THE USAGE OF FULLY IMMERSIVE HEAD-MOUNTED DISPLAYS IN SOCIAL EVERYDAY CONTEXTS

DISSERTATION

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CHRISTIAN MAI

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Erstgutachter:	Prof. Dr. Heinrich Hußmann
Zweitgutachter:	Prof. Dr. Frank Steinicke
Drittgutachter:	Prof. Dr. Enrico Rukzio

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ABSTRACT

Technology often evolves from decades of research in university and industrial laboratories and changes people's lives when it becomes available to the masses. In the interaction between technology and consumer, established designs in the laboratory environment must be adapted to the needs of everyday life. This paper deals with the challenges arising from the development of fully immersive Head Mounted Displays (HMD) in laboratories towards their application in everyday contexts.

Research on virtual reality (VR) technologies spans over 50 years and covers a wide field of topics, e.g., technology, system design, user interfaces, user experience or human perception. Other disciplines such as psychology or the teleoperation of robots are examples for users of VR technology. The work in the previous examples was mainly carried out in laboratories or highly specialized environments. The main goal was to generate systems that are ideal for a single user to conduct a particular task in VR.

The new emerging environments for the use of HMDs range from private homes to offices to convention halls. Even in public spaces such as public transport, cafés or parks, immersive experiences are possible. However, current VR systems are not yet designed for these environments. Previous work on problems in the everyday environment deals with challenges such as preventing the user from colliding with a physical object. However, current research does not take into account the new social context for an HMD user associated with these environments. Several people who have different roles are around the user in these contexts. In contrast to laboratory scenarios, the non-HMD user, for example, does not share the task with or is aware of the state of the HMD user in VR.

This thesis contributes to the challenges introduced by the social context. For this purpose I offer solutions to overcome the visual separation of the HMD user. I also suggest methods for investigating and evaluating the use of HMDs suitable for everyday context.

First, we present concepts and insights to overcome the challenges arising from an HMD covering the user's face. In the private context, e.g., living rooms, one of the main challenges is the need for an HMD user to take off the HMD to be able to communicate with others. Reasons for taking off the HMD are the visual exclusion of the surrounding world for HMD users and the HMD covering the users' face, hindering communication. Additionally, the Non-HMD users do not know about the virtual world the HMD user is acting in. Previous work suggests to visualize the bystanding Non-HMD user or its actions in VR to address such challenges. The biggest advantage of a fully immersive experience, however, is the full separation from the physical surrounding with the ultimate goal of being at another place. Therefore I argue not to integrate a non-HMD users directly into VR. I introduce the approach of using a shared surface that provides a common basis for information and interaction between a non-HMD and a HMD user. Such a surface can be utilized by using a smartphone. The same information is presented to the HMD in VR and the Non-HMD user on the shared surface in the same physical position, enabling joint interaction at the surface. By examining four feedback modalities, we provide design guidelines for touch

interaction. The guidelines support interaction design with such a shared surface by an HMD user. Further, we explore the possibility to inform the Non-HMD user about the user's state during a mixed presence collaboration, e.g., if the HMD user is inattentive to the real world. For this purpose I use a frontal display attached to the HMD. In particular we explore the challenges of disturbed socialness and reduced collaboration quality, by presenting the users state on the front facing display. In summary, our concepts and studies explore the application of a shared surface to overcome challenges in a co-located mixed presence collaboration.

Second, we look at the challenges of using HMDs in a public environment that have not yet been considered. The use of HMDs in these environments is becoming a reality due to the current development of HMDs, which contain all necessary hardware in one portable device. Related work, in particular, the work on public displays, already addresses the interaction with technology in public environments. The form factor of the HMD, the need to take an HMD onto the head and especially the visual and mental exclusion of the HMD user are new and not yet understood challenges in these environments. We propose a problem space for semi-public (e.g., conference rooms) and public environments (e.g., market places). With an explorative field study, we gain insight into the effects of the visual and physical separation of an HMD user from surrounding Non-HMD users. Further, we present a method that helps to design and evaluate the unsupervised usage of HMDs in public environments, the *audience funnel flow model for HMDs*.

Third, we look into methods that are suitable to monitor and evaluate HMD-based experiences in the everyday context. One core measure is the experience of being present in the virtual world, i.e., the feeling of "being there". Consumer-grade HMDs are already able to create highly immersive experiences, leading to a strong presence experience in VR. Hence we argue it is important to find and understand the remaining disturbances during the experience. Existing methods from the laboratory context are either not precise enough, e.g, questionnaires, to find these disturbances or cause high effort in their application and evaluation, e.g., physiological measures. In a literature review, we show that current research heavily relies on questionnaire-based approaches. I improve current qualitative approaches – interviews, questionnaires – to make the temporal variation of a VR experience assessable. I propose a drawing method that recognizes breaks in the presence experience. Also, it helps the user in reflecting an HMD-based experience and supports the communication between an interviewer and the HMD user. In the same paper, we propose a descriptive model that allows the objective description of the temporal variations of a presence experience from beginning to end. Further, I present and explore the concept of using electroencephalography to detect an HMD user's visual stress objectively. Objective detection supports the usage of HMDs in private and industrial contexts, as it ensures the health of the user.

With my work, I would like to draw attention to the new challenges when using virtual reality technologies in everyday life. I hope that my concepts, methods and evaluation tools will serve research and development on the usage of HMDs. In particular, I would like to promote the use in the everyday social context and thereby create an enriching experience for all.

