized at CHI 2019 focusing on the topic of *Challenges Using Head-Mounted Displays in Shared and Social Spaces* [All12].

4.2.2 Physical Environmental Context as an Opportunity

Similar to the human factors of the context, the physical environmental factors are currently often ignored in most designs of VR HMDs and their experiences. Most HMDs are still designed to be mainly operated in a traditional home setting. One of the first challenges here is to handle the physical environment in a form that it does not interfere with the experience (e.g., using a VR HMD inside a moving vehicle results in involuntarily rotational inputs). This first step could detect the physical context and cope with it to allow for a similar experience as in stationary settings. However, similar to the progress of smartphones, the physical environment should not only be coped with but can actually be leveraged to enhance the overall experience. Similar to the rise of location based services, VR HMDs can embrace and incorporate factors of the physical environment to either address inherent problems of the technology (e.g., simulator sickness) or enhance the overall experiences (e.g., incorporate kinesthetic forces from motion of the physical environment). To be able to achieve these types of experiences the physical environment has to be sensed and be in constant communication with the virtual world as already presented in visions of Ubiquitous Computing and the Internet of Things. This combination would be one step forward towards the vision of ubiquitous mixed reality as defined and presented within this thesis.

To explore the potential of this approach, we presented two projects in this thesis showing how to build and design VR applications inside moving vehicles (*CarVR*) and how to leverage parts of the infrastructure inside of a virtual environment (*SwiVRChair*). Both projects had to face the initial challenge on having to instrument the environment with additional sensors to have highly accurate measures of the rotation of the chair (magnetic rotary position sensor) or orientation and speed of the car (inertial measurement unit and OBD reader). Having these measurements allows either to correct or even incorporate the associated motion inside the virtual world. The project *CarVR* was able to not only compensate the issues arising from the physical environment (motion of the vehicle) but actually designed the VR experience around this motion to leverage it. This allowed for solving the conflict between the visual and vestibular system and subsequently reduce simulator sickness significantly [Core4]. A similar effect was also achieved in the *SwiVRChair* project. Both projects used a one to one mapping of the physical environment and the corresponding virtual representation (e.g., a 90 degree right turn in the physical world was also represented as a 90 degree right turn in the virtual world). However, prior work already showed that while immersed in a virtual world a user can not perfectly distinguish his real physical motion if a different virtual motion is shown (e.g., a 45 degree physical turn could be represented as being a higher degree virtual turn) [9, 40, 27]. This effect allows to design virtual experiences that do not have to perfectly match the forces in the physical environment.

4.2.3 The Unfinished Device Type

This thesis was referring to the parallels between the evolution from stationary VR to mobile VR and the evolution of stationary personal computers to mobile devices. Following this parallel we can compare the first smartphone (IBM Simon or Nokia 9000 Communicator [243]) to the recent consumer oriented HMDs (Oculus Rift, HTC Vive, PSVR). This comparison enables a glimpse into the potential transformation lying ahead of current VR HMDs. Comparing the sensors and actuators of the first smartphones shows a lack of technology that is currently considered an essential part of a smartphone (e.g., camera, IMU, accelerometer, proximity sensor, vibration motor, speaker). Applying this perspective to current mobile VR HMDs we can assume that we are working with an unfinished and transforming device type.

Potential extensions are already explored where the proximity of the technology to the human face can be leveraged to collect unobtrusive physiological data (e.g., eye tracker [All11], skin conductance [14]) or give additional feedback in the facial area (e.g., heating [174], vibration and EMS [249], kinesthetic feedback [Core2]). This thesis proposed several additional extensions of the HMD to either allow for a novel form of input (*FaceTouch*), a new type of feedback (*GyroVR*) and a new form of communicating the content that is presented inside the virtual world to outside users (*FaceDisplay*). All these projects were designed with the constraint of being part of a mobile VR HMD and not function as additional or separate hardware. This further justifies the engineering research approach applied to current HMDs and should not be dismissed as "tinkering", since similar approaches in early mobile computing research were able to predict future extensions such as a rotational sensor [206, 87].

> *"In this demonstrator, the orientation of the user interface is adapted to the orientation of the device: if the device is held upright the user interface is displayed in the usual portrait mode, if it is turned sideways the user interface is switched to landscape mode [...]"* (Schmidt et al. "More to Context then Location" - 1999)

In his work, Schmidt et al. predicted the benefits of automatically rotating the screen of a mobile device, based on the rotation it was hold in [206]. Similarly, Hinckley et al. showed in his work *Sensing Techniques for Mobile Interaction* a variety of sensing capabilities (e.g., proximity sensor, accelerator) and how they can be incorporated into future mobile devices to achieve new types of interactions (e.g., powering up the device when a user picks it up) [87]. Some of these modifications seemed initially to solve a non-existing problem, but became an integral part of current mobile devices due to the usability benefits they provided on a daily basis.

5 CONCLUSION

> *You'll never stumble upon the unexpected if you stick only to the familiar.*
> — **Ed Catmull**

This thesis presented and explored *nomadic VR*, a new interaction scenario focusing on a stationary usage for mobile VR HMDs in public and social spaces. The interaction scenario was further embedded in a larger vision of ubiquitous mixed reality, based on the Milgram-Weiser continuum (a combination of Milgram et al.'s reality-virtuality continuum and Mark Weiser's ubiquitous computing). The thesis draws a parallel between the transformation of stationary VR HMDs to mobile VR HMDs and the transformation of personal computers to mobile phones. The transformation of the personal computers was strongly influenced by the changing context of usage and was partially explored in the research field of context-aware computing. Drawing from these parallels, the thesis took a similar approach and explored the *nomadic VR* interaction scenario along three different challenges (*input*, *output* and *context*).

For each of these challenges, case studies were presented that each consisted of the design, implementation and evaluation of a potential extension for mobile VR HMDs. The *input* was extended via a touch sensitive input on the back of the HMD allowing the user to point at and select virtual content inside their field-of-view by touching the corresponding location at the backside of the HMD. To enable ungrounded kinesthetic feedback (*output*), *GyroVR* attached flywheels to the back of an HMD, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. The *context* was explored from a human perspective and a physical environment perspective. For the human perspective the thesis presented two prototypes that visualized the virtual world to non-HMD users in the environment either via projection or via displays attached to the HMD. For the physical environment, the thesis showed two use cases how external physical motion can be included into the virtual world and leveraged to reduce simulator sickness and increase immersion and presence.

Overall, the thesis makes an argument that *nomadic VR* will be one specific interaction scenario in a future where HMDs will be capable of both augmented reality and virtual reality. In this future scenario, the hard boundaries between virtual and augmented reality HMDs will become blurred and users will not actively choose to use AR or VR but will rather focus on the underlying task which then implicitly will operate somewhere on Milgram's reality-virtuality continuum. To achieve this future, AR and VR HMDs will have to merge and go through a similar transformation as personal computers did when they in parts evolved into smartphones.

5.1 LIMITATIONS

All of the studies were mostly conducted inside a laboratory setting. This allows to create a fully controlled setup and increases the internal validity of the findings [90, 145] but reduces the external validity [167]. This methodology was necessary, since most of the projects consisted of a custom hardware prototype that could not be operated outside of the laboratory. This resulted also often in prototypes that were mainly optimized for the user study and had several impediments (e.g., weight). Additionally, the distribution of HMDs is currently not wide enough to be able to conduct "in the wild" experiments as previously done with smartphones. To be able to understand and discuss these unique challenges arising from HMDs leaving the laboratory and being used in social and public spaces, a workshop was organized and held at CHI 2019 in Glasgow called *Challenges Using Head-Mounted Displays in Shared and Social Spaces* [All12]. The main goal was to discuss and start a research agenda inside the scientific community about HMDs being operated in public and social spaces.

Each presented case study of this dissertation is only one possible approach of handling the specific challenge (*input*, *output* and *context*) inside the *nomadic VR* interaction scenario. Each approach was implemented and evaluated, but could have been addressing each challenge in a variety of different ways (e.g., enabling *input* using an HMD-integrated BCI). The purpose of these case studies was not to solve each challenge in a final way, but should rather be seen as a first exploration of each challenge to find and understand individual characteristics. Additionally, only a subset of the possible factors inside the *context* were explored. The selected factors were the ones considered to be able to nicely span and present the whole design space of the *nomadic VR* interaction scenario. Having said that, there is still potential in exploring different factors (e.g., sensing the user state) in future work.

5.2 FUTURE WORK

Inclusive AR HMDs

The focus of this thesis was on presenting and exploring *nomadic VR*, a new interaction scenario for mobile VR HMDs. The two identified issues inside the social context were: *exclusion* of non-HMD users and *isolation* of the HMD user. These two, do not only occur for VR but can also be expected to occur for AR in a slightly different form. When an AR HMD user is interacting with virtual content in front of him, all non-HMD users in the environment are similarly excluded as for VR HMDs. The *isolation* challenge for AR HMDs is more subtle, since the wearer is able to see non-HMD users and the surrounding environment. Nevertheless, being the only person in the environment capable of seeing certain digital content can create a different form of *isolation*. Similar to *FaceTouch* [Core1] and *ShareVR* [Core5], future projects could explore how current AR HMDs can be enhanced to include people without an HMD into the interaction.

Social HMDs for Co-Located Communication

A different upcoming research direction for HMDs, occurs on the intersection of social science, psychology and computer science. We can already observe the potential impact smartphones can have on social gatherings (e.g., phubbing[1]). Believing the argument, that HMDs will become the dominant computing platform in the future, we can start asking the question on how constant access to digital information in our visual field will impact our co-located social interactions. Realizing that this potential future changes the interaction paradigm of co-located scenarios from a pure human-human interaction to a human-computer-computer-human interaction, allows us to start designing devices in a form that they won't impose breaks in a conversation, but rather enhance our co-located communication [All6]. This could be possible to achieve if the technology would be designed using insights and approaches from the field of computer-supported collaborative work [56].

1 The term 'phubbing' was coined by the Macquarie Dictionary and describes 'The act of snubbing someone in a social setting by looking at your phone instead of paying attention' [242]

BIBLIOGRAPHY

[1] Virtual reality — definition of virtual reality by merriam-webster. https://www.merriam-webster.com/dictionary/virtual%20reality. (Accessed on 12/09/2019).

[2] Oculus rift, Feb 2019. (Accessed on 03/04/2019). URL: https://en.wikipedia.org/wiki/Oculus_Rift.

[3] Gregory D. Abowd, Anind K. Dey, Peter J. Brown, Nigel Davies, Mark Smith, and Pete Steggles. Towards a better understanding of context and context-awareness. In *Proceedings of the 1st International Symposium on Handheld and Ubiquitous Computing*, HUC '99, pages 304–307, London, UK, UK, 1999. Springer-Verlag. URL: http://dl.acm.org/citation.cfm?id=647985.743843.

[4] Mariano Alcañiz and Beatriz Rey. New technologies for ambient intelligence. *Ambient Intelligence*, 3:3–15, 2005.

[5] Judith Amores, Xavier Benavides, and Pattie Maes. Psychicvr: Increasing mindfulness by using virtual reality and brain computer interfaces. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '16, pages 2–2, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2851581.2889442, doi:10.1145/2851581.2889442.

[6] Ferran Argelaguet and Carlos Andujar. A survey of 3d object selection techniques for virtual environments. *Computers & Graphics*, 37(3):121 – 136, 2013. URL: http://www.sciencedirect.com/science/article/pii/S0097849312001793, doi:https://doi.org/10.1016/j.cag.2012.12.003.

[7] Daniel Ashbrook, Patrick Baudisch, and Sean White. Nenya: Subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 2043–2046, New York, NY, USA, 2011. ACM. URL: http://doi.acm.org/10.1145/1978942.1979238, doi:10.1145/1978942.1979238.

[8] Takumi Azai, Shuhei Ogawa, Mai Otsuki, Fumihisa Shibata, and Asako Kimura. Selection and manipulation methods for a menu widget on the human forearm. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '17, pages 357–360, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3027063.3052959, doi:10.1145/3027063.3052959.

[9] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 1968–1979, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858226, doi:10.1145/2858036.2858226.

[10] Ronald T. Azuma. A survey of augmented reality. *Presence: Teleoper. Virtual Environ.*, 6(4):355–385, August 1997. URL: http://dx.doi.org/10.1162/pres.1997.6.4.355, doi:10.1162/pres.1997.6.4.355.

[11] Mihai Bâce, Teemu Leppänen, David Gil de Gomez, and Argenis Ramirez Gomez. ubigaze: Ubiquitous augmented reality messaging using gaze gestures. In *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications*, SA '16, pages 11:1–11:5, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2999508.2999530, doi:10.1145/2999508.2999530.

[12] H. Benko, E. W. Ishak, and S. Feiner. Collaborative mixed reality visualization of an archaeological excavation. In *Third IEEE and ACM International Symposium on Mixed and Augmented Reality*, pages 132–140, Nov 2004. doi:10.1109/ISMAR.2004.23.

[13] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16, pages 717–728, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2984511.2984526, doi:10.1145/2984511.2984526.

[14] Guillermo Bernal, Tao Yang, Abhinandan Jain, and Pattie Maes. Physiohmd: A conformable, modular toolkit for collecting physiological data from head-mounted displays. In *Proceedings of the 2018 ACM International Symposium on Wearable Computers*, ISWC '18, pages 160–167, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3267242.3267268, doi:10.1145/3267242.3267268.

[15] M. Billinghurst, H. Kato, and I. Poupyrev. The magicbook - moving seamlessly between reality and virtuality. *IEEE Computer Graphics and Applications*, 21(3):6–8, May 2001. doi:10.1109/38.920621.

[16] M. Billinghurst, I. Poupyrev, H. Kato, and R. May. Mixing realities in shared space: an augmented reality interface for collaborative computing. In *2000 IEEE International Conference on Multimedia and Expo. ICME2000. Proceedings. Latest Advances in the*

Fast Changing World of Multimedia (Cat. No.00TH8532), volume 3, pages 1641–1644 vol.3, July 2000. doi:10.1109/ICME.2000.871085.

[17] Mark Billinghurst and Hirokazu Kato. Collaborative augmented reality. *Commun. ACM*, 45(7):64–70, July 2002. URL: http://doi.acm.org/10.1145/514236.514265, doi:10.1145/514236.514265.

[18] J. Blake and H. B. Gurocak. Haptic glove with mr brakes for virtual reality. *IEEE/ASME Transactions on Mechatronics*, 14(5):606–615, Oct 2009. doi:10.1109/TMECH.2008.2010934.

[19] Richard A. Bolt. Put-that-there: Voice and gesture at the graphics interface. In *Proceedings of the 7th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '80, pages 262–270, New York, NY, USA, 1980. ACM. URL: http://doi.acm.org/10.1145/800250.807503, doi:10.1145/800250.807503.

[20] M. Bouzit, G. Burdea, G. Popescu, and R. Boian. The rutgers master ii-new design force-feedback glove. *IEEE/ASME Transactions on Mechatronics*, 7(2):256–263, June 2002. doi:10.1109/TMECH.2002.1011262.

[21] D. A. Bowman, D. B. Johnson, and L. F. Hodges. Testbed evaluation of virtual environment interaction techniques. *Presence*, 10(1):75–95, Feb 2001. doi:10.1162/105474601750182333.

[22] Doug A Bowman. The encyclopedia of human-computer interaction, 32. 3d user interfaces. 2013.

[23] Doug A. Bowman and Larry F. Hodges. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, I3D '97, pages 35–ff., New York, NY, USA, 1997. ACM. URL: http://doi.acm.org/10.1145/253284.253301, doi:10.1145/253284.253301.

[24] Doug A. Bowman, Ernst Kruijff, Joseph J. LaViola, and Ivan Poupyrev. An introduction to 3-d user interface design. *Presence: Teleoper. Virtual Environ.*, 10(1):96–108, February 2001. URL: http://dx.doi.org/10.1162/105474601750182342, doi:10.1162/105474601750182342.

[25] Doug A. Bowman, Ernst Kruijff, Joseph J. LaViola, and Ivan Poupyrev. *3D User Interfaces: Theory and Practice*. Addison Wesley Longman Publishing Co., Inc., Redwood City, CA, USA, 2004.

[26] Harry Brignull and Yvonne Rogers. Enticing people to interact with large public displays in public spaces. In *Human-Computer Interaction INTERACT '03: IFIP TC13 International Conference on Human-Computer Interaction, 1st-5th September 2003, Zurich, Switzerland*, 2003.

[27] Gerd Bruder, Victoria Interrante, Lane Phillips, and Frank Steinicke. Redirecting walking and driving for natural navigation in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):538–545, April 2012. URL: http://dx.doi.org/10.1109/TVCG.2012.55, doi:10.1109/TVCG.2012.55.

[28] Richard Buchanan. Wicked problems in design thinking. *Design Issues*, 8(2):5–21, 1992. URL: http://www.jstor.org/stable/1511637.

[29] Andreas Butz, Tobias Höllerer, Steven Feiner, Blair MacIntyre, and Clifford Beshers. Enveloping users and computers in a collaborative 3d augmented reality. In *Proceedings of the 2Nd IEEE and ACM International Workshop on Augmented Reality*, IWAR '99, pages 35–, Washington, DC, USA, 1999. IEEE Computer Society. URL: http://dl.acm.org/citation.cfm?id=857202.858143.

[30] William Buxton. Human-computer interaction. chapter There's More to Interaction Than Meets the Eye: Some Issues in Manual Input, pages 122–137. Prentice Hall Press, Upper Saddle River, NJ, USA, 1990. URL: http://dl.acm.org/citation.cfm?id=87725.87734.

[31] Han Joo Chae, Jeong-in Hwang, and Jinwook Seo. Wall-based space manipulation technique for efficient placement of distant objects in augmented reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 45–52, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3242587.3242631, doi:10.1145/3242587.3242631.

[32] Liwei Chan and Kouta Minamizawa. Frontface: Facilitating communication between hmd users and outsiders using front-facing-screen hmds. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '17, pages 22:1–22:5, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3098279.3098548, doi:10.1145/3098279.3098548.

[33] Hong-Yu Chang, Wen-Jie Tseng, Chia-En Tsai, Hsin-Yu Chen, Roshan Lalintha Peiris, and Liwei Chan. Facepush: Introducing normal force on face with head-mounted displays. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 927–935, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3242587.3242588, doi:10.1145/3242587.3242588.

[34] Guanling Chen and David Kotz. A survey of context-aware mobile computing research. Technical report, Hanover, NH, USA, 2000.

[35] Zikun Chen, Roshan Lalintha Peiris, and Kouta Minamizawa. A thermal pattern design for providing dynamic thermal feedback on the face with head mounted displays. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '17, pages 381–388, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3024969.3025060, doi:10.1145/3024969.3025060.

[36] Zikun Chen, Wei Peng, Roshan Peiris, and Kouta Minamizawa. Thermoreality: Thermally enriched head mounted displays for virtual reality. In *ACM SIGGRAPH 2017 Posters*, SIGGRAPH '17, pages 32:1–32:2, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3102163.3102222, doi:10.1145/3102163.3102222.

[37] Li-Te Cheng, Rick Kazman, and John Robinson. Vibrotactile feedback in delicate virtual reality operations. In *Proceedings of the Fourth ACM International Conference on Multimedia*, MULTIMEDIA '96, pages 243–251, New York, NY, USA, 1996. ACM. URL: http://doi.acm.org/10.1145/244130.244220, doi:10.1145/244130.244220.

[38] Lung-Pan Cheng, Li Chang, Sebastian Marwecki, and Patrick Baudisch. iturk: Turning passive haptics into active haptics by making users reconfigure props in virtual reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA '18, pages D308:1–D308:1, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3170427.3186482, doi:10.1145/3170427.3186482.

[39] Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. Haptic turk: A motion platform based on people. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, pages 3463–3472, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2556288.2557101, doi:10.1145/2556288.2557101.

[40] Lung-Pan Cheng, Eyal Ofek, Christian Holz, Hrvoje Benko, and Andrew D. Wilson. Sparse haptic proxy: Touch feedback in virtual environments using a general passive prop. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 3718–3728, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3025753, doi:10.1145/3025453.3025753.

[41] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. Turkdeck: Physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, pages 417–426,

New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2807442.2807463, doi:10.1145/2807442.2807463.

[42] Adrian David Cheok, Xubo Yang, Zhou Zhi Ying, Mark Billinghurst, and Hirokazu Kato. Touch-space: Mixed reality game space based on ubiquitous, tangible, and social computing. *Personal and Ubiquitous Computing*, 6(5):430–442, Dec 2002. URL: https://doi.org/10.1007/s007790200047, doi:10.1007/s007790200047.

[43] Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, pages 119–130, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3126594.3126599, doi:10.1145/3126594.3126599.

[44] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 654:1–654:13, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3174228, doi:10.1145/3173574.3174228.

[45] Damien Clergeaud, Joan Sol Roo, Martin Hachet, and Pascal Guitton. Towards Seamless Interaction between Physical and Virtual Locations for Asymmetric Collaboration. In *VRST 2017 - 23rd ACM Symposium on Virtual Reality Software and Technology*, pages 1–5, Gothemburg, Sweden, November 2017. URL: https://hal.archives-ouvertes.fr/hal-01649262, doi:10.1145/3139131.3139165.

[46] Carolina Cruz-Neira, Daniel J. Sandin, Thomas A. DeFanti, Robert V. Kenyon, and John C. Hart. The cave: Audio visual experience automatic virtual environment. *Commun. ACM*, 35(6):64–72, June 1992. URL: http://doi.acm.org/10.1145/129888.129892, doi:10.1145/129888.129892.

[47] SuperData Research — Games data and market research. Virtual reality headsets — sell-through shipments: Q1 2018 - q4 2018. https://www.superdataresearch.com/xrupdate/. (Accessed on 03/05/2019).

[48] Nicolas J. Dedual, Ohan Oda, and Steven K. Feiner. Creating hybrid user interfaces with a 2d multi-touch tabletop and a 3d see-through head-worn display. In *Proceedings of the 2011 10th IEEE International Symposium on Mixed and Augmented Reality*, ISMAR '11, pages 231–232, Washington, DC, USA, 2011. IEEE Computer

Society. URL: http://dx.doi.org/10.1109/ISMAR.2011.6092391, doi:10.1109/ISMAR.2011.6092391.

[49] Anind K. Dey. Understanding and using context. *Personal Ubiquitous Comput.*, 5(1):4–7, January 2001. URL: http://dx.doi.org/10.1007/s007790170019, doi:10.1007/s007790170019.

[50] ISO DIS. 9241-210: 2010. ergonomics of human system interaction-part 210: Human-centred design for interactive systems. *International Standardization Organization (ISO). Switzerland*, 2009.

[51] L. Dominjon, A. Lecuyer, J. . Burkhardt, P. Richard, and S. Richir. Influence of control/display ratio on the perception of mass of manipulated objects in virtual environments. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pages 19–25, March 2005. doi:10.1109/VR.2005.1492749.

[52] Paul Dourish. What we talk about when we talk about context. *Personal Ubiquitous Comput.*, 8(1):19–30, February 2004. URL: https://doi.org/10.1007/s00779-003-0253-8, doi:10.1007/s00779-003-0253-8.

[53] H. Du, W. Xiong, Z. Wang, and L. Chen. Design of a new type of pneumatic force feedback data glove. In *Proceedings of 2011 International Conference on Fluid Power and Mechatronics*, pages 292–296, Aug 2011. doi:10.1109/FPM.2011.6045775.

[54] Clive L. Dym, Alice M. Agogino, Ozgur Eris, Daniel D. Frey, and Larry J. Leifer. Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, 94(1):103–120, 2005. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2168-9830.2005.tb00832.x, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/j.2168-9830.2005.tb00832.x, doi:10.1002/j.2168-9830.2005.tb00832.x.

[55] T. Endo, H. Kawasaki, T. Mouri, Y. Ishigure, H. Shimomura, M. Matsumura, and K. Koketsu. Five-fingered haptic interface robot: Hiro iii. *IEEE Transactions on Haptics*, 4(1):14–27, January 2011. doi:10.1109/TOH.2010.62.

[56] Thomas Erickson and Wendy A. Kellogg. Social translucence: An approach to designing systems that support social processes. *ACM Trans. Comput.-Hum. Interact.*, 7(1):59–83, March 2000. URL: http://doi.acm.org/10.1145/344949.345004, doi:10.1145/344949.345004.

[57] Facebook. Oculus rift: Vr headset for vr ready pcs — oculus. https://www.oculus.com/rift/#oui-csl-rift-games=mages-tale. (Accessed on 03/04/2019).

[58] Josef Faller, Brendan Z. Allison, Clemens Brunner, Reinhold Scherer, Dieter Schmalstieg, Gert Pfurtscheller, and Christa Ne-

uper. A feasibility study on ssvep-based interaction with motivating and immersive virtual and augmented reality. *CoRR*, abs/1701.03981, 2017. URL: http://arxiv.org/abs/1701.03981, arXiv:1701.03981.

[59] Kevin Fan, Liwei Chan, Daiya Kato, Kouta Minamizawa, and Masahiko Inami. Vr planet: Interface for meta-view and feet interaction of vr contents. In *ACM SIGGRAPH 2016 VR Village*, SIGGRAPH '16, pages 24:1–24:2, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2929490.2931001, doi:10.1145/2929490.2931001.

[60] Tiare Feuchtner and Jörg Müller. Ownershift: Facilitating overhead interaction in virtual reality with an ownership-preserving hand space shift. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 31–43, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3242587.3242594, doi:10.1145/3242587.3242594.

[61] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In *2016 IEEE Haptics Symposium (HAPTICS)*, pages 140–146, April 2016. doi:10.1109/HAPTICS.2016.7463168.

[62] R. Gal, L. Shapira, E. Ofek, and P. Kohli. Flare: Fast layout for augmented reality applications. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 207–212, Sep. 2014. doi:10.1109/ISMAR.2014.6948429.

[63] S. Ghosh, L. Winston, N. Panchal, P. Kimura-Thollander, J. Hotnog, D. Cheong, G. Reyes, and G. D. Abowd. Notifivr: Exploring interruptions and notifications in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1447–1456, April 2018. doi:10.1109/TVCG.2018.2793698.

[64] David Goedicke, Jamy Li, Vanessa Evers, and Wendy Ju. Vr-oom: Virtual reality on-road driving simulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 165:1–165:11, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3173739, doi:10.1145/3173574.3173739.

[65] David Goldberg and Cate Richardson. Touch-typing with a stylus. In *Proceedings of the INTERACT '93 and CHI '93 Conference on Human Factors in Computing Systems*, CHI '93, pages 80–87, New York, NY, USA, 1993. ACM. URL: http://doi.acm.org/10.1145/169059.169093, doi:10.1145/169059.169093.

[66] Google. Daydream. https://vr.google.com/daydream/. (Accessed on 03/04/2019).

[67] Google. Glass. https://www.x.company/glass/. (Accessed on 03/04/2019).

[68] Google. Google cardboard – google vr. https://vr.google.com/cardboard/. (Accessed on 03/04/2019).

[69] Raphael Grasset, Andreas Dunser, and Mark Billinghurst. The design of a mixed-reality book: Is it still a real book? In *Proceedings of the 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*, ISMAR '08, pages 99–102, Washington, DC, USA, 2008. IEEE Computer Society. URL: https://doi.org/10.1109/ISMAR.2008.4637333, doi:10.1109/ISMAR.2008.4637333.

[70] M. S. A. Graziano and M. M. Botvinick. How the brain represents the body: insights from neurophysiology and psychology. *Common Mechanisms in Perception and Action: Attention and Performance*, 19:136–157, 2002. URL: http://www.princeton.edu/~{}graziano/Papers/Attn_Perf19.pdf.

[71] Tovi Grossman, Xiang Anthony Chen, and George Fitzmaurice. Typing on glasses: Adapting text entry to smart eyewear. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '15, pages 144–152, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2785830.2785867, doi:10.1145/2785830.2785867.

[72] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in vr. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 1991–1995, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858487, doi:10.1145/2858036.2858487.

[73] S. Gupta and C. Jaynes. The universal media book: tracking and augmenting moving surfaces with projected information. In *2006 IEEE/ACM International Symposium on Mixed and Augmented Reality*, pages 177–180, Oct 2006. doi:10.1109/ISMAR.2006.297811.

[74] Sean Gustafson, Christian Holz, and Patrick Baudisch. 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, pages 283–292, New York, NY, USA, 2011. ACM. URL: http://doi.acm.org/10.1145/2047196.2047233, doi:10.1145/2047196.2047233.

[75] Sean G. Gustafson, Bernhard Rabe, and Patrick M. Baudisch. Understanding palm-based imaginary interfaces: The role of visual and tactile cues when browsing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, pages

889–898, New York, NY, USA, 2013. ACM. URL: http://doi.acm.org/10.1145/2470654.2466114, doi:10.1145/2470654.2466114.

[76] T. Ha, S. Feiner, and W. Woo. Wearhand: Head-worn, rgb-d camera-based, bare-hand user interface with visually enhanced depth perception. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 219–228, Sep. 2014. doi:10.1109/ISMAR.2014.6948431.

[77] Jonas Haeling, Christian Winkler, Stephan Leenders, Daniel Kebelheim, Axel Hildebrand, and Marc Necker. In-car 6-dof mixed reality for rear-seat and co-driver entertainment. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018, Tuebingen/Reutlingen, Germany, 18-22 March 2018*, pages 757–758, 2018. URL: https://doi.org/10.1109/VR.2018.8446461, doi:10.1109/VR.2018.8446461.

[78] Jooyeun Ham, Jonggi Hong, Youngkyoon Jang, Seung Hwan Ko, and Woontack Woo. Smart wristband: Touch-and-motion–tracking wearable 3d input device for smart glasses. In Norbert Streitz and Panos Markopoulos, editors, *Distributed, Ambient, and Pervasive Interactions*, pages 109–118, Cham, 2014. Springer International Publishing.

[79] Ping-Hsuan Han, Yang-Sheng Chen, Kong-Chang Lee, Hao-Cheng Wang, Chiao-En Hsieh, Jui-Chun Hsiao, Chien-Hsing Chou, and Yi-Ping Hung. Haptic around: Multiple tactile sensations for immersive environment and interaction in virtual reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18, pages 35:1–35:10, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3281505.3281507, doi:10.1145/3281505.3281507.

[80] Blake Hannaford and Allison M. Okamura. *Haptics*, pages 1063–1084. Springer International Publishing, Cham, 2016. URL: https://doi.org/10.1007/978-3-319-32552-1_42, doi:10.1007/978-3-319-32552-1_42.

[81] Chris Harrison, Hrvoje Benko, and Andrew D. Wilson. Omnitouch: Wearable multitouch interaction everywhere. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, pages 441–450, New York, NY, USA, 2011. ACM. URL: http://doi.acm.org/10.1145/2047196.2047255, doi:10.1145/2047196.2047255.

[82] Chris Harrison and Haakon Faste. Implications of location and touch for on-body projected interfaces. In *Proceedings of the 2014 Conference on Designing Interactive Systems*, DIS '14, pages 543–552, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2598510.2598587, doi:10.1145/2598510.2598587.

[83] Chris Harrison, Desney Tan, and Dan Morris. Skinput: Appropriating the skin as an interactive canvas. *Commun. ACM*, 54(8):111–118, August 2011. URL: http://doi.acm.org/10.1145/1978542.1978564, doi:10.1145/1978542.1978564.

[84] Anders Henrysson and Mark Ollila. Umar: Ubiquitous mobile augmented reality. In *Proceedings of the 3rd International Conference on Mobile and Ubiquitous Multimedia*, MUM '04, pages 41–45, New York, NY, USA, 2004. ACM. URL: http://doi.acm.org/10.1145/1052380.1052387, doi:10.1145/1052380.1052387.

[85] Anuruddha Hettiarachchi and Daniel Wigdor. Annexing reality: Enabling opportunistic use of everyday objects as tangible proxies in augmented reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 1957–1967, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858134, doi:10.1145/2858036.2858134.

[86] Ken Hinckley, Randy Pausch, John C. Goble, and Neal F. Kassell. Passive real-world interface props for neurosurgical visualization. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '94, pages 452–458, New York, NY, USA, 1994. ACM. URL: http://doi.acm.org/10.1145/191666.191821, doi:10.1145/191666.191821.

[87] Ken Hinckley, Jeff Pierce, Mike Sinclair, and Eric Horvitz. Sensing techniques for mobile interaction. In *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology*, UIST '00, pages 91–100, New York, NY, USA, 2000. ACM. URL: http://doi.acm.org/10.1145/354401.354417, doi:10.1145/354401.354417.

[88] Teresa Hirzle, Jan Gugenheimer, Florian Geiselhart, Andreas Bulling, and Enrico Rukzio. A design space for gaze interaction on head-mounted displays. *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019)*, 5 2019. doi:10.1145/3290605.3300855.

[89] R. Holm, E. Stauder, R. Wagner, M. Priglinger, and J. Volkert. A combined immersive and desktop authoring tool for virtual environments. In *Proceedings IEEE Virtual Reality 2002*, pages 93–100, March 2002. doi:10.1109/VR.2002.996511.

[90] Kasper Hornbæk. Some whys and hows of experiments in human–computer interaction. *Found. Trends Hum.-Comput. Interact.*, 5(4):299–373, June 2013. URL: http://dx.doi.org/10.1561/1100000043, doi:10.1561/1100000043.

[91] HTC/VALVE. Vive — discover virtual reality beyond imagination. https://www.vive.com/de/. (Accessed on 03/04/2019).

[92] Da-Yuan Huang, Liwei Chan, Shuo Yang, Fan Wang, Rong-Hao Liang, De-Nian Yang, Yi-Ping Hung, and Bing-Yu Chen. Digitspace: Designing thumb-to-fingers touch interfaces for one-handed and eyes-free interactions. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 1526–1537, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858483, doi:10.1145/2858036.2858483.

[93] Hikaru Ibayashi, Yuta Sugiura, Daisuke Sakamoto, Natsuki Miyata, Mitsunori Tada, Takashi Okuma, Takeshi Kurata, Masaaki Mochimaru, and Takeo Igarashi. Dollhouse vr: A multi-view, multi-user collaborative design workspace with vr technology. In *SIGGRAPH Asia 2015 Emerging Technologies*, SA '15, pages 8:1–8:2, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2818466.2818480, doi:10.1145/2818466.2818480.

[94] Sylvia Irawati, Scott Green, Mark Billinghurst, Andreas Duenser, and Heedong Ko. "move the couch where?": Developing an augmented reality multimodal interface. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality*, ISMAR '06, pages 183–186, Washington, DC, USA, 2006. IEEE Computer Society. URL: https://doi.org/10.1109/ISMAR.2006.297812, doi:10.1109/ISMAR.2006.297812.

[95] Hiroshi Ishii and Brygg Ullmer. Tangible bits: Towards seamless interfaces between people, bits and atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, CHI '97, pages 234–241, New York, NY, USA, 1997. ACM. URL: http://doi.acm.org/10.1145/258549.258715, doi:10.1145/258549.258715.

[96] Hiroo Iwata, Takashi Nakagawa, and Takahiro Nakashima. Force display for presentation of rigidity of virtual objects. *Journal of Robotics and Mechatronics*, 4(1):39–42, 1992. doi:10.20965/jrm.1992.p0039.

[97] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. Reality-based interaction: A framework for post-wimp interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, pages 201–210, New York, NY, USA, 2008. ACM. URL: http://doi.acm.org/10.1145/1357054.1357089, doi:10.1145/1357054.1357089.

[98] Seiie Jang, Sehwan Kim, and Woontack Woo. When vr meets ubicomp. In *The Third Young Inverstigator's Forum in Virtual Reality*, 2005.

[99] Brett Jones, Rajinder Sodhi, Michael Murdock, Ravish Mehra, Hrvoje Benko, Andrew Wilson, Eyal Ofek, Blair MacIntyre,

Nikunj Raghuvanshi, and Lior Shapira. Roomalive: Magical experiences enabled by scalable, adaptive projector-camera units. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST '14, pages 637–644, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2642918.2647383, doi:10.1145/2642918.2647383.

[100] W. Jung, W. Cho, H. Kim, and W. Woo. Boosthand : Distance-free object manipulation system with switchable non-linear mapping for augmented reality classrooms. In *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, pages 321–325, Oct 2017. doi:10.1109/ISMAR-Adjunct.2017.96.

[101] Takayuki Kameoka, Yuki Kon, and Hiroyuki Kajimoto. Haptopus: Haptic vr experience using suction mechanism embedded in head-mounted display. In *SIGGRAPH Asia 2018 Virtual & Augmented Reality*, SA '18, pages 5:1–5:2, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3275495.3275512, doi:10.1145/3275495.3275512.

[102] Hsin-Liu (Cindy) Kao, Artem Dementyev, Joseph A. Paradiso, and Chris Schmandt. Nailo: Fingernails as an input surface. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 3015–3018, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2702123.2702572, doi:10.1145/2702123.2702572.

[103] H. Kato, M. Billinghurst, I. Poupyrev, K. Imamoto, and K. Tachibana. Virtual object manipulation on a table-top ar environment. In *Proceedings IEEE and ACM International Symposium on Augmented Reality (ISAR 2000)*, pages 111–119, Oct 2000. doi:10.1109/ISAR.2000.880934.

[104] Mohamed Khamis, Ludwig Trotter, Ville Mäkelä, Emanuel von Zezschwitz, Jens Le, Andreas Bulling, and Florian Alt. Cueauth: Comparing touch, mid-air gestures, and gaze for cue-based authentication on situated displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 2(4):174:1–174:22, December 2018. URL: http://doi.acm.org/10.1145/3287052, doi:10.1145/3287052.

[105] Wolf Kienzle and Ken Hinckley. Lightring: Always-available 2d input on any surface. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*, UIST '14, pages 157–160, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2642918.2647376, doi:10.1145/2642918.2647376.

[106] David Kim, Otmar Hilliges, Shahram Izadi, Alex D. Butler, Jiawen Chen, Iason Oikonomidis, and Patrick Olivier. Digits: Freehand 3d interactions anywhere using a wrist-worn gloveless sensor. In *Proceedings of the 25th Annual ACM Symposium on User*

Interface Software and Technology, UIST '12, pages 167–176, New York, NY, USA, 2012. ACM. URL: http://doi.acm.org/10.1145/2380116.2380139, doi:10.1145/2380116.2380139.

[107] Kangsoo Kim, Mark Billinghurst, Gerd Bruder, Henry Been-Lirn Duh, and Gregory F Welch. Revisiting trends in augmented reality research: A review of the 2nd decade of ismar (2008–2017). *IEEE transactions on visualization and computer graphics*, 24(11):2947–2962, 2018. doi:10.1109/TVCG.2018.2868591.

[108] Sehwan Kim, Youngho Lee, and Woontack Woo. How to realize ubiquitous vr? In *Pervasive: TSI Workshop*, pages 493–504, 2006.

[109] Leonard Kleinrock. Nomadic computing—an opportunity. *SIGCOMM Comput. Commun. Rev.*, 25(1):36–40, January 1995. URL: http://doi.acm.org/10.1145/205447.205450, doi:10.1145/205447.205450.

[110] Marion Koelle, Swamy Ananthanarayan, Simon Czupalla, Wilko Heuten, and Susanne Boll. Your smart glasses' camera bothers me!: Exploring opt-in and opt-out gestures for privacy mediation. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*, NordiCHI '18, pages 473–481, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3240167.3240174, doi:10.1145/3240167.3240174.

[111] Marion Koelle, Abdallah El Ali, Vanessa Cobus, Wilko Heuten, and Susanne CJ Boll. All about acceptability?: Identifying factors for the adoption of data glasses. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 295–300, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3025749, doi:10.1145/3025453.3025749.

[112] Marion Koelle, Matthias Kranz, and Andreas Möller. Don't look at me that way!: Understanding user attitudes towards data glasses usage. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '15, pages 362–372, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2785830.2785842, doi:10.1145/2785830.2785842.

[113] Eugenia M Kolasinski. Simulator sickness in virtual environments. Technical report, U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA., 1995.

[114] Yuki Kon, Takuto Nakamura, and Hiroyuki Kajimoto. Hangerover: Hmd-embedded haptics display with hanger reflex. In *ACM SIGGRAPH 2017 Emerging Technologies*, SIGGRAPH '17, pages 11:1–11:2, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3084822.3084842, doi:10.1145/3084822.3084842.

[115] Michinari Kono, Takashi Miyaki, and Jun Rekimoto. In-pulse: Inducing fear and pain in virtual experiences. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18, pages 40:1–40:5, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3281505.3281506, doi:10.1145/3281505.3281506.

[116] André Kunert, Alexander Kulik, Stephan Beck, and Bernd Froehlich. Photoportals: Shared references in space and time. In *Proceedings of the 17th ACM Conference on Computer Supported Cooperative Work & Social Computing*, CSCW '14, pages 1388–1399, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2531602.2531727, doi:10.1145/2531602.2531727.

[117] A. Kunz, P. Lochmatter, and G. Kovacs. Dielectric elastomer spring roll actuators for a portable force feedback device. In *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 347–353, March 2006. doi:10.1109/HAPTIC.2006.1627137.

[118] Mikko Kytö, Barrett Ens, Thammathip Piumsomboon, Gun A. Lee, and Mark Billinghurst. Pinpointing: Precise head- and eye-based target selection for augmented reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 81:1–81:14, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3173655, doi:10.1145/3173574.3173655.

[119] Magic Leap. Magic leap. https://www.magicleap.com/. (Accessed on 03/04/2019).

[120] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, and P. Coiffet. Pseudo-haptic feedback: can isometric input devices simulate force feedback? In *Proceedings IEEE Virtual Reality 2000 (Cat. No.00CB37048)*, pages 83–90, March 2000. doi:10.1109/VR.2000.840369.

[121] Anatole Lécuyer. Simulating haptic feedback using vision: A survey of research and applications of pseudo-haptic feedback. *Presence: Teleoper. Virtual Environ.*, 18(1):39–53, January 2009. URL: http://dx.doi.org/10.1162/pres.18.1.39, doi:10.1162/pres.18.1.39.

[122] S. J. Lederman and L. A. Jones. Tactile and haptic illusions. *IEEE Transactions on Haptics*, 4(4):273–294, October 2011. doi:10.1109/TOH.2011.2.

[123] Lik-Hang Lee and Pan Hui. Interaction methods for smart glasses. *CoRR*, abs/1707.09728, 2017. URL: http://arxiv.org/abs/1707.09728, arXiv:1707.09728, doi:10.1109/ACCESS.2018.2831081.

[124] Y. Lee, S. Oh, C. Shin, and W. Woo. Recent trends in ubiquitous virtual reality. In *2008 International Symposium on Ubiquitous Virtual Reality*, pages 33–36, July 2008. doi:10.1109/ISUVR.2008.27.

[125] Youngho Lee, Sejin Oh, Choonsung Shin, and Woontack Woo. Ubiquitous virtual reality and its key dimension. In *International Workshop on Ubiquitous Virtual Reality*, volume 9, pages 5–8, 2009.

[126] Hao Li, Laura Trutoiu, Kyle Olszewski, Lingyu Wei, Tristan Trutna, Pei-Lun Hsieh, Aaron Nicholls, and Chongyang Ma. Facial performance sensing head-mounted display. *ACM Trans. Graph.*, 34(4):47:1–47:9, July 2015. URL: http://doi.acm.org/10.1145/2766939, doi:10.1145/2766939.

[127] Nicola Liberati. Augmented reality and ubiquitous computing: the hidden potentialities of augmented reality. *AI & SOCIETY*, 31(1):17–28, Feb 2016. URL: https://doi.org/10.1007/s00146-014-0543-x, doi:10.1007/s00146-014-0543-x.

[128] Shu-Yang Lin, Chao-Huai Su, Kai-Yin Cheng, Rong-Hao Liang, Tzu-Hao Kuo, and Bing-Yu Chen. Pub - point upon body: Exploring eyes-free interaction and methods on an arm. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, pages 481–488, New York, NY, USA, 2011. ACM. URL: http://doi.acm.org/10.1145/2047196.2047259, doi:10.1145/2047196.2047259.

[129] Robert W. Lindeman, John L. Sibert, and James K. Hahn. Towards usable vr: An empirical study of user interfaces for immersive virtual environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '99, pages 64–71, New York, NY, USA, 1999. ACM. URL: http://doi.acm.org/10.1145/302979.302995, doi:10.1145/302979.302995.

[130] Roman Lissermann, Jochen Huber, Aristotelis Hadjakos, and Max Mühlhäuser. Earput: Augmenting behind-the-ear devices for ear-based interaction. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '13, pages 1323–1328, New York, NY, USA, 2013. ACM. URL: http://doi.acm.org/10.1145/2468356.2468592, doi:10.1145/2468356.2468592.

[131] CyberGlove Systems LLC. Cyberglove. http://www.cyberglovesystems.com/. (Accessed on 03/04/2019).

[132] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, pages 11–19, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2807442.2807443, doi:10.1145/2807442.2807443.

[133] Pedro Lopes, Alexandra Ion, Willi Müller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. Proprioceptive interaction. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '15, pages 175–175, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2702613.2732490, doi:10.1145/2702613.2732490.

[134] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 1471–1482, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3025600, doi:10.1145/3025453.3025600.

[135] Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch. Adding force feedback to mixed reality experiences and games using electrical muscle stimulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 446:1–446:13, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3174020, doi:10.1145/3173574.3174020.

[136] P. Lubos, G. Bruder, and F. Steinicke. Analysis of direct selection in head-mounted display environments. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 11–18, March 2014. doi:10.1109/3DUI.2014.6798834.

[137] Christian Mai and Mohamed Khamis. Public hmds: Modeling and understanding user behavior around public head-mounted displays. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, PerDis '18, pages 21:1–21:9, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3205873.3205879, doi:10.1145/3205873.3205879.

[138] Christian Mai, Lukas Rambold, and Mohamed Khamis. Transparenthmd: Revealing the hmd user's face to bystanders. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*, MUM '17, pages 515–520, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3152832.3157813, doi:10.1145/3152832.3157813.

[139] Christian Mai, Tim Wiltzius, Florian Alt, and Heinrich Hußmann. Feeling alone in public: Investigating the influence of spatial layout on users' vr experience. In *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*, NordiCHI '18, pages 286–298, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3240167.3240200, doi:10.1145/3240167.3240200.