ZUSAMMENFASSUNG

Technologie entwickelt sich oft aus jahrzehntelanger Forschung in Universitäts- und Industrielabors und verändert das Leben der Menschen, wenn sie für die Masse verfügbar wird. Im Zusammenspiel von Technik und Konsument müssen im Laborumfeld etablierte Designs an die Bedürfnisse des Alltags angepasst werden. Diese Arbeit beschäftigt sich mit den Herausforderungen, die sich aus der Entwicklung voll immersiver Head Mounted Displays (HMD) in Labors, hin zu ihrer Anwendung im täglichen Kontext ergeben.

Die Forschung zu Virtual-Reality-Technologien erstreckt sich über mehr als 50 Jahre und deckt ein breites Themenspektrum ab, wie zum Beispiel Technologie, Systemdesign, Benutzeroberflächen, Benutzererfahrung oder menschliche Wahrnehmung. Andere Disziplinen wie die Psychologie oder die Teleoperation von Robotern sind Beispiele für Anwender von VR Technologie. in der Vergangenheit Arbeiten wurden Arbeiten mit VR Systemen überwiegend in Labors oder hochspezialisierten Umgebungen durchgeführt. Der Großteil dieser Arbeiten zielte darauf ab, Systeme zu generieren, die für einen einzigen Benutzer ideal sind, um eine bestimmte Aufgabe in VR durchzuführen.

Die neu aufkommenden Umgebungen für den Einsatz von HMDs reichen vom privaten Haushalt über Büros bis hin zu Kongresssälen. Auch in öffentlichen Räumen wie öffentlichen Verkehrsmitteln, Cafés oder Parks sind immersive Erlebnisse möglich. Allerdings sind die aktuellen VR Systeme noch nicht für diese Umgebungen ausgelegt. Vorangegangene Arbeiten zu den Problemen im Alltags Umfeld befassen sich daher mit Herausforderungen, wie der Vermeidung von Kollisionen des Benutzers mit einem physischen Objekt. Die aktuelle Forschung berücksichtigt allerdings nicht den neuen sozialen Kontext für einen HMD-Anwender, der mit den Alltagsumgebungen verbunden ist. Mehrere Personen, die unterschiedliche Rollen haben, sind in diesen Kontexten um den Benutzer herum. Im Gegensatz zu Szenarien im Labor teilt der Nicht-HMD-Benutzer beispielsweise nicht die Aufgabe und ist sich nicht über den Zustand des HMD-Benutzers in VR bewusst.

Diese Arbeit trägt zu den Herausforderungen bei, die durch den sozialen Kontext eingeführt werden. Zu diesem Zweck bieten ich in meiner Arbeit Lösungen an, um die visuelle Abgrenzung des HMD-Anwenders zu überwinden. Ich schlage zudem Methoden zur Untersuchung und Bewertung des Einsatzes von HMDs in öffentlichen Bereichen vor.

Zuerst präsentieren wir Konzepte und Erkenntnisse, um die Herausforderungen zu meistern, die sich durch das HMD ergeben, welches das Gesicht des Benutzers abdeckt. Im privaten Bereich, z.B. in Wohnzimmern, ist eine der größten Herausforderungen die Notwendigkeit, dass der HMD-Nutzer das HMD abnimmt, um mit anderen kommunizieren zu können. Gründe für das Abnehmen des HMDs sind die visuelle Ausgrenzung der Umgebung für die HMD-Anwender und das HMD selbst, welches das Gesicht des Anwenders bedeckt und die Kommunikation behindert. Darüber hinaus wissen die Nicht-HMD-Benutzer nichts über die virtuelle Welt, in der der HMD-Benutzer handelt. Bisherige Konzepte schlugen vor, den Nicht-HMD-Benutzer oder seine Aktionen in VR zu visualisieren, um diese Herausforderungen zu adressieren. Der größte Vorteil einer völlig immersiven Erfahrung ist jedoch die

vollständige Trennung der physischen Umgebung mit dem ultimativen Ziel, an einem anderen Ort zu sein. Daher schlage ich vor die Nicht-HMD-Anwender nicht direkt in VR einzubinden. Stattdessen stelle ich den Ansatz der Verwendung einer geteilten Oberfläche vor, die eine gemeinsame Grundlage für Informationen und Interaktion zwischen einem Nicht-HMD und einem HMD-Benutzer bietet. Eine geteile Oberfläche kann etwa durch die Verwendung eines Smartphones realisiert werden. Eine solche Oberfläche präsentiert dem HMD und dem Nicht-HMD-Benutzer an der gleichen physikalischen Position die gleichen Informationen. Durch die Untersuchung von vier Feedbackmodalitäten stellen wir Designrichtlinien zur Touch-Interaktion zur Verfügung. Die Richtlinien ermöglichen die Interaktion mit einer solchen geteilten Oberfläche durch einen HMD-Anwender ermöglichen. Weiterhin untersuchen wir die Möglichkeit, den Nicht-HMD-Benutzer während einer Zusammenarbeit über den Zustand des HMD Benutzers zu informieren, z.B., wenn der HMD Nutzer gegenüber der realen Welt unachtsam ist. Zu diesem Zweck schlage ich die Verwendung eines frontseitigen Displays, das an dem HMD angebracht ist. Zusätzlich bieten unsere Studien Einblicke, die den Designprozess für eine lokale, gemischt präsente Zusammenarbeit unterstützen.

Zweitens betrachten wir die bisher unberücksichtigten Herausforderungen beim Einsatz von HMDs im öffentlichen Umfeld. Ein Nutzung von HMDs in diesen Umgebungen wird durch die aktuelle Entwicklung von HMDs, die alle notwendige Hardware in einem tragbaren Gerät enthalten, zur Realität. Verwandte Arbeiten, insbesondere aus der Forschung an Public Displays, befassen sich bereits mit der Nutzung von Display basierter Technologien im öffentlichen Kontext. Der Formfaktor des HMDs, die Notwendigkeit ein HMD auf den Kopf zu Ziehen und vor allem die visuelle und mentale Ausgrenzung des HMD-Anwenders sind neue und noch nicht verstanden Herausforderung in diesen Umgebungen. Ich schlage einen Design Space für halböffentliche (z.B. Konferenzräume) und öffentliche Bereiche (z.B. Marktplätze) vor. Mit einer explorativen Feldstudie gewinnen wir Einblicke in die Auswirkungen der visuellen und physischen Trennung eines HMD-Anwenders von umliegenden Nicht-HMD-Anwendern. Weiterhin stellen wir eine Methode vor, die unterstützt, den unbeaufsichtigten Einsatz von HMDs in öffentlichen Umgebungen zu entwerfen und zu bewerten, das *audience funnel flow model for HMDs*.

Drittens untersuchen wir Methoden, die geeignet sind, HMD-basierte Erfahrungen im Alltagskontext zu überwachen und zu bewerten. Eine zentrale Messgröße ist die Erfahrung der Präsenz in der virtuellen Welt, d.h. das Gefühl des "dort seins". HMDs für Verbraucher sind bereits in der Lage, hoch immersive Erlebnisse zu schaffen, was zu einer starken Präsenzerfahrung im VR führt. Daher argumentieren wir, dass es wichtig ist, die verbleibenden Störungen während der Erfahrung zu finden und zu verstehen. Bestehende Methoden aus dem Laborkontext sind entweder nicht präzise genug, z.B. Fragebögen, um diese Störungen zu finden oder verursachen einen hohen Aufwand in ihrer Anwendung und Auswertung, z.B. physilogische Messungen. In einer Literaturübersicht zeigen wir, dass die aktuelle Forschung stark auf fragebogenbasierte Ansätze angewiesen ist. Ich verbessern aktuelle qualitative Ansätze – Interviews, Fragebögen – um die zeitliche Variation einer VR-Erfahrung bewertbar zu machen. Ich schlagen eine Zeichnungsmethode vor die Brüche in der Präsenzerfahrung erkennt, den Benutzer bei der Reflexion einer HMD-basierten Erfahrung hilft und die Kommunikation zwischen einem Interviewer und dem HMD-Benutzer unterstützt. In der gleichen Veröffentlichung schlage ich ein Modell vor, das die objektive Beschreibung der zeitlichen Variationen einer Präsenzerfahrung von Anfang bis Ende ermöglicht. Weiterhin präsentieren und erforschen ich das Konzept der Elektroenzephalographie, um den visuellen Stress eines HMD-Anwenders objektiv zu erfassen. Die objektive Erkennung unterstützt den Einsatz von HMDs im privaten und industriellen Kontext, da sie die Gesundheit des Benutzers sicherstellt.

Mit meiner Arbeit möchte ich auf die neuen Herausforderungen beim Einsatz von VR-Technologien im Alltag aufmerksam machen. Ich hoffe, dass meine Konzepte, Methoden und Evaluierungswerkzeuge der Forschung und Entwicklung über den Einsatz von HMDs dienen werden. Insbesondere möchte ich den Einsatz im alltäglichen sozialen Kontext fördern und damit eine bereichernde Erfahrung für alle schaffen.

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1

Introduction

Since the presentation of the first head-mounted display (HMD) by Ivan Sutherland [68], HMDs were used in specifically designed laboratories. Laboratories are tidied up spaces that enable walking around when wearing an HMD without the fear of hitting a physical object. They integrate hardware required for a virtual reality (VR) experience and eliminate real-world interference, such as noise. They are also separated from other rooms to prevent bystanders from unintentionally interfering with the VR experience. *Fully immersive HMDs* have the advantage that they cover the whole view of the users, enabling them to dedicate their full visual attention to the virtual world. HMD based immersive systems are the technology addressed in this thesis. I define the term immersion based on the definition by Slater and Wilbur [62]. They define immersion as the measurable attributes of a system, such as frame rate or pixel density. Fully immersive systems have the ultimate goal of making an HMD users forget about the real world and experience the virtual world as their reality [67]. To improve the user experience in VR systems the development of better technology and the interaction within VR systems were most important for researchers and developers [39, 52]. Furthermore, they tried to understand the users' perception in virtual reality (VR) to improve the experience even further (e.g., [9, 48, 66]). The result of the work in the last decades are today's consumer-grade HMDs, which can create highly immersive experiences.