[140] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo. Evaluation of wearable haptic systems for the

fingers in augmented reality applications. *IEEE Transactions on Haptics*, 10(4):511–522, Oct 2017. doi:10.1109/TOH.2017.2691328.

[141] Steve Mann. Wearable computing: a first step toward personal imaging. *Computer*, 30(2):25–32, Feb 1997. doi:10.1109/2.566147.

[142] Thomas H Massie, J Kenneth Salisbury, et al. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, volume 55, pages 295–300. Citeseer, 1994.

[143] Keiichi Matsuda. Hyper-reality. *Video.(16 May 2016). Retrieved September*, 20:2016, 2016. URL: http://hyper-reality.co/.

[144] Mark McGill, Alexander Ng, and Stephen Brewster. I am the passenger: How visual motion cues can influence sickness for in-car vr. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 5655–5668, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3026046, doi:10.1145/3025453.3026046.

[145] Joseph E. McGrath. Human-computer interaction. chapter Methodology Matters: Doing Research in the Behavioral and Social Sciences, pages 152–169. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 1995. URL: http://dl.acm.org/citation.cfm?id=212925.212940.

[146] Microsoft. Microsoft hololens — mixed reality technology for business. https://www.microsoft.com/en-us/hololens. (Accessed on 03/04/2019).

[147] Microsoft. Voice input - mixed reality. (Accessed on 03/04/2019). URL: https://docs.microsoft.com/en-us/windows/mixed-reality/voice-input.

[148] Paul Milgram and Fumio Kishino. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, 77(12):1321–1329, 1994.

[149] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies*, volume 2351, pages 282–293. International Society for Optics and Photonics, 1995.

[150] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. Gravity grabber: Wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 Emerging Technologies*, SIGGRAPH '07, New York, NY, USA, 2007. ACM. URL: http://doi.acm.org/10.1145/1278280.1278289, doi:10.1145/1278280.1278289.

[151] Mark R. Mine. Virtual environment interaction techniques. Technical report, Chapel Hill, NC, USA, 1995.

[152] Mark R. Mine, Frederick P. Brooks, Jr., and Carlo H. Sequin. Moving objects in space: Exploiting proprioception in virtual-environment interaction. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '97, pages 19–26, New York, NY, USA, 1997. ACM Press/Addison-Wesley Publishing Co. URL: https://doi.org/10.1145/258734.258747, doi:10.1145/258734.258747.

[153] Keith Mitchell. Supporting the development of mobile context-aware computing. *Doktorarbeit der Informatik, Lancaster University*, 2002.

[154] M. Mohring, C. Lessig, and O. Bimber. Video see-through ar on consumer cell-phones. In *Third IEEE and ACM International Symposium on Mixed and Augmented Reality*, pages 252–253, Nov 2004. doi:10.1109/ISMAR.2004.63.

[155] Joseph Newman, Alexander Bornik, Daniel Pustka, Florian Echtler, Manuel Huber, Dieter Schmalstieg, and Gudrun Klinker. Tracking for distributed mixed reality environments. In *Workshop on Trands and Issues in Tracking for Virtual Environments at the IEEE Virtual Reality Conference (VR'07)*. Citeseer, 2007.

[156] Niantic. Ingress prime – ingress prime. https://www.ingress.com/. (Accessed on 03/04/2019).

[157] Niantic. Startseite — pokémon go. https://www.pokemongo.com/de-de/. (Accessed on 03/04/2019).

[158] Susanna Nilsson. *Augmentation in the wild: user centered development and evaluation of augmented reality applications*. PhD thesis, Linköping University Electronic Press, 2010.

[159] Donald A Norman and Stephen W Draper. *User centered system design: New perspectives on human-computer interaction*. CRC Press, 1986.

[160] Benjamin Nuernberger, Eyal Ofek, Hrvoje Benko, and Andrew D. Wilson. Snaptoreality: Aligning augmented reality to the real world. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 1233–1244, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858250, doi:10.1145/2858036.2858250.

[161] Oculus. Oculus go: Standalone vr headset — oculus. https://www.oculus.com/go/. (Accessed on 03/09/2019).

[162] Oculus. Oculus quest — oculus. https://www.oculus.com/quest/. (Accessed on 03/09/2019).

[163] Masa Ogata, Yuta Sugiura, Yasutoshi Makino, Masahiko Inami, and Michita Imai. Senskin: Adapting skin as a soft interface. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*, UIST '13, pages 539–544, New York, NY, USA, 2013. ACM. URL: http://doi.acm.org/10.1145/2501988.2502039, doi:10.1145/2501988.2502039.

[164] Masa Ogata, Yuta Sugiura, Hirotaka Osawa, and Michita Imai. iring: Intelligent ring using infrared reflection. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*, UIST '12, pages 131–136, New York, NY, USA, 2012. ACM. URL: http://doi.acm.org/10.1145/2380116.2380135, doi:10.1145/2380116.2380135.

[165] Sejin Oh, Woontack Woo, et al. Camar: Context-aware mobile augmented reality in smart space. *Proc. of IWUVR*, 9:48–51, 2009.

[166] Thomas Olsson, Tuula Kärkkäinen, Else Lagerstam, and Leena Ventä-Olkkonen. User evaluation of mobile augmented reality scenarios. *JAISE*, 4:29–47, 2012.

[167] A. Oulasvirta. Rethinking experimental designs for field evaluations. *IEEE Pervasive Computing*, 11(4):60–67, Oct 2012. doi:10.1109/MPRV.2011.84.

[168] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE Transactions on Haptics*, 10(4):580–600, Oct 2017. doi:10.1109/TOH.2017.2689006.

[169] Pablo E. Paredes, Stephanie Balters, Kyle Qian, Elizabeth L. Murnane, Francisco Ordóñez, Wendy Ju, and James A. Landay. Driving with the fishes: Towards calming and mindful virtual reality experiences for the car. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.*, 2(4):184:1–184:21, December 2018. URL: http://doi.acm.org/10.1145/3287062, doi:10.1145/3287062.

[170] Hyung Min Park, Seok Han Lee, and Jong Soo Choi. Wearable augmented reality system using gaze interaction. In *Proceedings of the 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*, ISMAR '08, pages 175–176, Washington, DC, USA, 2008. IEEE Computer Society. URL: https://doi.org/10.1109/ISMAR.2008.4637353, doi:10.1109/ISMAR.2008.4637353.

[171] Taiwoo Park, Mi Zhang, and Youngki Lee. When mixed reality meets internet of things: Toward the realization of ubiquitous mixed reality. *GetMobile: Mobile Comp. and Comm.*, 22(1):10–14, May 2018. URL: http://doi.acm.org/10.1145/3229316.3229320, doi:10.1145/3229316.3229320.

[172] Mr. Jason Pascoe. Adding generic contextual capabilities to wearable computers. In *Proceedings of the 2Nd IEEE International Symposium on Wearable Computers*, ISWC '98, pages 92–, Washington, DC, USA, 1998. IEEE Computer Society. URL: http://dl.acm.org/citation.cfm?id=857199.858020.

[173] Roshan Lalintha Peiris, Liwei Chan, and Kouta Minamizawa. Liquidreality: Wetness sensations on the face for virtual reality. In Domenico Prattichizzo, Hiroyuki Shinoda, Hong Z. Tan, Emanuele Ruffaldi, and Antonio Frisoli, editors, *Haptics: Science, Technology, and Applications*, pages 366–378, Cham, 2018. Springer International Publishing.

[174] Roshan Lalintha Peiris, Wei Peng, Zikun Chen, Liwei Chan, and Kouta Minamizawa. Thermovr: Exploring integrated thermal haptic feedback with head mounted displays. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 5452–5456, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3025824, doi:10.1145/3025453.3025824.

[175] Ken Pfeuffer, Benedikt Mayer, Diako Mardanbegi, and Hans Gellersen. Gaze + pinch interaction in virtual reality. In *Proceedings of the 5th Symposium on Spatial User Interaction*, SUI '17, pages 99–108, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3131277.3132180, doi:10.1145/3131277.3132180.

[176] Danakorn Nincarean Eh Phon, Mohamad Bilal Ali, and Noor Dayana Abd Halim. Collaborative augmented reality in education: A review. In *Proceedings of the 2014 International Conference on Teaching and Learning in Computing and Engineering*, LATICE '14, pages 78–83, Washington, DC, USA, 2014. IEEE Computer Society. URL: https://doi.org/10.1109/LaTiCE.2014.23, doi:10.1109/LaTiCE.2014.23.

[177] Jeffrey S. Pierce, Andrew S. Forsberg, Matthew J. Conway, Seung Hong, Robert C. Zeleznik, and Mark R. Mine. Image plane interaction techniques in 3d immersive environments. In *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, I3D '97, pages 39–ff., New York, NY, USA, 1997. ACM. URL: http://doi.acm.org/10.1145/253284.253303, doi:10.1145/253284.253303.

[178] Claudio S. Pinhanez. The everywhere displays projector: A device to create ubiquitous graphical interfaces. In *Proceedings of the 3rd International Conference on Ubiquitous Computing*, UbiComp '01, pages 315–331, Berlin, Heidelberg, 2001. Springer-Verlag. URL: http://dl.acm.org/citation.cfm?id=647987.741324.

[179] D. Pohl and C. F. de Tejada Quemada. See what i see: Concepts to improve the social acceptance of hmds. In *2016 IEEE Virtual*

Reality (VR), pages 267–268, March 2016. doi:10.1109/VR.2016.7504756.

[180] Michael I Posner, Mary J Nissen, and Raymond M Klein. Visual dominance: an information-processing account of its origins and significance. *Psychological review*, 83(2):157, 1976.

[181] I. Poupyrev, T. Ichikawa, S. Weghorst, and M. Billinghurst. Egocentric object manipulation in virtual environments: Empirical evaluation of interaction techniques. *Computer Graphics Forum*, 17(3):41–52, 1998. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/1467-8659.00252, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/1467-8659.00252, doi:10.1111/1467-8659.00252.

[182] Ivan Poupyrev, Mark Billinghurst, Suzanne Weghorst, and Tadao Ichikawa. The go-go interaction technique: Non-linear mapping for direct manipulation in vr. In *Proceedings of the 9th Annual ACM Symposium on User Interface Software and Technology*, UIST '96, pages 79–80, New York, NY, USA, 1996. ACM. URL: http://doi.acm.org/10.1145/237091.237102, doi:10.1145/237091.237102.

[183] Ivan Poupyrev and Tadao Ichikawa. Manipulating objects in virtual worlds: Categorization and empirical evaluation of interaction techniques. *Journal of Visual Languages & Computing*, 10(1):19 – 35, 1999. URL: http://www.sciencedirect.com/science/article/pii/S1045926X98901124, doi:https://doi.org/10.1006/jvlc.1998.0112.

[184] P. Punpongsanon, D. Iwai, and K. Sato. Flexeen: Visually manipulating perceived fabric bending stiffness in spatial augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, pages 1–1, 2018. doi:10.1109/TVCG.2018.2871044.

[185] Parinya Punpongsanon, Daisuke Iwai, and Kosuke Sato. Softar: Visually manipulating haptic softness perception in spatial augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, 21(11):1279–1288, November 2015. URL: http://dx.doi.org/10.1109/TVCG.2015.2459792, doi:10.1109/TVCG.2015.2459792.

[186] Andreas Pusch and Anatole Lécuyer. Pseudo-haptics: From the theoretical foundations to practical system design guidelines. In *Proceedings of the 13th International Conference on Multimodal Interfaces*, ICMI '11, pages 57–64, New York, NY, USA, 2011. ACM. URL: http://doi.acm.org/10.1145/2070481.2070494, doi:10.1145/2070481.2070494.

[187] Sharif Razzaque, Zachariah Kohn, and Mary C. Whitton. Redirected Walking. In *Eurographics 2001 - Short Presentations*. Eurographics Association, 2001. doi:10.2312/egs.20011036.

[188] G. Reitmayr, E. Eade, and T. Drummond. Localisation and interaction for augmented maps. In *Fourth IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR'05)*, pages 120–129, Oct 2005. doi:10.1109/ISMAR.2005.39.

[189] Jun Rekimoto. Gesturewrist and gesturepad: Unobtrusive wearable interaction devices. In *Proceedings of the 5th IEEE International Symposium on Wearable Computers*, ISWC '01, pages 21–, Washington, DC, USA, 2001. IEEE Computer Society. URL: http://dl.acm.org/citation.cfm?id=580581.856565.

[190] Jun Rekimoto and Katashi Nagao. The world through the computer: Computer augmented interaction with real world environments. In *Proceedings of the 8th Annual ACM Symposium on User Interface and Software Technology*, UIST '95, pages 29–36, New York, NY, USA, 1995. ACM. URL: http://doi.acm.org/10.1145/215585.215639, doi:10.1145/215585.215639.

[191] Jun Rekimoto and Masanori Saitoh. Augmented surfaces: A spatially continuous work space for hybrid computing environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '99, pages 378–385, New York, NY, USA, 1999. ACM. URL: http://doi.acm.org/10.1145/302979.303113, doi:10.1145/302979.303113.

[192] Max Rheiner. Birdly an attempt to fly. In *ACM SIGGRAPH 2014 Emerging Technologies*, SIGGRAPH '14, pages 3:1–3:1, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2614066.2614101, doi:10.1145/2614066.2614101.

[193] Michael Rietzler, Gabriel Haas, Thomas Dreja, Florian Geiselhart, and Enrico Rukzio. Virtual muscle force: Communicating kinesthetic forces through pseudo-haptic feedback and muscle input. In *Proceedings of the 32Nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, pages 913–922, New York, NY, USA, 2019. ACM. URL: http://doi.acm.org/10.1145/3332165.3347871, doi:10.1145/3332165.3347871.

[194] Michael Rietzler, Katrin Plaumann, Taras Kränzle, Marcel Erath, Alexander Stahl, and Enrico Rukzio. Vair: Simulating 3d airflows in virtual reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 5669–5677, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3026009, doi:10.1145/3025453.3026009.

[195] Irvin Rock and Jack Victor. Vision and touch: An experimentally created conflict between the two senses. *Science*, 143(3606):594–596, 1964. URL: http://www.jstor.org/stable/1713642.

[196] Joan Sol Roo, Jean Basset, Pierre-Antoine Cinquin, and Martin Hachet. Understanding users' capability to transfer information

between mixed and virtual reality: Position estimation across modalities and perspectives. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 363:1–363:12, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3173937, doi:10.1145/3173574.3173937.

[197] Joan Sol ROO and Martin Hachet. Towards a Hybrid Space Combining Spatial Augmented Reality and Virtual Reality. In *3DUI - IEEE Symposium on 3D User Interfaces*, 3DUI 17, Los Angeles, United States, March 2017. IEEE. URL: https://hal.archives-ouvertes.fr/hal-01453385.

[198] Samsung. Samsung gear vr - virtual reality brille — samsung. https://www.samsung.com/de/wearables/gear-vr-r323/. (Accessed on 03/04/2019).

[199] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. Head-mounted display with mid-air tactile feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology*, VRST '15, pages 51–58, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2821592.2821593, doi:10.1145/2821592.2821593.

[200] B. Schilit, N. Adams, and R. Want. Context-aware computing applications. In *1994 First Workshop on Mobile Computing Systems and Applications*, pages 85–90, Dec 1994. doi:10.1109/WMCSA.1994.16.

[201] Dieter Schmalstieg, Anton Fuhrmann, Gerd Hesina, Zsolt Szalavári, L. Miguel Encarnaçäo, Michael Gervautz, and Werner Purgathofer. The studierstube augmented reality project. *Presence: Teleoper. Virtual Environ.*, 11(1):33–54, February 2002. URL: http://dx.doi.org/10.1162/105474602317343640, doi:10.1162/105474602317343640.

[202] Dieter Schmalstieg and Gerhard Reitmayr. *The World as a User Interface: Augmented Reality for Ubiquitous Computing*, pages 369–391. Springer Berlin Heidelberg, Berlin, Heidelberg, 2007. URL: https://doi.org/10.1007/978-3-540-36728-4_28, doi:10.1007/978-3-540-36728-4_28.

[203] Albrecht Schmidt. Implicit human computer interaction through context. *Personal Technologies*, 4(2):191–199, Jun 2000. URL: https://doi.org/10.1007/BF01324126, doi:10.1007/BF01324126.

[204] Albrecht Schmidt. Context-aware computing: context-awareness, context-aware user interfaces, and implicit interaction. *The Encyclopedia of Human-Computer Interaction, 2nd Ed.*, 2013.

[205] Albrecht Schmidt, Kofi Asante Aidoo, Antti Takaluoma, Urpo Tuomela, Kristof Van Laerhoven, and Walter Van de Velde. Ad-

vanced interaction in context. In *Proceedings of the 1st International Symposium on Handheld and Ubiquitous Computing*, HUC '99, pages 89–101, London, UK, UK, 1999. Springer-Verlag. URL: http://dl.acm.org/citation.cfm?id=647985.743849.

[206] Albrecht Schmidt, Michael Beigl, and Hans w. Gellersen. There is more to context than location. *Computers and Graphics*, 23:893–901, 1998.

[207] Matthew Schnipper, Adi Robertson, Michael Zelenko, Ellis Hamburger, Christian Mazza, Sam Thonis, Casey Newton, Ellis Hamburger, Michael Zelenko, and Sean O'Kane. The rise and fall and rise of virtual reality. (Accessed on 03/04/2019). URL: https://www.theverge.com/a/virtual-reality.

[208] Marcos Serrano, Barrett M. Ens, and Pourang P. Irani. Exploring the use of hand-to-face input for interacting with head-worn displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, pages 3181–3190, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2556288.2556984, doi:10.1145/2556288.2556984.

[209] L. Shapira and D. Freedman. Reality skins: Creating immersive and tactile virtual environments. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 115–124, Sep. 2016. doi:10.1109/ISMAR.2016.23.

[210] H. Si-Mohammed, J. Petit, C. Jeunet, F. Argelaguet, F. Spindler, A. Évain, N. Roussel, G. Casiez, and A. Lécuyer. Towards bci-based interfaces for augmented reality: Feasibility, design and evaluation. *IEEE Transactions on Visualization and Computer Graphics*, pages 1–1, 2018. doi:10.1109/TVCG.2018.2873737.

[211] Hakim Si-Mohammed, Ferran Argelaguet, Géry Casiez, Nicolas Roussel, and Anatole Lécuyer. Brain-computer interfaces and augmented reality: A state of the art. In *Graz Brain-Computer Interface Conference*, 2017.

[212] Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. Substitutional reality: Using the physical environment to design virtual reality experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 3307–3316, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2702123.2702389, doi:10.1145/2702123.2702389.

[213] Joan Sol Roo and Martin Hachet. One Reality: Augmenting How the Physical World is Experienced by combining Multiple Mixed Reality Modalities. In *UIST 2017 - 30th ACM Symposium on User Interface Software and Technology*, ACM UIST'17, Quebec City, Canada, October 2017. ACM. URL: https://hal.archives-ouvertes.fr/hal-01572490, doi:10.1145/3126594.3126638.

[214] M. Solazzi, A. Frisoli, and M. Bergamasco. Design of a cutaneous fingertip display for improving haptic exploration of virtual objects. In *19th International Symposium in Robot and Human Interactive Communication*, pages 1–6, Sep. 2010. doi:10.1109/ROMAN.2010.5654681.

[215] Sony. Playstation vr — das vr-gaming-system für ps4 — playstation. https://www.playstation.com/de-de/explore/playstation-vr/. (Accessed on 03/05/2019).

[216] Maximilian Speicher, Brian D. Hall, and Michael Nebeling. What is mixed reality? In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19. ACM, 2019.

[217] Misha Sra, Sergio Garrido-Jurado, Chris Schmandt, and Pattie Maes. Procedurally generated virtual reality from 3d reconstructed physical space. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology*, VRST '16, pages 191–200, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2993369.2993372, doi:10.1145/2993369.2993372.

[218] Aaron Stafford, Wayne Piekarski, and Bruce Thomas. Implementation of god-like interaction techniques for supporting collaboration between outdoor ar and indoor tabletop users. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality*, ISMAR '06, pages 165–172, Washington, DC, USA, 2006. IEEE Computer Society. URL: https://doi.org/10.1109/ISMAR.2006.297809, doi:10.1109/ISMAR.2006.297809.

[219] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, Jan 2010. doi:10.1109/TVCG.2009.62.

[220] Richard Stoakley, Matthew J. Conway, and Randy Pausch. Virtual reality on a wim: Interactive worlds in miniature. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '95, pages 265–272, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co. URL: http://dx.doi.org/10.1145/223904.223938, doi:10.1145/223904.223938.

[221] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. Haptic links: Bimanual haptics for virtual reality using variable stiffness actuation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 644:1–644:12, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3174218, doi:10.1145/3173574.3174218.

[222] Youngjung Suh, Kiyoung Kim, Jonghyun Han, and Woontack Woo. Virtual reality in ubiquitous computing environment. In *International Symposium on Ubiquitous VR*, page 1, 2007.

[223] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte. Leveraging change blindness for redirection in virtual environments. In *2011 IEEE Virtual Reality Conference*, pages 159–166, March 2011. doi:10.1109/VR.2011.5759455.

[224] Qi Sun, Anjul Patney, Li-Yi Wei, Omer Shapira, Jingwan Lu, Paul Asente, Suwen Zhu, Morgan Mcguire, David Luebke, and Arie Kaufman. Towards virtual reality infinite walking: Dynamic saccadic redirection. *ACM Trans. Graph.*, 37(4):67:1–67:13, July 2018. URL: http://doi.acm.org/10.1145/3197517.3201294, doi:10.1145/3197517.3201294.

[225] Qi Sun, Li-Yi Wei, and Arie Kaufman. Mapping virtual and physical reality. *ACM Trans. Graph.*, 35(4):64:1–64:12, July 2016. URL: http://doi.acm.org/10.1145/2897824.2925883, doi:10.1145/2897824.2925883.

[226] Ivan E. Sutherland. Sketch pad a man-machine graphical communication system. In *Proceedings of the SHARE Design Automation Workshop*, DAC '64, pages 6.329–6.346, New York, NY, USA, 1964. ACM. URL: http://doi.acm.org/10.1145/800265.810742, doi:10.1145/800265.810742.

[227] Ivan E Sutherland. The ultimate display. *Multimedia: From Wagner to virtual reality*, pages 506–508, 1965.

[228] Ivan E Sutherland. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, pages 757–764. ACM, 1968.

[229] Katsuhiro Suzuki, Fumihiko Nakamura, Jiu Otsuka, Katsutoshi Masai, Yuta Itoh, Yuta Sugiura, and Maki Sugimoto. Facial expression mapping inside head mounted display by embedded optical sensors. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16 Adjunct, pages 91–92, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2984751.2985714, doi:10.1145/2984751.2985714.

[230] Z. Szalavári, D. Schmalstieg, A. Fuhrmann, and M. Gervautz. "studierstube": An environment for collaboration in augmented reality. *Virtual Real.*, 3(1):37–48, March 1998. URL: https://doi.org/10.1007/BF01409796, doi:10.1007/BF01409796.

[231] Vildan Tanriverdi and Robert J. K. Jacob. Interacting with eye movements in virtual environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '00, pages 265–272, New York, NY, USA, 2000. ACM. URL: http://doi.acm.org/10.1145/332040.332443, doi:10.1145/332040.332443.

[232] Justus Thies, Michael Zollhöfer, Marc Stamminger, Christian Theobalt, and Matthias Nießner. Facevr: Real-time gaze-aware

facial reenactment in virtual reality. *ACM Trans. Graph.*, 37(2):25:1–25:15, June 2018. URL: http://doi.acm.org/10.1145/3182644, doi:10.1145/3182644.

[233] D. Tsetserukou, S. Hosokawa, and K. Terashima. Linktouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-dof force feedback at the fingerpad. In *2014 IEEE Haptics Symposium (HAPTICS)*, pages 307–312, Feb 2014. doi:10.1109/HAPTICS.2014.6775473.

[234] Matthew Turk. Review article: Multimodal interaction: A review. *Pattern Recogn. Lett.*, 36:189–195, January 2014. URL: http://dx.doi.org/10.1016/j.patrec.2013.07.003, doi:10.1016/j.patrec.2013.07.003.

[235] Cheng-Yao Wang, Wei-Chen Chu, Po-Tsung Chiu, Min-Chieh Hsiu, Yih-Harn Chiang, and Mike Y. Chen. Palmtype: Using palms as keyboards for smart glasses. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '15, pages 153–160, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2785830.2785886, doi:10.1145/2785830.2785886.

[236] Cheng-Yao Wang, Min-Chieh Hsiu, Po-Tsung Chiu, Chiao-Hui Chang, Liwei Chan, Bing-Yu Chen, and Mike Y. Chen. Palmgesture: Using palms as gesture interfaces for eyes-free input. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '15, pages 217–226, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2785830.2785885, doi:10.1145/2785830.2785885.

[237] D. Wang, M. Song, A. Naqash, Y. Zheng, W. Xu, and Y. Zhang. Toward whole-hand kinesthetic feedback: A survey of force feedback gloves. *IEEE Transactions on Haptics*, pages 1–1, 2018. doi:10.1109/TOH.2018.2879812.

[238] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. iskin: Flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 2991–3000, New York, NY, USA, 2015. ACM. URL: http://doi.acm.org/10.1145/2702123.2702391, doi:10.1145/2702123.2702391.

[239] Martin Weigel, Aditya Shekhar Nittala, Alex Olwal, and Jürgen Steimle. Skinmarks: Enabling interactions on body landmarks using conformal skin electronics. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, pages 3095–3105, New York, NY, USA, 2017. ACM. URL: http://doi.acm.org/10.1145/3025453.3025704, doi:10.1145/3025453.3025704.

[240] Mark Weiser. The computer for the 21st century. *SIGMOBILE Mob. Comput. Commun. Rev.*, 3(3):3–11, July 1999. URL: http://doi.acm.org/10.1145/329124.329126, doi:10.1145/329124.329126.

[241] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. Haptic revolver: Touch, shear, texture, and shape rendering on a reconfigurable virtual reality controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 86:1–86:12, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3173574.3173660, doi:10.1145/3173574.3173660.

[242] Wikipedia. Phubbing - wikipedia. https://en.wikipedia.org/wiki/Phubbing. (Accessed on 03/09/2019).

[243] Wikipedia. Smartphone - wikipedia. https://en.wikipedia.org/wiki/Smartphone. (Accessed on 03/09/2019).

[244] Julie R. Williamson, Mark McGill, and Khari Outram. Planevr: Social acceptability of virtual reality for aeroplane passengers, January 2019. URL: http://eprints.gla.ac.uk/178196/.

[245] Christian Winkler. *Nomadic projection within reach - overcoming deficiencies in nomadic information management through mobile projected interfaces*. PhD thesis, Universität Ulm, 2016. URL: https://oparu.uni-ulm.de/xmlui/handle/123456789/3287, doi:10.18725/OPARU-3260.

[246] Christian Winkler, Julian Seifert, David Dobbelstein, and Enrico Rukzio. Pervasive information through constant personal projection: The ambient mobile pervasive display (amp-d). In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, pages 4117–4126, New York, NY, USA, 2014. ACM. URL: http://doi.acm.org/10.1145/2556288.2557365, doi:10.1145/2556288.2557365.

[247] Jacob O. Wobbrock and Julie A. Kientz. Research contributions in human-computer interaction. *Interactions*, 23(3):38–44, April 2016. URL: http://doi.acm.org/10.1145/2907069, doi:10.1145/2907069.

[248] D. Wolf, M. Rietzler, L. Hnatek, and E. Rukzio. Face/on: Multimodal haptic feedback for head-mounted displays in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 25(11):3169–3177, Nov 2019. doi:10.1109/TVCG.2019.2932215.

[249] Dennis Wolf, Leo Hnatek, and Enrico Rukzio. Face/on: Actuating the facial contact area of a head-mounted display for increased immersion. In *The 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings*, UIST '18 Adjunct, pages 146–148, New York, NY, USA, 2018. ACM.

URL: http://doi.acm.org/10.1145/3266037.3271631, doi:10.1145/3266037.3271631.

[250] R. Xiao, J. Schwarz, N. Throm, A. D. Wilson, and H. Benko. Mr-touch: Adding touch input to head-mounted mixed reality. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1653–1660, April 2018. doi:10.1109/TVCG.2018.2794222.

[251] Keng-Ta Yang, Chiu-Hsuan Wang, and Liwei Chan. Sharespace: Facilitating shared use of the physical space by both vr head-mounted display and external users. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 499–509, New York, NY, USA, 2018. ACM. URL: http://doi.acm.org/10.1145/3242587.3242630, doi:10.1145/3242587.3242630.

[252] Xing-Dong Yang, Tovi Grossman, Daniel Wigdor, and George Fitzmaurice. Magic finger: Always-available input through finger instrumentation. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*, UIST '12, pages 147–156, New York, NY, USA, 2012. ACM. URL: http://doi.acm.org/10.1145/2380116.2380137, doi:10.1145/2380116.2380137.

[253] Yasuyoshi Yokokohji, Ralph L. Hollis, and Takeo Kanade. What you can see is what you can feel – development of visual/haptic interface to virtual environment. In *Proceedings of the 1996 Virtual Reality Annual International Symposium (VRAIS 96)*, VRAIS '96, pages 46–, Washington, DC, USA, 1996. IEEE Computer Society. URL: http://dl.acm.org/citation.cfm?id=832290.836042.

[254] Chun Yu, Ke Sun, Mingyuan Zhong, Xincheng Li, Peijun Zhao, and Yuanchun Shi. One-dimensional handwriting: Inputting letters and words on smart glasses. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 71–82, New York, NY, USA, 2016. ACM. URL: http://doi.acm.org/10.1145/2858036.2858542, doi:10.1145/2858036.2858542.

[255] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1285–1294, April 2017. doi:10.1109/TVCG.2017.2656978.

[256] Feng Zhou, Henry Been-Lirn Duh, and Mark Billinghurst. Trends in augmented reality tracking, interaction and display: A review of ten years of ismar. In *Proceedings of the 7th IEEE/ACM International Symposium on Mixed and Augmented Reality*, ISMAR '08, pages 193–202, Washington, DC, USA, 2008. IEEE Computer Society. URL: https://doi.org/10.1109/ISMAR.2008.4637362, doi:10.1109/ISMAR.2008.4637362.

DECLARATION

Ich versichere hiermit, dass ich die Arbeit selbständig angefertigt habe und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die zur Zeit gültige Satzung der Universität Ulm zur Sicherung guter wissenschaftlicher Praxis beachtet habe (§ 8 Abs. 1 Nr. 5 Rahmenpromotionsordnung).

Ich bin damit einverstanden, dass die Dissertation auch zum Zweck der Überprüfung der Einhaltung allgemein geltender wissenschaftlicher Standards benutzt wird, insbesondere auch unter Verwendung elektronischer Datenverarbeitungsprogramme (§ 8 Abs. 1 Nr. 8 Rahmenpromotionsordnung).

Ulm, Deutschland, April 2019

Jan Gugenheimer

Part II

PUBLICATIONS

SWIVRCHAIR

Jan Gugenheimer, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. 2016. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). Association for Computing Machinery, New York, NY, USA, 1996–2000. DOI:https://doi.org/10.1145/2858036.2858040

SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality

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ABSTRACT
We present *SwiVRChair*, a motorized swivel chair to nudge users' orientation in 360 degree storytelling scenarios. Since rotating a scene in virtual reality (VR) leads to simulator sickness, storytellers currently have no way of controlling users' attention. *SwiVRChair* allows creators of 360 degree VR movie content to be able to *rotate* or *block* users' movement to either show certain content or prevent users from seeing something. To enable this functionality, we modified a regular swivel chair using a 24V DC motor and an electromagnetic clutch. We developed two demo scenarios using both mechanisms (*rotate* and *block*) for the Samsung GearVR and conducted a user study (n=16) evaluating the presence, enjoyment and simulator sickness for participants using *SwiVRChair* compared to self control (*Foot Control*). Users rated the experience using *SwiVRChair* to be significantly more immersive and enjoyable whilst having a decrease in simulator sickness.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords
SwiVRChair; Virtual Reality; Consumer Virtual Reality; Virtual Environments; 360 Degree Video; 360 Degree Storytelling

INTRODUCTION
Whilst VR Head-Mounted Displays (HMDs) have been researched for a long time in labs, we argue that upcoming research will have to focus on actual domestic/consumer use of HMDs and therefore address new upcoming problems and opportunities. Since Oculus announced the formation of the Oculus Story Studio[1], a team focusing solely on creating virtual reality movies, the field of 360 degree story telling has received more public attention and can become one big selling point of consumer virtual reality (VR).

Since 360 degree movies are a fairly new medium, creators are facing several challenges such as controlling the attention of a user. In traditional movies this is done by applying cuts and tracking shots which is not possible or advisable in VR since rotating the virtual scene in front of the user's eyes will lead to simulator sickness [11]. One of the reasons this effect occurs is when the physical movement (measured by the vestibular system) and the visual movement are not coherent.

Figure 1. Left: A participant being rotated inside a virtual scene sitting on the *SwiVRChair*. Right: The physical prototype of the *SwiVRChair*

Since most current VR content is advisable to be consumed using a swivel chair [3], we propose the concept of physically moving the user by rotating the chair with an attached motor (figure 1). We implemented *SwiVRChair* by adding a 24V motor and an electromagnetic clutch connected through a timing belt (figure 3). The magnetic clutch allows the user to still resist and break free of the controls of *SwiVRChair* without harming the motor. Therefore, we do not try to fully control the user's view but consider it more as a nudging and an immersing of the user into the scene.

In a user study (n=16) we evaluated the effect of *SwiVRChair* compared to *Foot Control* in terms of presence, enjoyment and simulator sickness. Participants watched two 360 degree scenes we designed using Unity3D containing both mechanics (*rotate* and *block*) resulting in a significantly higher rating for *SwiVRChair* in terms of presence and enjoyment while having a decrease in terms of simulator sickness compared to *Foot Control*. We offer the source code and building instructions as an open source platform.[2]

CONCEPT AND DESIGN SPACE
OculusVR founded Oculus Story Studio which is a company of former Pixar employees who focus on creating movies in VR which immerse the users in the story and are happening in 360 degree around them (figure 1). The goal of *SwiVRChair* is to offer a low-cost motion platform which can be used in current households and enhance the experience for VR content such as 360 degree movies. *SwiVRChair* uses a common swivel chair which is already

[1]https://storystudio.oculus.com/en-us/

[2]http://www.uni-ulm.de/?swivrchair

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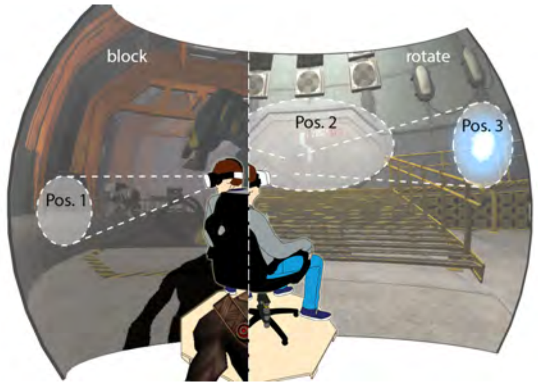

Figure 2. On the left, the concept of *block*: The user is turned away from the monster (Pos. 1) and only sees its shadow in front of them. The user can either accept this or fight the blockage using his feet to turn the chair. On the right, the concept of *rotate*: The user is guided through the scene and certain content such as the purpose of the door (Pos. 2) is explained in more detail. In case the user gets bored, they can start turning away from the current content.

wide spread in households and enhances it by adding a motor and a clutch (figure 3) to be able to automatically rotate the chair.

This offers a design space based around rotational movements to control the user's orientation inside a virtual 360 degree scene. We emphasize in our concept two basic actions *rotate* and *block* which we offer as a tool for content creators to use inside a 360 degree immersive virtual environment (IVE).

rotate. In the basic scenario the user is rotated towards certain content inside the IVE (figure 2). This allows the content creator of 360 degree IVE to simulate aspects of movies such as cuts or tracking shots. Similar to traditional movies these can be used to introduce the scene or have a more artistic aspect. The rotation can also be used to immerse the user more into the scene (e.g. as the result of an explosion the users will twist around). The rotation can be controlled by the parameters speed (how fast will the user rotate) and target (what angle should the user face at the end of the rotation).

block. The concept of blocking allows for the orientation of *SwiVRChair* to be kept at a certain angle (figure 2). This can be used to hide certain information from the user (e.g. a monster approaching from behind). This is a novel technique to story telling which derives from the freedom of looking around inside a 360 degree scene which was not possible in traditional cinema. Similar to *rotate*, *block* can either be used as a cinematic technique or to immerse the user even more into the IVE (e.g. some virtual character is holding the user).

Little is known about 360 degree storytelling, therefore we refer to the currently only available insights, "5 Lessons Learned While Making Lost" which were released by Oculus Story Studio [1]. One of the lessons was "Let go of forcing the viewer to look somewhere" which firstly sounds contrary to the *SwiVRChair* concept but is something that we built as an essential part into the concept of *SwiVRChair*. Both concepts of *SwiVRChair* (*block* and *rotate*) always allow the user to break out of the chair's movement. Therefore we see both concepts just as a nudging, which the user can either accept and enjoy or can choose to break out of and explore the whole environment by themselves. This was one of the reasons why we decided to use a magnetic clutch (more details in the implementation section) and did not use a footrest. We wanted the user to still feel (and be) in control throughout the whole experience.

IMPLEMENTATION

SwiVRChair is powered by a type G42x40 24V DC Dunkermotor having a torque of 5.7 Ncm and 3100 rpm. In addition we use a planetary gearbox (PLG G42 S) consisting of metal gear rings having a 32:1 gear reduction. In a prior version we used a gearbox (PLG 42 K) made out of plastic rings which broke due to the force which was applied by fast rotation and direction changes. We added a further gear reduction using a toothed belt with a ratio of 3:1 resulting in an overall torque of $\approx$5.5 Nm and $\approx$33 rpm (without any load). This is enough to theoretically create a full rotation of an $\approx$100kg person 30 times a minute. However, the angular acceleration starting from a non-moving chair is more relevant, since it is unlikely that a participant will be rotated more than twice around its own axis. Using our setup (running on 20V) we are able to rotate an up to 100kg heavy participant from a standing position in 2.3 seconds half a revolution.

The magnetic clutch (Kendrion) consists of two parts, one attached to the drive shaft on the gearbox and the other attached to the toothed belt wheel. These two parts are not connected mechanically. The electromagnetic field created by applying 24V locks the two parts and the rotation of the motor is transfered through the toothed belt to the chair shaft. Once a user blocks the rotation using their feet the force generated exceeds the maximum capacity of the clutch and the electromagnetic field breaks. This principle allows the user always to break free of the movement of *SwiVRChair* without harming the gearbox and without having to apply too much force. To measure the precise orientation of the chair we attached a magnetic rotary positions sensor by arms (AS5047D) at the bottom of the chair shaft.

Figure 3 shows the implementation of *SwiVRChair*. We removed the rollers from a standard office swivel chair to block movement during a rotation and placed the chair on a wooden platform to position all the cables underneath. The motor and clutch were placed inside a metal frame and attached to the chair shaft. Both the motor and the clutch are controlled using a motor shield (figure4) connected to an Arduino Mega 2560. The motor shield is connected to a 24V power supply and transfers an incoming PWM signal from the Arduino to a Voltage (0 - 24 V). The Arduino communicates via a bluetooth shield (BLE Shield) with the Samsung GearVR headset running a Unity3D application of the IVE. This allows us to control the rotation of the chair from within the Unity scene.

The rotation algorithm of *SwiVRChair* is modeled using a *"critical-damped-spring"* system. This simulates a spring between the start and the target point having a certain stiffness (determined empirically) whereby the *"ciritical-damping"* ensures that the spring returns to equilibrium as quickly as possible without oscillating. Using this model allowed to compensate for friction and rubbing which a user generates with their feet and resulted in an overall smooth rotation.

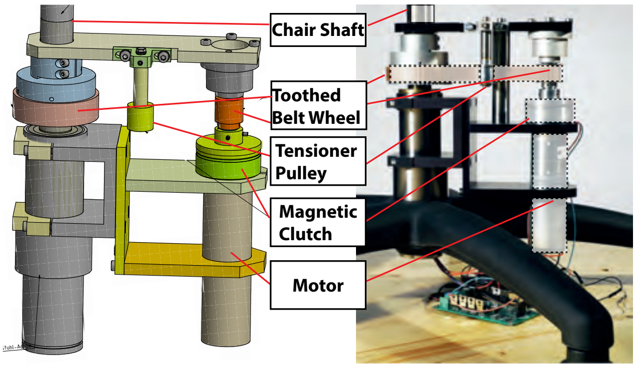

Figure 3. On the left, the 3D model of the chair construction and on the right the actual implementation showing the attachment to the chair

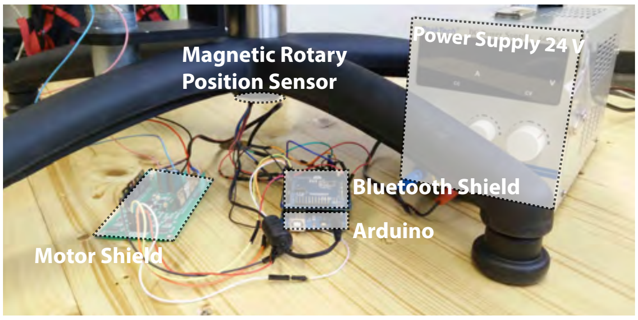

Figure 4. The electronic components which were used to power *SwiVRChair* and getting rotational commands from the GearVR

RELATED WORK

We grounded our work in the field of Interactive Digital Storytelling and VR motion platforms.

SwiVRChair is motivated by the work of Vosmeer et al. [15]. They present the different levels of engagement a cinema experience has ('lean back'), compared to a game experience ('lean forward'). They argue that 360 storytelling is a combination of both and raises the research question 'can we indeed establish this engagement style that is neither fully lean-back nor lean forward'. SwiVRChair contributes to this exact question and can be seen as an extension of a 'system's' output capabilities and contains new 'potential narratives' as defined by the framework of Koenitz [10]. As for the use of block and rotate, we used the most fundamental primitives SwiVRChair can physically offer, which allows for novel 'Narrative vectors'. One of the early applications of these concepts of story telling to virtual reality was done by Pausch et al. [13].

Most current motion platforms for VR were designed based on the Steward platform [14] offering a six degree of freedom platform mostly driven by six hydraulic cylindric actuators. These platforms were suited for research laboratories [4] but are not suitable for a domestic scenario. Some prior research implemented motion platforms and feedback devices designed for domestic usage. *HapSeat* [6] presented a low cost motion simulation by letting the user experience motion through three force feedback devices (one in each arm and one behind the head). This simplistic approach was also used in *TactileBrush* [8] where a grid of vibrotactile actuators attached to a chair render strokes on the user's back to simulate motion. These systems both leverage the fact that users perceive motion mainly through their visual, auditory, vestibular and kinesthetic system [5, 7], whereas *SwiVRChair* actually moves the users instead of simulating motion. In contrast to *rotovr* [2], *SwiVRChair* does not create a motion platform which is controlled by the user, but instead focuses on the user being controlled by the environment. This is why *SwiVRChair* deliberately abstained from using footrests and artificial controls such as a gamepad, to enable the user to naturally interfere with the rotation.

USER STUDY

Procedure

To measure what impact *SwiVRChair* has on simulator sickness, presence and enjoyment we conducted a user study. We randomly recruited 16 participants (7 female) between 23 and 30 years old (M=26.1, SD=2.0) from our institution. Every participant watched two 360 degree movies we modeled in Unity3D wearing the Samsung GearVR and sitting on *SwiVRChair*. The scenes were watched directly after another (not removing the HMD in between) to have a longer experience (≈6 Minutes). As a baseline condition we used the *SwiVRChair* setup without the motorization allowing the user to rotate freely throughout the whole experience (*Foot Control*). Both the scenes and the motor conditions were fully counterbalanced. Simulator sickness was measured using the RSSQ [9] before and after each motor condition (*SwiVRChair*, *Foot Control*) and presence and enjoyment were measured using the E^2I questionnaire [12] after each motor condition.

The scenes were created based on the lessons learned by Oculus story studio [1]. The first scene took place in a space warehouse having the participant sit on a virtual chair in the center of the scene. A visual guide leads the user through the scene and introduces them to the environment. At the end a power breakdown shuts down the lights of the scene and simulates a malfunction of the virtual chair, turning the user away from an entrance (figure 5 a). The user now has to fight *SwiVRChair* to turn towards the door seeing only the shadow of a creature approaching them from behind. The scene ends with the user being turned towards the creature and virtually punched in the face to end the scene spinning (figure 5 b). The second scene takes place in a forest inside a house of a fairy. The fairy enchants and spins several items (as well as the user) inside her home and brews a magic potion. After enchanting and scaring the user (figure 5 c), the fairy's kettle explodes spinning her and the user out of the house. The whole experience consists of 3 full rotations (360°),6 half rotations (180°) and 18 minor turns (90°).

Results

Simulator Sickness: The simulator sickenss (figure 6 a) was low for both conditions (*SwiVRChair*: M=0.76 SD=4.05 and *Foot Control*: M=3.0 SD=4.40 on a practical scale of -8.44 to 82.04 [9]). However, a Wilcoxon signed-rank tests showed no significance between *SwiVRChair* and *Foot Control* (Z=-0.909, $p =$ n.s.)

Presence and Enjoyment: In the E^2I questionnaire (figure 6 b) participants rated to have a significantly higher presence (Wilcoxon signed-rank test: Z=-2.14, $p<.05$) and enjoyment

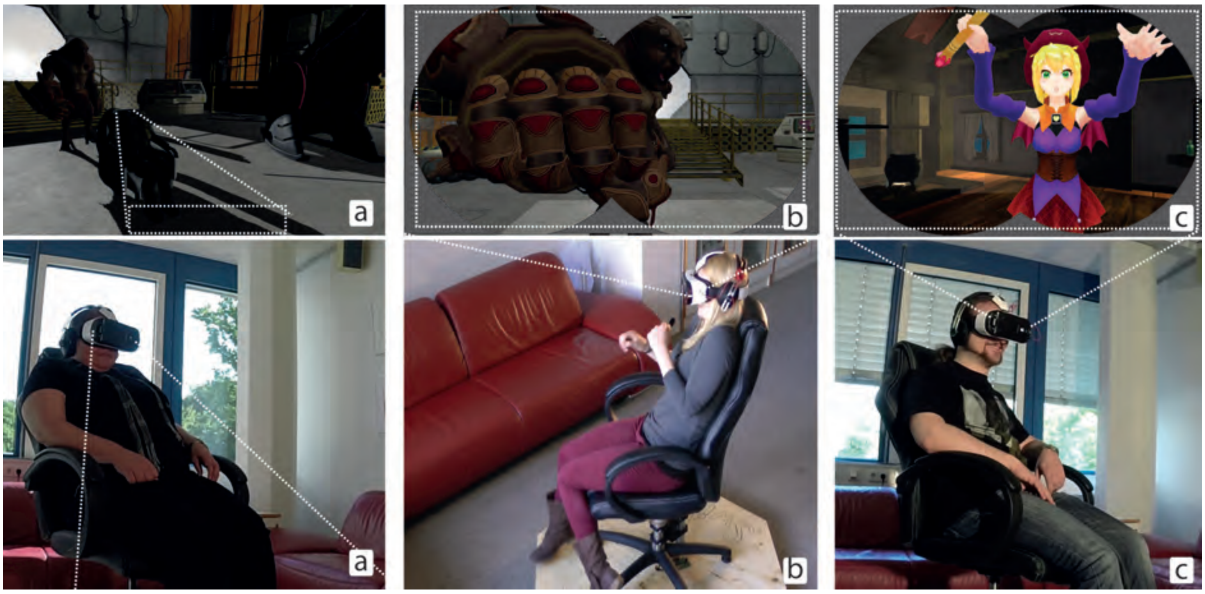

Figure 5. Pictures taken from the users and their emotions during the study, where participants experience the two scenes. a) fighting against the chair b) getting punched by the space creature c) being scared by the fairy.

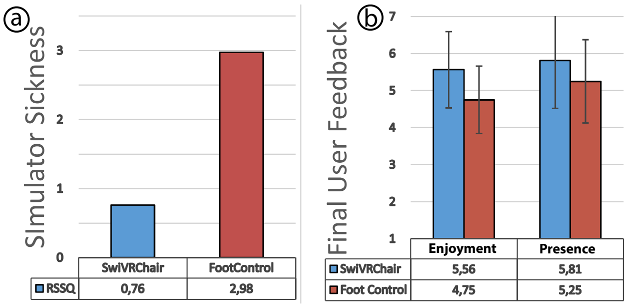

Figure 6. Participants rated enjoyment and presence (b) significantly higher using *SwiVRChair*while having less simulator sickness (a).

(Wilcoxon signed-rank test: Z=-2.80, $p<.01$) using *SwiVR-Chair* (pre.: M=5.81 SD=0.9, enjoy.: M=5.6 SD=1.0)) vs *Foot Control* (pre.:M=5.2 SD=1.1, enjoy.: M=4.75 SD=1.3).

Usage Data: We measured the overall movement of the head and the chair for both conditions. In addition to the chair movement, participants moved their head more using *Foot Control* (M=2478°, SD=757°) than with *SwiVRChair* (M=2815° SD=1554°). After the study we let participants comment on their experience. Participants reported that using *SwiVRChair*, they "*had a lot of fun*", "*felt comfortable using the device over a longer period of time*" and did not have the pressure of "*missing out on something*". Finally, 14 participants said they preferred using *SwiVRChair*, wanted to have such a device at home and would pay approx 200 *currency*.

DISCUSSION AND CONCLUSION

The overall very low simulator sickness of *SwiVRChair* surprised us as well as the participants. We partially explain this effect with the overall lower head movement of the participants using *SwiVRChair*. Participants were more "*leaning back*" and enjoying the experience and did not have the pressure of having to explore the whole environment to "*not miss anything*". While we offered the ability of always breaking free of the chair's movement participants often did not see the need for it since they got directed towards the relevant content. One can imagine that future 360 degree movies will ideally end up having the same duration as current movies. Having to actively browse the scene and explore the environment for more then 1.5 hours will probably exhaust users. Therefore, we argue that this combination of directional nudging and freedom of exploring the scene offers an important mix of comfort allowing to enhance the experiencing of future 360 degree videos.

In the future, we are planing to systematically investigate the influence of parameters such as rotation speed or rotation distance on the simulator sickness and user experience to generate guidelines of how and where techniques such as *rotate* and *block* should be used in 360 degree movies.

In this work we presented *SwiVRChair*, a motorized swivel chair to control user orientation in 360 degree movies. We introduced the concept of nudging the user's orientation by rotating the chair. We presented how to build *SwiVRChair* and release the source code and building instructions as an open source platform. We presented the results of a user study, showing that participants rated *SwiVRChair* significantly higher in terms of enjoyment and presence compared to *Foot Control* whilst having lower simulator sickness.

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REFERENCES

1. 5 Lessons Learned While Making Lost. https://storystudio.oculus.com/en-us/blog/5-lessons-learned-while-making-lost/. Accessed: 2015-09-15.
2. RotoVR. http://www.rotovr.com/. Accessed: 2015-09-17.
3. Samsung Gear VR Innovator Edition FAQ. https://support.oculus.com/hc/en-us/articles/204358883-Samsung-Gear-VR-Innovator-Edition-FAQ. Accessed: 2015-09-17.
4. Bimal Aponso, Duc Tran, Jeffery Schroeder, and Steven D Beard. 2008. Rotorcraft Research at the NASA Vertical Motion Simulator. In *ANNUAL FORUM PROCEEDINGS-AMERICAN HELICOPTER SOCIETY*, Vol. 64. AMERICAN HELICOPTER SOCIETY, INC, 2390.
5. A Berthoz. 2000. The brain's sense of movement: perspectives in cognitive neuroscience. (2000).
6. Fabien Danieau, Julien Fleureau, Philippe Guillotel, Nicolas Mollet, Anatole Lécuyer, and Marc Christie. 2012. HapSeat: Producing Motion Sensation with Multiple Force-feedback Devices Embedded in a Seat. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology (VRST '12)*. ACM, New York, NY, USA, 69–76. DOI:http://dx.doi.org/10.1145/2407336.2407350
7. Laurence R Harris, MR Jenkin, D Zikovitz, Fara Redlick, P Jaekl, UT Jasiobedzka, HL Jenkin, and Robert S Allison. 2002. Simulating self-motion I: Cues for the perception of motion. *Virtual Reality* 6, 2 (2002), 75–85.
8. Ali Israr and Ivan Poupyrev. 2011. Tactile Brush: Drawing on Skin with a Tactile Grid Display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2019–2028. DOI:http://dx.doi.org/10.1145/1978942.1979235
9. DH Kim. 1999. Development of method for quantification and analysis of simulator sickness in a driving simulation environment. *Doctoral dissertation, Hanyang University, Seoul, South Korea* (1999).
10. Hartmut Koenitz. 2010. Towards a Theoretical Framework for Interactive Digital Narrative. In *Interactive Storytelling*, Ruth Aylett, MeiYii Lim, Sandy Louchart, Paolo Petta, and Mark Riedl (Eds.). Lecture Notes in Computer Science, Vol. 6432. Springer Berlin Heidelberg, 176–185. DOI:http://dx.doi.org/10.1007/978-3-642-16638-9_22
11. Eugenia M Kolasinski. 1995. *Simulator Sickness in Virtual Environments.* Technical Report. DTIC Document.
12. J.J.-W. Lin, H.B.L. Duh, D.E. Parker, H. Abi-Rached, and T.A. Furness. 2002. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*. 164–171. DOI:http://dx.doi.org/10.1109/VR.2002.996519
13. Randy Pausch, Jon Snoddy, Robert Taylor, Scott Watson, and Eric Haseltine. 1996. Disney's Aladdin: First Steps Toward Storytelling in Virtual Reality. In *Proceedings of the 23rd Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '96)*. ACM, New York, NY, USA, 193–203. DOI:http://dx.doi.org/10.1145/237170.237257
14. Doug Stewart. 1965. A platform with six degrees of freedom. *Proceedings of the institution of mechanical engineers* 180, 1 (1965), 371–386.
15. Mirjam Vosmeer and Ben Schouten. 2014. Interactive Cinema: Engagement and Interaction. In *Interactive Storytelling*, Alex Mitchell, Clara Fernndez-Vara, and David Thue (Eds.). Lecture Notes in Computer Science, Vol. 8832. Springer International Publishing, 140–147. DOI:http://dx.doi.org/10.1007/978-3-319-12337-0_14

FACETOUCH

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FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality

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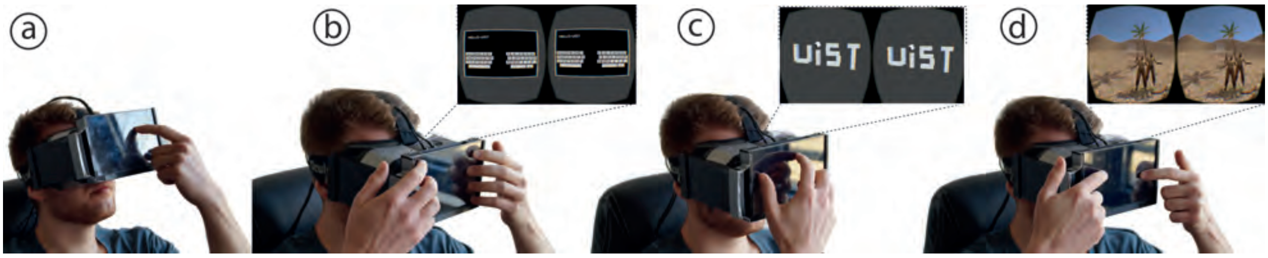

Figure 1. (a) A user interacting with *FaceTouch*, a multi-touch surface mounted on the back of a VR HMD. *FaceTouch* allows for precise interactions which can be used to implement applications such as text entry (b) or 3D modeling (c). Leveraging the sense of proprioception a user is able to blindly interact with control elements such as used in a gamepad to control a shooter game (d).

ABSTRACT
We present *FaceTouch*, a novel interaction concept for mobile Virtual Reality (VR) head-mounted displays (HMDs) that leverages the backside as a touch-sensitive surface. With *FaceTouch*, the user can point at and select virtual content inside their field-of-view by touching the corresponding location at the backside of the HMD utilizing their sense of proprioception. This allows for rich interaction (e.g. gestures) in mobile and nomadic scenarios without having to carry additional accessories (e.g. a gamepad). We built a prototype of *FaceTouch* and conducted two user studies. In the first study we measured the precision of *FaceTouch* in a *display-fixed* target selection task using three different selection techniques showing a low error rate of ≈2% indicate the viability for everyday usage. To asses the impact of different mounting positions on the user performance we conducted a second study. We compared three mounting positions of the touchpad (*face*, *hand* and *side*) showing that mounting the touchpad at the back of the HMD resulted in a significantly lower error rate, lower selection time and higher usability. Finally, we present interaction techniques and three example applications that explore the *FaceTouch* design space.

ACM Classification Keywords
H.5.2. [Information Interfaces and Presentation] : User Interfaces: Input Devices and Strategies, Interaction Styles

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Author Keywords
Back-of-device interaction; Mobile VR; VR interaction; Virtual Reality; Nomadic VR; VR input

INTRODUCTION
Virtual Reality (VR) head-mounted displays (HMD) are having a consumer revival with several major companies such as Facebook, Sony and Samsung releasing their consumer devices this year. In contrast to VR HMDs that are operated by a computer (such as OculusRift and HTC Vive), mobile HMDs have been presented which are operated solely by a mobile phone (e.g. Samsung GearVR and Google Cardboard). These mobile VR HMDs allow new usage scenarios where users can access Immersive Virtual Environments (IVEs) anywhere they want. Based on aspects of nomadic computing [17], we define this as *nomadic VR*.

Due to the omnipresence of mobile phones and the relatively low price, mobile VR HMDs (e.g. Google CardBoard) are expected to penetrate the consumer market more easily. However, current VR input research such as [1] and consumer products are focusing on stationary HMDs and input modalities that would not be available in nomadic scenarios. These include the instrumentation of the environment (e.g. Oculus' positional tracking, HTC VIVE's Lighthouse) or the usage of peripheral devices like 3D mice or game controllers. Hand tracking technology such as the Leap Motion strives for enabling "natural" interaction inside an IVE and lead to a higher level of immersion for certain scenarios (e.g. immersive experiences) but discounts utilitarian interactions such as browsing a menu or entering text, where the goal is on performance and less on immersion. We argue that interaction for VR should not only focus on enabling those "natural" interaction concepts but also enable a "super natural" interaction where users can interact and manipulate the virtual environment with little physical effort and enable interactions beyond human capability.

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We therefore investigate the concept of touch interaction inside an IVE as a first step towards that direction.

Current mobile VR UIs are designed to be operated using *Head-Rotation* with a crosshair cursor or a gamepad. Since gamepads are not bundled with any mobile HMD (and do not fit the nomadic usage) the most targeted and used selection technique is *HeadRotation*. This leads to a limitation in the UI design space. With *HeadRotation*, a crosshair cursor is centered in the middle of the view, so that the user can aim at the target by rotating their head and select by using another means of input, such as a button or touch panel at the side of the VR device. The area of view has to be centered around the target location and as an implication, it is not possible to design *display-fixed* user interface elements (e.g. targets that are always at the bottom of the display). For this reason, current UI elements are implemented to be at a fixed location in 3D space (*world-fixed* UI). This forces either the content creator to embed every possible UI element (consider a keyboard for text input) inside the 3D scene or the user to leave their current scene to control UI elements (e.g. Samsung GearVR settings menu).

FaceTouch

To address these shortcomings, we present *FaceTouch*, an interaction technique for mobile VR HMDs leveraging the backside of the HMD as a touch surface (see Fig. 1). Adding touch input capabilities to the backside allows for direct interaction with virtual content inside the users field-of-view by selecting the corresponding point on the touch surface. Users cannot see their hands while wearing the HMD, but due to their proprioceptive senses [20] they have a good estimate of their limbs in relation to their body. Supported by visual feedback as soon as fingers are touching the surface, as well as their kinesthetic memory, users find in *FaceTouch* a fast and precise alternative interaction technique for nomadic VR scenarios that does not require them to carry an additional accessory (e.g. a gamepad).

In order to explore the design space we built a hardware prototype consisting of an Oculus Rift and a 7 inch capacitive touchpad mounted to the backside (see Fig. 3). We ran two user studies to investigate the precision and interaction time of *FaceTouch* for *display-fixed* UIs and measure the impact of the *mounting position* on those factors. In a first user study (n=18) we conducted a target selection task in a *display-fixed* condition showing a possible throughput [22] of ≈2.16 bits/s. Furthermore, we present a selection point cloud, showing how precise users can point at targets relying only on proprioception. In a second user study (n=18), we investigated the impact of the *mounting position* on performance, comparing three different locations (*face*, *hand* and *side*) and showing a significantly lower error rate and lower selection time when mounting the touchpad on the backside of the HMD, justifying our design decision for *FaceTouch*.

CONTRIBUTIONS

The main contributions of this paper are:

- The concept of *FaceTouch*, an interaction technique for mobile VR HMDs allowing for fast and precise interaction in nomadic VR scenarios. It can be used on its own or combined with *HeadRotation* to further enrich the input space in mobile VR.
- Showing the feasibility of *FaceTouch* for *display-fixed* user interfaces, offering a low selection error rate (≈3%) and fast selection time (≈1.49 s), making it viable for everyday usage.
- Comparing three different mounting positions of the touchpad and showing the advantages (≈8% less errors then *hand* and ≈29% less then *side*) and user preference for the *face* mounting location.
- Exploration of the design space of *FaceTouch* through the implementation of three example applications (gaming controls, text input, and 3D content manipulation) showing how the interaction can be utilized in *display-fixed* as well as *world-fixed* VR applications.

RELATED WORK

Our work is related to the research fields of back-of-device interaction, proprioceptive interaction and input techniques for IVEs.

Back-of-Device Interaction

In order to eliminate finger occlusion during touch interaction, researchers proposed back-of-device interaction [14, 18, 35, 2] which leverages the backside of a mobile device as an input surface.

Several implementations and prototypes where proposed which either used physical buttons on the backside [14, 18] or used the backside as a touch surface [31, 35]. Wigdor et al. enhanced the concept by introducing "pseudo-transparency" which allowed the users to see a representation of their hand and fingers allowing the users to precisely interact with the content independent of finger sizes [37]. Furthermore, Baudisch et al. showed that the concept of back-of-device interaction works independent of device sizes [2]. Wigdor et al., applied the concept further to stationary devices such as a tabletop [38]. Without seeing their hands and using only the sense of proprioception, participants interacted with a tabletop display by selecting targets under the table.

FaceTouch extends the field by being the first work utilizing back-of-device interaction in VR. In contrast to existing techniques, the user is completely visually decoupled from their body and by that means not able to see their arms while approaching a target. This forces the user to rely even more on proprioception to interact with the content.

Proprioceptive Interaction

The human capability of knowing the position and relation of the own body and its several body parts in space is called proprioception [3]. It usually complements the visual sense when reaching for a target, but even when being blindfolded from their physical environment, users can utilize their proprioceptive sense especially well to reach parts of their own body, such as being able to blindly touch their own nose [15].

Wolf et al. showed that due to the proprioceptive sense, participants were able to select targets on the backside of an iPad without visual feedback having no significant decrease in accuracy compared to visual feedback [39]. Serrano et al. explored the design space of "hand-to-face" input, where participants used gestures such as strokes on their cheeks for interacting with an HMD [33]. Lopes et al. showed how the sense of proprioception can be used as an output modality [20]. Similar to *FaceTouch*, most work in the field of back-of-device interaction leverages the sense of proprioception. A novelty of *FaceTouch* is that a back-of-device touchpad is attached to the user's body and as a result the user can utilize proprioception while being immersed in a virtual environment. Also the user's hands are not constrained by holding a device and can unrestrictedly be used for touch interaction.

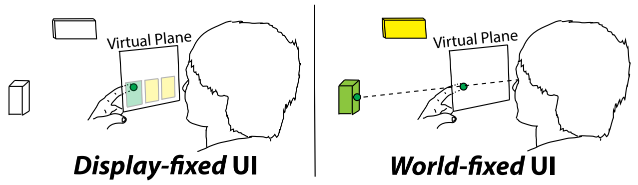


Figure 2. User interface elements for *FaceTouch* can be fixed to both: the *display* (left) and the *world* (right). The virtual plane has a 1:1 direct mapping to the physical touch surface. By touching this plane, users can select *display-fixed* elements on the virtual plane (left) and ray-cast into the scene to select *world-fixed* elements (right).

Further, the use of proprioception was often explored in IVEs [24, 7, 19]. Mine at al. showed the benefits of proprioception in IVEs by letting participants interact with physical props in the non-dominant hand [24]. Similar to this approach, Lindeman et al. used a paddle in the non-dominant hand to leverage proprioception and passive haptic feedback in virtual hand metaphors [19].

Input Techniques for Virtual Environments

Besides novel feedback mechanisms [9, 10], a big part of recent VR research revolves around interaction concepts. The focus of interaction concepts for IVEs in related work is mostly on 3D interaction techniques [1] which can be classified as *exocentric* and *egocentric* interaction metaphors [28], distinguishing between whether the user interacts in a first-person view (*egocentric*) or a third-person view (*exocentric*) with the environment. Our focus will be on *egocentric* interaction concepts of which the most prevalent are the virtual hand and virtual pointer metaphors [1, 29].

The virtual hand metaphor is applied by tracking the user's hand and creating a visual representation of it allowing the user to interact with content within arm's reach [21]. Lindeman et al. presented how using a physical paddle in the user's non-dominant hand to create passive haptic feedback can increase user performance for hand metaphor selection tasks [19]. *FaceTouch* offers the same advantages in terms of passive haptic feedback without forcing the user to hold a physical proxy. To enable virtual hand metaphor interaction with UI elements not in the user's vicinity, researchers proposed concepts such as GoGo [27] or HOMER [4] which apply non-linear scaling of the hand position.

Virtual pointer metaphors rely on casting a ray into the virtual scene to enable user interaction [23]. Several techniques were proposed to determine the ray's orientation which mostly rely on tracking the user's hand similar to the virtual hand metaphor. The orientation of the ray can either be controlled by the hand position and wrist orientation or as a ray cast from the user's viewpoint through the hand [26]. Different approaches combine either both hands [24] or use eye tracking [36]. The *HeadRotation* interaction of Samsung's GearVR can be considered a virtual pointer metaphor where the ray is cast perpendicular to the center of the user's viewpoint.

In contrast to previous work, *FaceTouch* enables direct interaction with content in and outside of the user's vicinity without external tracking or additional accessories (as had been used in [30, 25]) and can be easily implemented in future mobile VR devices. Furthermore, *FaceTouch* offers passive haptic feedback which typically results in a higher selection performance [6].

INTERACTION CONCEPT

The basic principle of *FaceTouch* is to leverage the large unexploited space on the backside of current HMDs as a touch sensitive surface. This allows for the creation of a mapping between the physical touch surface in front of the user and their field-of-view within the IVE. By touching the surface, the user is touching a virtual plane within their field-of-view (see Fig. 2) with the same ratio and resolution as the physical touchpad resulting in a 1:1 direct mapping of physical touch and virtual selection. When aiming for a target, users can see the touch position of their fingers visualized on the virtual plane as soon as touching the surface. We refer to this step as *LandOn*. To commit a selection, we use two different techniques that can both complement each other for different selections. With *LiftOff*, a selection is committed when lifting a finger above a target, while with *PressOn*, a target is selected by applying pressure. Both techniques allow the user to correct the position of a finger on the virtual plane, before committing the selection. User interface elements for *FaceTouch* can be both: fixed to the *display* or to the *world* [8] (see Fig. 2).

World-fixed UIs

In current mobile VR HMDs, such as Samsung Gear VR, user interface elements are fixed within the virtual world and selectable by rotating the head and thereby turning the target into the center of the user's view. This concept of interaction is suitable for UIs which try to immerse the user into the scene. However, it also poses the drawback that only elements within the centered focus (e.g. a crosshair in the center of the display) can be selected and a lot of head rotation is required for successive selections. With *FaceTouch*, *world-fixed* user interface elements can be selected alike, however the user does not have to center their view at the target. It is possible to select targets anywhere within the field-of-view by selecting the corresponding point on the virtual plane. Hence, users can keep their focus wherever they like.

Display-fixed UIs

In addition to *world-fixed* interfaces, *FaceTouch* allows to place *display-fixed* UI elements. These are always attached to the virtual plane and are independent of the users orientation (being always inside the users field-of-view). Examples for this are menu buttons that prove to be useful throughout interaction, such as reverting the last action in a modeling software, opening a settings menu, or virtual controls for gaming applications (more details in the *Applications* section). *Display-fixed* UI elements can be transparent to not occlude the field-of-view or even completely hidden for more experienced users. These kind of interfaces are crucial to realize utilitarian concepts such as data selection or text entry which focus more on user performance than on immersion. Therefore, the rest of this paper will focus on investigating parameters and performances with *display-fixed* UIs.

IMPLEMENTATION

We built a hardware prototype of *FaceTouch* by mounting a 7 inch capacitive touchpad (15.5cm x 9.8cm) to the backside of a Oculus Rift DK2 (see Fig. 3). Even though we do not consider the Oculus Rift a mobile VR HMD since it has to be connected to a computer, it allowed us to easily integrate the rest of the hardware and was sufficient for our study designs. The touchpad is embedded in a 3D-printed case and attached to the HMD via 5 small buttons to enable the detection of finger presses on the touchpad. An Arduino Pro Mini is used to control these buttons. The *side*

Figure 3. The *FaceTouch* prototype. A capacitive touchpad is embedded into a 3D-printed case and attached to the backside of an Oculus Rift DK2 via 5 small buttons that allow for pressure sensing on the touchpad. The side touchpad was only used in the second user study and does not have any buttons attached to it.

touchpad was mounted on the right side of the HMD to simulate an often used mounting location for HMDs which is considered ergonomic (e.g. GearVR and Google Glass). The *side* touchpad has the same resolution and aspect ratio as the *face* touchpad. The size is approximately 10.8cm x 6.8cm. Both touchpad were picked so that they would offer as much touch space as possible for the mounting position used. Oculus Rift, the touchpad and the Arduino are tethered to a computer running Windows 8.1. The VR environments are rendered with Unity 5.0.1.

DISPLAY-FIXED UI - USER-STUDY

To show that *FaceTouch* can be used on daily basis with mobile/nomadic VR HMDs we ran a user study which simulates the interaction with *display-fixed* interfaces. We conducted a target selection user study for *display-fixed* UIs to investigate parameters relevant for *FaceTouch*. Since users rely on proprioception, we were interested in how accurate and fast users could hit targets of different sizes and locations, especially without visual feedback. Depending on size and distance, we expect users to get close to the target while blindly attempting a selection, but not being able to accurately select the target. For this reason we compared *LandOn*, as a selection technique without visual feedback as a baseline to *LiftOff* and *PressOn*. The latter two allow for the correction of the initial selection by first visualizing the touch location and requiring an additional *commit method* afterwards.

By positioning the virtual touch plane at the actual distance of the physical surface, we expect less interference with the proprioceptive sense. However, the Oculus guidelines [40] suggest *display-fixed* virtual planes to fill out only a third of the field of view leading to less "eye strain". For that reason, we were also interested in the effect of changing the virtual plane distance.

Study Design

The study was conducted as a target selection task using a repeated measures factorial design with three independent variables. As independent variables we chose *commit method* (*LandOn*, *LiftOff* and *PressOn*), *plane distance* (*NearPlane*, *MidPlane* and *FarPlane*) and *target size* (*small* and *large*).

Commit method. We implemented three methods to commit a selection. With *LandOn*, a target is immediatley selected at the initial point of contact of a finger. By this, no visual feedback is

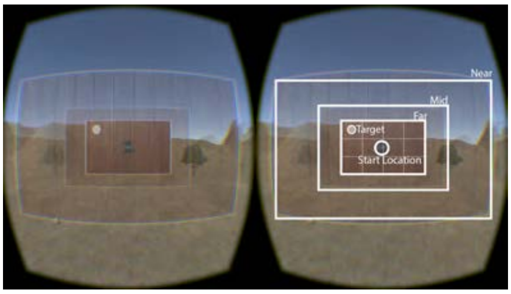


Figure 4. The interface of the *display-fixed* UIs user study, showing the distances of the planes and the arrangement of the targets (for illustration).

given prior to selection. *LiftOff*, selects the target that was touched when lifting the finger from the surface, while *PressOn* selects the target below the finger when physical pressure is applied to the touchpad. For *LiftOff* and *PressOn*, a cursor is presented on the virtual plane as visual feedback to represent the finger.

Plane distance. We used three different ratios for the field-of-view and the size of the virtual plane. *NearPlane* positioned the virtual plane at the same virtual distance as the touchpad was attached to the HMD. *FarPlane* positioned the virtual plane at a distance to fill out approximately a third of the field of view, as suggested by the guidelines of OculusVR [40]. The *MidPlane* was positioned in-between *NearPlane* and *FarPlane*, filling out approximately half of the field-of-view.

Target size. The *small* circular targets were picked based on the Android Design Guidelines for the smallest target having the size of 48dp (density-independent pixels) approximately 7.8mm. *large* targets received double the size (96dp approximately 15.6mm).

This resulted in nine combinations (3 *commit methods* x 3 *plane distances*) which were presented to the participants using a 9x9 Latin square for counterbalancing. *Target size* was randomized together with the target position as described in the *Procedure*.

The dependent variables were selection time, error rate and simulator sickness. The latter was measured using the RSSQ (Revised Simulator Sickness Questionnaire) [16]. We included the simulator sickness since we were particularly interested in the subscale "Ocular Discomfort" and expected the *plane distance* to influence this.

Procedure

For the first user study we only used the *face mounting position*. All participants performed a target selection task whilst wearing the *FaceTouch* prototype and sitting on a chair. Participants were instructed to lean back on the chair and were not allowed to rest their arms on a table to simulate the nomadic scenario. To begin with, participants were introduced to the concept of *FaceTouch* and filled out a demographic questionnaire. Based on the Latin square, each combination (*commit method* and *plane distance*) was presented and explained to the participants. Each participant filled out the RSSQ for simulator sickness before and after completing the target selection task with each combination. Participants were allowed to practice with each combination until they felt comfortable. At the end each participant filled out a final questionnaire comparing the presented combinations.

The target selection task consisted of 12 circular targets arranged in a 4x3 cellular grid across the virtual plane (Fig. 4). Similar to Lubos et al. [21], participants started with selecting the start button before each target which was located in the center of the plane having the target size *small*. This started the timer and randomly spawned a target in the center of one of the 12 cells. This allowed us not having to use a perfect circular arrangement of targets but cover the full surface of the touchpad (also the corners) and still have a fair measurement of time. Each cell was repeated 3 times with both target sizes resulting in at least six targets per cell and at least 72 targets per combination. If a participant failed to successfully select a target the target was repeated at a later point in time (similar to [2] this repetition was not applied for *LandOn* since a high error rate made it impracticable). For each participant, the study took on average 1.5 hours.

Participants

We randomly recruited 18 participants (12 male, 6 female) from our institution with an average age of 27 (range: 21 to 33). All had an academic background being either students or had studied at the university. On average participants had been using touchscreens for 10 years (range: 3 to 12). Eight of the participants had never used an HMD before. Each participant received 10 *currency*.

Results

Our analysis is based on 18 participants selecting targets of 2 sizes on 12 locations with 3 different plane distances using 3 different commit methods each with 3 repetitions resulting in over 11664 selections.

Error Rate

An error was defined as a selection attempt which did not hit the target (selecting the start button was not taken into consideration). Figure 5 shows the average error rate for each *commit method* with each *plane distance* and each *target size*. A 3x3x2 (*commit method* x *plane distance* x *target size*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) showed significant main effects for *commit method* ($F(1.078,18.332)=634.822$, $p<.001$, $\eta^2=0.97$), *plane distance* ($F(2,34)=8.928$, $p<.001$, $\eta^2=0.24$) and *target size* ($F(1,17)=801.810$, $p<.001$, $\eta^2=0.97$). We also found significant interaction effects for *target size* x *commit method* ($F(1.141,19.402)=437.581$, $p<.01$, $\eta^2=0.96$).

As we expected, pairwise comparisons (Bonferroni corrected) revealed that participants made significantly more errors ($p<.001$) using *LandOn* (M=54.7%, SD=9%) than *PressOn* (M=1.8%, SD=1.9%) and significantly ($p<.001$) more using *LandOn* than *LiftOff* (M=2.2%, SD=1.8%). It is worth pointing out, that the average *LandOn* error rates for the targets close to the start button (target 5 and 6 on Fig. 7) were only at 8%. This indicates that the precision drastically reduces when the user had to cover longer distances blindly.

A second interesting finding was that participants made significantly ($p<.05$) more errors using the *NearPlane* (M=20.9%, SD=4%) compared to the *MidPlane* (M=18.4%, SD=4%). One has to keep in mind that the *plane distance* only changed the visual target size, not the actual target size on the touchpad. This showed similar to prior work [41] that the target size which is presented to the user, significantly influences the accuracy of the pointing, even if the actual touch area stays the same. Finally, we found a significantly ($p<.001$) higher error rate of participants selecting *small* targets (M=25.6%, SD=3.8%) compared to *large* targets (M=13.6%, SD=2.9%).

Selection Time

As the selection time we defined the time between selecting the start button and the target. Only successful attempts were taken into consideration. Figure 6 shows the average selection time for each *commit method*, *plane distance* and *target size*. We excluded *LandOn* from the analysis since it resulted in a too high error rate. A 2x3x2 (*commit method* x *plane distance* x *target size*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) showed significant main effects for *plane distance* ($F(2,34)=8.928$, $p<.05$, $\eta^2=0.17$) and *target size* ($F(1,17)=345.773$, $p<.001$, $\eta^2=0.95$).

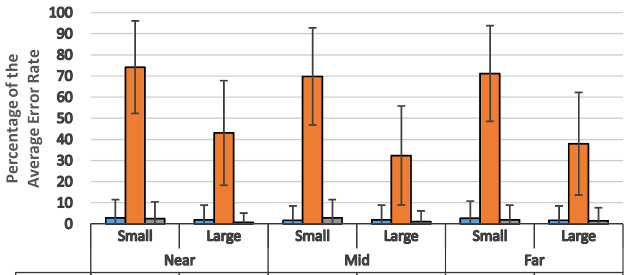
Confirming with Fitts' Law, pairwise comparisons (Bonferroni corrected) revealed that participants were significantly ($p<.001$) faster in selecting *large* targets (M=1.22s, SD=0.17s) than *small* targets (M=1.51s, SD=0.19s). For comparisons, we calculated the mean selection time of *LandOn* (M=0.84s, SD=0.14s). Unlike for the error rate, *plane distance* had no significant influence on the selection time.

Using this data we calculated an average throughput (following the methodology of [34]) for *LiftOff* of around (M=2.16 *bps*, SD=0.28 bps). The average throughput values for the mouse range from 3.7bps to 4.9bps [34] whereas touch has an average of 6.95bps [32].

LandOn Precision

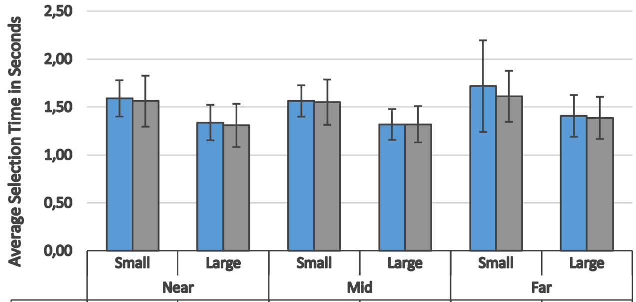
Bonferroni corrected pairwise comparisons of means revealed that within their three attempts, participants' touches resulted in a significantly ($p<.001$) higher amount of overshoots with *small* targets (M=1.44, SD=0.2) than with *large* targets (M=1.19, SD=0.29). Additionally, participants' touches resulted in a significantly ($p<.001$) higher amount of overshoots using *NearPlane* (M=1.6, SD=0.25) than *MidPlane* (M=1.3, SD=0.25) and significantly ($p<.001$) higher amount of overshoots using *NearPlane* than *FarPlane* (M=1.0, SD=0.4). To be able to understand and optimize the interaction using *LandOn*, we did an in-depth analysis of the selection locations. We were hoping to get a better insight into the level of accuracy people are able to achieve using the proprioceptive sense and how participants were using *FaceTouch*. We logged the location participants touched and defined an overshoot as a touch with a distance more than the length of the direct path. A 2x3x12 (*target size* x *plane distance* x *target location*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) on the number of overshoots (within the three attempts) showed a significant main effect for *target size* ($F(1,17)=24.179$, $p<.001$, $\eta^2=0.58$), *plane distance* ($F(2,34)=17.965$, $p<.001$, $\eta^2=0.51$) and *target location* ($F(11,187)=20.377$, $p<.001$, $\eta^2=0.54$). Furthermore, there were significant interactions between *target size* ×*target location* ($F(11,187)=2.103$, $p<.05$, $\eta^2=0.11$) and *plane distance* ×*target location* ($F(22,374)3.159$, $p<.001$, $\eta^2=0.16$).

To explore the differences between the cells, we numbered each cell of the *target location* (see Fig. 7). Pairwise comparisons of means between each cell revealed significant differences in the amount of overshoots. We could divide the cells in two groups, an overshoot (cells 2,3,6,7,10,11)and an undershoot group (cells 1,4,5,8,9,12), each containing half of the cells. Figure 7 shows the touch locations for *small* targets and *MidPlane* where the centroids for failed and successful selections are represented as a triangle, respectively a circle. One can easily see the two groups by comparing the relation between the success and the fail



	Near Small	Near Large	Mid Small	Mid Large	Far Small	Far Large
LiftOff	2,99	1,97	1,82	1,97	2,70	1,82
LandOn	74,23	43,06	69,86	32,41	71,19	37,96
PressOn	2,56	0,77	2,99	1,07	1,97	1,52

Figure 5. Error rates for the different variables (+/- standard deviation of the mean)



	Near Small	Near Large	Mid Small	Mid Large	Far Small	Far Large
LiftOff	1,59	1,34	1,56	1,32	1,72	1,41
PressOn	1,56	1,31	1,55	1,32	1,61	1,39

Figure 6. Average selection time for the *LiftOff* and *PressOn commit method* (+/- standard deviation of the mean).

centroids to the center. In the overshoot group the fail centroids are always further away from the start location, whereby in the undershoot group the fail centroids are between the start location and the target. This overshooting is related to the distance the users finger has to travel. These findings show that when relying solely on proprioception, users tend to overestimate their movement over longer distances, resulting in an undershooting and underestimate it when the target is close.

In a next step we created a function which calculates the optimal target size so 95% of the touch points would end up to be successful (this is only a rough estimate since the target size itself can influence performance [41]). The optimal target size would have a diameter of around 370px (30.06mm) which is smaller than targets of Wigdor et al. [38]. We assume this is due to the fact that people have a better sense of proprioception in their facial area than with a stretched out arm under the table.

Usability Data

In a final questionnaire we let participants rank the *commit method* and *plane distance* based on their preference. Participants ranked *LiftOff* unanimously to be the *commit method* they would like to use (second was *PressOn*). Furthermore, participants (17 votes) voted *MidPlane* to be the most comfortable to use followed by *NearPlane* and *FarPlane*. Commenting on open-ended questions, participants mentioned that they thought *FaceTouch* was a "*great idea*"(P16), worked "*surprisingly well*"(P10), had an "*intuitive and natural interaction*"(P2) and was "*fast to learn*"(P7). Analyzing the simulator sickness data we did not find any occurrence of simulator sickness (M=1.09 ,SD=0.56 on a practical scale of −8.44 to 82.04 [16]) nor significant differences for the different variables.

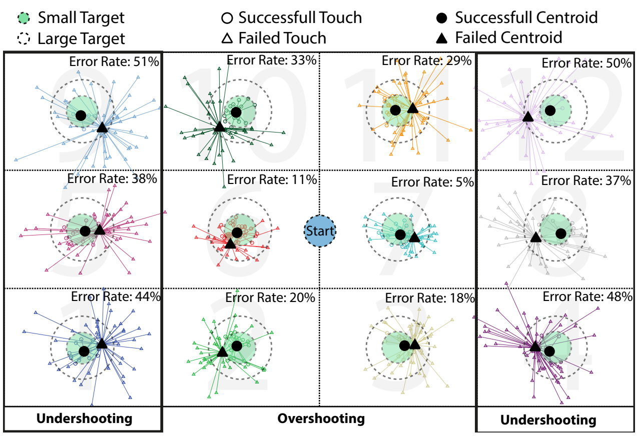


Figure 7. LandOn touch locations (mid distance with small targets) with centroids for failed and successful targets.

Discussion

Our research question for the first user study was to find out if *FaceTouch* is usable for *display-fixed* UIs and how the parameters *commit method*, *plane distance*, *target size* interact with the performance.

LiftOff. The low error rate and overall short selection time shows that *LiftOff* is overall suitable to interact with current UIs for VR HMDs. The UI elements can be picked being even smaller than the *small* targets (7.8mm), since the error rate was around 2.2%. However, calculating the perfect sizes needs further investigation. The touch data for *LiftOff* showed that participants mostly started from the center of the touchpad (on average 460px away from the target location) and did not try to place the initial touch close to the target. So for precise interaction, participants need one reference point where they start their movement and start seeing the position on the touchpad. We leveraged this in the implementation of one of our example applications (Text Entry Fig. 13) by splitting the keyboard into two parts and allowing the user to have one reference point for each hand leading to a reduced overall movement.

PressOn. The overall performance in terms of error rate and selection time of *PressOn* was similar to *LiftOff*, indicating that it would also be a valid choice for interacting with mobile VR HMDs. During the tasks, most participants never lifted the finger from the touchpad preferring to have the visual cue of the current touch location similar as for *LiftOff*. The biggest downside of *PressOn* was that pressing down on the touchpad resulted in the IVE to "*shake*" and led to a higher physical demand. This *shaking* only occurred in the *PressOn* condition, all other conditions had no negative effect since we used a capacitive touchpad that needs no pressure. However, this did not lead to a higher simulator sickness but was reported as being "*uncomfortable*". In a future prototype this can be solved using technology such as "ForceTouch" introduced by Apple.

As expected, *LandOn* performed significantly worse in terms of error rate in comparison to the other two *commit methods*. Nevertheless, it indicated a lower selection time (M=0.84s, SD=0.14s) and has therefore relevance for time critical UIs demanding less accuracy, such as a gamepad (see section *Interaction Scenarios*). Having analyzed the touch data for *LandOn* we are able to give some insights on how users blindly interact with *FaceTouch* and how this interaction can be improved.

The analysis showed that users undershoot for targets which were located far from the starting point (see Fig. 7). In combination with the theoretically optimal target size of 30.06mm, UIs can be optimized for the under-/overshoot. However, this is only valid for interactions which forces the user to select targets over a long distance. After the initial touch to "orientate" on the touchpad, participants have a high accuracy if the moving distance is fairly low (targets 6 and 7 have an average accuracy of 92% using *LandOn*, *large* targets and *MidPlane*). This can be utilized by designers (in combination with a two handed input) by placing two large buttons close to each other to simulate a gaming controller. We utilize this in a gaming application (see section *Applications* and Fig. 12).

An overall surprising finding was that the *plane distance* had a significant influence on the error rate even though the physical target size on the touchpad did not change. *FaceTouch* allowed for the decoupling of the physical target size from the visual target size and showed that the *plane distance* has to be chosen carefully. In our studies *MidPlane* led to the best performance by covering approximately half of the user's field of view (oppose to the Oculus Rift guidelines [40] suggesting to only cover a third of the user's field of view).

In summary, the results support our hypothesis that *FaceTouch* works as an interaction technique for *display-fixed* UIs. The precision and selection time suggests that *FaceTouch* is indeed a viable approach for bringing pointing input to mobile VR HMDs. Furthermore, our findings give design guidelines (which we used ourselves in the example applications) for UI designers on when to use which *commit method* and how to design for each *commit method*.

TOUCHPAD POSITIONING - USER STUDY

After showing the precision which *FaceTouch* offers with *display-fixed* UIs on the *face* mounting position we wanted to explore alternative mounting position of the touchpad and measure their impact on the users performance. We decided to compare three *mounting positions* (*face*, *hand*, *side*). We selected those positions since we expected *face* to have the highest level of perception and therefore the highest accuracy, *hand* because of its comfortable position over long use and *side* as a baseline to compare against the current state of the art of controlling HMDs with a touchpad at the temple (e.g. GearVR or Google Glass). Based on the optimal parameters for *target size* and *target location* we determined in the first user study, we conducted a target selection study with *display-fixed* UIs placing the touchpad either on the back of the HMD (*face*), in the hand of the user (*hand*) or similar to the GearVR on the side of the HMD (*side*) (see Fig. 8). The goal was to determine if placing the touchpad on the backside of the HMD would affect the the proprioceptive cues more compared to the other two positions.

Study Design

The study was conducted using a repeated measures factorial design with one independent variable (*mounting position*) having three levels (*face*, *hand* and *side*). As a selection technique we used *LandOn* and *LiftOff* however did not compare between those since we used different target sizes which were the optimal

Figure 8. Placement of the touchpads during the positioning user study

from the first user study (*LandOn* with *large* and *LiftOff* with *small*). We decided to use *large* for *LandOn* to be able to compare the results for *hand* and *side* with the first study. We omitted *PressOn* from the study since it yield similar results to *LiftOff*. The plane distance was *MidPlane*. The *mounting position* and *commit method* were counterbalanced.

The dependent variables were selection time, error rate, usability and workload. Usability was meassured using the SUS questionnaire [5] and workload using the raw NASA-TLX [12]. The touchpad on the *side* had the same aspect ratio and resolution as the *face* but was smaller in size (10.8 cm x 6.8 cm) to fit on the side of the HMD. The mapping from the touchpad on the side to the input plane in front of the user was evaluated in an informal pre-study with several colleges from the institution and set fix for all participants (from the users perspective back being right and front being left). For the *hand* condition the touchpad from *face* was taken out and put into a case which the participant would hold in his non dominant hand an interact using the dominant hand. Other than this, the same apparatus as in the first study was used.

Procedure

The same target selection task as in the first user study for *display-fixed* UIs was used. Participants were able to practice as long as they wanted and started with *LandOn* or *LiftOff* (counterbalanced). Each of the 12 targets were selected three times. After both *commit method* with each *mounting position* was done participants filled out the SUS and NASA-TLX questionnaire. At the end of the study participants ranked each *mounting position* in terms of comfort and could comment on the positioning. The whole study took on average 45 minutes.

Participants

We randomly recruited 18 participants (14 male, 4 female) with an average age of 26 (range: 20 to 36) and all having an academic background being either students or employed at the institute. On average participants had 6 years experience using touchscreens and 7 had experience in using VR HMDs. Each participant received 10 currency.