With the possibility to walk around with an HMD, researchers realized the physical limitation of the movement space in a laboratory environment. In particular, structures in the laboratory, such as walls and objects, limit the space that an HMD user can use when moving in VR. However, in a virtual environment, there are no borders. To address this challenge, researchers developed techniques such as redirected walking. Redirected walking uses a perceptual illusion to make users walk in circles within the boundaries of the physical space, while believing they are walking straight ahead [38, 49]. Another possibility is to make use of the physical world in the virtual. To achieve this, passive haptic feedback can be provided (e.g., [11, 27]), or real objects can be substituted by virtual ones [60, 64]. The same physical object can be used for multiple virtual objects by redirecting the touch [36]. The challenge of limited space possibly emerges from the experiences researchers or practitioners gained in traditional laboratory environments. However, today HMDs are not exclusively used in laboratory environments [59].

The affordability of highly immersive consumer-grade HMDs leads to new contexts in which HMDs are used. Additionally, the physical dimensions of hardware needed for a full virtual reality experience decrease, which makes it much easier to move around. Even self-contained HMDs, which fulfill all immersive requirements such as visual output, sound, and interaction in one device, are available. Hence, today's HMDs can be transported inside a backpack[1], which enables casual use of HMDs for private users in everyday life. The interaction of technology and consumer often leads to new applications and can lead to the need to rethink established designs from the laboratory context. Commercial users employ HMDs to promote their products[2], sell HMD-based experiences as a product or create prod-

[1] `https://www.oculus.com/go/`, accessed: Mai 15th, 2019

[2] `https://www.audi-mediacenter.com/en/audi-at-the-ces-2016-5294/the-audi-vr-experience-5304`, accessed: Mai 15th, 2019

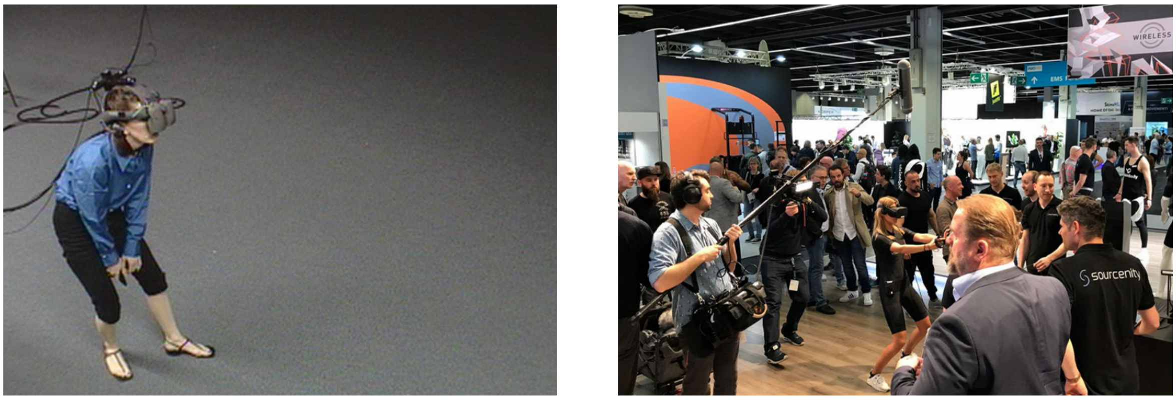


Figure 1.1: Transportability of modern HMD based systems leads to a growing number of new environments they are used in (e.g., right picture [63]). In contrast to the traditional clean laboratory context (left picture [1]), a number of new challenges arise. The particular challenge addressed in this thesis origins from the people surrounding the HMD user, the social context (right picture [63]). HMDs have been further developed to improve usability, but are not yet designed for the social context.

ucts based on HMDs, e.g., multiplayer arcades[3], fitness equipment[4] or in car entertainment[5]. The combination of affordable and portable devices and the private and commercial interest in these devices leads to increased usage in *everyday contexts*.

The main challenge in these contexts are the people surrounding an HMD user. These Non-HMD users can have different roles – being a spectator, supervising person or instructor – and have different social relations to the user – e.g., family or strangers –. In this thesis, I address the challenges arising from these *social contexts*. To illustrate the difference in social contexts, Figure 1.1 shows exemplarily a traditional laboratory environment (left) and a semi-public environment (right). Physical restrictions like walls already existed in the laboratory context. In contrast, in an everyday environment (Figure 1.1, right) an HMD user is surrounded by the team responsible for the HMD deployment, people from the press and passive bystanders in the background. As described above, the *everyday contexts* are diverse and so is the nature and role of the bystanders, making the situation even more complex. Not only HMD users might struggle with the world surrounding them. For bystanders, an HMD user is physically present and therefore remains a social actor [59, 24, 25], but with the face and eyes covered by the HMD. In this thesis, I aim at structuring and illuminating the arising challenges of HMD usage in *everyday social contexts*.

[3] `http://hologate.com/`, accessed February 20th, 2019

[4] `https://www.icaros.com/`, accessed February 20th, 2019

[5] `https://www.audi.com/en/experience-audi/mobility-and-trends/digitalization/holoride-virtual-reality-meets-the-real-world.html/`, accessed February 20th, 2019

1.1 The Everyday Contexts

As the everyday context is an important term in this thesis, I introduce it here.

In the progress of this thesis, I identified a scale that links different environments together (Figure 1.2). The classification by the environment indicates the social context in which the user is acting. In the following, I will first introduce the classification and then describe the social contexts one can expect. The scale starts on the left with *private environments*, has *semi-public environments* in the middle and shows the *public environments* on the right.

I identify a *private environment* as a secure place an HMD user knows well. The place protects the user from unexpected events. These unexpected events do not include for example other people that originally live in that place or visiting friends. However, a burglar breaking into the place would be an unexpected event. An obvious example of such a place is the personal household of an HMD user (Figure 1.2, left).