Results

Error Rate: An error was defined similar to the first study. Figure 10 shows the distribution of the error rate for each *mounting position*. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* ($F(2,34)=38.276$, $p<.001$, $\eta^2=0.69$) using *LandOn*. Bonferroni corrected pairwise comparisons revealed that *face* (M=0.35, SD=0.1) had a significant lower error rate than *hand* ($p<.05$) and *side* (M=0.65,

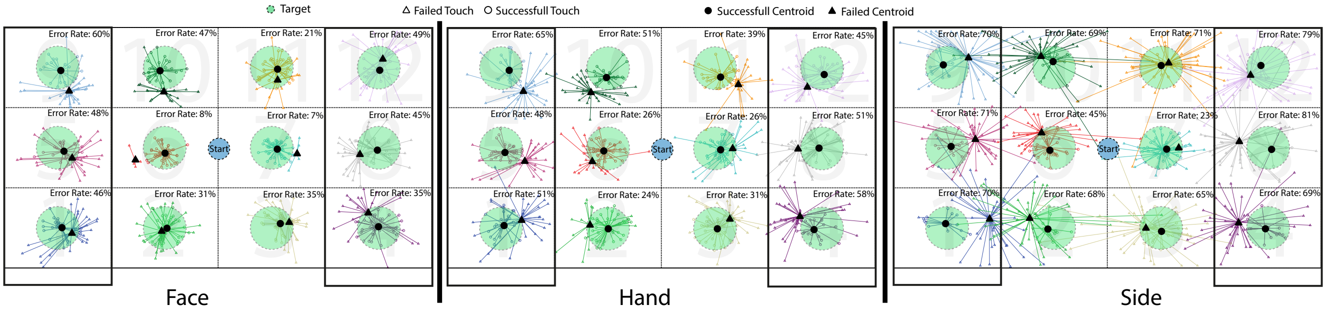


Figure 9. LandOn touch locations for each *mounting position* with centroids for failed and successful targets. One can see the high level of scatter for the *side* position and the relatively low scatter for *face*.

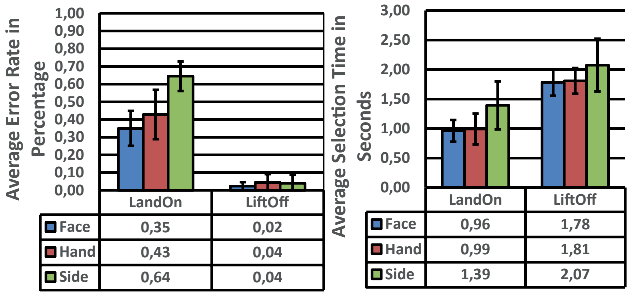


Figure 10. (left) The average error rate in percentage for the *mounting position* using *LandOn* and *LiftOff* (+/- standard deviation of the mean). (right) The average selection time for *mounting position* using *LandOn* and *LiftOff* (+/- standard deviation of the mean).

SD=0.09) (p<.001) and *hand* had a significant lower error rate compared to *side* (p<.001). No significant differences were found for *LiftOff* (F(2,34)=1.666, n.s.).

As a further metric for the precision of the touches for *LandOn* we calculated the euclidean distance for each touch point from its target center (see Fig. 9). This gives an estimate of how scattered points were and is a finer measure the just the boolean of hit or miss. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* (F(2,34)=69.302, p<.001, η^2=0.80). Bonferroni corrected pairwise comparisons revealed that *face* (M=91,70 px, SD=10.5 px) had a significant lower scatter compared to *hand* (M=110,81 px, SD= 18.40 px, p<.001) and *side* (M=160.70 px, SD= 28.84 px). Furthermore, *hand* had a significant lower scatter compared to *side* (p<.001). Combining these results with the significant lower error rate showed that participants could easier locate the targets when the touchpad was positioned at the *face*.

Selection Time: Similar to the first study, we measured the time between selecting the start button and selecting the target. Only successful attempts were taken into consideration. Figure 10 shows the average selection time for each *mounting position* using *LandOn* and *LiftOff*. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* (F(2,34)3.159, p<.001, η^2=0.34) using *LiftOff*. Bonferroni corrected pairwise comparisons revealed no significant difference between *face* (M=0.96 s, SD=0.18 s) and *hand* (M=0.99 s, SD=0.26 s), but a significant difference between *face* and *side* (M=2.10 s, SD=0.44 s) ((p<.05)), and *hand* and *side* (p<.05).

Usability, Workload and Fatigue: A one factorial ANOVA revealed a significant difference between the *mounting position* for the SUS (F(2,34)=25.134, p<.001, η^2=0.60) and NASA-TLX questionnaire (F(2,34)=29.149, p<.001, η^2=0.63). Bonferroni corrected pairwise comparisons revealed a significant higher SUS score of *face* (M=79.86, SD=10.72) versus *side* (M=51.11, SD=19.40) (p<.001) and *hand* (M=76.11, SD=14.84) versus *side* (p<.001). Furthermore, *side* (M=27.11, SD=5.48) had a significant higher workload compared to *face* (M=17.22, SD=4.21) and *hand* (M=18, SD=5.92) (p<.001). Overall, *face* had the highest SUS rating and lowest NASA-TLX workload score. This shows that users preferred the *face* location in terms of usability and workload.

To measure fatigue, we let participants state their physical demand on a 7 point Likert scale (subsacle of the NASA-TLX). A one factorial ANOVA revealed a significant difference between the *mounting position* for physical demand (F(2,34)=8.721, p<.001, η^2=0.34). Bonferroni corrected pairwise comparisons revealed a significant lower physical demand of *face* (M=3.1, SD=1.7) versus *side* (M=3.8, SD=1.35) (p<.01) and *hand* (M=2.2, SD=1.4) versus *side* (p<.01).

Discussion

The goal of the positioning study was to measure the impact of the location of the touchpad for *LandOn* and *LiftOff*. The *LiftOff commit method* showed no big differences between the different *mounting positions* even though *face* was slightly better in terms of error rate and selection time compared to *hand* and *side*. Interacting using *LiftOff* benefits from the visualization and therefore does not rely on the proprioceptive sense that much.

The biggest difference for the *mounting position* were found in the *LandOn* condition. Placing the touchpad at the backside of the HMD (*face*) resulted in the overall best result (significant lower errors, scatter of touchpoints and highest SUS and lowest workload). Participants mentioned that they had a better "understanding" and "perception" when trying to blindly find the touch points. This probably results from the fact that the proprioceptive sense works better around the facial location and has more cues that the participants know the location of (eyes, nose, mouth etc.). Holding the touchpad in the hands (*hand*) users only have two known relation points, the supporting hand and an approximate of the location from the finger touching. Participants also mentioned it was more difficult to coordinate those two actions (holding still and touching) which is easier in the *face* position. When positioning the touchpad on the *side* participants had to create a mental mapping from the physical touchpad located perpendicular to the virtual floating pad. Participants mentioned that this was inherently difficult (we let participants experience the reversed mapping aswell but noone perceived it as better fitting) whereby placing the touchpad at the back of the HMD (*face*) allowed "almost directly touching" the targets.

Fatigue

One of the big concerns when designing interaction for IVEs is the level of fatigue users will experience when interacting. Hand tracking technology such as the Leap Motion are a negative example here because of the 'touching the void' effect [6]. Furthermore, [11] and [13] showed that having the 'elbows tucked in' or 'bent the arm' results in significant less fatigue than stretching the arm away from the body. However, the last one is necessary for most hand tracking devices since they are attached on the backside of the HMD and the hands must be in their FoV.

Using *FaceTouch*, fatigue occurred after our user studies that took on average over 1h. However, the motivation for FT is that such an interaction is being often used for short utilitarian purposes. Furthermore, when comparing against the currently wide spread touchpad at the temple (*side*), *FaceTouch* resulted in significant lower physical demand. To further increase the comfort of the interaction, participants started already to apply techniques on how to support their arms or heads to avoid fatigue effects (e.g. 'The Thinker Pose', lean back into the chair wrap the non-dominant arm around your chest and rest the dominant arm on it). This position can easily be held over the envisioned period of interaction compared to stretching the arms away from the body [11, 13].

When using *FaceTouch* over a longer periode of time participants mentioned to expand the concept and allow to detach the touchpad and be able to hold it in the hand and using it with *LiftOff*. This would lower the fatique of holding the arm over a longer period and allow for a more comfortable position. However, for small and fast interactions, participants (8) preferred using the *face* location.

These results challenge the current location of the touchpad at consumer VR HMDs such as the GearVR which placed its touchpad at the *side*. The current concept for the GearVR only uses the touchpad for indirect interaction(e.g. swipes). If this would be extended to allow direct touch the positioning should be reconsidered.

APPLICATIONS

To present the advantages, explore the design space of *display-fixed* UIs and show that *FaceTouch* is also capable of being used with *world-fixed* UIs we implemented three example applications (cf. video figure). First, we are going to present a general UI concept which we used to embed *FaceTouch* into VR applications. Afterwards, we present three example applications (gaming controls, text input and 3D modeling) we developed to show how *FaceTouch* can enhance interaction for current VR applications.

General UI Concept

In consumer VR there are currently very little UI concepts to control the device at a general UI level (e.g. control settings inside an IVE). Most devices such as the Oculus Rift and Google Cardboard let the user select applications and content and only afterwards the user puts on the device and immerses into the scene. To change settings the user has to take of the HMD and change those. The reason of which is that VR requires new interaction paradigms incompatible to standard interfaces.

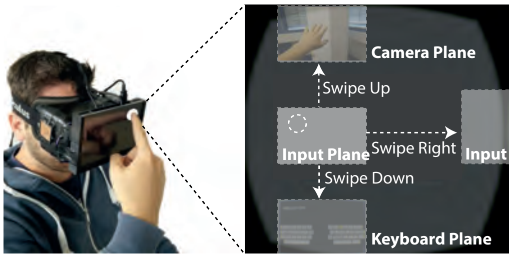


Figure 11. Users can switch through different types of planes (e.g. Keyboard Plane or Pass-Through-Camera Plane) using up or down swipe gestures. Swiping right or left opens the settings of a certain plane. This general model allows to navigate through menus without having to leave the current IVE.

By allowing the control of *display-fixed* UIs, *FaceTouch* enables a new way of navigation through UIs in IVEs without having to leave the current scene (Fig. 11). The virtual plane can be used to place UI elements similar to current smart phones (e.g Android). By swiping up and down users can navigate through different virtual planes containing features such as *Camera Passthrough*, *Application Plane* or *Settings Plane* (Fig. 11). Swiping right and left offers settings or further details to the currently selected virtual plane. This allows for interaction with *display-fixed* UIs without having to leave the current IVE. Since this interaction is not time critical, *LiftOff* or *PressOn* can be used as the *commit method*.

Figure 12. A user controls a first person zombie shooter using *FaceTouch* in combination with *LandOn*. Five buttons for the interaction were arranged in a cross over the full touchpad (the shown arrows are only used to visualize the locations of the buttons and are not displayed in the actual prototype). This allows for decoupling gaze from interactions such as walking.

Gaming Controls

Games that require the user to control gaze and actions independently from each other (e.g. walking whilst looking around) currently demand to be used with a game controller. Using *FaceTouch* in combination with *LandOn*, simple controller elements can be arranged on the touchpad (Fig. 12). *LandOn* seems most suitable for this application, as it delivered the shortest input times while still providing the low accuracy that this type of application requires. In our implementation of a zombie shooter game we arranged five buttons (four buttons for walking and one for shooting) in a cross over the full touch plane of *FaceTouch*. The accuracy of the touches is completely sufficient since users don't have to move their fingers over a great distance but mostly hover over the last touch point (resting the hand on the edges of *FaceTouch*). This allowed users to control movements independent from the gaze without having to carry around additional accessories.

Text Input

Current implementations of applications which need to search through a collection of data (e.g. 360° video databases) on mobile VR HMDs, require the user to browse through the whole library

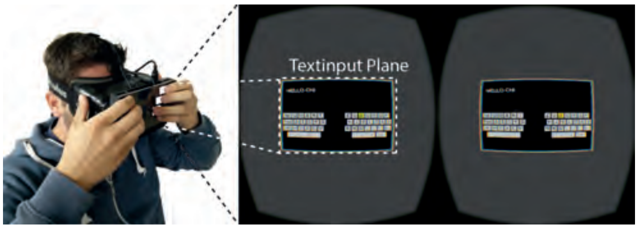


Figure 13. A user is typing text using *FaceTouch* in combination with *LiftOff*. The keyboard is split in half to support the hand posture which is resting at the HMD case.

to find a certain entry. We implemented a simple QWERTY keyboard to input text inside an IVE. Using *display-fixed* UIs, allows for implementing the keyboard without having to leave the IVE (Fig. 13). Since this scenario requires a precise interaction we used *LiftOff* as the *commit method*. In an informal user study we let three experts without training input text ("the quick brown fox..") resulting in approximately 10 words per minute. This shows the potential of *FaceTouch* for text input in IVEs, which of course needs further investigation.

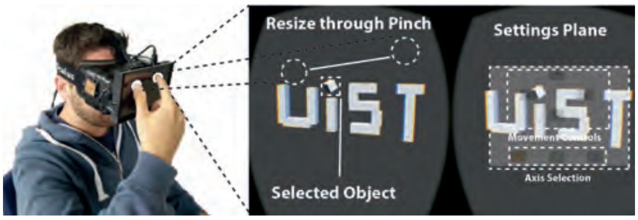


Figure 14. A user creating a 3D model of a UIST logo. The currently selected object is highlighted in a different color. A pinch gestures is used to resize the currently selected cube. The right eye shows a settings plane which can be opened using a swipe gesture

3D Modeling

FaceTouch allows not only to select a certain object in 3D space but to rotate, resize and translate the object by using multi-touch gestures. We implemented a simple "sandbox" 3D modeling application to show the capabilities of *FaceTouch*. For this application we used the general UI concept which we presented beforehand.

Initially the user starts in a blank environment with their touches visualized. Pushing down on the touchpad (*PressOn*) the user can spawn cubes inside the 3D world. After selecting one cube (*PressOn*), it can be resized using two fingers (pinch-to-zoom) or rotated using three fingers. By swiping down over the whole touchplane (using three fingers) the user can open a virtual plane showing some control buttons (Fig. 14 right). The user can either fly around the model (movement controls) or select the axis he wants to manipulate (e.g. rotate around x-axis).

LIMITATIONS AND FUTURE WORK

One limitation of the current implementation of *FaceTouch* is the weight the prototype puts on the user's head ($\approx$ 800g). This can be addressed in future prototypes by using more lightweight components. Furthermore, the interaction with a touchpad on the user's face leads to arm fatigue after a while (similar to the current touchpad at the side of the HMD) which can be counterfeited by supporting the arm and sitting in a comfortable position.

In the future we are planing to enhance the interaction with *FaceTouch* for multi-touch and two-handed interaction (e.g for text entry), further investigating the performance. Furthermore, we are planing to explore how gestural interaction can be further embedded into the concept of *FaceTouch*.

CONCLUSION

Our initial goal of this work was to create an interaction concept which, against the current trend in VR research, focuses on performance for input and not immersion (such as the Leap Motion). We envision touch to become a crucial input method in the future of mobile VR after the first run on "natural" interaction will wear of and people demand a more comfortable form of interaction on a daily basis (or for scenarios where the level of immersion is not essential such as navigating through a menu or even a virtual desktop). We therefore designed *FaceTouch* to fit into the demand of future mobile VR applications such as quick access to pointing interaction for navigating menus and furthermore the possibility to detach the touchpad and use it in the hands for a longer interaction.

In this paper we presented the novel concept of *FaceTouch* to enable touch input interaction on mobile VR HMDs. We have demonstrated the viability of *FaceTouch* for *display-fixed* UIs using *LiftOff* for precise interactions such as text entry and *LandOn* for fast interactions such as game controllers. Our first user study, besides very positive user feedback, revealed important insights into the design aspects of *FaceTouch* like the right plane distance (*MidPlane*), impacts of various input methods (*LandOn*, *LiftOff*, *PressOn*) and resulting overshooting behavior. Further we provided optimal target sizes for implementing UIs for *LandOn* interaction.

Our second user study compared the *mounting position* for the touchpad and their impact onto the performance of the interaction. We showed that mounting the touchpad on the *face* resulted in a significant lower error rate for *LandOn* (8% less than *hand* and 29% less than *side*) and *LiftOff* (2% less than *hand* and *side*) and the fastest interaction (*LandOn* .96 s and *LiftOff* 1.78 s). The concept of *FaceTouch* can be furthermore enhanced to also support the ability of removing the touchpad from the mounting position and holding it in the hand. By analyzing the touch behavior of users for all positions we give an indicator of how to implement the targets in terms of size and location.

More importantly, *FaceTouch* can be combined with other input techniques to further enrich the input space as has been exemplified by the 3D modeling application. Finally, we demonstrated the large design space of *FaceTouch* by implementing three example applications emphasizing on the advantages of *FaceTouch*. As *FaceTouch* can easily be implemented into current mobile VR HMDs such as the Samsung GearVR, we suggest deploying it in addition to *HeadRotation*. Thereby, for the first time, *FaceTouch* enables *display-fixed* UIs as general UI concept (e.g. for text input and menu selection) for mobile VR as well as combined *display-fixed* UI and *world-fixed* UI interaction for a much richer experience.

ACKNOWLEDGMENTS

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REFERENCES

1. Argelaguet, F., and Andujar, C. A survey of 3d object selection techniques for virtual environments. *Computers & Graphics 37*, 3 (2013), 121–136.
2. Baudisch, P., and Chu, G. Back-of-device interaction allows creating very small touch devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, ACM (New York, NY, USA, 2009), 1923–1932.
3. Boff, K. R., Kaufman, L., and Thomas, J. P. Handbook of perception and human performance.
4. Bowman, D. A., and Hodges, L. F. An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, I3D '97, ACM (New York, NY, USA, 1997), 35–ff.
5. Brooke, J., et al. Sus-a quick and dirty usability scale. *Usability evaluation in industry 189*, 194 (1996), 4–7.
6. Chan, L.-W., Kao, H.-S., Chen, M. Y., Lee, M.-S., Hsu, J., and Hung, Y.-P. Touching the void: Direct-touch interaction for intangible displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, ACM (New York, NY, USA, 2010), 2625–2634.
7. Ebrahimi, E., Altenhoff, B., Pagano, C., and Babu, S. Carryover effects of calibration to visual and proprioceptive information on near field distance judgments in 3d user interaction. In *3D User Interfaces (3DUI), 2015 IEEE Symposium on* (March 2015), 97–104.
8. Feiner, S., MacIntyre, B., Haupt, M., and Solomon, E. Windows on the world: 2d windows for 3d augmented reality. In *Proceedings of the 6th Annual ACM Symposium on User Interface Software and Technology*, UIST '93, ACM (New York, NY, USA, 1993), 145–155.
9. Gugenheimer, J., Wolf, D., Eyhtor, E., Maes, P., and Rukzio, E. Gyrovr: Simulating inertia in virtual reality using head worn flywheels. In *Conditionally Accepted UIST '16*, UIST '16, ACM (2016).
10. Gugenheimer, J., Wolf, D., Haas, G., Krebs, S., and Rukzio, E. Swivrchair: A motorized swivel chair to nudge users' orientation for 360 degree storytelling in virtual reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, ACM (New York, NY, USA, 2016), 1996–2000.
11. 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 (New York, NY, USA, 2012), 69–76.
12. Hart, S. G., and Staveland, L. E. Development of nasa-tlx (task load index): Results of empirical and theoretical research. *Advances in psychology 52* (1988), 139–183.
13. Hincapié-Ramos, J. D., Guo, X., Moghadasian, P., and Irani, P. Consumed endurance: A metric to quantify arm fatigue of mid-air interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 1063–1072.
14. Hiraoka, S., Miyamoto, I., and Tomimatsu, K. Behind touch, a text input method for mobile phones by the back and tactile sense interface. *Information Processing Society of Japan, Interaction 2003* (2003), 131–138.
15. Ito, M. Movement and thought: identical control mechanisms by the cerebellum. *Trends in Neurosciences 16*, 11 (1993), 448 – 450.
16. Kim, D. Development of method for quantification and analysis of simulator sickness in a driving simulation environment. *Unpublished doctoral dissertation, Hanyang University, Seoul, South Korea* (1999).
17. Kleinrock, L. Nomadic computing—an opportunity. *SIGCOMM Comput. Commun. Rev. 25*, 1 (Jan. 1995), 36–40.
18. Li, K. A., Baudisch, P., and Hinckley, K. Blindsight: Eyes-free access to mobile phones. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, ACM (New York, NY, USA, 2008), 1389–1398.
19. Lindeman, R. W., Sibert, J. L., and Hahn, J. K. Towards usable vr: An empirical study of user interfaces for immersive virtual environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '99, ACM (New York, NY, USA, 1999), 64–71.
20. Lopes, P., Ion, A., Müller, W., Hoffmann, D., Jonell, P., and Baudisch, P. Proprioceptive interaction. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, CHI EA '15, ACM (New York, NY, USA, 2015), 175–175.
21. Lubos, P., Bruder, G., and Steinicke, F. Analysis of direct selection in head-mounted display environments. In *3D User Interfaces (3DUI), 2014 IEEE Symposium on* (March 2014), 11–18.
22. MacKenzie, I. S. Fitts' law as a research and design tool in human-computer interaction. *Human-computer interaction 7*, 1 (1992), 91–139.
23. Mine, M. R. Virtual environment interaction techniques. Tech. rep., Chapel Hill, NC, USA, 1995.
24. Mine, M. R., Brooks, Jr., F. P., and Sequin, C. H. Moving objects in space: Exploiting proprioception in virtual-environment interaction. In *Proceedings of the 24th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '97, ACM Press/Addison-Wesley Publishing Co. (New York, NY, USA, 1997), 19–26.
25. Nguyen, A., and Banic, A. 3dtouch: A wearable 3d input device for 3d applications. In *IEEE Virtual Reality 2015*, IEEE (2015).
26. Pierce, J. S., Forsberg, A. S., Conway, M. J., Hong, S., Zeleznik, R. C., and Mine, M. R. Image plane interaction techniques in 3d immersive environments. In *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, I3D '97, ACM (New York, NY, USA, 1997), 39–ff.
27. Poupyrev, I., Billinghurst, M., Weghorst, S., and Ichikawa, T. The go-go interaction technique: Non-linear mapping for direct manipulation in vr. In *Proceedings of the 9th Annual*

ACM Symposium on User Interface Software and Technology, UIST '96, ACM (New York, NY, USA, 1996), 79–80.

28. Poupyrev, I., and Ichikawa, T. Manipulating objects in virtual worlds: Categorization and empirical evaluation of interaction techniques. *Journal of Visual Languages & Computing 10*, 1 (1999), 19–35.
29. Poupyrev, I., Weghorst, S., Billinghurst, M., and Ichikawa, T. Egocentric object manipulation in virtual environments: Empirical evaluation of interaction techniques, 1998.
30. Prätorius, M., Valkov, D., Burgbacher, U., and Hinrichs, K. Digitap: An eyes-free vr/ar symbolic input device. In *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*, VRST '14, ACM (New York, NY, USA, 2014), 9–18.
31. Schwesig, C., Poupyrev, I., and Mori, E. Gummi: A bendable computer. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '04, ACM (New York, NY, USA, 2004), 263–270.
32. Scott MacKenzie, I. Fitts throughput and the remarkable case of touch-based target selection. In *Human-Computer Interaction: Interaction Technologies*, M. Kurosu, Ed., vol. 9170 of *Lecture Notes in Computer Science*. Springer International Publishing, 2015, 238–249.
33. Serrano, M., Ens, B. M., and Irani, P. P. Exploring the use of hand-to-face input for interacting with head-worn displays. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 3181–3190.
34. Soukoreff, R. W., and MacKenzie, I. S. Towards a standard for pointing device evaluation, perspectives on 27 years of fitts' law research in hci. *Int. J. Hum.-Comput. Stud. 61*, 6 (Dec. 2004), 751–789.
35. Sugimoto, M., and Hiroki, K. Hybridtouch: An intuitive manipulation technique for pdas using their front and rear surfaces. In *Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services*, MobileHCI '06, ACM (New York, NY, USA, 2006), 137–140.
36. Tanriverdi, V., and Jacob, R. J. K. Interacting with eye movements in virtual environments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '00, ACM (New York, NY, USA, 2000), 265–272.
37. 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*, UIST '07, ACM (New York, NY, USA, 2007), 269–278.
38. Wigdor, D., Leigh, D., Forlines, C., Shipman, S., Barnwell, J., Balakrishnan, R., and Shen, C. Under the table interaction. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology*, UIST '06, ACM (New York, NY, USA, 2006), 259–268.
39. Wolf, K., Müller-Tomfelde, C., Cheng, K., and Wechsung, I. Does proprioception guide back-of-device pointing as well as vision? In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '12, ACM (New York, NY, USA, 2012), 1739–1744.
40. Yao, R., Heath, T., Davies, A., Forsyth, T., Mitchell, N., and Hoberman, P. Oculus vr best practices guide. *Oculus VR* (2015).
41. Zelaznik, H. N., Mone, S., McCabe, G. P., and Thaman, C. Role of temporal and spatial precision in determining the nature of the speed-accuracy trade-off in aimed-hand movements. *Journal of Experimental Psychology: Human Perception and Performance 14*, 2 (1988), 221.

GYROVR

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GyroVR: Simulating Inertia in Virtual Reality using Head Worn Flywheels

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ABSTRACT
We present GyroVR, head worn flywheels designed to render inertia in Virtual Reality (VR). Motions such as flying, diving or floating in outer space generate kinesthetic forces onto our body which impede movement and are currently not represented in VR. We simulate those kinesthetic forces by attaching flywheels to the users head, leveraging the gyroscopic effect of resistance when changing the spinning axis of rotation. GyroVR is an ungrounded, wireless and self contained device allowing the user to freely move inside the virtual environment. The generic shape allows to attach it to different positions on the users body. We evaluated the impact of GyroVR onto different mounting positions on the head (back and front) in terms of immersion, enjoyment and simulator sickness. Our results show, that attaching GyroVR onto the users head (front of the Head Mounted Display (HMD)) resulted in the highest level of immersion and enjoyment and therefore can be built into future VR HMDs, enabling kinesthetic forces in VR.

Author Keywords
gyroVR; haptics; virtual reality; mobile VR, nomadic VR

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
Virtual Reality HMDs strive to immerse the user inside a virtual environment and are currently mainly targeting the visual sense. Several research projects showed that including the haptic sense inside a virtual environment leads to an increased level of immersion [17].

GyroVR focuses on the kinesthetic part of the haptic perception and mainly on inertia, which occurs when being in fast motion (e.g. flying) or in an altered environment (e.g. underwater). The resistance of the wind, when flying in a wingsuit acts upon the human body as a kinesthetic force, which impedes the movements of the head or limbs similar to when people try to move underwater. This concept of motion is currently one of the most used for Oculus Rift experiences.

Figure 1. Left: A user wearing a VR HMD with GyroVR attached. Right: A prototype implementation of GyroVR attaching flywheels on the front of an Oculus Rift DK2.

We enable this sensation by attaching flywheels to the human head. These flywheels leverage the gyroscopic effect which occurs when the user tries to rotate his head against the rotational axis of the spinning flywheel. The gyroscopic effect will affect the motion of the users to the perpendicular axis of the motion which is mainly perceived as a resistance [19]. In combination with the visuals of the virtual scene the sensation of inertia is created. We conducted a user study (n=12) to explore how mounting GyroVR to different positions on the human head (back and front) impacts the level of immersion, enjoyment and simulator sickness inside a virtual environment.

Contributions
The main contributions of this work are: (1) the concept of simulating kinesthetic motion forces using head worn flywheels,(2) the implementation of GyroVR, a small, self containing and generic device capable of being attached to the human body, (3) the insights from our study on human perception and the impact of

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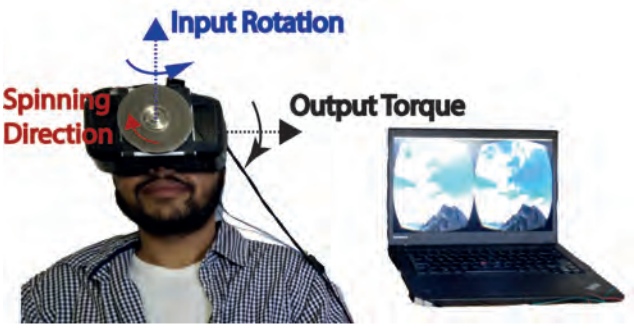

Figure 2. GyroVR is designed to render the simulated force of inertia occurring during movements. The key idea is that the flywheel mounted on the VR HMD impedes the motion of the users. Here the user is experiencing a flying simulation and tries to steer his direction using his head motion (Users' Motion). The rotation speed of GyroVR is correlated with the speed the user has in the virtual environment. GyroVR impedes this motion by generating a perpendicular force creating an experience for the user where it is more difficult to move his head when he is in high motion.

kinesthetic forces by head worn flywheels attached to different locations in terms of immersion, enjoyment and simulator sickness.

GYROVR

GyroVR is designed as an ungrounded haptic feedback device to simulate the kinesthetic force of inertia which fits to different VR experiences (e.g. flying). Ungrounded means that GyroVR has no grounding to counterbalance the output force such as Phantom or HapticMaster [13]. Figure 2 illustrates a setup where the user flies through an environment and depending on his speed perceives a higher or lower level of resistance during his head movements. The concept of GyroVR leverages the effect that the directional force is not perceived precisely enough and more like a general resistance [18]. One important concept of GyroVR is that the force generated does not necessarily have to be realistic (e.g. actual wind resistance). In informal pre-evaluation with colleagues we found that users mostly do not know the exact force which should be acting upon them in most situations but only expect some kind of force which is comprehensible.

Implementation

Similar to [3] we built GyroVR out of desktop computer hard drive components (Western Digital WD 2500). We removed the motor (7200 rpm overclocked to ≈12.000 rpm) and discs from the HDD. For our implementation we used three discs on each motor resulting in a total weight of 96g. We experimented with a different number of discs and found a balance between weight and performance using three. Furthermore, a higher number of discs resulted in the motors to struggle at start-up since they are not used to spin a higher number of discs. To control the three phase HDD motor we used a Hobbyking 30A ESC which receives a PWM signal from an Arduino Nano. After our initial tethered prototype with three motors on the HMD (Figure 6) we built a mobile version (Figure 3) by adding the Bluetooth HC-06 module for the communication between computer and Arduino and adding a 1500mAh Lipo-Battery (from an AR Drone 2.0). The use of off the shelf hardware allows researchers to easily rebuild our implementation.

To experiment with the force on different locations of the human body we built a mobile version (Figure 3 right) where we

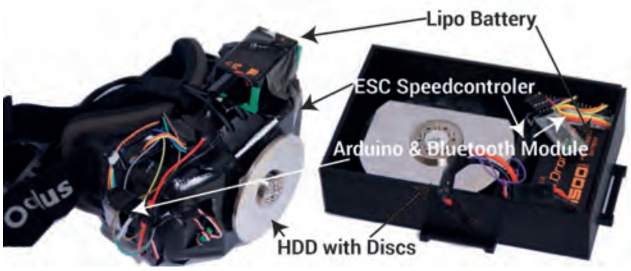

Figure 3. Two implementations of GyroVR. Left: The GyroVR prototype directly attached onto an Oculus Rift DK2. Right: A mobile implementation of GyroVR, built in a generic form factor to be mounted onto the human body.

assembled all components inside a 3D printed case (overall weight 390g). This prototype can be mounted onto the human body using straps (Figure 5). To reduce some of the weight we built a second prototype where we assembled all the components directly onto an Oculus Rift DK2 (Figure 3 left).

Gyroscopic Precession

The force generated by GyroVR is based on Newton's first law of motion which states that objects in motion try to stay in motion. The rotational pendant to this is the gyro effect which states that spinning masses will continue spinning in the same direction around the same axis. Once the user rotates his/her head at a desired angular velocity ω_{in}, a gyroscopic torque $\tau_o ut$ is experienced perpendicular to the head rotation axis. (Figure 4). The relationship is as follows

$$\tau_{out} = \omega_{in} \times L_s = \omega_{in} \times I\omega_s \quad (1)$$

where L_s is the spin angular momentum, I is the moment of inertia and ω_s is the angular velocity of the spinning mass.

By having a double gyroscope setup, sharing the same rotational axis and spinning in the same direction, the angular momentum contribution becomes additive. Effectively doubling the perceived effect and output torque τ_{out}. Figure 4 depicts such a double gyroscope setup where the gyroscopes have been mounted in such a way that they provide a counter balance of weight. Additionally, it illustrates the relationship between head rotation velocity ω_{in} and the gyroscopic torque τ_{out} experienced by the user around the yaw axis.

Mounting Positions

We experimented with several mounting position on the users body using the GyroVR mobile prototype (Figure 5). Our goal was to find mounting positions where users would perceive the force strong enough so it could be used in a user study. Since the force of GyroVR is a reactive force (only perceived if an input force is generated e.g. rotating the head) we experimented with mountings on the human body which are used frequently in motion when inside a virtual environment. The evaluation of the different mounting positions we report here are based on informal pre-evaluations the authors conducted on themselves to pre-select relevant mounting positions for the follow up user study. We evaluated the mounting positions based on *ease of attachment and level of perception*.

Hands: Mounting the device onto the palm (or holding it in the hand) resulted in the strongest perception of the force. This is

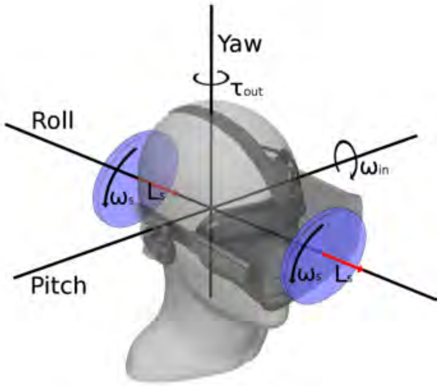

Figure 4. When disks are spun with angular velocity ω_s and the head is rotated around an input axis at angular velocity ω_{in}, the gyroscopic output torque τ_{out} around the yaw axis is experienced by the user.

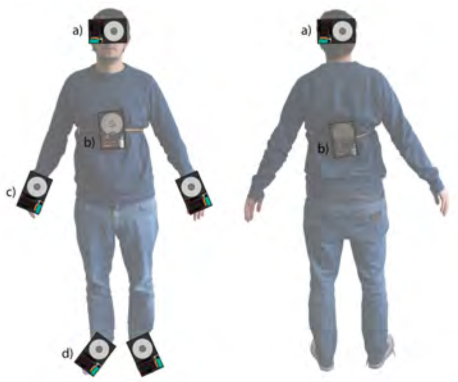

Figure 5. The different mounting positions on the human body which were explored with the mobile implementation of GyroVR.

probably because of the high density of muscle spindles which are responsible for perceiving the kinesthetic force [8]. The mounting onto the hand turned out to be more difficult since the prototype must be rigidly attached and thereby restricted motions of the hand. Furthermore, the size of the prototype lead to occlusion of the fingers which excluded simple hand tracking using the Leap Motion. The best result occurred from holding the prototype in the hand. We excluded that option of holding, since similar results were already reported in prior work [3, 21].

Torso: The least force was perceived when GyroVR was mounted on the torso. We experimented with different mounting locations but did not find a position which resulted in a force which could actually be perceived. As the torsos freedom of motion is by rotating around a vertical axis, the GyroVR must exert an output torque by twisting around the horizontal axis, essentially leveraging the entire body.

Legs/Feet: Attaching GyroVR to the legs resulted similar to the torso location in an easy mounting but low perception of the output force. We also experimented with mounting GyroVR to the feet (similar to a shoe). The force is only perceived when tilting the foot and is only of relevance for room scale VR such as HTC Vive.

Head: Mounting GyroVR onto the head resulted in a high perception of the force since the neck consists of most muscle spindles

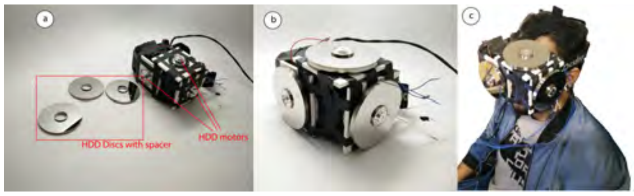

Figure 6. An early prototype of GyroVR on an Oculus Rift DK2 (a) which had a flywheel mounted onto each axis (b). We conducted informal evaluations to asses the output force (c)

[8]. We built one initial prototype (Figure 6) with flywheels on each rotational axis (yaw, pitch and roll). We then experimented with each individual flywheel and its possible combination and ended up with mounting the flywheel to the roll axis as the best result. The reason is that when mounted on the roll axis the gyroscopic effect is perceived when applying a force on the yaw and pitch axis (basically turning the head left/right or up/down). This position benefits from the fact that users explore the virtual environment by rotating the head. Even if the realistic case would be to perceive the force on the whole body, by bundling this haptic feedback with the main source of input (head rotation) the user gets an immediate feedback for an action and accepts the force as part of the immersive experience (see section user study).

APPLICATION EXAMPLES

To explore the design space for GyroVR we implemented three example applications which each create a different mapping of the force and the environment (Figure 7). We used those applications for the user study. For some applications we needed to let the participants generate input (e.g. press button to fly). We used a wireless bluetooth gamepad for this interaction. Applications which depend on virtual forward motion tend to induce simulator sickness (sensory conflict theory). Due to the nature of inertia which mostly appears during motion we took some precautions (e.g. Oculus Guidelines) during the application design to lower simulator sickness. In every scenario we used a different mapping between the virtual environment and the physical rotation to dynamically control the rpm. To generally shorten the ramp up time the flywheels are kept constantly spinning on low rpm (which did not generate enough torque for the participants to feel). All applications were implemented using Unity 3D.

Simulating Forces of Motion - Flying

In the flying game (Figure 7 a) the user can fly over a city. By holding down one button on the gamepad the user can speed up and control his direction by rotating the head. The rotational speed of the flywheel is mapped onto the virtual speed inside the game. For the flying game we used a linear mapping between virtual movement and rotation speed. This allows the user to perceive a higher resistance in turning his head when flying in higher speed. To encourage head rotation we placed stars inside the environment which the user has to collect. The placement is done in such a way that after collecting one star the users has to quickly rotate towards the next target.

Impeded Motion - 3D Shooter

Figure 7 b shows the implementation of the 3D shooter game. The user is located inside a warehouse and has to find two

Figure 7. Screenshots of the applications which users experienced in the user study. (a) The flying application showing a star in the distance. (b) A first person view of the warehouse from the 3D Shooter game. (c) The surface of the foreign planet showing the location of several parts which the user has to collect

weapons hidden in random locations. The controls work by having one button to run and a second one to jump. The direction of the running is controlled via head rotation. During the search the users get constantly shot by hidden enemies which they can't find. The more damage the user takes the faster the flywheel spins and the more difficult it becomes to move. At the start of the scene no rotation was used. Every time a user gets hit, the rpm are increased rapidly by a 6th of the maximum rpm. After seven hits the game ends. This allows the user to experience an impeded motion as if he is wounded.

Simulating new Environments - Space Jumper

The last game (Figure 7 c) locates the user on a new planet with new physical forces. The flywheel is constantly spinning at full speed thereby highly restricting head motion and simulating a new form of gravitation. The get off the planet the user has to collect three parts which he needs to repair his spaceship. To move on the planet users are encouraged to jump. To encourage a high head movement, users only have a certain "boost" which they can use to jump that has to be regenerated by shaking their head. The gravitation on the planet is set to almost zero. The user has visually the impression as if he moves in lower gravity, the flywheels generate a force as if he would actually be in an environment with a higher gravitation as earth (since moving the head is difficult). This application beautifully demonstrates the concept of non-realistic forces. Even if that scenario is physically impossible, participants inside our user study ignored this fact and perceived the forces as appropriate, some even calling it "realistic".

RELATED WORK

Our work builds upon the work in the field of ungrounded kinesthetic feedback and virtual reality.

The gyroscopic effect was often used to create an ungrounded kinesthetic force such as the GyroCube [19] which is a handheld gyroscope generating forces along each rotational axis. Sakai et al. evaluated the levels of perception inside the users palm using GyroCube [18]. Badshah et al. applied this concept into the field of HCI by attaching flywheels onto the back of a tablet to generate kinesthetic forces for the user [3]. Several authors presented a concept to make the gyroscopic effect proactive by attaching a flywheel onto a gimbal and control that gimbal [21, 2, 22] to give the user directional cues. Murer et al. presented this concept attached onto a tablet called "TorqueScreen" [16]. By rotating the gimbal with a flywheel attached, the authors could generate kinesthetic feedback allowing the user to feel a virtual ball on the tablet bounce of the edges. The main difference to

Figure 8. The study apparatus of GyroVR consisting of a Oculus Rift DK2 with GyroVR attached and a bicycle helmet having a mobile GyroVR prototype attached to the back.

GyroVR is that all those prototypes were designed to be handheld and not mounted onto the human body.

A different direction in the field of ungrounded kinesthetic feedback is work which tries to mount those flywheels onto the human body. Mostly the motivation is to assist human balance [1, 4, 14]. Those prototypes are often quite large to generate a strong enough force and too heavy for casual use. Ando et al. presented a concept for a body worn prototype based on brake change in angular momentum to create a directional force [1]. The prototype built, however, was not wearable but users had to hold it in their hand.

In the field of Virtual Reality, there is a big direction of work focusing on novel input concepts [5] and generating haptic feedback [11, 7, 12, 17, 6]. Early prototypes were used in CAVE environment and were attached to the users limbs using exoskeletons [20] or pulley systems [15]. Both systems are considered to use a grounded force. Recently, Lopes et al. presented a concept for simulating impact in VR using electrical muscular stimulation and a solenoid [11].

To our best knowledge, GyroVR is the first to use head-worn flywheels to simulate kinesthetic feedback in VR.

USER STUDY

To measure the impact of GyroVR onto immersion, engagement, enjoyment and simulator sickness we conducted a user study (n=12). We also evaluated the best position of GyroVR on the users head.

Study Design and Procedure

The study had one independent variable *motor location* with four levels (front, back, both and none). In the *both* condition both flywheels rotated in the same direction along the roll axis to sum up the force. For the user study we used a different apparatus (Figure 8) which consisted of a bicycle helmet which had a GyroVR prototype mounted on it. We used the helmet to ensure

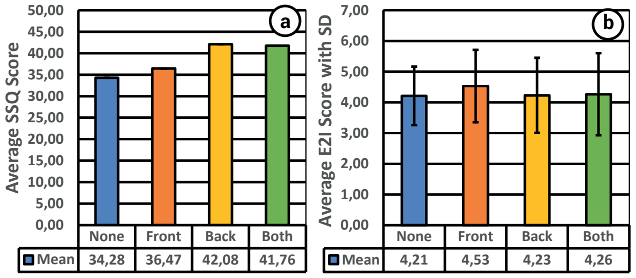

Figure 9. A distribution of the simulator sickness (a) and immersion, engagement and enjoyment questionnaire (b) of the user study.

a sturdy attachment of GyroVR onto the back of the participants' head. To ensure that the force was created equally, both flywheels were equidistant to the users head (≈ 8cm). The *none* condition was used as the baseline. The study took on average 30 minutes and participants received 5 currency. The flywheels generate a small rotation noise which was not heard by the participants due to the use of headphones. To avoid vibration we used hand moldable plastic to press fit a perfectly fitting layer of plastic between the HMD case and the flywheel mount. The battery lasted for at least 2 studies (1h) before charging.

Participants were introduced to the concept of GyroVR and could experience the force. Afterwards they put on the Oculus DK2 and the bicycle helmet and played all three applications (section *Application Examples*) with each of the four conditions of the motor (front, back, both and none). After each motor condition participants were asked to fill out the SSQ (Simulator Sickness Questionnaire) [9] and E^2I questionnaire (immersion, engagement and enjoyment) [10]. At the end participants rated all four conditions as what they perceived as the best experience. Applications and motor conditions were counterbalanced using a Latin-square.

Participants

We randomly recruited 12 participants (3 female) with an average age of 28.5 (range: 25 to 36) from our institution. Six participants had already experience with VR HMDs and all had an academic background.

Results

Quantitative: Figure 9 a shows the distribution of the simulator sickness of all levels of the motor condition. A repeated measures ANOVA revealed no significant differences (F(3,33)=.639, n.s.). Even if not significant, the trend shows that the front mount resulted in the lowest level of simulator sickness compared to the other motor levels. Participants in general mentioned that the applications induced a higher level of simulator sickness since they all dependent on virtual movement. The overall ranking of immersion, engagement and enjoyment over all motor levels can be found in Figure 9 b. A repeated measures ANOVA revealed no significant differences (F(3,33)=.745, n.s.) between the levels. Nevertheless, the front condition received a slightly higher ranking. This again correlates with the user feedback we received during the study.

Qualitative: In the final feedback after the user study participants comments can be categorized in three topics (*immersion*, *sickness*, *fatigue*): Rapid increase of RPM resulted in a little nudge in a direction and was partially perceived as 'unpleasant' and therefore fitting to increase the level of *immersion* of the 3D Shooter, where a hit from a bullet was simulated by a rapid increase of rpm. Participants said they perceived the front condition as being the strongest in terms of output force. In the final rating of the overall best experience participants preferred having a motor (7) vs having no motor (5). The participants which ranked the "no motor" condition the best mostly experienced an overall high level of *simulator sickness*, which they then correlated with the motor running. In a final ranking participants (6) reported that during the motor conditions, using both motors induced the most level of sickness. Participant 7 mentioned that if GyroVR was not tightly fixed to the head this potentially increased the sickness. High rpm were reported to potentially lead to less head movement due to *fatigue*. Participant 9 suggested to use this effect as a 'punishment' in an attention guidance scenarios. The overall weight of the study apparatus resulted in a certain level of fatigue over the duration of the whole study. However, removing one of the gyros would result in an unbalanced setup (and create an unfair comparison between conditions). Therefore, we decided the leave both gyros on the participants during the whole study. A possible solution to keep the same output force but reducing the weight would be by increasing the rpm. A future prototype which is based around a custom motor with higher rpm would be able to generate the same output force but avoid the high weight and resulting fatigue effects.

DISCUSSION

Our study showed that GyroVR creates an "immersive and realistic" (P3, P5) kinesthetic force which "enhances the experience" (P9). After experiencing a condition with either of the motors and afterwards the *none* condition, participants reported the experience to be "boring without the force" (P10). Overall participants reported they enjoyed the concept despite a certain base level of simulator sickness. Even though the user study did not quantitative show a clear benefit for immersion, engagement and enjoyment when using GyroVR, a possible trend does exist, which warrants further testing with a larger sample size to determine if the trend truly indicates significance.