A *semi-public environment* is a dedicated place for HMD usage in a context away from the household. There are two different perspectives on these spaces. The first possibility to look at it comes from the side of the private environments. These spaces are protected places that offer a high level of security to people while wearing an HMD. These environments may be unknown to the user, but they are still perceived as trustworthy places. An example of such a place is the traditional laboratory, or it might be a dedicated space in a company (Figure 1.2, second from left). Although environments of this kind include challenges similar to the other everyday contexts, the problems are often well known and addressed. Examples are VR simulators for training or testing and traditional research context, in which one can find established routines for the interplay between a supervising person and an HMD user. The current commercial success of solutions for these protected environments underline the assumption that many challenges in these controlled environments are solved. For example, Volkswagen and Wal-Mart train thousands of their employees with HMDs and location-based entertainment companies like Hologate[6] sold hundreds of systems all over the world. My research can still be applied to these kinds of environments. However, I focus my research on challenges that arise in other contexts that are less like traditional laboratory contexts. Looking at semi-public environments from the public side, the protection for the user is limited. The site may still provide some physical security or promote a sense of security during HMD use. The spatial separation of the user might add physical security. The context might foster mental security. E.g., most people would feel secure when being at a shop, as they expect the shop owner to care for their security. An example would be a shop offering the possibility to explore the products in a virtual reality experience that is integrated into the exhibition (e.g., Ikea VR Experience[7], Audi[8]).

[6] `http://www.hologate.com/`, accessed: Mai 15th, 2019

[7] `https://demodern.de/projekte/ikea-vr-showroom`, accessed: Mai 15th, 2019

[8] `https://www.audi-mediacenter.com/de/pressemitteilungen/audi-startet-virtual-reality-im-autohaus-9270`, accessed: Mai 15th, 2019

A *public environment* is a space that is not dedicated to the usage of HMDs. The usage of HMDs in these environments might be spontaneous or temporary. There is no physical or mental protection given by the environment to an HMD user. An example might be the usage of an HMD on a park bench.

Regarding the environment, also the *social context* changes.

> *"Human social environments encompass the immediate physical surroundings, social relationships, and cultural milieus within which defined groups of people function and interact."* (Barnett & Casper [5], p.465)

In my work, I take into account the *social context* – also known as *social environment* – as defined by Barnett and Casper [5]. Although there may be exceptions, the existence of people around an HMD user can have varying impact in different *social contexts*. In *private environments*, people surround an HMD user that have a close relation to him/her. In *semi-public environments*, many different people with different roles act around an HMD user. Hence, HMD users are not always in control about who is surrounding them. However, the environment, physical and social, can be adapted to support the needs of an HMD user. In *public environments*, HMD users are not in control about the people surrounding them. In particular, neither about the physical distance, nor the personal relationship. Bystanders could be family members or strangers. It is complicated to change anything about the surrounding environment or people to improve an HMD user's experience. Past research highlights the challenges of using HMDs in the public social context. The related work points out acceptance issues of wearing a bulky device on the head [59, 35], as well as privacy concerns caused by the continuous recording of sensors integrated into an augmented reality HMD [35].

The *environments* and *social contexts* in them are the guide through my work. As the real world is very complex, the connection between the environment and context may vary. However, knowing about those two aspects guides us when working on the challenges in HMD usage, as the needs on HMD system design between the contexts will also vary. In the following, I present the research questions that have arisen during the investigation of the single problem spaces.

1.2 Integration of HMDs in Private Environments

Studies on the use of HMDs in everyday life showed that the most annoying thing for the user is to put on and take off the HMD repeatedly [47]. One cause for taking of the HMD might be not knowing who is approaching. Further, as the HMD user is a social actor in the everyday contexts, there might be a need for interaction between HMD and Non-HMD users. Failing in interaction with the other, because the HMD covers the wearer's face, leads in turn to the removal of the HMD [47]. Exemplary scenarios are interruptions from family

Figure 1.2: The possible environments for HMD usage are diverse. To structure this thesis, I distribute the environments on a scale that shows the private environment on the left [30] followed by semi-public environments [4] that are more similar to private environments. These are traditional laboratory environments. Coming from the right the public environments [53] are shown, followed by semi-public installations, e.g., in a store [17].

members for an everyday decision, e.g., which kind of meal to prepare for dinner. Another example might be the need for feedback from an HMD user, while the Non-HMD user searches for a holiday destination on a private mobile phone. These interruptions are not only annoying because of the physical exertion and annoyance of putting on and taking off the HMD. In addition, the attention of the HMD user is drawn to the real world, distracting from the virtual world, which is called a break in presence (BIP) [61]. Smaller breaks are caused by touching the users or talking to them. Taking off the HMD is the strongest BIP as it ends the immersion and possibility to act in VR. Additionally, it is problematic as it takes some time until the experience of being present in the virtual world comes into being each time one puts on the HMD [20]. Therefore, these disturbances have to be avoided or at least limited.

To address the challenges arising due to a mixed presence situation one might give an HMD to the Non-HMD user and create a collaborative virtual environment. However, this scenario needs additional hardware, and there are plenty of situations in which the Non-HMD user just can not or does not want to be in VR.