CONCLUSION

We presented GyroVR, head worn flywheels designed to render inertia in Virtual Reality. These flywheels leverage the gyroscopic effect which impedes users head movement and thereby is perceived as inertia. We presented several implementations and initially explored the mounting positions on the human body. In three example applications we explore the design space and different concept of mapping the force inside of the virtual environment. In a user study we explored the effect of GyroVR attached to the users head on immersion, engagement, enjoyment and simulator sickness. Our results give a first understanding of the implications of attaching a flywheel to the front of a HMD to enable kinesthetic forces of inertia in virtual reality.

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REFERENCES

1. Ando, H., Obana, K., Sugimoto, M., and Maeda, T. A wearable force display based on brake change in angular momentum. *Proc Artificial Reality and Telexistence 2002* (2002), 16–21.
2. Antolini, M., Bordegoni, M., and Cugini, U. A haptic direction indicator using the gyro effect. In *World Haptics Conference (WHC), 2011 IEEE*, IEEE (2011), 251–256.
3. Badshah, A., Gupta, S., Morris, D., Patel, S., and Tan, D. Gyrotab: A handheld device that provides reactive torque feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '12, ACM (New York, NY, USA, 2012), 3153–3156.
4. Chiu, J., and Goswami, A. Design of a wearable scissored-pair control moment gyroscope (sp-cmg) for human balance assist. In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers (2014), V05AT08A023–V05AT08A023.
5. Gugenheimer, J., Dobbelstein, D., Winkler, C., Hass, G., and Rukzio, E. Facetouch: Enabling touch interaction in display fixed uis for mobile virtual reality. In *Conditionally Accepted UIST '16*, UIST '16, ACM (2016).
6. Gugenheimer, J., Wolf, D., Haas, G., Krebs, S., and Rukzio, E. Swivrchair: A motorized swivel chair to nudge users' orientation for 360 degree storytelling in virtual reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, ACM (New York, NY, USA, 2016), 1996–2000.
7. Hirose, M., Hirota, K., Ogi, T., Yano, H., Kakehi, N., Saito, M., and Nakashige, M. Hapticgear: the development of a wearable force display system for immersive projection displays. In *Virtual Reality, 2001. Proceedings. IEEE*, IEEE (2001), 123–129.
8. Jones, L. A. Kinesthetic sensing. In *in Human and Machine Haptics*, Citeseer (2000).
9. Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology 3*, 3 (1993), 203–220.
10. Lin, J. J.-W., Duh, H. B., Parker, D. E., Abi-Rached, H., and Furness, T. A. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*, IEEE (2002), 164–171.
11. Lopes, P., Ion, A., and Baudisch, P. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, ACM (New York, NY, USA, 2015), 11–19.
12. Maeda, T., Ando, H., Amemiya, T., Nagaya, N., Sugimoto, M., and Inami, M. Shaking the world: galvanic vestibular stimulation as a novel sensation interface. In *ACM SIGGRAPH 2005 Emerging technologies*, ACM (2005), 17.
13. Massie, T. H., and Salisbury, J. K. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, vol. 55, Chicago, IL (1994), 295–300.
14. Matsuzaki, R., and Fujimoto, Y. Walking assist device using control moment gyroscopes. In *Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE*, IEEE (2013), 6581–6586.
15. Murayama, J., Bougrila, L., Luo, Y., Akahane, K., Hasegawa, S., Hirsbrunner, B., and Sato, M. Spidar g&g: a two-handed haptic interface for bimanual vr interaction. In *Proceedings of EuroHaptics* (2004), 138–146.
16. Murer, M., Maurer, B., Huber, H., Aslan, I., and Tscheligi, M. Torquescreen: Actuated flywheels for ungrounded kinaesthetic feedback in handheld devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, ACM (New York, NY, USA, 2015), 161–164.
17. Ramsamy, P., Haffegee, A., Jamieson, R., and Alexandrov, V. Using haptics to improve immersion in virtual environments. In *Computational Science–ICCS 2006*. Springer, 2006, 603–609.
18. Sakai, M., Fukui, Y., and Nakamura, N. Effective output patterns for torque display'gyrocube'. In *Online Proceeding of the 13th International Conference on Artificial Reality and Telexistence*, vol. 13 (2003), 160–165.
19. Tanaka, Y., Yuka, K., Fukui, Y., Yamashita, J., and Nakamura, N. Mobile torque display and haptic characteristics of human palm. In *Proc. ICAT* (2001), 115–120.
20. Tsetserukou, D., Sato, K., and Tachi, S. Exointerfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation. In *Proceedings of the 1st Augmented Human International Conference*, ACM (2010), 1.
21. Winfree, K. N., Gewirtz, J., Mather, T., Fiene, J., and Kuchenbecker, K. J. A high fidelity ungrounded torque feedback device: The itorqu 2.0. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*, IEEE (2009), 261–266.
22. Yano, H., Yoshie, M., and Iwata, H. Development of a non-grounded haptic interface using the gyro effect. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings. 11th Symposium on*, IEEE (2003), 32–39.

CarVR

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CarVR: Enabling In-Car Virtual Reality Entertainment

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ABSTRACT
Mobile virtual reality (VR) head-mounted displays (HMDs) allow users to experience highly immersive entertainment whilst being in a mobile scenario. Long commute times make casual gaming in public transports and cars a common occupation. However, VR HMDs can currently not be used in moving vehicles since the car's rotation affects the HMD's sensors and simulator sickness occurs when the visual and vestibular system are stimulated with incongruent information. We present CarVR, a solution to enable VR in moving vehicles by subtracting the car's rotation and mapping vehicular movements with the visual information. This allows the user to actually feel correct kinesthetic forces during the VR experience. In a user study (n = 21), we compared CarVR inside a moving vehicle with the baseline of using VR without vehicle movements. We show that the perceived kinesthetic forces caused by CarVR increase enjoyment and immersion significantly while simulator sickness is reduced compared to a stationary VR experience. Finally, we explore the design space of in-car VR entertainment applications using real kinesthetic forces and derive design considerations for practitioners.

Figure 1. A player is sitting on the front passenger seat playing the game while the car is moving. Kinesthetic forces caused by the car match the movements in VR.

ACM Classification Keywords
H.1.2 User/Machine Systems:: Human factors; H.5.2 User Interfaces:: Haptic I/O, Prototyping, User-centered design

Author Keywords
force-feedback; motion platform; immersion; virtual reality; automotive; entertainment; gaming

INTRODUCTION
Mobile virtual reality (VR) is currently becoming a consumer product. Major companies such as Google (Cardboard), Samsung (GearVR) and Zeiss (VR One) are releasing high-quality and low-cost mobile VR head-mounted displays (HMDs). Due to their low price and easy accessibility, they are more likely to penetrate the consumer market. One of the major application scenarios for current consumer VR HMDs is entertainment, and gamin in particular. With its ability to generate highly immersive environments and manipulate a user's time perception [29] in a mobile scenario, mobile VR has the potential to revolutionize casual gaming for commuters.

However, current mobile VR HMDs cannot be used inside moving vehicles. Rotations of the vehicle are interpreted as the user's head movements resulting in unintended shifts of the virtual environment. Additionally, the mismatch between virtual movement (visual system) and the perceived physical movement (vestibular system) can lead to simulator sickness [25].

This work introduces CarVR, a solution to enable VR in moving vehicles by subtracting the car's rotation and mapping vehicular movements with the visual information (Figure 1). We present the design and implementation of a working prototype consisting of a Samsung GearVR, a mobile inertial measurement unit (IMU), and a car diagnostic tool (OBD-II). In a user study (n = 21), we show that CarVR significantly increases enjoyment and immersion over a stationary experience while reducing simulator sickness. Finally, we provide an analysis of the design space for developing VR entertainment in moving vehicles and present design considerations for practitioners.

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Our main contributions are (1) the concept and implementation of CarVR, a proof-of-concept prototype enabling VR in moving vehicles, (2) findings of our user study (n = 21), showing a significant increase of enjoyment and engagement and reduced simulator sickness using CarVR in comparison to a stationary setup, and (3) an analysis of the design space of VR entertainment applications inside moving vehicles and a set of design considerations for practitioners.

Our work shows that the usage of VR in moving vehicles is not only possible, it is more fun and less vertiginous than while not moving. Thus it can be used to bridge the time when traveling or to improve the traveling experience as an additional offer in general. Taxis and buses could provide VR entertainment as an additional offer. It can also be used to entertain children on the road, reducing the dangers of distractions.

RELATED WORK

The idea of combining VR with a moving vehicle has several related research topics. First, we give an overview of projects and research regarding VR in moving vehicles. Then, related work regarding the use of kinesthetic forces in VR is presented, followed by research that addresses game design in cars. Subsequently, related work regarding the design space of being a passenger while playing games is reported. Finally, we explain simulator and motion sickness.

In a PR campaign by Jaguar [17], participants were seated in a moving Jaguar F-Type while wearing a VR device. In their campaign, Jaguar pretended that the visual information was a simulation and kinesthetic forces were simulated by a hexapod hydraulic platform. In reality, the visual and kinesthetic forces were real, what people felt and saw was real motion caused by the car, instead of a VR simulation as alleged. In their PR video, Jaguar stated that participants had no idea that they were actually being driven. Though the whole VR impression was not real, the idea of our work is very close to Jaguar's campaign: improving the VR experience by using kinesthetic forces of the moving vehicle. A similar project was realized by Lockheed-Martin [2]. They prepared a school bus in a way that it could create the impression of driving on Mars. This was realized by projecting images of Mars' surface onto the windows of the bus. While the bus was driving through the city, movements of the bus were mapped to visualize a corresponding route on Mars with actual Mars images. The idea of the project is also very close to CarVR, however both the Mars and Jaguar projects lack an evaluation regarding immersion, enjoyment or any kind of sickness. Bock et al. [6] propose a driving experience in VR, but in contrast to CarVR, their work focuses on driving while wearing a VR device, allowing an augmentation of the driving experience, for example by virtually presenting other traffic or infrastructure. A combination of moving in reality and experiencing similar, sometimes even partially exaggerated visual information in VR, is found in the upcoming *VR coaster*, wherein people are sitting in real roller coasters while wearing VR HMDs [22].

Breaking it down to the very basic idea, CarVR enables kinesthetic forces in VR and therefore improves the VR experience. Gugenheimer et al. [14] proposed *SwiVRChair*; a VR storytelling device that enhances the VR experience by rotating the user to face certain directions. Their goal was to build a chair that generates kinesthetic feedback to match virtual movements. Findings were that the physical movement reduced simulator sickness and increased enjoyment.

Danieau et al. developed a chair equipped with force-feedback devices to apply forces while playing games or watching videos [10]. It was shown that in combination with visual information, their seat could trigger the sensation of motion thus improving the quality of the experience. In contrast to CarVR, motion is only applied to parts of the body, rather than the whole body. Their technique could be complementary applied to a car complementary alongside CarVR. *Haptic Turk* [8] aims to enhance the (VR) experience by applying kinesthetic forces. In their work, participants were used to apply forces to a single user that is wearing a VR device. *Birdly* [26] aims to enhance the VR experience of flying by adding wind that is blown into the user's face. The user lies in a belly-down position on a platform that acts as an input and output device for the user's extremities.

CarVR enhances the VR experience by exploiting real world properties, such as kinesthetic forces and movement. A similar concept was shown by Simeone et at. [30]. In their paper, they exploited physical objects like chairs, tables and walls to enhance the immersion. In CarVR, real forces of a moving vehicle are used to enhance the immersion.

Besides enhancing immersion, CarVR aims to enable VR gaming in moving vehicles. Bichard et al. developed *Backseat Playground* [4], a framework designed to enable playing games as passenger in the backseat of a car. Their framework adapts to the current environmental conditions, such as geo-location. Exploiting environmental conditions to build up the virtual scene is also a core idea of CarVR. Here, the player follows the same route that is driven by the car. In an advanced future implementation, the world could be built on the trajectory and route planning of the car. Sundström et al. [36] developed games where the sitting pose in the car is an integral part of the game. However, their intention was to teach children how to sit properly in cars.

Brunnberg et al. investigated the design space of passengers in [7]. In their work, they focus on location-based games, like interactive storytelling. An interesting finding is that movement speed has an influence on the perceived vulnerability. Participants stated that driving slowly or standing creates the feeling of being more vulnerable whereas driving fast feels more like observing the environment.

While sitting in a car, especially when being a passenger, the journey often seems never ending and time is wasted. Entertainment applications are useful tools to overcome boredom and make time pass by faster. VR can increase such an experience. In [29], Schatzschneider et al. show that the perception of time can be influenced in VR, for example by manipulating the movement of the sun.

Motion sickness is a wide-spread problem and affects nearly one-third of all people who travel by land, sea, or air [27]. It is a condition marked by symptoms of nausea, dizziness, and other physical discomfort. It has been shown that visual stimuli have the most impact on provoking motion sickness [16]. Activities like watching a video or reading, abruptly moving the head or looking down in a moving vehicle lead to symptoms of motion sickness [23]. The reduced ability to anticipate the direction of movement can also lead to motion sickness [5]. Passengers with no external forward view cannot see the road ahead and are not able to predict any further motion. Even the absence of a visual field by restricting the outside view [37], or the lack of control over the direction of motion can cause sickness [28].

Symptoms of simulator sickness include dizziness, drowsiness, headache, nausea, fatigue and general malaise [18], for which speed and acceleration are influencing factors [34]. Simulator sickness is a form of visually induced motion sickness and occurs without actual motion of the body [19]. People who are prone to motion sickness in vehicles tend also to experience simulator sickness [35]. Simulator sickness can occur in stationary driving and flight simulators. The user can see a visual motion but remains stationary in the simulator. Movement in the virtual environment can lead to illusory perception of self-motion (*vection*), which is one of the main reasons for simulator sickness [15].

VR IN CAR: CONCEPT

In our concept, the player has the role of a passenger sitting on the front passenger seat. Consisting of a mobile VR device and external sensors to measure vehicle dynamics, the lightweight and portable setup has affordable hardware requirements: an measured by an inertial measurement unit (IMU) to measure the rotation of the car, an on-board diagnostics (OBD) II reader to measure the speed of the car, and a VR HMD (see Figure 2). Although the driver is not involved in the game mechanics, their part of the game is to drive the vehicle. Driving the car is not intended to be the main purpose of the ride. Instead, playing the game is intended to be part of the ride.

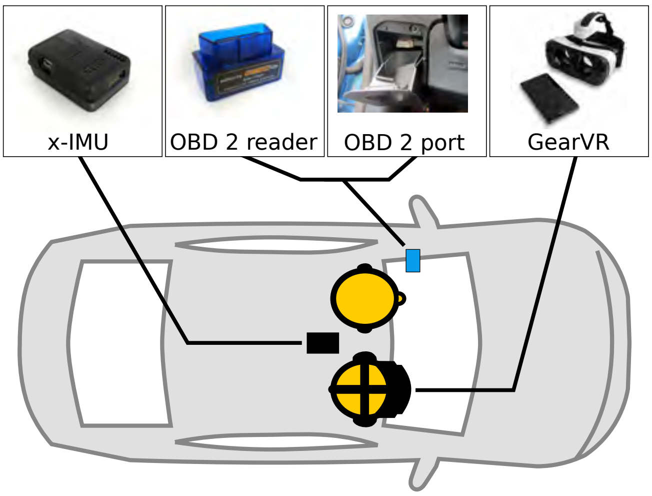

Figure 2. Schematic view of the position of devices and people involved in the apparatus. The driver acts as normal driver, following a route to a destination, the co-driver is playing the game on the font-passenger seat with a Samsung GearVR attached. An x-IMU measures the vehicle's inertia. An OBD-II reader attached to the car's diagnostic port is used to measure the car's velocity.

The movements of the vehicle influence the gaze direction in VR because the inertial sensor of the VR device cannot distinguish between head movements and the yaw-rotation of the vehicle. Increased nausea are likely to occur because of a combination of simulator and motion sickness.

To compensate for vehicle movements, two approaches are possible: (1) subtracting the vehicular rotation in the VR scene by an IMU placed inside the car. This allows for example VR scenarios where the player is not moving at all. Interfering forces are subtracted. (2) Mapping the vehicle movements with the movements in VR. The movement of the car is rendered in VR. The former has the benefit that the VR scene has no restriction in mobility. However, this approach does not address motion sickness, the incongruence of visual and vestibular information remains. The latter has the benefit that occurring acceleration forces of the vehicle are in line with the forces in VR. To enable VR in moving vehicles, we use the second approach: actual movements of the vehicle are used as input for the player movements. We show that this increases immersion, enjoyment, engagement and reduces simulator sickness.

This approach's drawback is that the movements in VR are predefined by the route of the vehicle. This restricts the content of the VR scene to some sort of guided tours, where the user has no or little influence on the provided route. A common application of this scenario is found in rail shooters, where movements of the player are predefined. Aiming and firing remaining the main task. Further, unpredictable changes in velocity or direction may not be adequately represented in VR. The virtual scene has to adapt to the driving conditions; for example, when the car suddenly stops, an appropriate reason for this should be presented in VR.

On the other hand, realizing continuous movement in VR while not actually moving in the appropriate direction, like moving forward in VR while sitting in reality, causes increased simulator sickness. Our approach solves this problem.

DESIGN SPACE

The design space for VR entertainment can be categorized into two applications, as discussed in the previous section: one that compensates the forces caused by movements of the vehicle, and applications that exploit these forces. An application that compensates these forces could be a seated in a VR cinema, where occurring kinesthetic forces must be compensated in a way that the VR device does not interpret these forces as head movements. This can be done by placing an IMU inside the vehicle and calculating a compensative rotation of the camera. The problems of increased simulator sickness, or in this case, motion sickness, remain. Following the approach of exploiting kinesthetic forces, we provide an analysis of the design spaces subsequently.

Level Design: The connection between real life movements and VR movements make level design important. The virtual world can be generated along a planned route, for example by using the route to create a depth map (see Figure 3).

If the car deviates from the planned route, the change in the environment must be somehow included in level design and

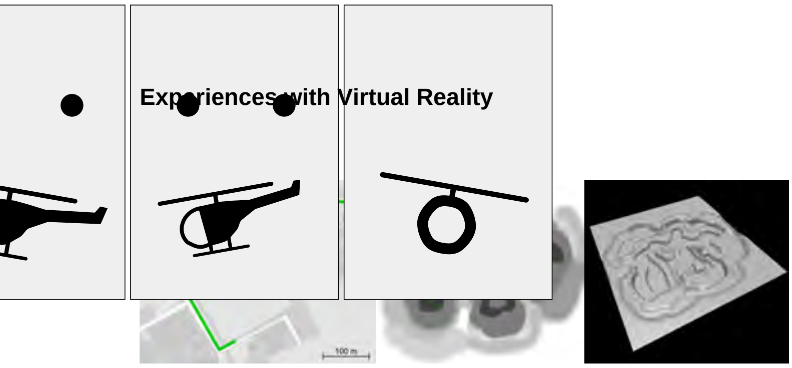

Figure 3. Route generation based on predefined route. (left) The trajectory is extracted from the topology, (center) A depth map based on the trajectory is generated. (right) The terrain according to the depth map is generated.

story. To address this, alternative routes or even a whole city could be modeled or generated. The integration of the story could be an important aspect when it comes to storytelling and immersion. The immersion of flying through a canyon can be disturbed when the car brakes due to traffic conditions, while in VR, no reason for a sudden stop is presented. The story of the VR scene should react to such changes. To overcome most of these problems, a route-independent world can be used, like space or air. The user then flies above obstacles. Sudden changes in speed can be interpreted as asteroids in space or debris. However, a lack of cues where the car and therefore the player is heading might be a problem: unpredictable directional changes result in increased simulator sickness.

Velocity: Visual cues are important for the perception of self-motion [13]. In an environment with few objects, for example in space, additional elements should be rendered in the scene that also react to player movements. Depending on the story, dust, rain, snow, and other particles can be used to provide visual cues to support the impression of velocity.

Acceleration: Acceleration is a change in velocity, therefore the visualization of movement also visualizes acceleration. To emphasize the effect of acceleration, game designers often use motion blur. However, using motion blur in VR will result in increased simulator sickness [24]. Alternatively, a warp effect can be used (see Figure 4).

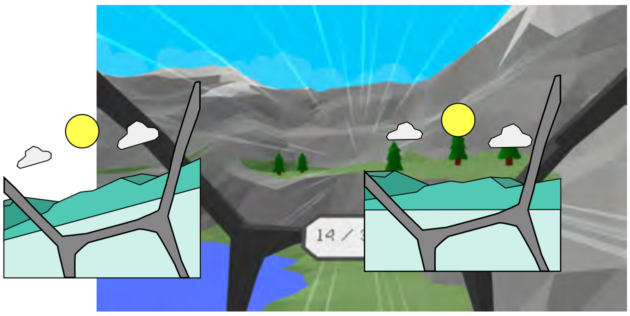

Figure 4. The warp effect can be used to visualize acceleration.

Rotation: The occurring forces while driving cause a weight transfer of the car. Braking, accelerating and turning result not only in rotations along the yaw axis, but also along the [illegible] is of the car, which [illegible] VR. The [illegible] es discourage fro[illegible] horizon line [1]. This limitation can be [illegible] ering the player inside a cockpit, where the rotation is applied instead. The horizon line stays as point of reference (see Figure 5).

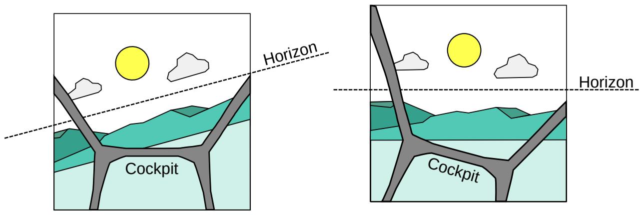

Figure 5. Two approaches of visualizing roll rotation. Left: the cockpit and the camera rotates along the roll axis. Right: only the cockpit rotates along the roll axis, the camera's roll rotation stays in line with the horizon. This concept also applies for the pitch axis.

The degree or even the direction of rotation can be altered. We tested altering the direction in an informal self-evaluation. When accelerating, the cockpit is normally rotated upwards, and when decelerating, downwards. When inverted, the cockpit rotates upwards on deceleration and vice versa (see Figure 6). For a rotation along the roll axis, a rotation as well as an inverse rotation were reported as realistic but the interpretation was different: when rotation is inversed, it would feel more like flying. This sounds reasonable because an airplane flying a curve, would roll towards the curvature. On a rotation along the pitch axis, participants stated that the inverted rotation feels unrealistic and uncomfortable. This is surprising because this would match a helicopter's behavior. Further research regarding force shifts is necessary. One possible explanation could be the dominance of our visual sense. Our mind often accepts visual information as the highest priority; this is known as the *Colavita visual dominance effect* [9, 20]. When the conflicting information is subtle enough, the visual impression might be dominant enough to suppress the incongruent information from the vestibular system. However, when the conflicting sensory information from the vestibular system is strong enough, the reported feeling of disturbance can occur. In the aforementioned situation, this could be the case: the lateral forces on the roll axis might be subtle enough that the dominance of the visual system is strong enough. The inverted roll movement is accepted despite incongruent visual and vestibular information. However, longitudinal forces along the pitch axis when accelerating are strong enough to be in conflict with the visual impression.

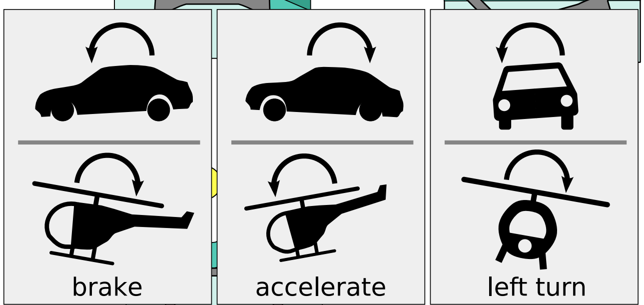

Figure 6. Effects of vehicular rotation while braking, accelerating and turning. The weight transfer due to inertia in a car forces the car to rotate forward when braking, backward when accelerating on the pitch axis, and towards the outside of a curve when turning on the roll axis. The rotation in a helicopter behaves inversely.

Springs: Occupants perceive vertical forces as shaking, vibrating, or bouncing in the vehicle. When driving and watching the road ahead, it remains stable because of the vestibulo-ocular reflex; the motion is visually filtered out. However, these forces can be recognized by observing dirt on the windshield. While the road remains stable, the dirt shakes and bounces up and down. This means that vertical forces are visually perceived by the moving interior of the vehicle, as is angular motion. To visualize vertical forces in virtual reality, they can be added to a virtual cockpit. To make the appearance of vibrating and bouncing realistic, springs and dampers of the vehicle can be simulated by a physics engine. Measured vertical acceleration from the moving vehicle is mapped to the mass of the cockpit and pulls it downwards. The attached spring tries to pull the cockpit back to the default position. The cockpit begins to oscillate up and down elastically. The damper weakens this motion and prevents the spring from oscillating endlessly. The strength of spring and damper can be configured. These values were heuristically evaluated and tested. Wrong configuration quickly leads to an unrealistic and disturbing behavior of the cockpit.

Force Shifts: The movement of the vehicle and the movement of the player in VR are not necessarily mapped 1:1. An altered representation in VR is possible, we call this *force shifts*. Forces can be exaggerated, understated or completely different. A 90 degree turn might result in a virtual 30 or 120 degree turn. Redirection techniques are used in other studies to distort the user's motions. Azmandian et al. showed that such illusions work on grabbing objects [3].

The *Einsteinian equivalence principle* states that the effects of gravity are indistinguishable from certain aspects of acceleration and deceleration [11]. This means that sensing acceleration of a car in VR cannot be distinguished from a gravitational force. This allows us to shift forces in VR, meaning that it is possible to render a completely different physical condition, like being attracted by gravitational forces, when the occupants are exposed to acceleration forces. Acceleration and deceleration could also result in rendering the player flying up and down. The concept of force shifts has to be investigated further; this concept has not been tested in user studies so far.

IMPLEMENTATION

As a proof of concept and study apparatus, we implemented our concept as a 3D VR rail shooter. The game is intended to be played by a passenger. While the car is moving, the player inside the VR scene moves the exact same way as the car does. The player position is defined by the vehicle. The player has the ability to aim and shoot a laser beam towards the gaze point by pressing a button on a wireless game controller. The view is from inside a cockpit (see Figure 8). In the scene, the player can shoot at 34 balloons, while a counter shows how much balloons are already hit and left. To support aiming, a target lock was implemented that helps the player to aim at the balloons because gaze aiming turned out to be frustrating without target lock due to subtle movements of the car that disturbed proper aiming which could not be filtered out. The vehicle in the game is realized as a helicopter, flying in a valley. The map is static, no dynamic route adaption is implemented. Therefore, the map is tailored to a fixed track. The map is shown in Figure 7.

Figure 7. The scene the player is flying through. The map is a valley with different highlights (a train, sheep, houses and a castle). The five small images show the view from the ego perspective but without the cockpit.

When moving, not only the vehicle's yaw axis, but also the roll and pitch axis are delegated to the game. The yaw axis is mapped to the helicopter and the player, whereas the pitch and roll axis influence only the helicopter, resulting in motions of the cockpit, but not the player. The horizon-fixed view with a rotating cockpit was chosen because this is already applied as best practice in VR to reduce simulator sickness.

The game starts as soon as the car moves. The environment is designed as a valley,which the player flies through. The map encompasses 810 km^2. The path of the corridor corresponds to a predefined track in reality. Visual cues and details were placed to make the scene more interesting: trees, houses, sheep, a castle and a train (see Figure 7). Snow flakes in the air were added to amplify the perception of movement in the scene, especially acceleration and deceleration. Acceleration is additionally supported by a warp effect. The graphical representation is optimized for maximum performance in order to achieve an adequate frame rate that ensures a minimal amount of simulator sickness.

The game was implemented with the Unity 3D game engine. A Samsung GearVR with a Samsung Galaxy S6 Edge mobile phone was used as the VR device.

Figure 8. The view from inside the cockpit. A balloon is shot through aiming via gaze and shooting via button press on a game controller.

Sensors

To measure the vehicle position, speed and direction, we combined different sensors. The sum of the car and head rotation are measured by the head-mounted display (HMD). When the vehicle rotates, e.g. when turning, the HMD's sensors measure such turns. Because the HMD is on the player's head, not only the car's rotations but also the player's rotation are measured by the HMD. The HMD cannot distinguish between these two rotations. Therefore, the car's rotation is measured by an IMU placed inside the car. With this, we can calculate the head rotation alone. This enables us to gather all rotations independent of any parent rotation. The car's movement is calculated by dead reckoning (using rotation and speed). Speed is measured by the OBD-II reader. The OBD-II reader was connected to the car's service port and via Bluetooth to the phone to measure the vehicle's speed and send it to the game. We used the OBD-II reader in combination with an x-IMU to measure the vehicle's location and speed instead of GPS, because GPS was not accurate enough and update cycles of the provided data were too slow. Increasing immersion and reducing simulator sickness demanded update cycles in rendering and sensors to be as fast as possible.

The information of the x-IMU represents the car's rotations. Therefore, the x-IMU sensor data is mapped to the cockpit. The OBD-II sensor data represents the car's speed, which is mapped to the player and the cockpit to move the cockpit with the player inside. The GearVR's inertial measurement sensor is mapped to the player, not the cockpit, to represent only the player movements. Because the GearVR's IMU measures also the rotation of the car, cockpit rotation and player are not linked in the game.

The inertial and magnetic as well as the quaternion data output rate of the IMU was set to 64 Hz. The update rate of the OBD-II reader was set to 10 times per second. To get an absolute reference for the heading, the internal algorithm mode was set to Attitude Heading Reference System (AHRS). In order to prevent lags, speed as well as the rotation data was interpolated linearly.

STUDY

Our research question in the study was whether the presence of real forces of a moving vehicle that match the forces of a player in VR, increase the player experience and reduce simulator sickness in our prototype. In the study, the independent variable was the vehicle's state. In one condition, the vehicle was moving (*moving condition*), in the other condition, the vehicle was not moving (*parking condition*). As dependent variables, simulator sickness, engagement, enjoyment and immersion were measured using the SSQ, E^2I and a questionnaire that directly compares the two conditions directly after both trials. According to our research question, we derived the following hypothesis: H1: *Participants will report more engagement, enjoyment and immersion in the driving condition compared to the parking condition.* H2: *Participants will report less simulator sickness in the driving condition compared to the parking condition.*

Procedure

The participants were seated on the front passenger seat. They were informed about the purpose of the study and the following procedure. A consent form was filled out subsequently. Before the first trial was started, participants filled out questionnaires about demographical data and motion sickness. In the latter questionnaire, questions were asked about situations in which participants might generally feel motion sick while traveling. Lenses and the head strap were adjusted. After the participants had familiarized themselves with the hardware and the game. The order of the conditions was chosen according a Latin square to ensure a counterbalanced setup. Either the parking condition or the moving condition was started first. During the trials, the participants played the game. In the moving condition, the vehicle moved along the same trajectory as the player in VR, albeit in a scene and context that differed from the real world. The game vehicle was a helicopter and the area was a canyon where the participant had to shoot at balloons. Shooting at balloons was achieved by directing a crosshair by gazing at a target and pressing a button on a gamepad. A target lock supported aiming by locking on the target when the crosshair was near the target. Before each trial, participants could shoot at three balloons to become accustomed to shooting. Shooting was added to the trails as an element of gameplay and to avoid boredom. In the parking condition, the vehicle was standing, but participants flew the same track and had the same task as in the moving condition, but without kinesthetic forces. To isolate them from surrounding noises, participants wore headphones in both conditions. After each trial, the participants were asked to complete the E^2I and SSQ. After the first trial, the GearVR could be adjusted again. As soon as participants felt comfortable to start, the second trial was started. After the second trial, an additional questionnaire was filled out that directly compared the two conditions regarding simulator sickness and enjoyment. Each trial took about five minutes. The study lasted about 40 minutes.

Participants

In the study, 23 participants (5 female) between 19 and 44 ($M = 26.17$, $SD = 5.04$) years old took part. Recruitment was achieved through flyers, social media advertising and personal approach of random people. Our sample was randomly selected, although the recruitment mainly took place at university. However, we do not consider this a limitation because we assume that potential consumers and early adopters are well represented by this sample. 10 participants were students of computer science or similar. One participant was excluded due to severe symptoms of simulator sickness in the parking condition. Another outlier was excluded because the values of simulator sickness was higher than the three-fold standard deviation. Post-study video analysis showed that the car had to drive backwards to turn during the study, this behavior was not correctly displayed in VR, which my have caused that reaction.

Therefore, from initially 23 participants, 21 participants were taken into the analysis. On average, the participants spent 3.17 ($SD = 1.42$) hours as driver and 1.43 ($SD = 1.43$) hours per week as passenger. 14 participants had never before worn a VR devices and reported this as a reason for participation. 5 Euros were paid for participation.

Apparatus

A Samsung GearVR with a Samsung Galaxy S6 Edge was used as the VR device. A wireless game controller was used for additional input to fire at balloons. Participants also wore around-ear headphones to isolate the experience from distractig outside sounds, for example car sound or construction site noise. Participants were recorded to capture their behavior during the study. The vehicle used was a Ford Fiesta with 5 seats and about 60 kW engine power. An x-IMU was used to measure the vehicle's kinesthetic forces, while an OBD-II reader was used to measure speed. For the communication between the x-IMU and smartphone, as well as between the OBD reader and smartphone, we used Bluetooth. The track was a 2.2 km circuit on a public road; because of the direct mapping, the track in VR was also 2.2 km (see Figure 9).

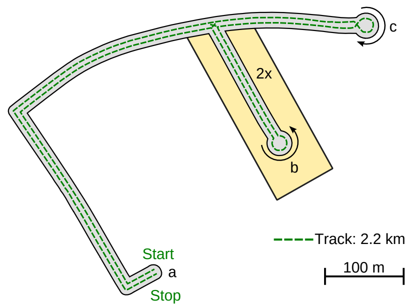

Figure 9. The track driven during the study consisted of 6 curves (3 left-hand and 3 right-hand 90-degree curves) and three 360-degree turn (2 left-hand and 1 right-hand). It started in the parking lot (a). After three right-hand curves, the first 360-degree turn (b) was reached. Followed by another right-hand curve, the second 360-degree turn (c) was reached. Then after a left curve, the track went back to the first 360-degree turn (b). After three further left-hand curves, the track ended in the parking lot from the beginning s(a).

Design

A within-subject design with repeated measures was chosen because we assumed that assessment of simulator sickness and enjoyment are dependent on personal at[illegible]s and therefore only meaningful in high sample sizes. A[illegible]ls we also asked participants for a compa[illegible]ss and enjoyment. This was done because we [illegible]d E^2I to be less accurate in measuring [illegible]cts. The conditions were counterbalanced by [illegible]are. Vehicle movement was used as the indepen[illegible]able, resulting in two conditions: a trial in which t[illegible]hicle was standing (parking condition) and a trial in which the vehicle was driving (driving condition). In both conditions, the same virtual route was driven in the game. As dependent variable, simulator sickness, engagement, enjoyment and immersion were elicited by the SSQ [18], E^2I [21] and a comparing questionnaire after both trials. Participants rated enjoyment, presence and general physical discomfort on the final questionnaire.

Results

For all items, a 7-point Likert-Scale was used. A Shapiro-Wilk test showed that all E^2I scores were distributed normally:

Table 1. Results of the Shapiro Wilk Test for the E^2I score and subscores showing that all scores were distributed normally.

	Shapiro Wilk		
	Statistic	df	Sig.
E^2I Total Score (Parking)	.929	21	.134
E^2I Total Score (Driving)	.973	21	.792
E^2I Presence Score (Parking)	.974	21	.825
E^2I Presence Score (Driving)	.985	21	.976
E^2I Enjoyment Score (Parking)	.946	21	.290
E^2I Enjoyment Score (Driving)	.911	21	.058

A subscale score for presence and enjoyment was calculated using separate items from the questionnaire. This allowed us to compare a total score, a presence score and an enjoyment score from the E^2I. Analysis of the three scores was performed by a paired-samples t-test (see Figure 10). In all three scales, a significant difference was found when comparing the two conditions driving and parking:

Table 2. Test statistic of the paired samples t-test for the E^2I score and subscores.

score	t(20)	p
total	-5.84	p < .001
presence	-4.11	p = .001
enjoyment	-6.30	p < .001

The according means and standard deviations are as follows:

Table 3. Means and standard deviations of the E^2I score and subscores.

	total		presence		enjoyment	
condition	mean	sd	mean	sd	mean	sd
parking	3.64	1.01	3.67	1.00	3.60	1.32
driving	4.53	.73	4.28	.73	4.90	.88

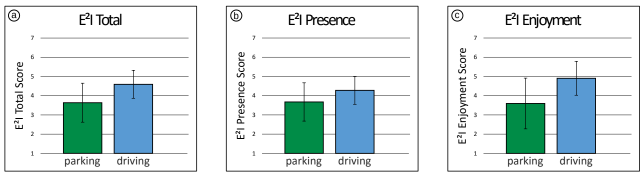

Figure 10. E^2I total score and subscale score for the two conditions parking and driving. It can be seen that the rating for driving in all three scores (total, presence and enjoyment) is higher than for the parking condition. The effect is significant. Error bars represent one standard deviation of uncertainty

These results suggest that vehicle movement really affect the E^2I score, and also that engagement, enjoyment, and immersion increases when playing the game in the moving condition. The effect size indicated that the effect was substantial.

To evaluate simulator sickness, the SSQ score for each condition was calculated. A Wilcoxon Signed-Ranks Test was used because no normal distribution was given. The test revealed no significant differences ($T = 58, Z = -.520, p > 0.05, Mdn_{parking} = Mdn_{driving} = 11.22$).

Additionally to the SSQ, participants had the chance to compare simulator sickness directly as an item in the final questionnaire. The question was about physical discomfort concerning both conditions.

A Shapiro-Wilk test showed, that the data significantly deviated from a normal distribution ($p < 0.05$). A Wilcoxon

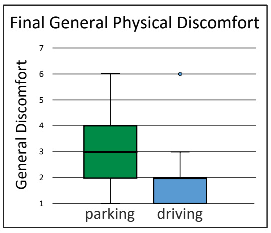

Figure 11. Directly compared simulator sickness between the parking condition and the driving condition.

signed-ranks test reveled a significant lower reported simulator sickness ($T = 84, Z = 2.72, p < .01$) in the driving condition ($Mdn = 2$) compared to the parking condition ($Mdn = 3$). Figure 11 shows the results of the final comparison regarding general discomfort between both conditions.

Discussion

Our study revealed significantly more presence, enjoyment and engagement in the moving condition. Also the calculated subscores for presence and enjoyment were significantly higher in the driving condition.

Results of the SSQ were not significant. This indicates that the driving condition did not cause less simulator sickness. However, we believe that in this case, the SSQ is not accurately enough to measure the differences of simulator sickness in the two conditions. The SSQ was designed for extreme situations in military aviation scenarios for pilot candidates for whom it is more likely that severe symptoms occur than in VR scenarios. The SSQ measures simulator sickness by asking for symptoms like headache, sweating, fatigue or burping. Therefore, we think that such questionnaires are generally good to measure the presence of simulator sickness but tend to deliver insignificant results when it comes to a comparison between two or more systems where only some of the symptoms occur at all. In other research the SSQ had no significant differences while other questionnaires showed significant results, for example [38, 12].

The results of the final direct comparison regarding general discomfort indicates that a difference in simulator sickness occurred between both conditions. During the study, self reports of participants clearly indicated that the sickness was lower in the driving condition.

The results of the E^2I and the final questionnaire indicate that both hypotheses can be confirmed: engagement, enjoyment and immersion is higher while simulator sickness is lower when the game is played in the moving vehicle compared to the condition where the car is standing while playing.

Participants reported the movement and visualization as realistic and that movements enhance the feeling of flying. One participant stated that the matching between the actual ride and the virtual ride feels great. Another mentioned that in the moving condition, an actual feeling of flying occurred. Our findings are in line with other research that states that perceived movements that match the visual information increase the sense of presence [31, 32, 33]. Participants completely lose their sense of where the car was moving in the real world. No participant could tell the pathway of the actual track afterwards. It was stated that feeling real motion to a corresponding visual impression was exciting and entertaining whereas visually perceived locomotion without kinesthetic forces was reported as uncomfortable, especially when flying curves and during acceleration. Overall participants reported playing in the moving condition as more enjoyable in the final questionnaire. Only two participants stated that the experience is equally enjoyable in both conditions.

Another interesting finding was that some participants reported that as a front-passenger, they felt engaged in the traffic situation as well. Being in VR creates a certain dissonance between the wish of participating in the real traffic scenario and being isolated in VR.

In the final questionnaire, situations with most discomfort were asked. In the moving condition, braking was reported as uncomfortable, the reason for this could be the surprising character of the action. Flying curves could be anticipated because the map was a valley where the player flies through, therefore the track was predictable. However, braking was not. This finding could also be interesting when designing levels. The map could also be designed without visual cues of the track, which may lead to an overall increase of simulator sickness.

Design Considerations

In this section, we present design considerations for developers based on (1) statements made by participants during the study, (2) observations by the developer and experimenter during developing, testing and conducting the study and (3) by qualitative user feedback at the end of each trial during the study.

Create an awareness of time: As mentioned in the discussion, participants completely lose their awareness of where they are in the real world. Furthermore, we experienced through the development of CarVR that the sense of how much time has passed since the beginning of the ride can also be distorted. Especially when driving in public transport, this awareness should be included in the game because missing a train station or bus stop while playing is very likely without such measures. This could be done by estimating the time of arrival and limiting the game duration to that amount.

Develop for visual dominance: In the design space section, we mentioned that the rotational axis can sometimes be inverted. While accelerating, the inversion of the pitch axis led to an uncomfortable feeling but inversion of the roll axis while turning was perceived as realistic. The situations where the visual representation of forces can be altered are not intuitive and may depend on several factors. Designers of VR entertainment systems should keep in mind that the sensory information is commonly the one that is accepted as truth while information that is diverging from the visual impression is interpreted as erroneous, and if this error increases, the feeling of discomfort might occur. Deviating the visual from the vestibular information is possible but only to a certain point. This point differs between users and use cases.

Prevent sickness through predictability: When designing levels, it might be a tempting approach to create levels that are independent of the track driven in real world. For example flying in the air, over a city or in space. However, an important aspect of increased simulator sickness is the absence of predictability. Sudden and unpredictable changes in direction are likely to increase simulator sickness. Therefore, some sort of visualization of upcoming turns should be included in the game. In our prototype, we visualized the route by generating a canyon along the track. This approach is a very intuitive and realistic realization but in real world scenarios hard to achieve. Not only generating a complete level along the track would be necessary, also reacting to unforeseeable changes of the actual route should be included in the story line and level generation algorithm. A rather simple approach could include some sort of open space where auditory information predict upcoming turns. In a space shooter, approaching asteroids could be used as an element of style to predict upcoming turns.

Deprive responsibility: Participants stated that on the front passenger seat, they normally feel responsible for being involved in the traffic but by playing a fully immersive game, their role comes into conflict with playing the game. Being not able to see what is going on in the real world could disturb users and might lead to an uncomfortable feeling while playing. A high level of trust in the driver or changing seat positions could be enough to counteract the feeling of being responsible. Some participants did not report such responsibility, therefore we assume that this kind of feeling depends on personality.

Consider involvement of the driver: While playing, we observed that the movements of the player's vehicle are accepted as part of the game and not performed by the driver sitting next to the player. Even though players were aware that a driver next to them was controlling the vehicle and the vehicle's movements were directly mapped to the player's vehicle, the awareness was not present during the game. During our study, participants did not ask to change the driving style, for example to hit a target. However, this feeling could have been so strong because the game elements are optimized to the track. Another explanation could be an experimenter bias. In this case, this means that participants did not want to participate in the driving style because the driver was the experimenter and a stranger. In situations where friends drive together, we assume communication between the player and the driver regarding the game.

Never persuade to risky driving: The passenger's wish to influence the driving behavior could be an element of the game as well and could be used to increase driving safety. For example, while driving on a road on which speeding is common, the number of targets in the scene could be increased. By this, the player might ask the driver to slow down a bit in order to be able to hit all targets in the scene. However, this would require the driver to be part of the game which might be triggered in any way. On the other hand, a specific game design could lead to a risky driving behavior. For example when chasing an object in front, the player could be incited to convince the driver to speed. A game design that could lead to risky driving should be avoided.

Design for incompleteness: When the player's vehicle drives in a way that targets are hard to reach or hit or other goals are impossible to achieve, the player might blame the driver or the game itself for this and frustration could occur. A target that is impossible to hit because the car is never moving in the required position should either be avoided or not punished by the game play. Levels and game goals should be designed that the feeling of incompleteness does not occur. This could be reached by not defining an upper limit for targets, e.g. by not defining a goal such as, hit all objects in the scene. Note that in our study, the goal was in fact to hit all targets, but the route was tailored to the targets in the game, therefore all targets could be reached properly.

Limitations

The study track was the same for each participant. However, because the study took place on public road, sudden brakes, longer waiting time on crossings or different acceleration rates could not be controlled for and differed between participants. The game in our study was specifically designed for the chosen track of 2.2 km, therefore different tracks with other road geometry, speed limits and overall duration, like driving on a highway, should be tested in further studies. Also our design considerations are based on the small sample size of the study and should be evaluated with a bigger sample size. Our study results could be influenced by the experimenter bias effect because when comparing between a standing and driving condition, we can assume that participants are aware of the experimenter's preferred condition.

CONCLUSION

In this work, we presented a functional prototype to enable virtual reality in moving vehicles. To enable this, we mapped the vehicle's movements and the visual information of the VR content. By this, the vestibular and visual information is congruent. We provide a technical implementation, an analysis of the design space and an evaluation based on a user study, in which we showed that our prototype reduces simulator sickness and increases enjoyment and immersion in comparison to a VR experience in a standing vehicle. We provided design considerations based on our experiences while developing and conducting our study that serves developers as guidelines when creating VR entertainment applications in moving vehicles.

Effects of the seat position regarding trust in the driver and the player's wish for being involved in the traffic situation could be the focus of future work. Also level design while being in a vehicle playing VR games regarding simulator sickness should be investigated further. Different kinds of force shifts should also be investigated, where kinesthetic forces are not only mapped 1:1 but altered from actual movements. For example, flying loopings or changing height while the car is accelerating.

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REFERENCES

1. 2016. Developer Center – Documentation and SDKs | Oculus. (2016). https://developer.oculus.com/documentation/intro-vr/latest/concepts/bp_intro/
2. 2016. Lockheed Martin school bus takes you on virtual journey to Mars. (2016). http://generation-beyond.com/mars-experience
3. Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D Wilson. 2016. Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.
4. John Bichard, Liselott Brunnberg, Marco Combetto, Anton Gustafsson, and Oskar Juhlin. 2006. *Backseat Playgrounds: Pervasive Storytelling in Vast Location Based Games*. Springer Berlin Heidelberg, Berlin, Heidelberg, 117–122. DOI: http://dx.doi.org/10.1007/11872320_14
5. Willem Bles, Jelte E Bos, and Hans Kruit. 2000. Motion sickness. *Current opinion in neurology* 13, 1 (2000), 19–25.
6. Dipl-Ing Thomas Bock, Prof Dr-Ing Markus Maurer, Dipl-Ing Franciscus van Meel, and Dipl-Ing Thomas Müller. 2008. Vehicle in the Loop. 110, 1 (2008), 10–16. DOI:http://dx.doi.org/10.1007/BF03221943
7. Liselott Brunnberg, Oskar Juhlin, and Anton Gustafsson. 2009. Games for Passengers: Accounting for Motion in Location-based Applications. In *Proceedings of the 4th International Conference on Foundations of Digital Games (FDG '09)*. ACM, New York, NY, USA, 26–33. DOI:http://dx.doi.org/10.1145/1536513.1536528
8. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic turk: a motion platform based on people. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 3463–3472.
9. Francis B Colavita. 1974. Human sensory dominance. *Perception & Psychophysics* 16, 2 (1974), 409–412.
10. Fabien Danieau, Julien Fleureau, Philippe Guillotel, Nicolas Mollet, Anatole Lecuyer, and Marc Christie. HapSeat: Producing Motion Sensation with Multiple Force-feedback Devices Embedded in a Seat. In *Proceedings of the 18th ACM Symposium on Virtual Reality Software and Technology* (2012) *(VRST '12)*. ACM, 69–76. DOI: http://dx.doi.org/10.1145/2407336.2407350
11. Albert Einstein and others. 1911. On the Influence of Gravitation on the Propagation of Light. *Annalen der Physik* 35, 898-908 (1911), 906.
12. Ajoy S Fernandes and Steven K Feiner. 2016. Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 201–210.
13. James J Gibson. 2014. *The ecological approach to visual perception: classic edition*. Psychology Press.
14. Jan Gugenheimer, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. 2016. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1996–2000. DOI: http://dx.doi.org/10.1145/2858036.2858040
15. Lawrence J Hettinger, Kevin S Berbaum, Robert S Kennedy, William P Dunlap, and Margaret D Nolan. 1990. Vection and simulator sickness. *Military Psychology* 2, 3 (1990), 171.
16. Makoto Igarashi, F Owen Black, and Includes Index. 1985. Vestibular and Visual Control on Posture and Locomotor Equilibrium. (1985).
17. Jaguar New Zealand. 2015. Jaguar creates Actual Reality prank. (2015). https://www.youtube.com/watch?v=_zpx0Eb1Tvo
18. Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. 1993. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology* 3, 3 (1993), 203–220.
19. Eugenia M Kolasinski. 1995. *Simulator Sickness in Virtual Environments.* Technical Report. DTIC Document.
20. Camille Koppen and Charles Spence. 2007. Seeing the light: exploring the Colavita visual dominance effect. *Experimental brain research* 180, 4 (2007), 737–754.
21. J. J. W. Lin, H. B. L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness. 2002. Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment. In *Virtual Reality, 2002. Proceedings. IEEE*. 164–171. DOI: http://dx.doi.org/10.1109/VR.2002.996519
22. Daniel Michaels. 2016. Roller Coasters Ride Into Dizzying Realm of Virtual Reality. (2016). http://goo.gl/qnzsCL
23. Akihiro Morimoto, Naoki Isu, Daisuke Ioku, Hitoshi Asano, Atsuo Kawai, and Fumito Masui. 2008. Effects of reading books and watching movies on inducement of car sickness. In *Proc. of FISITA 2008 World Automotive Congress, in print*.
24. Oculus VR, LLC. 2016. Virtual Reality Best Practices. (2016). https://docs.unrealengine.com/latest/INT/Platforms/VR/ContentSetup/
25. James T Reason and Joseph John Brand. 1975. *Motion sickness.* Academic press.
26. Max Rheiner. 2014. Birdly an Attempt to Fly. In *ACM SIGGRAPH 2014 Emerging Technologies (SIGGRAPH '14)*. ACM, New York, NY, USA, Article 3, 1 pages. DOI: http://dx.doi.org/10.1145/2614066.2614101

27. Rose Marie Rine, Michael C Schubert, and Thomas J Balkany. 1999. Visual-vestibular habituation and balance training for motion sickness. *Physical therapy* 79, 10 (1999), 949–957.

28. Arnon Rolnick and RE Lubow. 1991. Why is the driver rarely motion sick? The role of controllability in motion sickness. *Ergonomics* 34, 7 (1991), 867–879.

29. C. Schatzschneider, G. Bruder, and F. Steinicke. 2016. Who turned the clock? Effects of Manipulated Zeitgebers, Cognitive Load and Immersion on Time Estimation. 22, 4 (2016), 1387–1395. DOI: http://dx.doi.org/10.1109/TVCG.2016.2518137

30. Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 3307–3316. DOI: http://dx.doi.org/10.1145/2702123.2702389

31. Mel Slater, John McCarthy, and Francesco Maringelli. 1998. The influence of body movement on subjective presence in virtual environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 40, 3 (1998), 469–477.

32. Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of presence in virtual environments. *Presence: Teleoperators & Virtual Environments* 3, 2 (1994), 130–144.

33. Mel Slater, Martin Usoh, and Anthony Steed. 1995. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)* 2, 3 (1995), 201–219.

34. Richard HY So, WT Lo, and Andy TK Ho. 2001. Effects of navigation speed on motion sickness caused by an immersive virtual environment. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 43, 3 (2001), 452–461.

35. Kay M Stanney, Kelly S Hale, Isabelina Nahmens, and Robert S Kennedy. 2003. What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience. *Human Factors: The Journal of the Human Factors and Ergonomics Society* 45, 3 (2003), 504–520.

36. Petra Sundström, Axel Baumgartner, Elke Beck, Christine Döttlinger, Martin Murer, Ivana Randelshofer, David Wilfinger, Alexander Meschtscherjakov, and Manfred Tscheligi. 2014. Gaming to Sit Safe: The Restricted Body As an Integral Part of Gameplay. In *Proceedings of the 2014 Conference on Designing Interactive Systems (DIS '14)*. ACM, New York, NY, USA, 715–724. DOI: http://dx.doi.org/10.1145/2598510.2600882

37. Mark Turner and Michael J Griffin. 1999. Motion sickness in public road transport: the relative importance of motion, vision and individual differences. *British Journal of Psychology* 90, 4 (1999), 519–530.

38. Robert Xiao and Hrvoje Benko. 2016. Augmenting the Field-of-View of Head-Mounted Displays with Sparse Peripheral Displays. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1221–1232.

SHAREVR

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ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users

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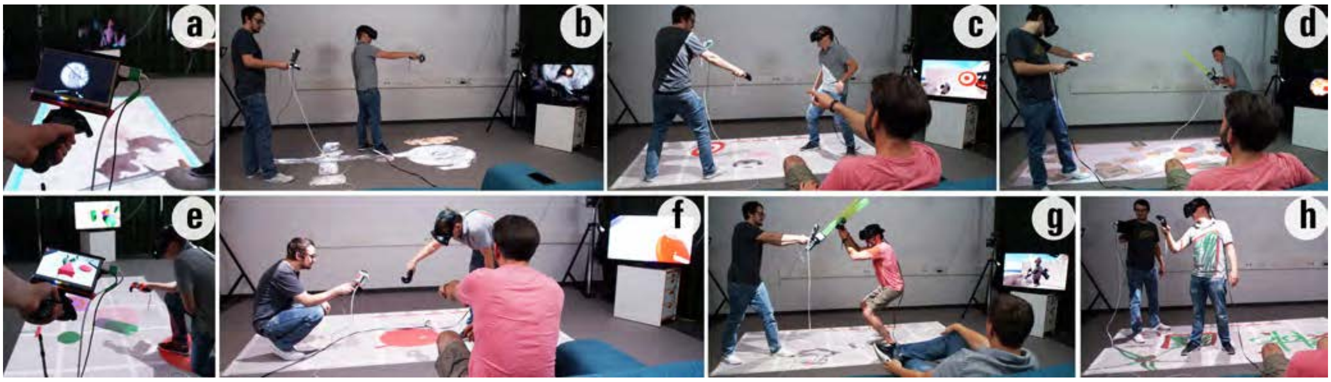

Figure 1. ShareVR enables co-located asymmetric interaction between users wearing an HMD and users without an HMD. ShareVR uses a tracked display (a, e) as a window into the virtual world and a floor projection to visualize the virtual environment to all Non-HMD users. It enables collaborative experiences such as exploring a dungeon together (b), drawing (h), sports (c) or solving puzzles (e, f) as well as competitive experiences such as "Statues" (d) or a swordfight (g). ShareVR facilitates a shared physical and virtual space, increasing the presence and enjoyment for both HMD and Non-HMD users.

ABSTRACT

Virtual reality (VR) head-mounted displays (HMD) allow for a highly immersive experience and are currently becoming part of the living room entertainment. Current VR systems focus mainly on increasing the immersion and enjoyment for the user wearing the HMD (*HMD* user), resulting in all the bystanders (*Non-HMD* users) being excluded from the experience. We propose *ShareVR*, a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for the *Non-HMD* user, enabling them to interact with the *HMD* user and become part of the VR experience. We designed and implemented *ShareVR* based on the insights of an initial online survey (n=48) with early adopters of VR HMDs. We ran a user study (n=16) comparing *ShareVR* to a baseline condition showing how the interaction using *ShareVR* led to an increase of enjoyment, presence and social interaction. In a last step we implemented several experiences for *ShareVR*, exploring its design space and giving insights for designers of co-located asymmetric VR experiences.

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Co-located virtual reality; shareVR; asymmetric virtual reality; multi-user virtual reality; consumer virtual reality

INTRODUCTION

Virtual Reality (VR) head-mounted displays (HMD) are currently getting released as consumer devices (e.g. Oculus Rift, HTC Vive, and PlayStation VR) and are becoming part of the home entertainment environment. The technical progress allows for creating highly immersive virtual environments (IVEs) where users can even physically walk around and interact using their hands (roomscale VR) [13]. Having this physical exploration leads to a higher spatial understanding and therefore further increases immersion and enjoyment for the *HMD* user [4].

Despite VR aiming to become an essential part of the future living room entertainment, most current VR systems focus mainly on the *HMD* user. However, Alladi Venkatesh describes the living room as a highly social environment where people experience content together and interact through technology [61]. Since the level of engagement may vary between members of the household (e.g. some want to watch, some want to have some form of interaction and some want to be fully part of the experience), a VR system has to cover a wide bandwidth of engagement [63]. Solely observing participants would benefit from a more spatial representation of the virtual world such as the approach of Valve, which uses a green screen in combination with a tracked camera to create a mixed reality video for the observer [60]. People who only want a brief experience without committing to an extensive gaming session would benefit from a form of interaction with this mixed reality representation without having to put on an HMD. We argue that for VR to become part of this social living room environment, a way of interaction between users with an HMD and without an HMD is essential. Therefore, the focus of our work was on including the *Non-HMD* users into the VR experience and enhancing their way to interact with the *HMD* user.

We propose *ShareVR* (Fig.1), a proof-of-concept prototype enabling *Non-HMD* users to be part of the VR experience and interact with the *HMD* user and the virtual environment. We use a tracked display and a floor projection to visualize the virtual space for the *Non-HMD* user (Fig.1 a,e) and potential bystanders. To increase the engagement and enjoyment of *Non-HMD* users, we bring both (*HMD* and *Non-HMD*) into the same physical space enabling the same form of interaction. Prior work showed that this physical interaction can potentially increase enjoyment, social interaction and has cognitive benefits [39, 21, 42].

We conducted an initial online survey (n=48) with early adopters of VR, investigating how they currently deal with interactions between *HMD* and *Non-HMD* users and what future concepts should provide to improve this interaction. Based on those insights, we designed and implemented *ShareVR*. In a user study (n=16), we compared *ShareVR* with a baseline condition (gamepad and television), showing the increase of enjoyment, presence and social interaction for *HMD* and *Non-HMD* users using *ShareVR*. We further explored the design space of *ShareVR* and implemented three example applications, showing the novel possibilities for asymmetric co-located experiences and give insights on how to design future experiences for asymmetric co-located VR interaction. The contributions of this work are:

- Concept, design and implementation of *ShareVR* – a proof-of-concept prototype for co-located asymmetric experiences in VR, based on the feedback (n=48) of VR early adopters.
- Insights from a user study (n=16), exploring the impact of *ShareVR* on enjoyment, presence and social interaction and showing its advantage compared to a baseline consisting of a gamepad and television.
- Exploration of the design space for co-located asymmetric VR experiences and implementation of three example applications, giving insights for designers of future asymmetric co-located VR experiences.

ENVISIONED SCENARIO

Our envisioned scenario is centered around a living room where VR already became an essential part of the home entertainment. Future systems will be designed having asymmetric co-located interaction in mind and provide appropriate visualization for *Non-HMD* users (e.g. embedded display in controllers) and an in-situ visualization of the physical tracking space (e.g. embedded projectors in already used hardware such as the tracking system of the HTC Vive).

Our final vision further incorporates additional devices such as nomadic VR *HMD*s [24], AR *HMD*s and smartphones. These devices are all additional points on the interaction gradient between fully immersed user (VR *HMD*) to bystander (*Non-HMD* user). This work will mainly focus on spanning and exploring this design space between *HMD* and *Non-HMD* users. Future research projects should further explore additional devices on this gradient which generate different asymmetries and come with different concepts of visualization and interaction (e.g. [17, 25, 30]). Each of these devices will presumably have an individual impact on enjoyment, presence and social interaction.

RELATED WORK

Our work builds upon three general fields of research: *Collaborative/Spatial Augmented Reality*, *Collaborative Virtual Environments* and *Asymmetric Co-located VR Gaming*. We will not specifically focus on prior art having a different research direction but sharing a similar technical setup such as [38, 43].

Collaborative/Spatial Augmented Reality

Since presented in 1998 by Raskar et al. [51], spatial augmented reality aims to augment the environment by using projection technology instead of head mounted displays [35, 34]. The field is closely related to projector camera systems which were developed to enable these kind of experiences [50]. A recent example of this approach is RoomAlive by Jones et al. which is closely related to our work [34]. Using a set of projector camera systems, an approach to transform the living room into a gaming environment and enable multiple users to play and interact together was presented. This work beautifully displays and explores the design space of spatial augmented reality inside the living room. Our work is closely related to Jones et al.'s RoomAlive since we apply a similar approach to visualize the virtual world, but we focus mainly on interaction between *HMD* and *Non-HMD* users.

Collaborative augmented reality [2, 49] focuses on enabling collaboration and interaction between people using AR technology and further incorporates work with asymmetric setups (e.g. different visualization and different input capabilities [7, 55, 26]). The Studierstube [53] by Schmalstieg et al. and "Shared Space" [2, 3] by Billinghurst et al., are systems presenting a variety of interaction and visualization concepts for co-located augmented reality collaboration. A similar approach was presented by Benko et al. with VITA, a collaborative mixed reality system for archaeological excavations [1]. VITA combined projected interfaces, a large screen and tracked handheld displays to enable collaboration in a multi-user scenario. Stafford et al. further presented "god-like interactions", an approach to enable asymmetric interaction between a user with an AR *HMD* and a user with a tablet [55]. *ShareVR* follows a similar approach by offering individual interaction and visualization concepts for users without an *HMD*.

Collaborative Virtual Environments

Churchill et al. initially defined Collaborative Virtual Environments (CVE) as distributed virtual reality systems that enable users to interact with the environment and each other [11]. The focus was initially mainly on the distributed aspect [47]. DIVE, a distributed interactive virtual reality environment was presented by Carlsson et al., focusing on multi-user and 3D interaction aspects in distributed collaborative virtual environments [8]. Oliveira et al. further presented a distributed asymmetric CVE, where an *HMD* user would receive guidance and instruction from a user sitting at a PC using a traditional GUI [45]. However, the focus of the work was mainly on training applications and e-commerce scenarios. *ShareVR* incorporates several concepts from distributed CVEs in its prototype but mainly focuses on co-located synchronous interaction as defined by Johansen et al. [33]. In C1x6, Kulik et al. presented a co-located CVE that was realized using six projectors and active shutter glasses to provide correct perspectives to six users inside a virtual environment. This allowed each user to perceive the same experience, whereby *ShareVR* focuses on creating different perceptions of the same experience leveraging the advantage of each individual visualization approach. Kulik et al. found that people are more enthusiastic about exploring a virtual environment as part of a group which was one of the main motivations for *ShareVR*.

Similar to prior work, one essential characteristic of *ShareVR* is the asymmetry of the experience [17, 44, 12, 30, 29, 18, 15]. Duval et al. presented an asymmetric 2D/3D interaction approach which allows users who are immersed in an IVE to interact with users sitting at a PC [17]. The approach works by leveraging the advantage of each individual representation (2D vs 3D). Oda et al. presented a further asymmetric interaction between a remote user and a local user wearing an AR *HMD* [44]. In a user study, the remote user had to explain a specific task to the local user either through a 2D interface or a VR *HMD*. The results show that local users understood faster when the remote users actually demonstrated the task wearing a VR *HMD* vs writing annotations with a 2D interface. *ShareVR* incorporates these findings by letting the *Non-HMD* user have the same way of interaction as the *HMD* user. Also closely relevant to our work were projects exploring an asymmetric “god-like interaction” with the goal to let people build worlds together [12, 29]. Users with an VR *HMD* could collaboratively create virtual environments with users at a PC. A similar approach was shown by Ibayashi et al. with DollhouseVR [30]. *ShareVR* differentiates itself from those approaches by strongly focusing on enabling a co-located experience which aims to increase enjoyment, presence and social interaction instead of increasing performance.

More recently Cheng et al. presented HapticTurk [9] and TurkDeck [10]. In contrast to prior work on generatic haptics in VR [27, 28], HapticTurk and TurkDeck leverage human workers to generate haptic feedback for the *HMD* user. Our work was highly inspired by both systems and the haptic feedback was incorporated into the concept (e.g. lightsaber duel). However, in contrast to Cheng et al. *ShareVR* tries to enable an equally enjoyable experience for the *Non-HMD* user by literally sharing the virtual world of the *HMD* user with all people in the surrounding. To the best of our knowledge, *ShareVR* is the first system to enhance co-located asymmetric experiences between *HMD* and *Non-HMD* users who share the same physical space. This is a scenario that we argue will become more relevant as consumer VR technology progresses and attempts to become part of the living room entertainment.

Asymmetric Co-located VR Gaming

Despite the recent popularity of online multiplayer, co-located multiplayer games are still highly appreciated by many players [22, 46, 48] and researched by the scientific community [62]. Gajadhar et al. found that players experience a higher positive affect and less tension in a co-located than in a mediated setting or against a computer [20]. In the VR context, co-located settings are difficult to provide as usually only one VR HMD is available and only one player can wear it at a time. However, there are a few co-located VR games that make use of other means to circumvent this limitation. Games such as *Black Hat Cooperative*, *Ruckus Ridge VR Party*, *Playroom VR* and *Keep Talking And Nobody Explodes* apply an asymmetric interaction approach by either providing the *Non-HMD* user with an additional controller [52, 19], mouse and keyboard [57] or relying solely on verbal communication [56]. Recently, Sajjadi et al. presented *Maze Commander*, a collaborative asymmetric game in that one player uses a VR HMD while the other interacts using Sifteo Cubes. Although game experience did not differ between both interaction methods, players generally did enjoy the asymmetric game play.

Although these games all feature local multiplayer for VR, most game mechanics would still function if the games were implemented online and players had some form of voice chat. In contrast, *ShareVR* strongly focuses on the shared physical space and the resulting physical interaction to enhance the experience. While playing in a co-located setting does have positive effects on players [20], we argue that physical interaction in particular does enable novel play experiences for VR. Prior research has already shown that enjoyment and social interaction can be increased through physical engagement and interaction [39, 21, 42]. Lindley et al. found that an input device leveraging natural body movements elicits higher social interaction and engagement compared to a classic gamepad [39]. Similar results were found by Brondi et al. who showed beneficial effects of body movement on player engagement and flow for a collaborative game in a virtual environment [6]. Recently, Marshall et al. [41] studied aspects of games that encourage physicality in an extreme manner and derived guidelines for such games. *Johann Sebastian Joust* [16], is a game in that players have physical interaction in a shared play space. The players hold motion controllers and have to grab the other players’ controllers in order to win while the played music restrains their allowed movement. To the best of our knowledge, *ShareVR* is the first VR system enabling physical gaming experiences between *HMD* and *Non-HMD* users.

ONLINE SURVEY

We conducted an online survey to elicit the demand for co-located asymmetric interaction and further explore how early adopters are currently coping with this (e.g. during demonstrations) and what they would expect from future technology to support co-located asymmetric interaction. The survey was posted in online forums (e.g. Reddit) and was sent out to mailing lists of early adopters. We were focusing on an audience which already uses the technology at home and falls under the category early adopter. Overall we received 48 responses.

Demographics

The majority of the early adopters were male (46 males, 2 females), held a college degree ($\approx 77\%$), and were on average 30.85 years old (*SD*=7.87, range: 19-49). The most used headsets were the HTC Vive (54%) followed by the Google

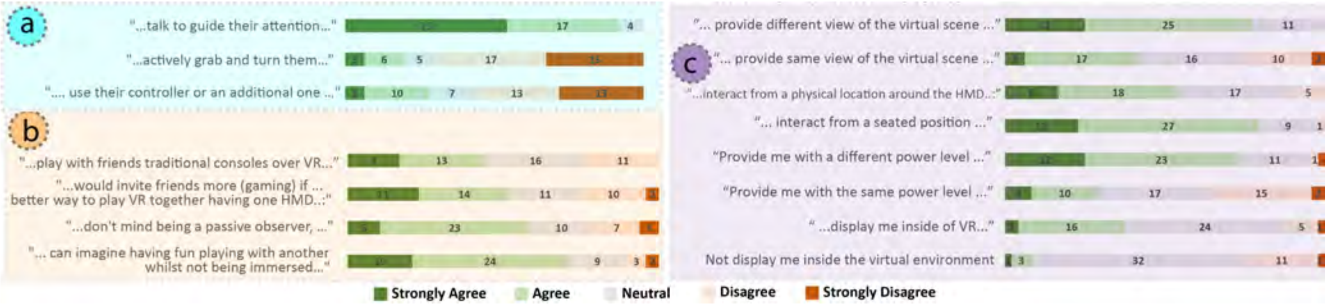

Figure 2. An excerpt from our online survey on the questions: (a) "When demonstrating my VR headset to friends and family I tend to:", (b) "Assuming that you own and actively use only one headset, please rate the following statements:", (c) "A technology which would allow me to actively influence the virtual environment of the immersed user should..." (Note: the statements are shortened and rephrased to fit into one figure.)

Cardboard (41%), Oculus Rift CV1 (33%), Oculus Rift DK2 (21%) and Samsung GearVR (19%). On average the respondents used the VR HMD 7.06 hours a week (*SD*=6.44, range: 0-30). Rated on a 5-point Likert scale, 73% stated a very high interest in virtual reality technology, 21% a high interest and 6% a moderate interest.

Current Coping Techniques

We asked people about the occurrence of asymmetric interaction (e.g. demoing a VR HMD) and how they are currently dealing with situations of asymmetric interaction (an overview of a subset of the questions can be found in Figure 2). The vast majority of our respondents reported they experienced asymmetric interaction during demoing of a VR HMD (94%) whereby only (38%) experienced it in a gaming scenario. Overall, only 13% played asymmetric co-located multi-user VR games (e.g. *Ruckus Ridge VR Party*) whereby 40% reported having regular ($\approx$ 4 times a month) gaming sessions sharing one HMD (average group size of $\approx$ 3 friends).

When asked about the form of communication used in such asymmetric scenarios, the majority agreed to use speech (91%)[1] followed by controllers (28%) and physical interaction (20%). When asked about their social coping, respondents agreed (48%) to prefer traditional consoles over VR HMDs when friends are around and would invite friends over more often (52%) for gaming sessions if there would be a better way of playing together having one HMD. Furthermore, respondents agreed that they would not mind being a passive observer (58%) and can imagine having fun playing with another person with an HMD whilst not having an HMD themselves (71%).

Demand and Future Requirements

When asked directly about asymmetric gameplay having one HMD, a vast majority agreed that they would love to be able to actively influence the virtual environment of the immersed user while not being immersed themselves (92%). When asked about specific aspects of asymmetric gameplay (Fig.2 c), respondents often preferred the asymmetric option (e.g. different view of the virtual scene: 77%, different power level: 75% and different way of interaction: 79%). Nevertheless, the alternative options such as same view (42%) and physical interaction (54%) were still more towards an agreement as towards a disagreement. When asked about the representation of the *Non-HMD* user inside the IVE respondents slightly preferred to be visualized inside the virtual world (38%).

[1] All the following reported percentages are based on the number of strongly agrees and agrees towards a statement

Discussion of the Online Survey

Our survey identified the users' desire to be able to actively influence and interact with *HMD* users while not not having an HMD themselves. We found dedicated co-located asymmetric games such as Ruckus Ridge VR Party are not widely known/spread, whereby 40% of the respondents already play with multiple users having one HMD. The main form of interaction between *HMD* and *Non-HMD* users is mainly speech. People further reported that they currently prefer using a traditional console with friends but would invite friends more often for VR gaming session if there would be a better way for playing together having one *HMD*. When asked about future concepts such a system should have, respondents preferred an asymmetric approach but still were interested in the alternatives. This indicated that these design decisions would have to be dependent on the underlying game dynamics. We used this feedback and incorporated it (e.g. speech as interaction, focus on asymmetry in visualization and power level) into our concept and implementation of *ShareVR* and its experiences.

SHAREVR CONCEPT AND IMPLEMENTATION

We designed and implemented *ShareVR* with the goal of enabling *Non-HMD* users to become a part of the virtual experience of the *HMD* user and enable them to interact and explore the environment together. Furthermore, we wanted to allow bystanders who are not interested in actively influencing the IVE to be able to follow and understand the events happening inside the IVE and be able to interact with the *HMD* and *Non-HMD* user (e.g. point and scream "watch out behind you"). A main goal for the design of *ShareVR* was to increase the enjoyment, presence and social interaction for *HMD* and *Non-HMD* users. We aimed for developing an entertainment system which would fit right into the social dynamics of a living room.

One of our major design decisions was not to design an *HMD* to *HMD* system but focus on asymmetric interaction with *Non-HMD* users. While we agree that the direction of *HMD* to *HMD* interaction is also highly relevant and (as presented in the related work section) a highly researched field, we decided to focus on scenarios where only one *HMD* is available. Similarly to Voida et al. [62], we argue that for the living room scenario, it is important to design a system which enables a gradient of participation. This allows users who are not eager to use an *HMD* to still be part of the virtual experience and maybe get interested in participating themselves. Furthermore, this approach allows a rich social interaction between *Non-HMD* users and bystanders since they both can see and talk to each other. This further creates an interesting social dynamic which we are going to discuss in more detail in our user study.

In our concept we focused on room-scale VR systems such as the HTC Vive and partially PlayStation VR, since they offer a larger design space, result in a high level of immersion and are expected to be widely spread systems in the future [59]. A second major design decision was to bring the *Non-HMD* user into the tracking space and let him explore the virtual world from the same position as the *HMD* user. This should result in an equal level of agency and engagement between *HMD* and *Non-HMD* users and further add the dimension of physical interaction (e.g. touch the *HMD* user). Prior research showed that this form of physical engagement and interaction results in an increase of enjoyment and social interaction [39, 21, 42].

Concept and Hardware Implementation

Our proof-of-concept prototype of *ShareVR* was built using an HTC Vive, two oppositely positioned short throw BenQ W1080ST projectors to visualize the tracking space and a 7 inch display attached to one of the HTC Vive controllers serving as a "window into the virtual world" for the *Non-HMD* user (Fig.3). We additionally added a TV which mirrored the view of the *HMD* user. The whole software was running on an i7 machine with an Nvidia GTX 970. The two main design variables we had were how to realize *interaction* and *visualization* for the *Non-HMD* users.

Interaction: Since we decided to bring both users in the same physical space we had to track the position and interaction of the *Non-HMD* user. We dedicated one of the HTC Vive controllers as the *Non-HMD* controller and used the Lighthouse tracking system of the HTC Vive to estimate the location of the *Non-HMD* user inside the physical space and let him interact with the IVE using the controller inputs. To leverage the advantage of sharing the same physical space we used physical props attached to the tracked controller as a second form of interaction between *HMD* and *Non-HMD* users. This enabled the *Non-HMD* user to generate haptic feedback for the *HMD* user (e.g. impact of lightsabers can be felt, cf. Fig.6). Based on the feedback of the online survey, we decided not to use headphones for the *HMD* user, to allow for oral communication between all users and directional sound (e.g. hearing the steps of the *Non-HMD* user).

Visualization: We designed the visualization having the *Non-HMD* user and additional users sitting on the couch in mind. To reduce the amount of shadows, we positioned two projectors opposite of each other directed towards the floor covering the full tracking space of the Lighthouse system. Both were calibrated through software to be perfectly aligned, visualizing the full tracking space to all people in the surrounding. This should help to develop a spatial understanding of the IVE for *Non-HMD* users. Furthermore, we attached a 7 inch display on top of the *Non-HMD* controller allowing to function as a "window" into the virtual world. We used a 5m hdmi cable to connect the display with the PC and supported it with power through a portable power bank inside the users pocket. We initially tried to remove all cables using wireless hdmi which resulted in a too big delay. Additionally, we used a TV to render the mirrored view of the *HMD* user.

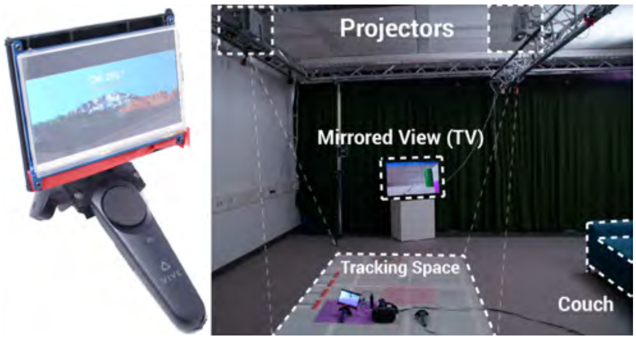

Figure 3. Left: Display mounted on the controller of the *Non-HMD* user. Right: Physical setup of *ShareVR*, replicating a living-room layout

Software Implementation

The whole software side was implemented using Unity® and the SteamVR Unity plugin. We used NewtonVR [58] as an additional layer on top of SteamVR to quickly prototype physical interaction such as grabbing virtual objects. We created a prefab in Unity consisting of the NewtonVR camera rig, an orthographic camera positioned above to cover the whole tracking space and a camera on the virtual *Non-HMD* controller. The orthographic camera rendered their image onto a mesh in which we could adjust individual vertices to correct for distortion and align both projectors. Two individual versions of this mesh were positioned in front of two additional cameras which rendered the projection images. We used this prefab throughout all our implemented experiences.

IMPLEMENTED EXPERIENCES

We implemented three different applications: *BeMyLight*, *SneakyBoxes*, and *SandBox* consisting of four smaller experiences (lightsaber duel, soccer, puzzle and drawing). The first two *BeMyLight* and *SneakyBoxes* were later used in our comparative user study, whereby the *SandBox* was used in the final exploratory study.

Collaborative: Be My Light

The experience *BeMyLight* places both users in a pitch black cave full of creatures and riddles to solve (Figure 4). The goal of the game is it to escape the cave system. Therefore, both users have to cooperate to be able to fight the monsters and solve the riddles. The *HMD* user plays an adventurer who holds a sword which he can swing to damage monsters and teleports[2] himself through the map. The *Non-HMD* user plays a magic fairy light which floats around the *HMD* user and is the only source of light inside the pitch black cave system. The fairy is furthermore able to cast a fireball which lights up the cave and damages monsters in its way. The riddles are designed in a way that both users have to work together to be able to solve them.

The *HMD* user sees the world through the eyes of the adventurer (point of view) and the fairy is visualized as a floating light (point light and spotlight in Unity). The *Non-HMD* user has

[2] we reimplemented a form of Valves The Lab teleport for locomotion

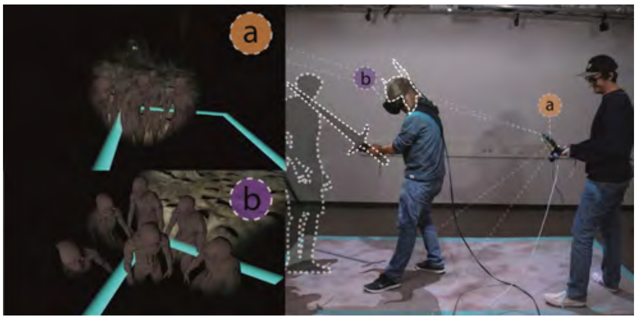

Figure 4. Two users (a: handheld view, b: HMD view) fighting monsters in the caves of *BeMyLight*. Note that the HMD user (b) only can see where the Non-HMD user (a) shines light on.

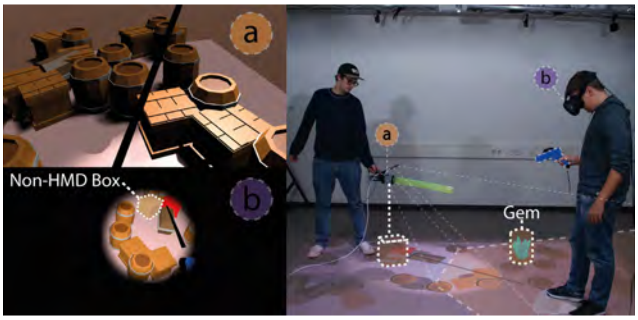

Figure 5. Two users playing SneakyBoxes and their individual views: (a) handheld (b) inside the HMD. Note that the HMD user (b) can not distinguish between a regular box and the Non-HMD box.

a top down view of the current tracking space visualized on the projection. This allows him to see the directions from which monsters are approaching or attacking the *HMD* user. He is further capable of controlling the scale of the projection (zooming) to use the projection as a map. The handheld screen is used as a "window into the world" metaphor and controls the direction of the spot light (flashlight metaphor). To further increase the dependency between both users, some information is only displayed to the fairy and some only to the adventurer, encouraging them to collaborate (e.g. "please shine some light here I think I saw something you can't see").

This basic dynamic highly encourages a form of collaboration since the *HMD* user needs a light to see monsters and the environment and the *Non-HMD* user can not explore the world on his own since only the *HMD* user can teleport. Both have an asymmetry of information (e.g. only the adventurer can see the key for the exit but the fairy has to shine light on the key to make it visible) and an asymmetry of power (e.g. the fairy knows the path through the cave system since he can see cues on the projection but only the adventurer can move both).

Competitive: Sneaky Boxes

SneakyBoxes is based on a popular children's game [64] which has different names through the world (e.g. RedLight, GreenLight in the US). *SneakyBoxes* is further highly inspired by Ruckus Ridge VR Party [19] which is one of few currently available co-located asymmetric VR games. The *HMD* user is positioned at the edge of the tracking space and uses one controller which represents a "marker" which can shoot projectiles. When looking into the tracking space the *HMD* user sees randomly positioned boxes, chests and barrels (Fig.5). The *Non-HMD* user is visualized as one of those boxes and is positioned inside the tracking space holding one controller which is mainly used for tracking his location. The goal of the *HMD* user is to find and "mark" the box which represents the *Non-HMD* user, whereby the *Non-HMD* user has to look through all the other boxes and find a randomly placed gem. All boxes are fixed in the scene and only the *Non-HMD* users' box moves when he physically moves his controller. This allows the *HMD* user to distinguish and tag the *Non-HMD* user.

To create a bigger challenge for the *HMD* user, the lights in the scene go out after approximately 10 seconds. To turn the lights back on, the *HMD* user has to turn away from the tracking space and hit a floating target behind him. This gives the *Non-HMD* user time to reposition himself and look through some of the boxes. To further exploit the physical proximity we attached an inflatable sword on the controller of the *Non-HMD* user. By hitting the *HMD* user with the inflatable sword, the lights inside the scene can be "hit out" every 15 seconds, forcing the *HMD* user to turn around and turn the lights back on. The handheld display is used as a "window" into the virtual world and the projection visualizes the tracking space (top down view of all boxes).

SneakyBoxes was designed to explore the competitive possibilities which arise from the co-located asymmetry enabled through *ShareVR*. We deliberately avoided the use of headphones for the *HMD* user, since the direction of the noise the *Non-HMD* user does is an essential part of the gameplay. We further actively decided to use a physical prop (inflatable sword) as a tool for the *Non-HMD* user to interact with the *HMD* user. We were mainly interested what implications this physicality has on the social dynamic.

Exploratory: Sandbox Application

In addition to *SneakyBoxes* and *BeMyLight*, we implemented a *SandBox* consisting of several smaller experiences which individually explore a novel aspect of the unique design space of *ShareVR*.

Soccer: The soccer application further explores the concept of high interaction asymmetry. The *Non-HMD* user uses both HTC Vive controllers and becomes the "Curator/Master" of the experience (Fig. 6 a). He can position targets inside the scene and spawn balls which he then can throw for the *HMD* user. The *HMD* user has to redirect the ball into the target using his head (header in soccer). The soccer application explores how an experience can be designed for *ShareVR* which puts the *HMD* user in a passive role and the *Non-HMD* user into an active and dominant position.

Lightsaber Duel: With the lightsaber duel we wanted to explore an interaction where the *Non-HMD* user is capable of interacting with the *HMD* user without the need for a visualization. To achieve this we mounted an inflatable light saber onto each of the HTC Vive controllers (Fig. 6 d). For the *HMD* user, we modeled a virtual lightsaber instead of the controllers which is exactly the same length resulting in a 1-to-1 mapping of the physical lightsaber and the virtual lightsaber. This allows the *Non-HMD* user to adjust his actions based on the physical location of the *HMD* user and his inflatable

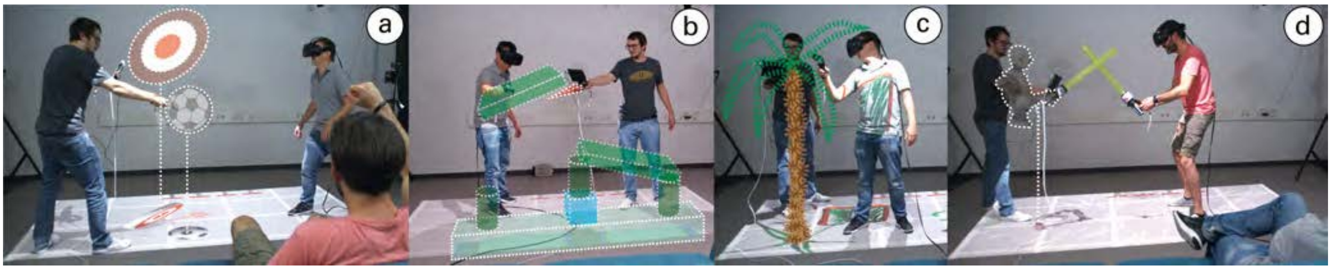

Figure 6. An overview of the individual applications with overlaid visualizations from the Sandbox: (a) throwing a ball to the HMD user in the soccer application, (b) instructing the HMD user in the puzzle application, (c) drawing a palm tree together and (d) having a lightsaber duel.

lightsaber. To represent the *Non-HMD* user inside the virtual scene, we used a robot avatar with simple inverse kinematics. The *HMD* user benefits from the high fidelity of the experience (e.g. feel the actual impact of the lightsaber).

Puzzle: The puzzle application was designed to explore the capabilities of more user involvement. Several 3D geometrical shapes are spawned around the *HMD* user with which he can interact using an HTC Vive controller (Fig. 6 b). His goal is to bring them into a certain arrangement. Only the *Non-HMD* user sees the building instructions on the projection and the handheld display on his controller. The only form of interaction between *HMD* and *Non-HMD* user is a virtual arrow attached to the *Non-HMD* user controller he can use to point at objects. The main form of communication is verbal, which includes all the potential additional users sitting on the couch. The puzzle application was designed so everyone can be involved in the experience since the building instruction is prominently visible and people on the couch can also direct actions of the *HMD* user (e.g. the red piece behind you should be a little more left).

Drawing: We implemented a drawing application to show how simple it is to extend an existing VR experience to be working with *ShareVR* and multiple users (Fig. 6 c). The basic principles are simple, both the *HMD* and *Non-HMD* user have one controller which they can use to draw with one color in midair (similar to Google's Tilt Brush [23]). The projection shows a top-down view of the tracking space (drawing space) and the handheld display works again as a "window" into the virtual world.

USER STUDY

To explore the interaction with *ShareVR* and measure the impact *ShareVR* has on the enjoyment, presence and social interaction between *HMD* and *Non-HMD* user, we conducted a user study. We compared *ShareVR* to a baseline condition consisting of a gamepad and a TV. In the baseline condition the *Non-HMD* user would sit on the couch and interact with the *HMD* user using a gamepad and a TV screen. This setup is currently used in most asymmetric co-located VR games (e.g. Ruckus Ridge VR Party [19], PlayStationVR [14]). The main difference between *ShareVR* and the *Baseline* was the shared physical space and physical engagement of the *Non-HMD* user.

Study Design

The study was conducted using a repeated measures factorial design with three independent variables. As independent variables we selected System (*ShareVR*, *Baseline*), HMD (*HMD*, *Non-HMD*), and Experience (*BeMyLight*, *SneakyBoxes*). For the *Baseline* system separate versions of *BeMyLight* and *SneakyBoxes* were created that were played with a regular gamepad instead of a tracked Vive controller. Further, smaller changes to the *Baseline* versions of games were made in order to provide a fair comparison of the systems (e.g. a button press can be used to trigger a sword hit in *SneakyBoxes*).

Independent variables were *enjoyment* measured with the post-game Game Experience Questionnaire (GEQ) [32, 31] as well as valence and arousal from the SAM questionnaire [5], *presence* measured with Slater, Usoh, and Steed's presence questionnaire [54] and *social interaction* measured using the *behavioural involvement* component of the GEQ's social presence module [32, 31]. In addition to these questionnaires we added a final comparison and asked participants to rate their enjoyment, presence and social engagement on a 7-point Likert scale.

Procedure

The study took place in a university lab that was prepared to resemble a realistic living room scenario containing a couch, a TV screen, and the play area of the HTC Vive (see Fig. 3). Participants were recruited in pairs. After a brief introduction, they played all 8 possible permutations of our independent variables (System x HMD x Experience). The order was counterbalanced using a Latin square. All play sessions were interrupted after 5 minutes in order to guarantee fair comparisons. After each play session, participants completed a questionnaire measuring their experience and additional data (e.g. visual attention). The study took on average 1.5h and participants received 10 currency.

Participants

For this study we recruited 16 participants (5 female, 11 male) with an average age of 27.63 (SD=3.181). Participants were recruited in pairs and with the premise that they have such a social connection that they feel comfortable playing with each other. They reported an average experience with VR devices of 8.76 months (SD=7.22). Their average interest in VR technology was very high (M=6.13, SD=0.62), but their intention to buy a VR HMD in the next 12 months was low (M=2.81, SD=2.04, both variables measured on 7-point Likert scales).

Results

Scores for positive experience and presence were analysed using a 2x2x2 (System x HMD x Experience) repeated-measures ANOVA. As the other variables were not normally distributed, nonparametric Aligned Rank Transform [65, 36] was applied. Figure 7 summarizes the collected data of the GEQ and SUS

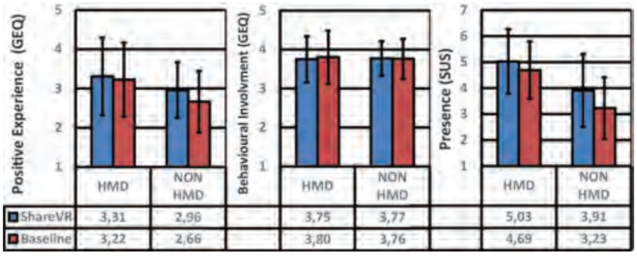

Figure 7. Averages (with standard deviation) of the positive experiences subscale (GEQ), behavioural involvement (GEQ) and presence (SUS).

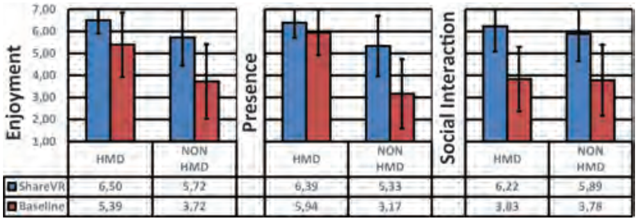

Figure 8. Averages (+/- sd) of the final questions on enjoyment ("I enjoyed using *{System}*"), presence ("I felt being in the game using *{System}*") and social interaction ("I felt engagement with the other using *{System}*").

questionnaire and Figure 8 shows an overview of the final comparison (enjoyment, presence and social interaction).

Enjoyment

The post-game GEQ consists of four components: *positive experience*, *negative experience*, *tiredness*, and *returning to reality*. *HMD* users reported a significant higher positive experience compared to *Non-HMD* players ($F(1,15)=11.573$, $p=0.004$, $r=0.660$). As expected, *Non-HMD* participants reported significantly higher scores for tiredness using *ShareVR* compared to *Baseline* ($F(1,15)=12.060$, $p=0.003$, $r=0.829$). Participants further reported significantly higher scores for *"returning to reality"* when using an *HMD* compared to *Non-HMD* ($F(1,15)=33.067$, $p < 0.001$, $r=0.668$).