Another approach is the use of tools utilized in distributed environments in a co-located everyday scenario [29, 51, 57, 65]. Traditional tele-presence systems, e.g., a video chat, are used to communicate between remote places. Users wearing a fully immersive HMD report to be at another place. Therefore, a tele-presence system seems to be ideal for the usage in co-located mixed presence, as an HMD and a Non-HMD user are cognitively in different places. Even more, it might be beneficial, as the separation prevents a Non-HMD user from disturbing an HMD user. For example in the concept of Ibayashi and colleagues [29] a Non-HMD user interacts with an HMD user by using a tabletop display. A video stream of the Non-HMD user's face is presented in the virtual world. The HMD user is acting in the virtual world but is located physically next to the Non-HMD users. All information is transmitted between an HMD user and a Non-HMD user via visualizations in the HMD and at the tabletop display. There is no interaction through physical space, in order not to interrupt the HMD user's experience. The need for physical interaction, e.g., touching the HMD user, is overcome as the Non-HMD users interact with the tabletop display. However, there might be practical reasons that prevent the usage of a tele-presence system. Examples are the physical space needed to separate an HMD user and the Non-HMD user or the additional hardware effort to provide the interactive system for the a-HMD user. Additionally, in the everyday contexts, an HMD user is a social actor within a household. Artificial separation of the people living in a household could disturb their social togetherness.

The third approach is to make use of the co-location between HMD and Non-HMD user. McGill and colleagues [47] suggested integrating a Non-HMD user into the virtual world of an HMD user. A video stream to the VR is an explicit approach to integrate the Non-HMD user. The concept has the advantage that HMD users feel more secure as they know who is approaching them. Interaction is supported as an HMD user can see the others. However, they found that an integration of a 2D video stream is annoying as it conflicts with the virtual content [47]. Gugenheimer and colleagues [24] match the actions of a Non-HMD towards an HMD user with events in the virtual world. For example, the Non-HMD user can hit the HMD user on the head which results in turning off a headlight in the HMD user's experience. Ideally, the integration of the Non-HMD user's actions makes the HMD user forget about the Non-HMD user. Still, there is a social interaction ongoing. Also, the situation is asymmetrical. The HMD user alone sees the virtual world and only the Non-HMD user can see the interaction partner, in particular, the HMD user. By supporting the strengths of the interaction partners, the situation becomes more asymmetrical. However, the overall experience is better for both. Gugenheimer designed the system for an entertaining context. In the entertaining context making use of asymmetry creates tension in the interaction. Tension makes the experience interesting because it brings in unpredictable events in the course of the experience. However, in everyday tasks people are very likely to be goal-oriented and do not want surprises during solving collaborative tasks. There are other examples that use the implicit approach as it combines the need for interaction with an HMD user's need to avoid distracting stimuli from the real world [2, 10, 12, 24, 25, 74]. The integration of Non-HMD user actions creates playfull experiences [10, 12, 24, 25], supports HMD users in their interaction in VR [2] or prevents collision between both [74]. Although these related work examples offer an new and feasible solution, they do not address the everyday problems in social context that McGill [47] has identified.

In summary, the first and second approach does not take into account spatial and hardware limitation, as well as the dynamics of everyday life. In addition, the adaption of tele-presence systems does not improve social interaction, although the users are in the same place. Making use of the co-location was shown to support the socialness of a VR experience in the everyday by examples from approach three. Therefore I argue that making use of the co-location is beneficial. In the following, I argue why current approaches that make use of the co-location might not be ideal for everyday situations.

The explicit or implicit integration of the other, as proposed by related work does not address everyday challenges of social interaction. In all implicit examples integration of a Non-HMD user is tailored for the one specific experience. The substituted interactions are disturbing the HMD user, and the designed asymmetry might negatively affect collaboration as discussed above. Additionally, the complexity of the systems and demand on space is still very high.

For example, McGill's [47] explicit approach needed a green colored room. Further, it might fail in a scenario with an HMD user and a Non-HMD user sitting on a couch or laying next to each other. In this situation, the camera on the HMD does not see the other person anymore.

The research on creating collaborative systems demonstrates that successful collaboration needs a common awareness for the other and for the workspace [13, 28]. Therefore, I argue that supporting the collaboration by using a shared workspace instead of fostering the awareness for each other might be a feasible approach. The benefit is that an HMD user is not disturbed by the Non-HMD users' appearance in VR anymore. Still, a Non-HMD user can see and get in contact with an HMD user to conduct everyday interactions. The HMD user will feel a togetherness due to behavioral engagement which is known to be a factor of social presence [6]. Also, I argue for the use of symmetric instead of asymmetric information and interaction. The symmetry limits the number of possible conflicts and therefore reduces the risk of failing in interaction.

Gugenheimer emphasizes with his work [24], designing virtual reality systems for the household should not lead to further social exclusion of an HMD user. The social exclusion through the use of HMDs could be even higher than the effects created from today's smartphone usage in households (e.g., [56]). Although there is no evidence yet, there are some indications that people have a critical perspective on HMDs when they are used in a social context [59]. Nintendo shared this critique and did not officially invest in VR, as they said VR is not social yet [14]. However, the president of Nintendo America, Reggie Fils-Aime, also said:

> *"What we believe is that, in order for this technology to move forward, you need to make it fun and you need to make it social."* (Reggie Fils-Aime, 2015 in [14])

I take this quote as a challenge.