Participants playing with *ShareVR* ($M=7.47$, $SD=1.01$) reported significantly higher valence scores compared to *Baseline* ($M=6.95$, $SD=0.92$) ($F(1,15)=10.952$, $p=0.005$, $r=0.650$). Additionally, using an *HMD* led to significantly higher scores for valence than without ($F(1,15)=7.213$, $p=0.017$, $r=0.570$). Furthermore, significantly higher scores of arousal were reported using *ShareVR* ($M=6.1$, $SD=1.61$) compared to *Baseline* ($M=5.36$, $SD=1.50$) ($F(1,15)=7.145$, $p=0.017$, $r=0.568$), as well as for *HMD* ($M=6.01$, $SD=1.28$) compared to *Non-HMD* (M=5.31, SD=1.60) ($F(1,15)=8.809$, $p=0.010$, $r=0.515$).

For the concluding questionnaire ("I enjoyed using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree)), a Kruskal–Wallis test revealed that ratings were significantly affected by the system ($H(3)=19.995$, $p < 0.001$). {*ShareVR* x *HMD*} was rated significantly more fun than {*Baseline* x *Non-HMD*} ($U=27.781$, $p < 0.001$). Furthermore, participants stated that they enjoyed {*ShareVR* x *Non-HMD*} significantly more than {*Baseline* x *Non-HMD*} ($U=-19.062$, $p=0.016$, adjusted significances are indicated for the Dunn-Bonferroni post-hoc tests).

Presence

Participants felt significantly more present (SUS) using *ShareVR* (M=4.5, SD=1.3) compared to the *Baseline* system (M=4.0, SD=1.1) ($F(1,15)=10.024$, $p=0.006$, $r=0.633$) as well as while using an *HMD* (M=4.9, SD=1.2) compared to *Non-HMD* (M=3.6, SD=1.3) ($F(1,15)=52.745$, $p < 0.001$, $r=0.882$).

In the concluding questionnaire ("I felt being in the game using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree)), we found a significant effect of the system used ($H(3)=29.240$, $p < 0.001$). {*Baseline* x *Non-HMD*} was rated significantly lower than {*Baseline* x *HMD*} ($U=25.844$, $p < 0.001$) as well as {*ShareVR* x *HMD*} ($U=32.812$, $p < 0.001$) and also lower as {*ShareVR* x *Non-HMD*} ($U=-20.469$, $p=0.008$).

Social Interaction

Regarding social interaction, *SneakyBoxes* led to significantly higher scores for the *behavioural involvement* component of the GEQ social presence module compared to *BeMyLight* ($F(1,15)=6.877$, $p=0.019$, $r=0.560$).

In the concluding questionnaire ("I felt engagement with the other using *{System}*", Likert scale from 1 (= strongly disagree) to 7 (= strongly agree), the system significantly affected the reported social engagement ($H=26.942$, $p < 0.001$). {*ShareVR* x *HMD*} was rated significantly more engaging than {*Baseline* x *Non-HMD*} ($U=25.656$, $p < 0.001$) as well as {*Baseline* x *HMD*} (U=-24,781, $p=0.001$. Further, ratings show that {*ShareVR* x *Non-HMD*} was significantly more socially engaging than {*Baseline* x *Non-HMD*}, $U=22.094$, $p=0.004$) and {*Baseline* x *HMD*} ($U=-21.219$, $p=0.006$).

Additional Observations

Between each gaming session, we asked *Non-HMD* participants to state their visual attention on a 7-point Likert scale (7=most attention) between player, projection, tracked display and mirrored view (TV). Playing *BeMyLight*, participants reported a high focus on the handheld display (M=5.63) and a moderate on the projection (M=3.81). However, playing *SneakyBoxes* the focus switched to high on the projection (M=6.75) and low on the handheld display (M=1.37). This indicates the importance of alternative visualizations between experiences. Finally, participants were asked if they would want to have a system like *ShareVR* at home. Results show that *ShareVR* was highly positively perceived, $M=6.31$, $SD=0.873$ (measured on a 7-point Likert scale). This is also confirmed by the qualitative feedback we received, where participants actively stated that they want the system and asked about availability.

Discussion

The goal of our study was to examine the impact of *ShareVR* on enjoyment, presence and social interaction for *HMD* and *Non-HMD* players in comparison to the *Baseline* condition. Even if no significant differences were found for the GEQ questionnaire, in the final comparison we found a significantly higher rating of enjoyment using *ShareVR* for *Non-HMD* users. Even if not significant, we were surprised that overall participants rated using (*Non-HMD* x *ShareVR*) slightly higher than (*HMD* x *Baseline*). Furthermore, *ShareVR* did elicit more positive emotions, higher valence and higher arousal which can be both linked to positive player experience [37, 40]. These findings further correlate with our observations and qualitative feedback of participants *"I think both games should be further developed ... they are really fun"*. These findings confirm that with *ShareVR* we could increase enjoyment for *Non-HMD* users for co-located asymmetric experiences in VR.

Similar to enjoyment, no significant differences were found using the GEQ behavioural involvement subscale. This can be explained with the strong effect each individual game had. The GEQ measures how much a player's actions depend on the other player. This was in fact very different for both games which might have had more impact on participants than the system used. However, when rating only the systems regarding how engaged they felt with the other player, participants reported a significantly higher rating using *ShareVR* for both *HMD* and *Non-HMD* players. We explain these findings with the aspect of the shared physical space. When wearing an *HMD*, users are visually isolated from the space around them. Even if playing with another user located on the couch, not actually seeing the other reduces the experience to something similar to online gaming. This was similarly mentioned by participant 2: *"The projection helps to be part of the experience but using the controller felt more like playing online since you don't share any physical space"*. This further shows how *ShareVR* not only positively impacts the overall experiences for *Non-HMD* users, but also for *HMD* users.

Compared to the *Baseline*, *ShareVR* overall significantly increased the presence of the *Non-HMD* user measured by the SUS questionnaire and in the final comparison. Interestingly, in the final comparison participants rated (*Non-HMD* x *ShareVR*) only slightly lower than playing with an *HMD* in the *Baseline*. This suggests that *ShareVR* did in fact improve presence over the *Baseline*. Further, it might even be possible that the system can elicit presence in the *Non-HMD* player that is comparable to playing with an *HMD*.

Summarized, we found that *ShareVR* did improve enjoyment, social engagement and presence over the *Baseline* condition. Unsurprisingly, we found several effects of playing as *HMD* or *Non-HMD* player as well as effects from the individual experience. This suggests that although *ShareVR* showed promising results, experiences have to be specifically designed for the co-located asymmetric approach. Therefore, the next section is going to focus on the design space of *ShareVR*.

DESIGN SPACE AND GUIDELINES

To gain a deeper understanding of the design space, its implications and to be able to derive design considerations we conducted a second smaller exploratory study with two groups of 3 participants (n=6). The main goal was to further expose participants with the system and observe behavior and interactions using *ShareVR*.

Exploratory Study

We invited two groups of three participants each into our lab and let them experience an approximately 30-40 minutes long gaming session with the *SandBox* application (see Video Figure). Participants were again recruited as a group with a strong social bond and enjoying playing together. The first recruited group were three male HCI researchers (age: M=31, SD=3.56) and the second group consisted of three male VR enthusiasts (age: M=28.7, SD=0.47). After a short introduction into the control mechanics of *ShareVR*, participants were free to explore each application and had no further restrictions. Our only request was that each participant should experience each possible role (*HMD*, *Non-HMD*, and observer on the couch). Afterwards, we conducted a semi structured group interview on aspects of *ShareVR*, each individual role and the experienced gameplay. During the study three of the authors were present taking notes about observed behaviour and the group discussion afterwards. After both sessions the three authors had one shared coding session (thematic analysis) in which notes were compared and themes identified and discussed.

Additional Findings

The overall findings were directly integrated into the *Design Guidelines* and the *Design Space*. In this part we will briefly give insights on findings not covered by these two sections but seemed noteworthy to us.

Non-HMD users tend to form a certain bond with the observer since they both experience a similar perception of the virtual world and the *HMD* user. Participants often teased the *HMD* user with his inability of seeing the physical space (e.g. poke with a not tracked inflated sword). Nevertheless, *HMD* participants reported feeling safe when immersed to not bump into things and walk out of the tracking space since two *Non-HMD* users were around watching out for them. This shows that both accepted the teasing as part of the individual game without a negative influence on the whole experience. We further observed several occasions where the *HMD* user made mistakes resulting in a group laughter that started simultaneously. This shows that everyone was fully capable of understanding what is going on in the scene. Participants further reported they felt as they were entertaining the observer on the couch and that this feeling could potentially be higher if there would be several people on the couch. In terms of experiences, participants reported they had fun in every role but would prefer games which are not based on activities they can experience in real life (e.g. soccer).

Design Space

In the following we will present four variables of the design space we identified as essential factors and explain their implications. This categorization is based on insights we gained from actively implementing and testing *ShareVR* and both user studies.

Asymmetry in Visualization and Interaction: The main variable of every experience implemented for *ShareVR* is the level of asymmetry in visualization and interaction. The starting situation already has a strong asymmetry in terms of visualization, since the *HMD* user has stereoscopic perception of the virtual world and the *Non-HMD* user gets his understanding of the world through flat displays. Both have inherent advantages and disadvantages and should be considered when designing interactions for both users (see first guideline). The goal here is not to bring both on the same level but to leverage the advantages of each individual visualization. When done right, a high degree of asymmetry can lead to two entirely different experiences which results in a high replay value.

Dependency: The level of dependency in an experience controls how much coordination is necessary between *HMD* and *Non-HMD* user to achieve a goal. Dependency must be controlled and balanced in collaborative and competitive games. A too high degree of dependency will slow down the overall gameplay but a too low dependency results in both players having two separate experiences. Each user should contribute something to the games progress by leveraging the advantage of their modality in a non-artificial form (not a "job creation scheme"). In *BeMyLight*, we used several iterations to balance the dependency in such a way that both users felt they played a vital role for the progress of the game.

Power Distribution: Throughout our work with *ShareVR* we observed that the power level one has over the other user or the virtual environment highly influenced the enjoyment of the experience. The more I can impact the virtual environment or the other user (e.g. hit him with a sword) the more I enjoy the experience. It is hereby not necessary to fully balance the power between both users since users mostly wanted to have both experiences and will switch roles eventually. Throughout our study participants were always aware of this switch of roles and therefore restrained themselves from over using their power. However, for collaborative experiences the power level should be equally balanced so that both users have a feeling of playing a vital role in the progress of the game.

Physical Proximity: Each individual experience implicitly controls the allocation of the tracking space between *HMD* and *Non-HMD* users. If the physical proximity is embedded as part of the virtual experience, it can potentially lead to an increase of presence for the *HMD* user. However, if incoherent information is perceived acoustically or tactile it can break the presence and immersion for the *HMD* user (see fourth guideline). In general we observed that participants enjoyed a high level of physical involvement and were able to coordinate their position inside the tracking space easily. Here, it is a great advantage to have a *Non-HMD* user inside the tracking space since he was mostly in charge of the coordination.

Guidelines

From both studies and our own experience we derived four guidelines which we consider essential when designing for asymmetric co-located VR experiences such as *ShareVR*.

Leverage Asymmetry: Instead of assigning irrelevant tasks to the *Non-HMD* user to create any form of dependence and force collaboration, leverage the inherent advantages of each role. Offer isometric or orthogonal visualizations to the *Non-HMD* user since those help to perceive spatial relations in the virtual scene and allow the *Non-HMD* user to engage with further observers on the couch.

Design for the whole living room: Create visualizations not only for the engaged *Non-HMD* user but keep in mind that more participants can be around. We actively decided to use an orthographic camera for the projection and not a view dependent which could easily be adapted for the position of the *Non-HMD* user but only work from his perspective. Include as many observing roles as you wish in your application but keep in mind that *Non-HMD* users may tend to team up with observers against the *HMD* user.

Physical engagement is fun in moderation: Throughout our whole experience with *ShareVR* participants (both *HMD* and *Non-HMD* users) highly valued the ability to physically engage with each other. Introduce physical props which you can either mount onto one controller or track otherwise. Those can highly increase the presence of the *HMD* user. But be careful of physical engagement which is not visualized/transparent to the *HMD* user since this can result in discomfort.

Design for mixed reality in shared physical space: Keep in mind that your players are both located in the same physical space but perceive two different realities. Even if you do not visualize the movement and actions of your *Non-HMD* user, the *HMD* user will hear him interact in the surrounding. In some cases this can break the presence and immersion of the *HMD* user (e.g. hearing footsteps while his character is visually floating), but when considered in the game design can enhance the experience for both (e.g. physical props positioned by the *Non-HMD* user inside the tracking space).

CONCLUSION

In this work we presented *ShareVR*, a proof-of-concept prototype using floor projection and mobile displays in combination with positional tracking to visualize the virtual world for *Non-HMD* users and enable them to interact with the *HMD* user and become part of the VR experience. We designed and implemented *ShareVR* based on the feedback of early adopters (n=48) of VR technology. We implemented three experiences for *ShareVR* which each explore a different aspect of the novel design space. In a next step we conducted a user study (n=16) comparing *ShareVR* to a baseline condition (TV + gamepad) showing its advantage in terms of enjoyment, presence and social interaction. In a final step we conducted a short exploratory evaluation (n=6) which we used to help us explore the design space of *ShareVR* and give insights and guidelines for designers of co-located asymmetric VR experiences.

Limitations and Future Work

To entirely cover the gradient of engagement, an *HMD* to *HMD* interaction has to be modeled as well. We focused on asymmetric VR collaboration since it is likely to occur in the early days of consumer VR and appropriate concepts could benefit social acceptance. Furthermore, our findings are currently based on two or three people playing together. More research with a higher number of observers has to be conducted to fully understand the social dynamics happening in this asymmetric setup.

In the future, we are planning to extend *ShareVR* to incorporate more players and further integrate an additional *HMD*. This allows us to fully investigate the novel design space of asymmetric co-located virtual reality experiences and their impact on social dynamics.

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REFERENCES

1. Hrvoje Benko, Edward W Ishak, and Steven Feiner. 2004. Collaborative mixed reality visualization of an archaeological excavation. In *Mixed and Augmented Reality, 2004. ISMAR 2004. Third IEEE and ACM International Symposium on*. IEEE, 132–140.

2. Mark Billinghurst and Hirokazu Kato. 2002. Collaborative Augmented Reality. *Commun. ACM* 45, 7 (July 2002), 64–70. DOI:http://dx.doi.org/10.1145/514236.514265

3. Mark Billinghurst, Ivan Poupyrev, Hirokazu Kato, and Richard May. 2000. Mixing realities in shared space: An augmented reality interface for collaborative computing. In *Multimedia and Expo, 2000. ICME 2000. 2000 IEEE International Conference on*, Vol. 3. IEEE, 1641–1644.

4. Doug A. Bowman and Ryan P. McMahan. 2007. Virtual Reality: How Much Immersion Is Enough? *Computer* 40, 7 (July 2007), 36–43. DOI: http://dx.doi.org/10.1109/MC.2007.257

5. Margaret M Bradley and Peter J Lang. 1994. Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry* 25, 1 (1994), 49–59.

6. Raffaello Brondi, Leila Alem, Giovanni Avveduto, Claudia Faita, Marcello Carrozzino, Franco Tecchia, and Massimo Bergamasco. 2015. *Evaluating the Impact of Highly Immersive Technologies and Natural Interaction on Player Engagement and Flow Experience in Games*. Springer International Publishing, Cham, 169–181. DOI: http://dx.doi.org/10.1007/978-3-319-24589-8_13

7. Andreas Butz, Tobias Hollerer, Steven Feiner, Blair MacIntyre, and Clifford Beshers. 1999. Enveloping users and computers in a collaborative 3D augmented reality. In *Augmented Reality, 1999.(IWAR'99) Proceedings. 2nd IEEE and ACM International Workshop on*. IEEE, 35–44.

8. Christer Carlsson and Olof Hagsand. 1993. DIVE A multi-user virtual reality system. In *Virtual Reality Annual International Symposium, 1993., 1993 IEEE*. IEEE, 394–400.

9. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic Turk: A Motion Platform Based on People. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3463–3472. DOI: http://dx.doi.org/10.1145/2556288.2557101

10. Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 417–426. DOI: http://dx.doi.org/10.1145/2807442.2807463

11. Elizabeth F Churchill and Dave Snowdon. 1998. Collaborative virtual environments: an introductory review of issues and systems. *Virtual Reality* 3, 1 (1998), 3–15.

12. K. Coninx, F. Van Reeth, and E. Flerackers. 1997. A Hybrid 2D / 3D User Interface for Immersive Object Modeling. In *Proceedings of the 1997 Conference on Computer Graphics International (CGI '97)*. IEEE Computer Society, Washington, DC, USA, 47–. http://dl.acm.org/citation.cfm?id=792756.792856

13. HTC Corporation. 2016a. HTC Vive. https://www.htcvive.com. (2016). Accessed: 2016-09-07.

14. Sony Corporation. 2016b. PlayStation VR. https://www.playstation.com/en-us/explore/playstation-vr/. (2016). Accessed: 2016-09-19.

15. N. J. Dedual, O. Oda, and S. K. Feiner. 2011. Creating hybrid user interfaces with a 2D multi-touch tabletop and a 3D see-through head-worn display. In *2011 10th IEEE International Symposium on Mixed and Augmented Reality*. 231–232. DOI: http://dx.doi.org/10.1109/ISMAR.2011.6092391

16. Die Gute Fabrik. 2016. *Johann Sebastian Joust*. Game [PlayStation 4]. (2016). Die Gute Fabrik, Copenhagen, DK.

17. Thierry Duval and Cédric Fleury. 2009. An asymmetric 2d pointer/3d ray for 3d interaction within collaborative virtual environments. In *Proceedings of the 14th international Conference on 3D Web Technology*. ACM, 33–41.

18. Kevin Fan, Liwei Chan, Daiya Kato, Kouta Minamizawa, and Masahiko Inami. 2016. VR Planet: Interface for Meta-view and Feet Interaction of VR Contents. In *ACM SIGGRAPH 2016 VR Village (SIGGRAPH '16)*. ACM, New York, NY, USA, Article 24, 2 pages. DOI: http://dx.doi.org/10.1145/2929490.2931001

19. Foreign VR. 2016. *Ruckus Ridge VR Party*. Game [HTC Vive]. (2016). Foreign VR, Palo Alto, USA.

20. Brian Gajadhar, Yvonne de Kort, and Wijnand IJsselsteijn. 2008. Influence of Social Setting on Player Experience of Digital Games. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. ACM, New York, NY, USA, 3099–3104. DOI: http://dx.doi.org/10.1145/1358628.1358814

21. Yue Gao and Regan Mandryk. 2012. The Acute Cognitive Benefits of Casual Exergame Play. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 1863–1872. DOI: http://dx.doi.org/10.1145/2207676.2208323

22. Chaim Gartenberg. 2015. The future of gaming is lonely (and online only). (June 2015). http://www.theverge.com/2015/6/25/8844073/goodbye-local-multiplayer-we-will-miss-you-and-the-goldeneye-days-of-yore Accessed: 2016-09-07.

23. Google. 2016. Tilt Brush. https://www.tiltbrush.com/. (2016). Accessed: 2016-09-07.

24. Jan Gugenheimer. 2016. Nomadic Virtual Reality: Exploring New Interaction Concepts for Mobile Virtual Reality Head-Mounted Displays. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 9–12. DOI: http://dx.doi.org/10.1145/2984751.2984783

25. Jan Gugenheimer, David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. 2016a. FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 49–60. DOI: http://dx.doi.org/10.1145/2984511.2984576

26. Jan Gugenheimer, Frank Honold, Dennis Wolf, Felix Schüssel, Julian Seifert, Michael Weber, and Enrico Rukzio. 2016b. How Companion-Technology can Enhance a Multi-Screen Television Experience: A Test Bed for Adaptive Multimodal Interaction in Domestic Environments. *KI - Künstliche Intelligenz* 30, 1 (2016), 37–44. DOI:http://dx.doi.org/10.1007/s13218-015-0395-7

27. Jan Gugenheimer, Dennis Wolf, Eythor R. Eiriksson, Pattie Maes, and Enrico Rukzio. 2016c. GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 227–232. DOI: http://dx.doi.org/10.1145/2984511.2984535

28. Jan Gugenheimer, Dennis Wolf, Gabriel Haas, Sebastian Krebs, and Enrico Rukzio. 2016d. SwiVRChair: A Motorized Swivel Chair to Nudge Users' Orientation for 360 Degree Storytelling in Virtual Reality. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 1996–2000. DOI: http://dx.doi.org/10.1145/2858036.2858040

29. Roland Holm, Erwin Stauder, Roland Wagner, Markus Priglinger, and Jens Volkert. 2002. A combined immersive and desktop authoring tool for virtual environments. In *Virtual Reality, 2002. Proceedings. IEEE*. IEEE, 93–100.

30. Hikaru Ibayashi, Yuta Sugiura, Daisuke Sakamoto, Natsuki Miyata, Mitsunori Tada, Takashi Okuma, Takeshi Kurata, Masaaki Mochimaru, and Takeo Igarashi. 2015. Dollhouse VR: a multi-view, multi-user collaborative design workspace with VR technology. In *SIGGRAPH Asia 2015 Emerging Technologies*. ACM, 8.

31. WA IJsselsteijn, YAW De Kort, and K Poels. 2013. The Game Experience Questionnaire: Development of a self-report measure to assess the psychological impact of digital games. (2013).

32. Wijnand IJsselsteijn, Yvonne De Kort, Karolien Poels, Audrius Jurgelionis, and Francesco Bellotti. 2007. Characterising and measuring user experiences in digital games. In *International conference on advances in computer entertainment technology*, Vol. 2. 27.

33. Robert Johansen. 1988. *Groupware: Computer support for business teams*. The Free Press.

34. Brett Jones, Rajinder Sodhi, Michael Murdock, Ravish Mehra, Hrvoje Benko, Andrew Wilson, Eyal Ofek, Blair MacIntyre, Nikunj Raghuvanshi, and Lior Shapira. 2014. RoomAlive: Magical Experiences Enabled by Scalable, Adaptive Projector-camera Units. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology (UIST '14)*. ACM, New York, NY, USA, 637–644. DOI:http://dx.doi.org/10.1145/2642918.2647383

35. Brett R. Jones, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2013. IllumiRoom: Peripheral Projected Illusions for Interactive Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 869–878. DOI: http://dx.doi.org/10.1145/2470654.2466112

36. Matthew Kay and Jacob O. Wobbrock. 2016. *ARTool: Aligned Rank Transform for Nonparametric Factorial ANOVAs*. https://github.com/mjskay/ARTool R package version 0.10.2.

37. J Matias Kivikangas, Guillaume Chanel, Ben Cowley, Inger Ekman, Mikko Salminen, Simo Järvelä, and Niklas Ravaja. 2011. A review of the use of psychophysiological methods in game research. *Journal of Gaming & Virtual Worlds* 3, 3 (2011), 181–199.

38. Pascal Knierim, Markus Funk, Thomas Kosch, Anton Fedosov, Tamara Müller, Benjamin Schopf, Marc Weise, and Albrecht Schmidt. 2016. UbiBeam++: Augmenting Interactive Projection with Head-Mounted Displays. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction (NordiCHI '16)*. ACM, New York, NY, USA, Article 112, 6 pages. DOI: http://dx.doi.org/10.1145/2971485.2996747

39. Siân E. Lindley, James Le Couteur, and Nadia L. Berthouze. 2008. Stirring Up Experience Through Movement in Game Play: Effects on Engagement and Social Behaviour. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 511–514. DOI: http://dx.doi.org/10.1145/1357054.1357136

40. Regan L. Mandryk and M. Stella Atkins. 2007. A Fuzzy Physiological Approach for Continuously Modeling Emotion During Interaction with Play Technologies. *Int. J. Hum.-Comput. Stud.* 65, 4 (April 2007), 329–347. DOI: http://dx.doi.org/10.1016/j.ijhcs.2006.11.011

41. Joe Marshall, Conor Linehan, and Adrian Hazzard. 2016. Designing brutal multiplayer video games. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 2669–2680.

42. Florian Mueller, Stefan Agamanolis, and Rosalind Picard. 2003. Exertion Interfaces: Sports over a Distance for Social Bonding and Fun. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 561–568. DOI: http://dx.doi.org/10.1145/642611.642709

43. Haruo Noma, Tsutomu Miyasato, and Fumio Kishino. 1996. A Palmtop Display for Dextrous Manipulation with Haptic Sensation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '96)*. ACM, New York, NY, USA, 126–133. DOI: http://dx.doi.org/10.1145/238386.238454

44. Ohan Oda, Carmine Elvezio, Mengu Sukan, Steven Feiner, and Barbara Tversky. 2015. Virtual Replicas for Remote

Assistance in Virtual and Augmented Reality. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 405–415. DOI: http://dx.doi.org/10.1145/2807442.2807497

45. Jauvane C Oliveira, Xiaojun Shen, and Nicolas D Georganas. 2000. Collaborative virtual environment for industrial training and e-commerce. *IEEE VRTS* 288 (2000).

46. Mat Ombler. 2015. Why Split-Screen Gaming is Dying (And Why We Should Mourn It). http://www.highsnobiety.com/2015/09/09/split-screen-gaming-dead/. (Sept. 2015). Accessed: 2016-09-15.

47. Oliver Otto, Dave Roberts, and Robin Wolff. 2006. A review on effective closely-coupled collaboration using immersive CVE's. In *Proceedings of the 2006 ACM international conference on Virtual reality continuum and its applications*. ACM, 145–154.

48. Robin Parker. 2014. Opinion: Is Split-Screen Dead? http://www.godisageek.com/2014/06/opinion-split-screen-dead/. (June 2014). Accessed: 2016-09-15.

49. Danakorn Nincarean Eh Phon, Mohamad Bilal Ali, and Noor Dayana Abd Halim. 2014. Collaborative Augmented Reality in Education: A Review. In *Teaching and Learning in Computing and Engineering (LaTiCE), 2014 International Conference on*. IEEE, 78–83.

50. Ramesh Raskar, Jeroen van Baar, Paul Beardsley, Thomas Willwacher, Srinivas Rao, and Clifton Forlines. 2003. iLamps: Geometrically Aware and Self-configuring Projectors. *ACM Trans. Graph.* 22, 3 (July 2003), 809–818. DOI:http://dx.doi.org/10.1145/882262.882349

51. Ramesh Raskar, Greg Welch, and Henry Fuchs. 1998. Spatially augmented reality. In *First IEEE Workshop on Augmented Reality (IWAR'98)*. Citeseer, 11–20.

52. SCE Japan Studio. 2016. *The Playroom VR*. Game [PS4/PS VR]. (2016). SCCE, London, UK.

53. Dieter Schmalstieg, Anton Fuhrmann, Gerd Hesina, Zsolt Szalavári, L Miguel Encarnaçao, Michael Gervautz, and Werner Purgathofer. 2002. The studierstube augmented reality project. *Presence: Teleoperators and Virtual Environments* 11, 1 (2002), 33–54.

54. Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of presence in virtual environments. *Presence: Teleoperators & Virtual Environments* 3, 2 (1994), 130–144.

55. Aaron Stafford, Wayne Piekarski, and Bruce Thomas. 2006. Implementation of God-like Interaction Techniques for Supporting Collaboration Between Outdoor AR and Indoor Tabletop Users. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '06)*. IEEE Computer Society, Washington, DC, USA, 165–172. DOI: http://dx.doi.org/10.1109/ISMAR.2006.297809

56. Steel Crate Games. 2015. *Keep Talking And Nobody Explodes*. Game [HTC Vive]. (2015). Steel Crate Games, Ottawa, CA.

57. Team Future. 2016. *Black Hat Cooperative*. Game [HTC Vive]. (2016). Team Future, Boston, USA.

58. TomorrowTodayLabs. 2016. NewtonVR. https://github.com/TomorrowTodayLabs/NewtonVR. (2016). Accessed: 2016-09-07.

59. Valve. 2016. Valve Data Suggests Developers Should Seriously Consider Room-Scale VR. http://uploadvr.com/steamvr-usage-data-room-scale/. (2016). Accessed: 2016-09-07.

60. VALVE. 2016. Virtual Reality - SteamVR featuring the HTC Vive. https://www.youtube.com/watch?v=qYfNzhLXYGc. (2016). Accessed: 2016-09-07.

61. Alladi Venkatesh, Erik Kruse, and Eric Chuan-Fong Shih. 2003. The networked home: an analysis of current developments and future trends. *Cognition, Technology & Work* 5, 1 (2003), 23–32. DOI: http://dx.doi.org/10.1007/s10111-002-0113-8

62. Amy Voida, Sheelagh Carpendale, and Saul Greenberg. 2010. The individual and the group in console gaming. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work*. ACM, 371–380.

63. Amy Voida and Saul Greenberg. 2009. Wii all play: the console game as a computational meeting place. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1559–1568.

64. Wikipedia. 2016. Statues (game). https://en.wikipedia.org/wiki/Statues_(game). (2016). Accessed: 2016-09-07.

65. Jacob O Wobbrock, Leah Findlater, Darren Gergle, and James J Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 143–146.

FACEDISPLAY

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FaceDisplay: Towards Asymmetric Multi-User Interaction for Nomadic Virtual Reality

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Figure 1. FaceDisplay is a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back (a-c). This allows people in the surrounding to perceive the virtual world through the displays and interact with the HMD user either through touch (e) or gestures (d).

ABSTRACT
Mobile VR HMDs enable scenarios where they are being used in public, excluding all the people in the surrounding (*Non-HMD Users*) and reducing them to be sole bystanders. We present *FaceDisplay*, a modified VR HMD consisting of three touch sensitive displays and a depth camera attached to its back. People in the surrounding can perceive the virtual world through the displays and interact with the HMD user via touch or gestures. To further explore the design space of *FaceDisplay*, we implemented three applications (*FruitSlicer*, *SpaceFace* and *Conductor*) each presenting different sets of aspects of the asymmetric co-located interaction (e.g. gestures vs touch). We conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications and showing a high level of enjoyment and social interaction with and without an HMD. Based on the findings we derive design considerations for asymmetric co-located VR applications and argue that VR HMDs are currently designed having only the HMD user in mind but should also include *Non-HMD Users*.

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INTRODUCTION
Mobile VR (Virtual Reality) HMDs (Head-mounted Displays) are currently mostly based on smartphones and a case outfitted with lenses (e.g. Samsung GearVR, Google Daydream). A recent development focuses on mobile VR HMDs which are not based on smartphones but offer an untethered headset with embedded hardware, inside-out tracking and some form of input capabilities (e.g. Intel Alloy). Both these device types enable the interaction scenario of Nomadic VR [18, 29], where users can immerse themselves inside a virtual world wherever and whenever they wish.

This nomadic interaction scenario comes with several challenges such as the unknown and uninstrumented environment [18]. Since current mobile VR HMDs are designed exclusively for the wearing user (*HMD User*), every other person in this environment

(*Non-HMD User*) is excluded and reduced to be a sole bystander [20]. This further leads to a complete isolation of the *HMD User* and could potentially lead to less social acceptance of the technology [40]. We identified two main challenges for this specific problem: *(1) How can we visualize parts of the virtual environment to Non-HMD users and (2) how can we enable a form of interaction between HMD and Non-HMD user inside the uninstrumented environment*. The overarching goal is to reduce *exclusion* for the *Non-HMD User* and reduce the *isolation* of the *HMD User* and enable a cohesive and enjoyable experience for both.

We propose *FaceDisplay*, a concept for a mobile VR HMD that is designed having the *HMD User* and the environment with all other people (e.g. friends, family and strangers) in mind. *FaceDisplay* consists of three displays arranged around the backside of the HMD to function as a visualization for the *Non-HMD User* (Fig. 1). To further enable a form of interaction, we attached a Leap Motion facing outwards allowing for gestural interaction. Additionally, we used capacitive touch displays to enable a second form of interaction by actually touching the HMD. We implemented three example applications (*FruitSlicer*, *SpaceFace* and *Conductor*) to show how different visualization and interaction metaphors can be used inside each application.

To investigate what specific interaction implications and social dynamics arise from such a concept, we conducted an exploratory user study (n=16). We recruited participants in pairs and let them interact with two applications (*SpaceFace* and *Conductor*) each as the *HMD User* and *Non-HMD User*, focusing on enjoyment, presence, social interaction and discomfort. We found that *FaceDisplay* enables the *Non-HMD User* to understand what the *HMD User* is doing and results in an equally enjoyable experience for *HMD User* and *Non-HMD User*. Additionally, we found a strong imbalance of the power level, putting the *Non-HMD User* in a more dominant position and derive design considerations based on our insights for co-located asymmetric virtual reality. We conclude by proposing a change in design perspective for future mobile VR HMDs. We argue that mobile VR HMDs should be designed having not only the wearer in mind (*HMD User*) but also the surrounding and everyone part of it. To truly overcome the future challenges for mobile VR, the negative aspect of isolation of the *HMD User* should be reduced.

The main contributions of this work are:

- The concept of *FaceDisplay* and the broader vision of designing mobile VR HMDs not only for the wearer, but also including people in the surrounding.
- A prototypical implementation of such a VR HMD and three example applications – each presenting multiple aspects of this novel design space.
- Results of an exploratory evaluation (n=16) explaining the implications such a design has on enjoyment, presence, social interaction and discomfort and deriving design considerations from these findings.

RELATED WORK

Our work is strongly influenced by the fields of *Mobile/Nomadic VR*, *Asymmetric Interaction/Collaboration for VR/AR* and *Asymmetric Co-located Gaming*.

Mobile/Nomadic VR

Since 90s' VR technology was not mature enough, the field of mobile and nomadic VR only became relevant in the more recent rise of VR around the 2010s. By combining a piece of cardboard, two lenses and a smartphone a simple VR viewer can be realised [4]. Google created Cardboard VR, one of the currently most spread mobile VR HMDs [17]. Following this trend, more smartphone-based (e.g. Samsung GearVR, Google Daydream) and self-contained (e.g. VIVE Focus) mobile VR HMDs were presented as consumer devices. This spread of VR technology into everyday consumer devices created the demand for HCI researchers to understand and design interaction concepts suitable for the nomadic VR usage scenario [18].

Several projects explored different input techniques designed for uninstrumented environments that work solely by modifying the HMD and without additional accessories [45, 28, 19, 31]. Smus et al. presented in [45] the original implementation of the magnetic input concept used throughout most first generation Cardboard VR viewers. Kent Lyons further enhanced this approach by extending the input from a binary selection to 2D input capabilities by applying magnetic field sensing to track the magnet on the side of the enclosure [31]. Instead of enhancing the magnet based interaction on the Google Cardboard, Kato et al. presented an modified Cardboard viewer that uses capacitive stripes attached to the case and running onto the normally unreachable touchscreen of the smartphone. This allowed users to create custom interaction interfaces and further extended the input space from the side of the HMD onto the backside of the HMD [28]. This form of back-of-device interaction for mobile VR was further explored and presented by Gugenheimer et al. [19].

A variety of research on mobile VR is conducted within the field of haptic feedback. Having the constraints of an uninstrumented environment and no accessories, researchers focused either on ungrounded haptic feedback systems [21, 41] or tried to leverage the feedback in the environment [23, 34]. Pohl et al. presented with "See what I see" a display attached to the back of a mobile HMD [40]. This work is conceptually closes to *FaceDisplay* but focuses only on the visualization and not the interaction and presents no user study. Most recently Chan et al. presented with "FrontFace" a single screen attached to the back of a mobile VR HMD to lower the communication barrier between *HMD User* and *Non-HMD User* [8]. The technical setup is similar to *FaceDisplay* but the focus lies on enabling a form of communication rather than letting the *Non-HMD User* be part of the experience (lower exclusion) or allow the *Non-HMD User* to interact with the virtual world. *FaceDisplay* on the other hand focuses more on exploring the design space of the interaction and uncover the underlying social dynamics occurring from this co-located asymmetric scenario. Misawa et al. presented a similar technical setup having a display attached to an HMD [35]. However, the focus was on enhancing telepresence and not in the field of virtual reality. To the best of our knowledge, *FaceDisplay* is the first concept enabling co-located asymmetric interaction for mobile virtual reality.

Asymmetric Interaction/Collaboration for VR/AR

Since augmented reality faces a similar challenge as virtual reality in terms of asymmetric interaction, a variety of approaches were presented. Collaborative augmented reality [2, 39] aims to enable collaboration and interaction between people using AR technology and further incorporates work with asymmetric setups (e.g. different visualization and different input capabilities [7, 46]). The Studierstube [43] by Schmalstieg et al. and Shared Space [2, 3] by Billinghurst et al., are systems presenting a variety of interaction and visualization concepts for co-located augmented reality collaboration.

Similar approaches for asymmetric collaboration were also explored in the field of virtual reality [12, 36, 11, 25, 20]. Duval et al. presented an asymmetric 2D/3D interaction approach which allowed *Non-HMD Users* to interact with users sitting at a PC [12], leveraging the advantage of each individual representation (2D and 3D). Oda et al. presented another asymmetric interaction between a remote user and a local user wearing an AR *HMD* [36]. In a user study, the remote user had to explain a specific task to the local user either through a 2D interface or a VR *HMD*. The results show that local users understood faster when the remote users actually demonstrated the task wearing a VR *HMD* in comparison to writing annotations with a 2D interface. Also closely relevant to our work were projects exploring an asymmetric "god-like interaction" with the goal to enable people build worlds together [11, 24]. *HMD Users* could collaboratively create virtual environments with users at a PC. A similar approach was shown by Ibayashi et al. with DollhouseVR [25]. Most recently Gugenheimer et al. presented ShareVR, a projection-based concept that enables asymmetric co-located collaboration between a *HMD User* and *Non-HMD Users*. *FaceDisplay* follows a similar motivation but needs a different solution to satisfy the restrictions (e.g. no instrumentation, no accessories) of the nomadic interaction scenario. Additionally, we expected different social dynamics than with ShareVR due to our on body touch interaction and more extreme level of asymmetry.

Asymmetric Co-located Gaming

Despite the overall popularity of online multiplayer, co-located multiplayer games are still highly appreciated by many players [15, 37, 38] and researched by the scientific community [50]. Gajadhar et al. even showed that players experience a higher positive affect and less tension in a co-located than in a mediated setting or against a computer [14]. Since symmetric co-located settings are currently difficult to achieve for VR, developers tend to build asymmetric setups such as *Black Hat Cooperative*, *Ruckus Ridge VR Party*, *Playroom VR* and *Keep Talking And Nobody Explodes*. The *Non-HMD User* is either provided with an additional controller [42, 13], mouse and keyboard [49] or relying solely on verbal communication [47]. Recently, Sajjadi et al. presented *Maze Commander*, a collaborative asymmetric game in that one player uses a VR HMD while the other interacts using Sifteo Cubes. Although game experience did not differ between both interaction methods, players generally did enjoy the asymmetric game play. Furthermore, Harris et al. presented additional guidelines for leveraging asymmetries in multiplayer games which we partially incorporated in some of our applications [22].

Although the aforementioned games all feature local multiplayer for VR, most game mechanics would still function if the games were implemented online and players had voice communication. For *FaceDisplay*, we strongly focus on the shared physical space and the resulting physical interaction (particularly in *SpaceFace*). Playing in co-located settings has been shown to have positive effects on players [14] and having physical engagement was further shown to increase enjoyment and social interaction. Lindley et al. found that an input device leveraging natural body movements elicits higher social interaction and engagement compared to a classic gamepad [30]. Similar results were found by Brondi et al. who showed beneficial effects of body movement on player engagement and flow for a collaborative game in a virtual environment [6]. Recently, Marshall et al. [32] showed how aspects of games can encourage physicality in an extreme manner and derived guidelines for such games.

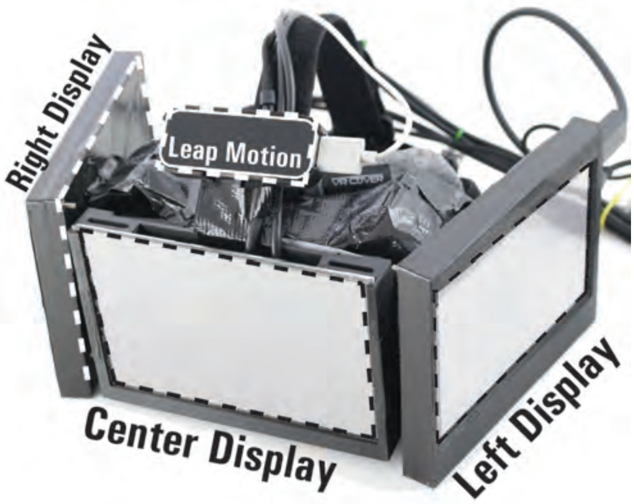

Figure 2. The hardware prototype of FaceDisplay, consisting of three touchscreens and a Leap Motion depth camera attached to the back and the sides of an Oculus Rift DK2

FACEDISPLAY

We designed *FaceDisplay* for the Nomadic VR interaction scenario [18], wherein an *HMD User* picks a location in which he wants to immerse himself and stays rather stationary[1] for the duration of the experience. This location can be either a public environment (e.g. subway) or a private one (e.g. at a friends home). Such a nomadic form of gaming was also recently presented by Nintendo with the Nintendo Switch. We consider the Switch as a nomadic device which was designed having the environment in mind, since its modular controllers (Nintendo Joy-Cons) allow users to spontaneously include people in the environment into their gaming experience.

The big difference between the Switch and the *FaceDisplay* concept is the asymmetry of the interaction. Since a single VR HMD can only offer the stereoscopic view to one user (*HMD User*) we had to come up with a different visualization concept for the *Non-HMD User*. We also had to create interaction concepts that work without additional accessories (nomadic context) and allow for different levels of engagement (socially familiar *Non-HMD User* and unknown *Non-HMD User*). We strive to cover the whole gradient of familiarity/engagement, since a mobile VR HMD could potentially be used in a public transport (unknown *Non-HMD User*) or at a friends home (socially familiar *Non-HMD User*). Both

[1] With rather stationary we mean a sitting or standing position with only little positional movement

scenarios would result in a vastly different form of interaction (e.g. observing by the unknown *Non-HMD User* vs playing with the socially familiar *Non-HMD User*) but should both be included to cover the wide range of engagement. Our goal was to allow for a similarly easy extension from single user to multi-user interaction as provided by the Nintendo Switch. However, similarly to ShareVR [20], our goal was not to create an identical experience, but embrace the asymmetry and allow the *Non-HMD User* to fully understand the virtual environment of the *HMD User*, allow the *Non-HMD User* to engage in an interaction and further enable a gradient of engagement from observing to participating.

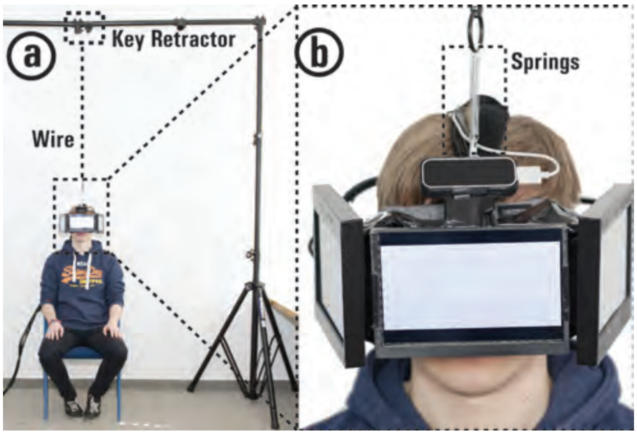

Figure 3. The technical setup used to reduce the weight of the FaceDisplay prototype, using a key retractor (a) and a pair of springs (b).

Technical Implementation

Our prototype consists of an Oculus Rift DK2, three touch displays and a Leap Motion on the back facing outwards (Fig. 2). We used two 7 inch Waveshare[2] screens for the sides (resolution: 1024x600) and a 7 inch ChalkBoard Electronics display on the back (resolution: 1280x800). The two screens on the side are attached with an angle of 75 degree to be still partially visible when looking straight onto the HMD. Each display is capable of capacitive multi-touch. The displays are attached using 3D-printed cases that match the shape of an Oculus Rift DK2. The Leap Motion controller was tilted by approximately 45 degrees, facing slightly upwards (Fig. 2). This allowed us to mainly see the hands of the *Non-HMD User* and a further away background (e.g. ceiling). This was necessary to increase the tracking accuracy since the Leap Motion has to conduct figure-ground separation of the depth image and fails if something (e.g. human torso) is at approximately equal distance as the hands. The overall weight of *FaceDisplay* is approximately 1.5kg. To compensate for the weight, we constructed a ceiling attachment similar to Sutherland's *Sword of Damocles* [48]. Our attachment consists of a 1.5m Key-Bak retractable keyholder, connecting the HMD and the keyholder through springs (Fig. 3 b). Furthermore, we hot glued additional padding around the nose and lens area. This allowed us to reduce the perceived weight, while keeping the freedom of looking around. We argue that in the future (and by a professional company) the prototype can be build significantly lighter to avoid this kind of apparatus.

[2]Each Waveshare screen was flashed with a custom firmware by Yannic Staudt – https://k16c.eu

The entire software was developed using Unity3D. The engine offers the *multi-display* feature which allows to open several rendering windows that can be later arranged onto each individual screen. Since the *multi-display* feature is currently under development, it does not offer touch capabilities for each window. Therefore, we implemented a second fully transparent application lying on top of our main application detecting the touches and sending them through a socket connection to the main application.

Interaction Concepts

When designing interaction concepts for *FaceDisplay* we had to initially realize the severity of the asymmetry of our setup. Similarly to the ShareVR concept [20], we created a highly asymmetric setup where a *HMD User* should be able to interact with an *Non-HMD User*. However, the big difference to ShareVR is that with *FaceDisplay*, the interface for visualization and interaction is physically attached to the *HMD User*. This results in the unique constellation that the interaction interface itself is not rigid but also moving around and every physical contact with the interface is perceived by the *HMD User*. During the design we kept our two goals in mind to reduce *exclusion* for the *Non-HMD User* and reduce the *isolation* of the *HMD User*.