> **RQ1:** *How can we support HMD usage in private everyday social contexts?*

Contribution. To address *RQ1* I introduced the concept of using a shared surface as a common ground between a Non-HMD and an HMD user in publication [P1] [40]. A shared surface is a physical screen, e.g., a smartphone. A Non-HMD user interacts with the screen and an HMD user interacts with a virtual copy, but at the same position as the physical proxy. In contrast to related work, this creates a symmetric form of interaction and information, the HMD user does not have to shift is attention to the real world surrounding him. Still, social interaction happens through the collaborative actions on the smartphone.

In my thesis, I present a selection of publications that deal with particular challenges when working with a shared surface. The papers are described in more detail in chapter 2. As we focused on developing the shared surface, our research was conducted in laboratory environments. Hence, I encourage future researchers to adapt and evaluate the concepts in the field.

The presented contributions for RQ1 base on the idea of having a collaborative task that demands more than one modality for collaboration. The task is inspired by the work of Andrist and colleagues [3]. The main concept of the task is to vary design factors of a puzzle – color, shape, texture – to provoke communication. As a result of the task and addressing single aspects of the shared surface separately, all studies are conducted as laboratory experiments.

To explore the concept of a shared surface on the user experience and quality of collaboration we conducted a lab study, applying the task of Andrist [3]. We found that the shared surface enables successful collaboration, is satisfying for the users but has drawbacks in the quality of collaboration. Therefore, it fulfills our minimum goal of preventing the need for taking off the HMD during a collaborative task. Hence, we argue that a shared surface is a feasible approach to support the usage of HMDs in everyday social context. Especially, if it is realized with a smartphone. Adding an Avatar, as proposed by McGill [47], leads to better collaborative performance. Due to technical limitations of the avatar representation, the collaborative performance is still worse compared to the real world collaboration baseline. In contrast to McGill [47], people did not perceive the existence of the real world user's representation in VR as disturbing. The reason might be that we, unlike McGill, implemented a 3D representation of the Non-HMD user and the virtual world was designed for the task.

The first contribution [40] did not require precise interaction with the shared surface. To make the shared surface a practical tool, we have examined the interface design for the HMD user contained in publication [P2] [45]. As the HMD covers the eyes, HMD users do not see the physical surface and own hands by default. The resulting restriction in interaction is the limiting factor for the interface design of a shared surface in terms of button size. To address the needs of an HMD user for different system designs, we conducted a controlled experiment on three feedback designs. We offer dimensions for the button sizes of a user interface, depending on the available feedback and the learning curve when using the feedback method. From the results, we further derive design recommendations when creating a touch surface for an HMD user.

From the point of view of a Non-HMD user, an HMD hinders social interaction and collaboration. An HMD covers the wearer's face and therefore makes it hard for the Non-HMD user to interpret the state the HMD user is in. We contribute by introducing design categories that can be used to create display based information systems for this situation in contribution [P3] [44]. In a laboratory study, we explored the effects of abstract information visualization and presenting the information by showing a realistic face on the HMD with simulated depth. Further, we give design recommendations for the visualization of the user's state on a front facing display attached to an HMD.

With the first part of my work, I contribute in the field of co-located mixed presence with the concept of a shared surface and its design.

1.3 Usage of HMDs in Public Environments

As described in Chapter 1.2, the usage of HMDs in semi-public and public environments is driven by the advance in technology and commercial interests. In particular, commercial applications in semi-public environments are successful. These applications enable a scripted experience from the arrival of users untill they leave again. Therefore, the difference between a classical laboratory environment and a semi-public environment of that kind is small, which makes the introduction of HMDs easier. Besides artistic exhibitions (e.g., [10]), examples for the research on HMDs in less protected public contexts is still limited. Public environments seem to be of particular interest for marketing purposes, as the new technology is used to attract attention [18]. Related scientific work starts to recognize the semi-public environment and public environment as a possible influencing factor [32, 59]. In an online survey, Schwind and colleagues [59] found that the public acceptance of HMDs depends on the context and the expectation on social interaction in this context. It should be noted that only the perception as a Non-HMD user was asked and not the perception as an HMD user. However, it motivates our work as it shows that there are open challenges to address in the research on HMD usage in public. This is also reflected in activities within the scientific community that address explicitly the missing discussion of the topic [23, 34, 71].

There is a long tradition in the research on public deployments of technology. Research gives valuable insight on the challenges arising from the everyday contexts [8]. In particular, I built upon the research on public displays [16]. As the application of related work is a contribution of [43], I refer to this for a more detailed discussion.

While RQ1 was looking for concrete solutions, this part of the work deals with the search for a methodical approach to structuring, understanding and solving challenges in the public use of HMDs.

> **RQ2:** *What are the challenges in the public usage of HMDs and how should we approach them?*

Contribution. To provide answers to RQ2, we have decided for an exploratory approach based on observations and measurements in field studies. The work selected for this thesis includes the proposal of a problem space and its exploration in contribution [P4] [46]. Further, it offers a method that helps in understanding and analyzing the user flow around unsupervised HMDs deployed in public by contribution [P5] [43]. A closer discussion in Chapter 3, points out the possibilities my work provides for future research and development.