Visualization: We incorporated this insight in the visualisation by using more than just one screen (in contrast to [40, 8]). Our initial prototype that consisted only of one display on the back led to the problem that users outside of the HMD had to follow the fast and unpredictable head rotations of the immersed user to be able to see the screen. The slightly angled side screens allow the *Non-HMD User* to be able to still see what is happening when the *HMD User* rotates left and right. This arrangement of displays allowed us to experiment with different visualization metaphors. The content on the screens displays the virtual environment mostly using a "window" metaphor. This should overall reduce the *exclusion*.

Interaction: Our goal for the interaction concept was that a wide gradient of engagement is covered (from observing to fully engaging Fig. 4) [51]. Observing was covered by offering the three screens as a visualization.

To be able to initiate a form of interaction from the outside, we implemented hand tracking for the *Non-HMD User* by attaching a Leap Motion to the backside of the HMD. This allowed us to visualize the hands of the *Non-HMD User* to the *HMD User*. This further enabled simple gestures (e.g. waving, pointing) as form of communication and interaction between the two users. Being able to know that a *Non-HMD User* is in the surrounding and where he is located should further help the *HMD User* to reduce the isolation and allows to further incorporate content outside of the HMD to the *HMD User* [33].

For the final level of engagement, we wanted to create a form of interaction that is capable of fast-paced gameplay and enables a strong social perception between *HMD User* and *Non-HMD User* to counter the isolation of the *HMD User*. We focused on FaceTouch [19] as an interaction technique since it fits the nomadic scenario and allows for physical contact (reduce isolation [20]). Both users interact with the virtual world by using the touch screens. Based on findings of Gugenheimer et al. on touch interactions for mobile VR HMDs, we decided to mainly use the screen on the back as a form of input for the *HMD User* [19]. The *Non-HMD*

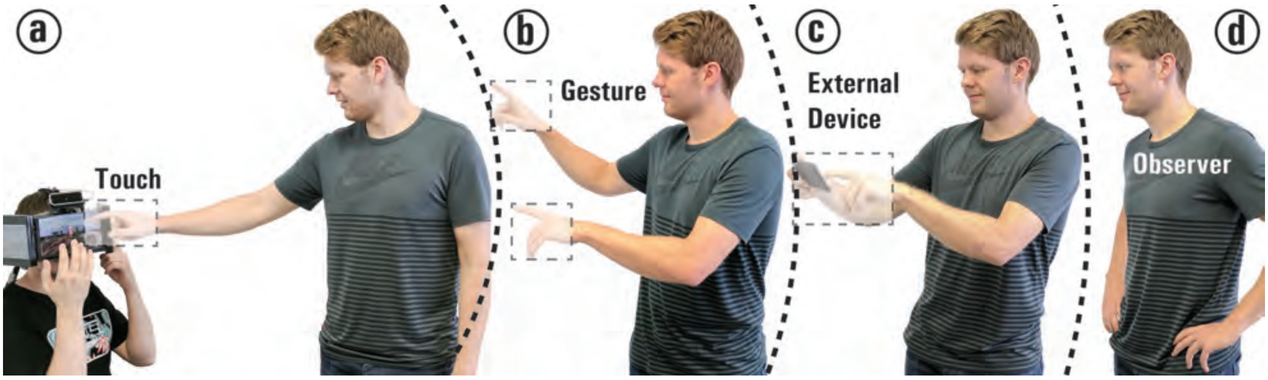

Figure 4. Interaction Gradient for *FaceDisplay*. Starting from the most engaged a: touch to b:gesture, c: external device and d: observing.

User influences the virtual environment by touching the corresponding point on any of the touch displays. This allows the *HMD User* to locate which of the attached screens was touched and further opens the interaction space to more physical forms of engagement (e.g. jousting hands or blocking head rotation). This additional physical contact can potentially increase the level of immersion for the *HMD User* [20, 9, 10]. We were particularly interested in how this form of interaction is perceived by both parties (*HMD User* and *Non-HMD User*) and which social dynamics arise from this (see section *Evaluation* for more details on these aspects).

Design Space/Interaction Gradient

Displaying the content of an immersed *HMD User* to the outside world, opens up a new and wide design space for different forms of interaction. Figure 4 shows the interaction/engagement gradient starting from the most engaged (touch) to the least engaged (observing). The displays on the *HMD* allow for multiple observers to understand the virtual environment and the current interaction state. The two outer most interaction concepts (observing and external device) additionally allow for multi-user interaction. One can imagine a scenario where several *Non-HMD User* observer the current virtual environment and interact with the *HMD* user via their own smartphone (e.g. spawn fruits in fruit slicer). Having the screens additionally on the HMD allows for observers be still part of the interaction.

In our user study, we focused on two concepts where the Non-HMD user is going to be in the immediate surrounding of the HMD user and use voice, gesture and touch as form of interaction so the HMD user can feel the presence (reduce feeling of *isolation*) of a second entity (Figure 4 a,b). Therefore, we did not explore interactions from slightly safer distances which lead to interactions that might as well be remote over the Internet. We also used touch deliberately to explore how far can we go with our 'close/intimate' interaction and tried to leverage the touch impact as active haptic feedback for the HMD user (e.g. SpaceFace: impact of an asteroid not only visual but also haptic). We wanted to explore what social dynamics arise when we bring the *Non-HMD User* close to the *HMD User* and design an interaction which is more physical. However, we do acknowledge that the smartphone is also an interesting form of input for *FaceDisplay* and should be considered for future research but was not in the scope of this work. Focusing on interactions from a slightly safer distance (Figure 4 c,d) enables additional applications without the need to battle exclusion and isolation (e.g. *Non-HMD User* guides *HMD User* through an application using gestures or an external smartphone).

APPLICATIONS

A general application scenario of *FaceDisplay* is the visualization of VR content to the environment (*Non-HMD Users*). It is important to realize that the content displayed on the screens should be under full control of the *HMD User* to still be able to keep a certain level of privacy and security. In its simplest form, this content visualization could be the title of the VR application or the face (or an avatar of the face) of the *HMD User* to try to conceal the fact that the user is wearing an HMD [16]. Since we were particularly interested in how to enable interaction between *HMD User* and *Non-HMD User* in a nomadic context, we focused on designing applications which offer a form of interaction by and between both users. In the following we will present three example applications (*FruitSlicer*, *SpaceFace* and *Conductor*) and discuss their design rationales.

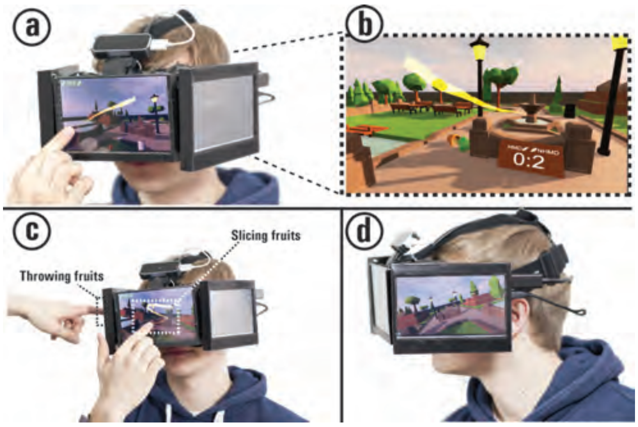

Figure 5. The FruitSlicer application with its outside view (a), inside view (b), interaction concepts (c) and visualization metaphor (d).

Fruit Slicer

FruitSlicer is a VR adaption of the popular Fruit Ninja game. The *HMD User* is located inside a virtual environment and different sorts of fruits and vegetables are thrown towards him. To collect points the *HMD User* has to slice all the fruits and vegetables and avoid slicing the bombs. The *Non-HMD User* can decide

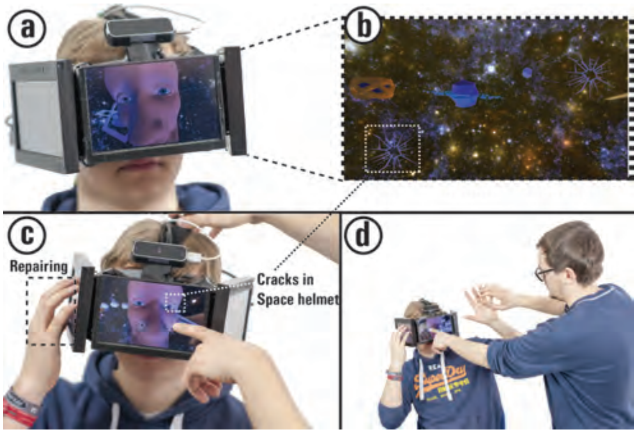

Figure 6. The SpaceFace application and its outside view (a), inside view (b) interaction and visualization concept (c) and physical interaction scenario (d).

at which frequency and what location the next object is going to spawn and "throw" them towards the *HMD User*. When the *HMD User* misses a fruit or slices a bomb, he loses one point and for every rightfully sliced fruit or vegetable, he gains a point. The first to get 10 points wins.

The *HMD User* sees the world from a first person perspective and can generate slices inside the virtual world by touching and moving his finger on the corresponding location on the center display (Fig. 5 a). This form of interaction was shown to be suitable for mobile VR HMDs [19]. The *Non-HMD User* is looking from a far distance into the virtual world and can see a visualization of the *HMD User* and the spawning objects and slices (Fig. 5 c). By touching one of the screens the *Non-HMD User* spawns a random object (fruit/vegetable/bomb) and throws it towards the *HMD User*.

We decided not to use a one to one mapping of the screen positioning and the camera positioning inside the virtual environment (i.e. no window metaphor). This allowed us to explore whether people would be able to understand the less intuitive visualization concept and how they would perceive it. We conducted a preliminary evaluation with two of the authors and gave several demonstrations to members and visitors of our institution. We mainly used *FruitSlicer* to gain an initial understanding of the interaction and social dynamics arising from it. We did not use *FruitSlicer* in the final evaluation but used it to gain knowledge for designing the two games used in the study (*SpaceFace* and *Conductor*).

Space Face

In *SpaceFace*, the *HMD User* is playing an astronaut who escaped an exploding spaceship and is now floating in outer space waiting to get rescued by another spaceship. The *Non-HMD User* is taking the role of the vicious space/cosmos and wants the astronaut to die before he gets rescued. In order to achieve this goal, the *Non-HMD User* can launch small comets at the glass of the astronaut's helmet. These comets generate an impact, sound (cracking of glass) and can be seen as a crack in the display by *HMD User* and *Non-HMD User* (Fig 6 b,c). Each screen can take up to 10 hits before it breaks and the astronaut suffocates. To avoid this, the astronaut is capable of repairing a screen by applying a special foam over a certain time period. After 2.5 minutes the astronaut gets rescued and wins the round.

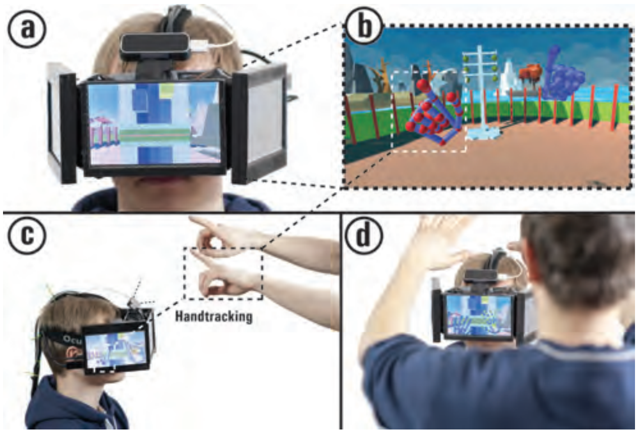

Figure 7. The Conductor application showing its outside view (a), inside view (b), hand tracking region (c) and interaction scenario (d).

The *HMD User* sees the environment from the first-person perspective of the astronaut. The *Non-HMD User* is looking directly onto the *HMD User* and the attached displays are functioning as a "window" metaphor into the virtual world. The *FaceDisplay* prototype itself is representing the space helmet. The external screens show an androgynous avatar starting from nose to hairline to create the impression of the *Non-HMD User* user looking at a virtual representation of the *HMD User* (Fig. 6 a). Additionally, the *Non-HMD User* can look past the avatar and see parts of the space environment. The *Non-HMD User* can create the comets/cracks by touching any location on one of the three screens. This further generates a physical impact simulating the impact of a comet on the space helmet. To avoid constant attacking we implemented a cool down of approx. 1 second. The *HMD User* can repair a screen by holding down 5 fingers for approx. 1-6 seconds, depending on the amount of damage (Fig. 6 c).

We designed *SpaceFace* to explore what implications on social dynamics the physical interaction brings. The fact that the *Non-HMD User* is not visualized to the *HMD User* results in unpredicted impacts on the HMD. We further balanced the game so that the when played perfectly by both users, the *Non-HMD User* would always lose. This should further encourage the *Non-HMD User* to start using physical means to win the round (e.g. pushing away or even blocking the hand of the *HMD User*).

Conductor

Conductor is a VR adaption of a rhythm game such as Guitar Hero or AudioShield [1]. The *HMD User* is placed inside a virtual equalizer and listens to a music track (Fig. 7 b). Similarly to Guitar Hero, the music is also represented as blocks on three lanes and the *HMD User* has to tap one of each lane respectively to the rhythm and the visual indication (Figure 7 a). However, this block representation is only visible to the *Non-HMD User* who has to communicate (conduct) their timing and location using his hands (Fig. 7 c,d). The *HMD User* can only see the virtual hands of the *Non-HMD User* inside his virtual equalizer environment (Fig. 7 a). Every time the *HMD User* selects the correct lane with the correct timing, the score and the song volume increase and the visual equalizer starts to spark. Every missed block results in a decrease of volume and no points. To avoid frustration the thresholds of acceptance of a correct block are selected generously (approximately 0.5 seconds of tolerance). The goal of the game is to achieve the biggest high score.

The *Non-HMD User* sees the same block representation of the music track with indicators when to play which lane on each display. Furthermore, the hands are visualized so the *Non-HMD User* can notice occasional tracking imperfections. The *HMD User* sees the virtual equalizer and the hands of the *Non-HMD User* instructing him what lane to select and when. The lanes can only be selected by the *HMD User* through touching anywhere and with an arbitrary amount of fingers on one of the screens (left, center, right).

We intentionally designed a high level of asymmetry in the visualization and interaction of *Conductor* to explore how this impacts the already highly asymmetric setup. We further focused only on gestural interaction between *HMD User* and *Non-HMD User*. We were particularly interested if the *HMD User* perceives the virtual hands as part of the *Non-HMD User* or if they will be perceived as a computer generated part of the environment. Additionally, we wanted to explore how people incorporate the gestures inside their communication.

EVALUATION

To be able to understand the social and interaction dynamics arising from such a highly asymmetric scenario, we conducted an exploratory user study. We consider our evaluation exploratory since we chose a study method which is a mix between a quantitative and qualitative approach aimed towards better understanding the interaction and social dynamics arising from *FaceDisplay*.

Our main research questions were: *(1) What social and interaction dynamics arise from FaceDisplay, (2) how do people perceive the physical interaction as HMD User and Non-HMD User and (3) how do the roles (HMD User and Non-HMD User) and interaction concepts (touch and gesture) impact enjoyment, presence and emotional state*.

Study Design

The quantitative part of the study was conducted using a repeated measures factorial design with two independent variables *Role* (*HMD User*, *Non-HMD User*) and *Experience* (*SpaceFace*, *Conductor*). We designed each experience around the underlying form of interaction (gesture, touch). For the touch interaction we implemented a competitive game (*SpaceFace*) and for the gestures a collaborative one (*Conductor*).

Independent variables were *enjoyment* measured with the in-game Game Experience Questionnaire (GEQ) [27, 26] as well as dominance, valence and arousal from the SAM questionnaire [5], *presence* measured with Slater, Usoh, and Steed's presence questionnaire [44] and *social interaction* measured using the *social presence* module of the GEQ [27, 26]. In addition to these questionnaires, we added own questions asking about comfort of the interaction, agency of the interaction and understanding of the interaction. For the qualitative part of the study we recorded every session and two of the authors watched the footage and conducted an initial coding about observed behaviour. Afterwards, the two authors had one shared coding session (thematic analysis) in which notes were compared and themes identified and discussed.

The study took place inside a lab at our institution consisting of our technical setup (Fig. 3) and enough space so the *Non-HMD User* was capable to walk around the *HMD User* (Fig. 10). Participants were recruited in pairs being comfortable playing with each other. After a brief introduction they played each experience (*SpaceFace*, *Conductor*) and changed roles (*HMD User*, *Non-HMD User*) after 5 minutes (total of 4 x 5 minutes of pure play time). The experience and roles were both counterbalanced. After each role change, participants filled out the aforementioned questionnaires. Participants were instructed that they should behave as if they just bought *FaceDisplay* and visited their friend to try the new device. Therefore, no restrictions in terms of behaviour were given and participants were allowed to interact as they wish. The study took on average 1h and participants received 10 Euro.

Participants

We recruited 16 participants (4 female) in pairs so they would be comfortable playing with each other. The average age was 27.94 years (SD=2.94). Participants reported an average experience with VR devices of 17.6 months (range: 1 to 48) and a self-reported interest in VR technology of 6.3 (SD=0.7) on a 7-point Likert scale.

Quantitative Results

Scores from the GEQ ans SUS were analyzed using a 2x2 (*Role* x *Experience*) repeated-measures ANOVA with Bonferroni correction. All other single score items (SAM and own questions) were analyzed using a Wilcoxon signed-rank test. Figure 8 summarizes the scores of the GEQ, SUS and SAM and Figure 9 shows responses for our own questions. The focus in the following analysis is mainly on the *Role* as a variable. All the comparisons of the *Experience* are later combined with qualitative findings to abstract from the underlying application and highlight more general findings.

Enjoyment: The in-game GEQ consists of several components measuring each on a scale from 0 to 4. We used the positive affect component to get an overall enjoyment. There were no significant differences between *Role* and *Experience*. However, the average scores were all around 2.6 (scale: 0 to 4) indicating an overall enjoyment of the interaction. This is also in line with our single question *"I enjoyed using FaceDisplay"* that got in each condition (Role x Experience) on average a score of over 5 on a 7-point Likert scale. Therefore, we conclude that both experiences and both roles resulted in enjoyable play sessions.

Social Interaction: The social presence module of the GEQ consists of three subscales (empathy, negative feelings and behavioral involvement). Participants reported significantly ($F(1,15) = 7.899, p < .05$) more empathy playing *Conductor* (M=2.70, SD=0.52) than playing *SpaceFace* (M=2.03, SD=0.75) and significantly ($F(1,15) = 6.881, p < .05$) more empathy playing as the *Non-HMD User* (M=2.5, SD=0.65) than playing as the *HMD User* (M=2.25, SD=0.77). Participants also reported significantly ($F(1,15) = 41.472, p < .001$) more negative feelings playing *SpaceFace* (M=2.04, SD=0.95) than *Conductor* (M=1.01, SD=0.52). It is interesting that these negative feelings did not reflect negatively on the enjoyment.

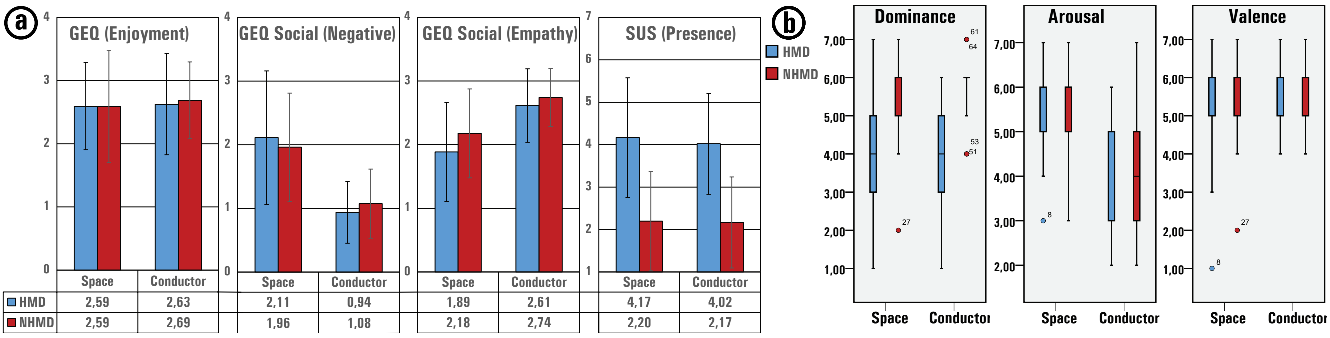

Figure 8. The distribution of our data from (a) the GEQ In-Game Module, GEQ Social Module, the SUS and (b) the SAM questionnaire. All bar charts showing the mean with standard deviation.

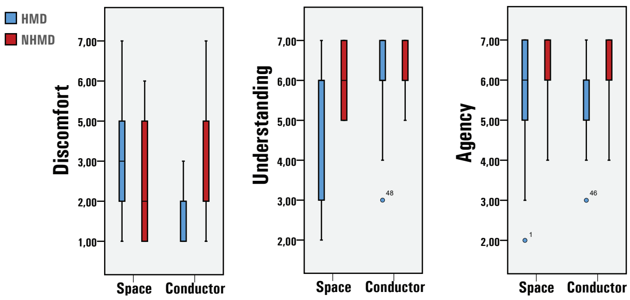

Figure 9. Boxplots of our own questions on discomfort *"I felt uncomfortable touching/being touched/gesturing/being gestured at"*, understanding *"I was always able to understand the current state of the game"* and agency *"I was always able to influence the outcome of the game"*

Presence: Participants reported feeling significantly ($F(1, 15) = 38.399, p < .001$) more present (SUS) in the experience being the *HMD User* (M=4.09, SD=1.30) than being the *Non-HMD User* (M=2.18, SD=1,12). There were no significant differences between the experiences.

Emotional State: For *SpaceFace* ($Z = -2.567, p < .01$) and for *Conductor* ($Z = -2.939, p < .01$) participants reported a significantly higher level of dominance being the *Non-HMD User* (Mdn=6) than being the *HMD User* (Mdn=4). Participants also reported a significantly higher level of arousal as *HMD User* ($Z = -2.811, p < .01$) and *Non-HMD User* ($Z = -2.979, p < .01$) playing *SpaceFace* (Mdn=5.5) than *Conductor* (Mdn=4). There were no significant differences in terms of valence.

Discomfort, Agency and Understanding: For the *Conductor*, participants reported a significantly ($Z = -3.219, p < .001$) higher level of discomfort (*"I felt uncomfortable touching/being touched/gesturing/being gestured at"*) of the interaction as *Non-HMD User* (Mdn=2) than as the *HMD User* (Mdn=1). As the *HMD User*, participants reported a significantly ($Z = -3.103, p < .01$) higher level of discomfort playing *SpaceFace* (Mdn=3) than playing *Conductor* (Mdn=1). This was expected, since the touch interaction of *SpaceFace* is far more intrusive than the gestural interaction in *Conductor*. For *SpaceFace*, participants also reported a significantly higher level of agency (*"I was always able to influence the outcome of the game"*) being the *Non-HMD User* (Mdn=7) than being the *HMD User* (Mdn=6). For *SpaceFace*, participants reported a significantly ($Z = -2.555, p < .01$) higher level of understanding (*"I was always able to understand the current state of the game"*) being the *Non-HMD User* (Mdn=6) than being the *HMD User* (Mdn=5.5).

Qualitative Feedback and Observations

Based on the coding of the video footage, qualitative feedback of the participants after the study and our own experience with *FaceDisplay* we derived the following social and interaction dynamics. Since those dynamics were highly different for each experience, we will present our observations for each individual experience.

SpaceFace had a bigger variety of different interaction dynamics in comparison to *Conductor* (Figure 10). Both participants (*HMD User* and *Non-HMD User*) were often in constant motion and at the end of a round were often times exhausted. Couples (two in our sample) tended to have an overall more intimate form of interaction (e.g. hugging, tickling). After the game pace increased, the *Non-HMD User* often times started to ignore the content on the screens and only focused on the actions of the *HMD User* and used the screens only as a form of input. *Non-HMD Users* often used the whole physical space around the *HMD User* and gained a level of advantage by not giving away their location and sneaking up and around to the *HMD User*. One participant reported after the study that he even felt bad abusing this level of power. The *HMD User* on the other hand, had to constantly repair his space helmet (hold 5 fingers to one screen) with one hand and used the other hand to either locate and repel the *Non-HMD User* or repair a second screen. Physical interactions (e.g. stretching feet, grabbing hand, waving arms) were often times initiated by the *HMD User* to estimate the location of the *Non-HMD User* around them. Overall, the level of power asymmetry (due to the game design and due to the role) resulted in highly different gaming experiences for *HMD User* and *Non-HMD User*.

When playing *Conductor*, participants had a more or less similar procedure. At the start participants negotiated the gestures they want to use for the directions (left, right and center) and the *HMD User* communicated his vision and tracking boundaries. When each song started, the *Non-HMD User* focused strongly on the "score sheet" while the *HMD User* was sitting mostly still, trying to hit each note. Both (*HMD User* and *Non-HMD User*) were spending the whole experience in almost the same posture (*HMD User*: facing towards the hands, *Non-HMD User*: standing right in front of the *HMD User*). *Non-HMD Users* often mentioned

Figure 10. A variety of physical interaction poses participants used during the study emphasizing the vast possibilities of physical interaction arising from SpaceFace: (a) *The Kraken*: The *Non-HMD User* abused his power and wraps around the *HMD User* to restrict his motions. (b) *The Leg-press*: the *HMD User* utilizes his legs to either find or push the *Non-HMD User* away. (d) *The Hedgehog:* the *HMD User* rolls in like a hedgehog to hide from the attacks.

a certain level of fatigue holding their arms up over the duration of one play session and came up with coping mechanisms (e.g. conducting with one hand and supporting with the other). Since gestures were occupied indicating game-relevant actions, the main form of communication between the participants happened verbally. Similarly to *SpaceFace*, the *Non-HMD User* had a more dominant role but was perceived as having the more "responsible" role. When one note was missed or falsely selected, the *HMD User* often tended to blame the *Non-HMD User* since he was considered "the one in charge". Overall, the *Non-HMD User* had again a higher level of power but in the collaborative context this power was not abused but resulted in responsibility (*Non-HMD Users* often adapted to the *HMD Users*).

Combining these qualitative observations with the quantitative measures we found the following dynamics between *HMD User* and *Non-HMD User*. The *HMD User* had a higher understanding and control over the virtual world, while the *Non-HMD User* had a higher understanding and control of the real world. Using *FaceDisplay*, we allowed both users to have a certain level of understanding and control of the other users environment. Having the control over the real environment pushes the *Non-HMD User* in the role where he has more dominance over the physical body of the *HMD User* but also more responsibility that no physical harm occurs. Being the *HMD User*, we found that people enjoyed the additional haptic feedback from the outside and the fact that they were able to share a VR experience with someone in the surrounding, but needed a high level of trust in the *Non-HMD User*.

DISCUSSION

The goal of our study was to understand: *(1) What social and interaction dynamics arise from* FaceDisplay*, (2) how do people perceive the physical interaction as* HMD User *and* Non-HMD User *and (3) how do the roles (*HMD User *and* Non-HMD User*) and interaction concepts (touch and gesture) impact enjoyment, presence and emotional state*.

(1) Social and interaction dynamics: We found that the concept of *FaceDisplay* resulted in a highly imbalanced power level between *HMD User* and *Non-HMD User* (see SAM:Dominance, GEQ:empathy/negative feelings). The *Non-HMD User* can either abuse this (e.g. *SpaceFace*) or ends up with a higher level of responsibility (e.g. *Conductor*). This power level arises from the fact that the *Non-HMD User* can now see the virtual environment and the *HMD User*, whereas the *HMD User* only sees the *Non-HMD User* when he decides to show himself. This asymmetry of power could potentially be abused and impair the experience of the *HMD User*. However, since this form of interaction would only occur within a certain social familiarity, the *Non-HMD User* constantly balanced this out, resulting in a high level of enjoyment for both users (see GEQ, SAM:Valence).

(2) Impact of physical interaction: The physical interaction was overall used by the *HMD User* to somehow balance out the power level. When asked directly about the level of discomfort when touching the screen or being touched, participants reported a significantly higher level of discomfort compared to the gestural interaction (see Fig 9). However, when looking at the level of enjoyment (see GEQ, SAM:Valence) participants accepted this discomfort as part of the experience (impact of a comet on the helmet) and were less concerned being "touched" due to their social connection to the *Non-HMD User*. Despite being unconventional at first sight, we argue that touch interaction for *FaceDisplay* can lead to an immersive and enjoyable experience when played with a closely familiar partner.

(3) Enjoyment, presence and emotion: Overall, the majority of participants reported they had fun during the study and generally liked both game concepts. Since our goal was to include the *Non-HMD User* into the virtual environment and experience of the *HMD User*, we consider these high levels of enjoyment and presence to be a positive outcome. The *Non-HMD User* had an even higher level of agency of the interaction and a higher level of understanding of the virtual environment (see Fig. 9). The different interaction approaches (touch and gestures) had no

significant impact on the experience and can therefore both be used according to the envisioned experience.

Our overall goal was to include the *Non-HMD User* into the experience of the *HMD User* and to break out of the isolation current VR HMDs force upon the *HMD User*. This has been partially tried already through the concept of "social VR" where an *HMD User* can experience games and videos with other *HMD Users* online. We argue that for the nomadic VR scenario this must be also done for *Non-HMD Users* in the surrounding. This could potentially break the isolation *HMD Users* experience when using VR HMDs with friends and family in the surrounding. Therefore, HMDs should not only be designed having the *HMD User* in mind but should also include all people (*Non-HMD Users*) in the environment.

DESIGN CONSIDERATIONS/INSIGHTS

The following design considerations and insights are derived from the observations during our study, user feedback and our experience demonstrating *FaceDisplay* on several occasions.

Comfort and Safety. We found that touch on the screen is perceived as part of the experience when it is synchronized with events inside the virtual environment (e.g. crack in screen). However, game designs including heavy movements can results in too strongly perceived touch impacts on the *HMD User*. Having an unpredictably moving user could also result in safety hazards for the *Non-HMD User*. We observed that the *Non-HMD User* takes the responsible role of "protecting" the *HMD User* and therefore we never had an incident during our studies or demos. Nevertheless, experiences involving heavy movement should be played using an alternative input such as gestures or remote displays (Fig. 4 b,c).

Responsibility and Dominance. Since the *HMD User* is exposed to the impact from outside and is automatically in a less dominant role (see SAM score of results) fitting game designs can be selected to make this asymmetry part of the experience (e.g. *Conductor*). Embracing this asymmetry and using it as part of the narrative, results in experiences that feel more tailored towards the scenario and interaction. Similar to [20], we suggest to embed this asymmetry inside the game design to create novel types of experiences.

Physical Interaction. The physical interaction on the screen can be embedded inside the VR experience to generate haptic feedback for the *HMD User*. When embedded smoothly (e.g. *SpaceFace* impact of asteroids) it increases the immersion of the *HMD User* and results in a more enjoyable experience. However, due to the strong dominance asymmetry an over usage can lead to a negative experience since the *HMD User* feels exposed to the surrounding. We observed this in several scenarios where multiple users played the outside part in *SpaceFace*, resulting in an even stronger outside dominance and a quite claustrophobic experience. This could potentially be used in strong horror experiences or psychological experiments but goes beyond the entertainment scenario.

Exposure to Outside Observers. Sitting practically 'blindfolded' in front of one or several users lead to a highly exposed perspective of the *HMD User*. We actively created a friendly environment (only interaction with close friends) where this feeling is not negatively amplified. *HMD Users* were mostly capable to perceive outside users based on sounds, voices and motion. However, this effect can also be used as part of a story narrative (e.g. being monitored, stalked) to increase the emotions of the experience. Overall, designers should be aware of the fact that the *HMD User* often feels observed due to the head mounted displays.

CONCLUSION

In this work, we presented the design and implementation of *FaceDisplay*, a mobile VR HMD prototype consisting of three touch sensitive displays and a depth camera attached to its back. *FaceDisplay* enables people in the surrounding to perceive the virtual world through the displays and interact with the *HMD User* via touch or gestures. We presented three applications (*FruitSlicer*, *SpaceFace* and *Conductor*), each focusing on one specific aspect of the asymmetric co-located interaction. We further conducted an exploratory user study (n=16), observing pairs of people experiencing two of the applications. Our results showed that *FaceDisplay* was able to let the *Non-HMD User* perceive and interact with the *HMD User* but resulted also in a high level of dominance and responsibility of the *Non-HMD User* over the *HMD User*. We argue that VR HMDs are currently designed having only the HMD user in mind but should also include all the people in the environment to break out of the current isolation an *HMD User* experiences when using VR HMDs.

Limitations and Future Work

The applications we implemented only outline a small subset of all possibilities arising from the *FaceDisplay* concept. We also tailored our applications around specific forms of interaction to create an overall enjoyable experience. It is therefore difficult to distinguish between the impact of the experience and the interaction on the measurements. That is why we did not follow a standard comparative study design, but had a more exploratory approach also including codings of the observations of the interaction. Since our goal was to reduce isolation and exclusion, which both currently mainly occur in social settings with entertainment applications (e.g games, movies), we argue that within this entertainment scenario our findings are more generalizable.

In the future we are planning to explore each individual form of interaction and its impact on the experience. We also plan to extend *FaceDisplay* to incorporate not only one *Non-HMD User* but create experiences where multiple *Non-HMD Users* can interact with one or multiple *HMD Users*.

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REFERENCES

1. Audiosurf LLC. 2017. Audioshield: The VR Music Game for Your Entire Music Collection. Game [HTC Vive], `http://audio-shield.com/`. (2017). Accessed: 2017-04-02.
2. Mark Billinghurst and Hirokazu Kato. 2002. Collaborative Augmented Reality. *Commun. ACM* 45, 7 (July 2002), 64–70. DOI: `http://dx.doi.org/10.1145/514236.514265`
3. Mark Billinghurst, Ivan Poupyrev, Hirokazu Kato, and Richard May. 2000. Mixing Realities in Shared Space: An

Augmented Reality Interface for Collaborative Computing. In *Multimedia and Expo, 2000. ICME 2000. 2000 IEEE International Conference on*, Vol. 3. IEEE, 1641–1644.

4. M. Bolas, J. Iliff, P. Hoberman, N. Burba, T. Phan, I. McDowall, P. Luckey, and D. M. Krum. 2013. Open Virtual Reality. In *2013 IEEE Virtual Reality (VR)*. 183–184. DOI: http://dx.doi.org/10.1109/VR.2013.6549423
5. Margaret M Bradley and Peter J Lang. 1994. Measuring Emotion: The Self-assessment Manikin and the Semantic Differential. *Journal of behavior therapy and experimental psychiatry* 25, 1 (1994), 49–59.
6. Raffaello Brondi, Leila Alem, Giovanni Avveduto, Claudia Faita, Marcello Carrozzino, Franco Tecchia, and Massimo Bergamasco. 2015. *Evaluating the Impact of Highly Immersive Technologies and Natural Interaction on Player Engagement and Flow Experience in Games*. Springer International Publishing, Cham, 169–181. DOI: http://dx.doi.org/10.1007/978-3-319-24589-8_13
7. Andreas Butz, Tobias Hollerer, Steven Feiner, Blair MacIntyre, and Clifford Beshers. 1999. Enveloping Users and Computers in a Collaborative 3D Augmented Reality. In *Augmented Reality, 1999.(IWAR'99) Proceedings. 2nd IEEE and ACM International Workshop on*. IEEE, 35–44.
8. Liwei Chan and Kouta Minamizawa. 2017. FrontFace: Facilitating Communication Between HMD Users and Outsiders Using Front-Facing-Screen HMDs. In *19th International Conference on Human-Computer Interaction with Mobile Devices and Services*. IEEE.
9. Lung-Pan Cheng, Patrick Lühne, Pedro Lopes, Christoph Sterz, and Patrick Baudisch. 2014. Haptic Turk: A Motion Platform Based on People. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3463–3472. DOI: http://dx.doi.org/10.1145/2556288.2557101
10. Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. 2015. TurkDeck: Physical Virtual Reality Based on People. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 417–426. DOI: http://dx.doi.org/10.1145/2807442.2807463
11. K. Coninx, F. Van Reeth, and E. Flerackers. 1997. A Hybrid 2D / 3D User Interface for Immersive Object Modeling. In *Proceedings of the 1997 Conference on Computer Graphics International (CGI '97)*. IEEE Computer Society, Washington, DC, USA, 47–55. http://dl.acm.org/citation.cfm?id=792756.792856
12. Thierry Duval and Cédric Fleury. 2009. An Aymmetric 2D Pointer/3D Ray for 3D Interaction Within Collaborative Virtual Environments. In *Proceedings of the 14th international Conference on 3D Web Technology*. ACM, 33–41.
13. Foreign VR. 2016. *Ruckus Ridge VR Party*. Game [HTC Vive], http://www.ruckusridgegame.com/. (2016). Palo Alto, USA, Accessed: 2017-04-03.
14. Brian Gajadhar, Yvonne de Kort, and Wijnand IJsselsteijn. 2008. Influence of Social Setting on Player Experience of Digital Games. In *CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08)*. ACM, New York, NY, USA, 3099–3104. DOI: http://dx.doi.org/10.1145/1358628.1358814
15. Chaim Gartenberg. 2015. The Future of Gaming is Lonely (And Online Only). (June 2015). http://www.theverge.com/2015/6/25/8844073/goodbye-local-multiplayer-we-will-miss-you-\and-the-goldeneye-days-of-yore Accessed: 2017-04-03.
16. Google. 2017a. Headset "Removal" for Virtual and Mixed Reality. https://research.googleblog.com/2017/02/headset-removal-for-virtual-and-mixed.html. (2017). Accessed: 2017-04-02.
17. Google. 2017b. (Un)folding a Virtual Journey with Google Cardboard. https://blog.google/products/google-vr/unfolding-virtual-journey-cardboard/. (2017). Accessed: 2017-04-02.
18. Jan Gugenheimer. 2016. Nomadic Virtual Reality: Exploring New Interaction Concepts for Mobile Virtual Reality Head-Mounted Displays. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16 Adjunct)*. ACM, New York, NY, USA, 9–12. DOI: http://dx.doi.org/10.1145/2984751.2984783
19. Jan Gugenheimer, David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio. 2016. FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 49–60. DOI: http://dx.doi.org/10.1145/2984511.2984576
20. Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users. In *Proc. (CHI '17)*. ACM, New York, NY, USA.
21. Jan Gugenheimer, Dennis Wolf, Eythor R. Eiriksson, Pattie Maes, and Enrico Rukzio. 2016. GyroVR: Simulating Inertia in Virtual Reality Using Head Worn Flywheels. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 227–232. DOI: http://dx.doi.org/10.1145/2984511.2984535
22. John Harris, Mark Hancock, and Stacey D. Scott. 2016. Leveraging Asymmetries in Multiplayer Games: Investigating Design Elements of Interdependent Play. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. ACM, New York, NY, USA, 350–361. DOI: http://dx.doi.org/10.1145/2967934.2968113

23. Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proc. (CHI '17)*. ACM, New York, NY, USA.

24. Roland Holm, Erwin Stauder, Roland Wagner, Markus Priglinger, and Jens Volkert. 2002. A Combined Immersive and Desktop Authoring Tool for Virtual Environments. In *Virtual Reality, 2002. Proceedings. IEEE*. IEEE, 93–100.

25. Hikaru Ibayashi, Yuta Sugiura, Daisuke Sakamoto, Natsuki Miyata, Mitsunori Tada, Takashi Okuma, Takeshi Kurata, Masaaki Mochimaru, and Takeo Igarashi. 2015. Dollhouse VR: A Multi-view, Multi-user Collaborative Design Workspace with VR Technology. In *SIGGRAPH Asia 2015 Emerging Technologies*. ACM, 8.

26. WA IJsselsteijn, YAW De Kort, and K Poels. 2013. The Game Experience Questionnaire: Development of a Self-report Measure to Assess the Psychological Impact of Digital Games. (2013).

27. Wijnand IJsselsteijn, Yvonne De Kort, Karolien Poels, Audrius Jurgelionis, and Francesco Bellotti. 2007. Characterising and Measuring User Experiences in Digital Games. In *International conference on advances in computer entertainment technology*, Vol. 2. 27.

28. Kunihiro Kato and Homei Miyashita. 2015. Creating a Mobile Head-mounted Display with Proprietary Controllers for Interactive Virtual Reality Content. In *Adjunct Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15 Adjunct)*. ACM, New York, NY, USA, 35–36. DOI: http://dx.doi.org/10.1145/2815585.2817776

29. Leonard Kleinrock. 1995. Nomadic Computing — an Opportunity. *SIGCOMM Comput. Commun. Rev.* 25, 1 (Jan. 1995), 36–40. DOI: http://dx.doi.org/10.1145/205447.205450

30. Siân E. Lindley, James Le Couteur, and Nadia L. Berthouze. 2008. Stirring Up Experience Through Movement in Game Play: Effects on Engagement and Social Behaviour. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08)*. ACM, New York, NY, USA, 511–514. DOI:http://dx.doi.org/10.1145/1357054.1357136

31. Kent Lyons. 2016. 2D Input for Virtual Reality Enclosures with Magnetic Field Sensing. In *Proceedings of the 2016 ACM International Symposium on Wearable Computers (ISWC '16)*. ACM, New York, NY, USA, 176–183. DOI: http://dx.doi.org/10.1145/2971763.2971787

32. Joe Marshall, Conor Linehan, and Adrian Hazzard. 2016. Designing Brutal Multiplayer Video Games. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 2669–2680.

33. Mark McGill, Daniel Boland, Roderick Murray-Smith, and Stephen Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 2143–2152. DOI: http://dx.doi.org/10.1145/2702123.2702382

34. Mark McGill, Alexander Ng, and Stephen Brewster. 2017. I Am The Passenger: How Visual Motion Cues Can Influence Sickness For In-Car VR. In *Proc. (CHI '17)*. ACM, New York, NY, USA.

35. Kana Misawa and Jun Rekimoto. 2015. Wearing Another's Personality: A Human-surrogate System with a Telepresence Face. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers (ISWC '15)*. ACM, New York, NY, USA, 125–132. DOI: http://dx.doi.org/10.1145/2802083.2808392

36. Ohan Oda, Carmine Elvezio, Mengu Sukan, Steven Feiner, and Barbara Tversky. 2015. Virtual Replicas for Remote Assistance in Virtual and Augmented Reality. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 405–415. DOI: http://dx.doi.org/10.1145/2807442.2807497

37. Mat Ombler. 2015. Why Split-Screen Gaming is Dying (And Why We Should Mourn It). http://www.highsnobiety.com/2015/09/09/split-screen-gaming-dead/. (Sept. 2015). Accessed: 2017-04-03.

38. Robin Parker. 2014. Opinion: Is Split-Screen Dead? http://www.godisageek.com/2014/06/opinion-split-screen-dead/. (June 2014). Accessed: 2017-04-03.

39. Danakorn Nincarean Eh Phon, Mohamad Bilal Ali, and Noor Dayana Abd Halim. 2014. Collaborative Augmented Reality in Education: A Review. In *Teaching and Learning in Computing and Engineering (LaTiCE), 2014 International Conference on*. IEEE, 78–83.

40. D. Pohl and C. F. de Tejada Quemada. 2016. See What I See: Concepts to Improve the Social Acceptance of HMDs. In *2016 IEEE Virtual Reality (VR)*. 267–268. DOI: http://dx.doi.org/10.1109/VR.2016.7504756

41. Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted Display with Mid-air Tactile Feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology (VRST '15)*. ACM, New York, NY, USA, 51–58. DOI:http://dx.doi.org/10.1145/2821592.2821593

42. SCE Japan Studio. 2016. *The Playroom VR*. Game [PS4/PS VR], https://www.playstation.com/en-gb/games/the-playroom-vr-ps4/. (2016). SCCE, London, UK, Accessed: 2017-04-03.

43. Dieter Schmalstieg, Anton Fuhrmann, Gerd Hesina, Zsolt Szalavári, L Miguel Encarnaçao, Michael Gervautz, and Werner Purgathofer. 2002. The Studierstube Augmented Reality Project. *Presence: Teleoperators and Virtual Environments* 11, 1 (2002), 33–54.

44. Mel Slater, Martin Usoh, and Anthony Steed. 1994. Depth of Presence in Virtual Environments. *Presence: Teleoperators & Virtual Environments* 3, 2 (1994), 130–144.

45. Boris Smus and Christopher Riederer. 2015. Magnetic Input for Mobile Virtual Reality. In *Proceedings of the 2015 ACM International Symposium on Wearable Computers (ISWC '15)*. ACM, New York, NY, USA, 43–44. DOI: http://dx.doi.org/10.1145/2802083.2808395

46. Aaron Stafford, Wayne Piekarski, and Bruce Thomas. 2006. Implementation of God-like Interaction Techniques for Supporting Collaboration Between Outdoor AR and Indoor Tabletop Users. In *Proceedings of the 5th IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR '06)*. IEEE Computer Society, Washington, DC, USA, 165–172. DOI: http://dx.doi.org/10.1109/ISMAR.2006.297809

47. Steel Crate Games. 2015. *Keep Talking And Nobody Explodes*. Game [HTC Vive], http://www.keeptalkinggame.com. (2015). Steel Crate Games, Ottawa, CA, Accessed: 2017-04-03.

48. Ivan E. Sutherland. 1968. A Head-mounted Three Dimensional Display. In *Proceedings of the December 9-11, 1968, Fall Joint Computer Conference, Part I (AFIPS '68 (Fall, part I))*. ACM, New York, NY, USA, 757–764. DOI: http://dx.doi.org/10.1145/1476589.1476686

49. Team Future. 2016. *Black Hat Cooperative*. Game [HTC Vive, Oculus Rift], http://www.teamfuturegames.com. (2016). Team Future, Boston, USA, Accessed: 2017-04-03.

50. Amy Voida, Sheelagh Carpendale, and Saul Greenberg. 2010. The Individual and the Group in Console Gaming. In *Proceedings of the 2010 ACM conference on Computer supported cooperative work*. ACM, 371–380.

51. Amy Voida and Saul Greenberg. 2009. Wii All Play: The Console Game as a Computational Meeting Place. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1559–1568.

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