The problem space introduces eight factors that can be split into three groups: *apparatus*, *HMD user* and *people surrounding* the HMD user [46]. In particular, the paper discusses the possible influence of by-standing people in regards to known psychological effects, e.g., proxemics. In a user study, we confirm our problem space and derive insights on the influence of physical and visual separation of the user in public environments. The paper gives a design recommendation for the public use of HMDs, provided that a supervising person is present. Further, we found that the supervising person has a strong influence on the user's experience in public. Hence, we have started to investigate what happens when HMDs are used unattended in public [43]. We contribute to this question by offering a model that describes the user flow over time when interacting with an unsupervised HMD. The *Audience Funnel Flow Model for HMDs* enables to identify critical phases from the moment the HMD should attract the attention of the users till they left the scene. Through a field study, we were able to confirm our theoretical model. In addition, we gained insights into the challenges that prevented people from passing through the stages of the flow model.

1.4 Methods for Monitoring and Evaluation of HMD usage in Everyday Social Contexts

Everyday contexts lead to user groups and types of developers that are different from traditional laboratories. Monitoring and evaluation challenges arising from the new contexts and user groups are different from lab studies in many ways. The context of use makes it difficult to use available measuring approaches, as I discuss in the following.

Derived from Insko [31], tools for monitoring and evaluating a VR experience can be sorted in (1) physiological measurements, (2) behavioral observations, (3) questionnaires and (4) interviews. *Interviews* should mainly be used to support the interpretation of other measures. Previous work has found a strong dependence on questionnaires in the scientific community, presumably because they are easy to use. *Questionnaires* are criticized in particular for the evaluation of the presence experience [15, 69]. The main reason for this is a high dependence on the conceptualization of the presence concept by the creator of the questionnaire. A meta-analysis, which summarizes the results of many different studies, is therefore limited in its ability to generate results [15, 55]. Questionnaires do not take temporal fluctuations into account. In addition, the time frame of the experience the user refers to when answering the questionnaire is unclear and thus the resulting presence value. Naive users tend not to detect or report issues in the usage of an HMD based system. They might accept disturbances as state of the art. Another reason might be the high immersive capabilities of a modern HMD based system. Since users do not have much experience to compare, they may be overwhelmed by the unexpected good experience and may not notice any errors. *Behavioral measurements* are the most promising methods to validate an experience. Especially if it is important for the research carried out that the user behaviour in the virtual world is the same as in the physical world. The disadvantage is the effort to embed such a measure into the desired experience and to analyze it. Furthermore, the measure itself can influence the experience, e.g., by creating provoking strong reactions in the user [19, 54, 72]. *Physiological measurements* are the only way to objectively quantify a system, enable real-time monitoring, and detect variations over time. However, most physiological measures require hardware to be applied to the user's body, and a complex calibration must be performed. When used in public environments, people do not take the time for such actions and may feel intimidated by being touched or undressing to put sensors on. Additionally, the cause and effect of physiological measures might not always be clear. For example, increasing level of arousal of the user can be caused either by the VR system itself – a malfunction – or the VR experience – a game including action scenes.

I argue that most modern HMD systems are of very high quality, which is supported by VR authoring and rendering software that helps to avoid general mistakes. Therefore, only singular events might have a negative impact on the VR experience. Examples might be a tedious experience influencing the feeling to be involved in the actions, elements that are not interactive or flickering textures. Therefore, I argue that tools are needed that work without additional effort. At least they should be easy to use in everyday life and find as many BIPs as possible in the VR experience.

> **RQ3:** *How do we monitor and evaluate HMD experiences in the everyday contexts?*

Contribution. To contribute to RQ3 we provide a literature review and evaluation of existing methods to assess the *presence* experience in VR by contribution [P6] [26]. Also, we contribute by proposing and evaluating the use of electroencephalography to detect visual stress in an HMD with [P7] [41]. Our method to analyze user flow around public deployments of HMDs adds to the contribution of tools for evaluation in [P5] [43] . The *Audience Funnel Flow Model for HMDs* was presented in Section 1.3. The contributions are a set of tools supporting the analysis of VR experiences in general and are particularly suitable for assessing public VR experiences [26, 41, 43].

Our work on *RQ3* includes a literature review on research methods, in particular, questionnaires. There was a need, as publications utilizing consumer grade HMDs were increasing, while related work indicates that existing methods might not be appropriate in the past. With it, the number of departments not specialized in the application of VR devices grows and therefore the type of chosen methods might change. We have found that there is a strong dependence on questionnaires in general. A clear preference for the criticized Witmer and Singer presence questionnaire and its often incomplete application by the omission of the *immersive tendency questionnaire* [73] could be shown. The heavy reliance on questionnaires has reflected our own experience that there seems to be a lag of feasible solutions for the evaluation of VR systems. In particular, the evaluation of variations over time still needs feasible tools for analysis. Therefore, we introduce electroencephalography to detect visual stress in an HMD by [P7] [41]. Disturbances due to visual stress can be caused by for example by flickering textures or to strong disparity of the stereoscopic picture [37]. These are typically short term events that are not recognized by current evaluation methods but can negatively affect the presence experience. We could show that it is possible with consumer grade hardware and a minimum of computing, to achieve a good detection rate of visual stress. Furthermore, we have identified the electrodes providing the most promising signal to identify the experience of visual stress. These are situated at the top and the back of the head, which provides the opportunity to integrate them into the head straps of HMDs.

To identify breaks in presence (BIP), we introduce a post-experience method based on user drawings with publication [P8] [42]. After taking off the HMD participants are asked to draw their presence experience over time. For the drawing, we provide a template with the horizontal axis representing the experienced time and the vertical axis being the presence state. The amplitude of the line along the time axis indicates the experienced presence state. A break is drawn as a negative peak, which enables a participant to express its strength. The contribution additionally provides a model that summarizes all known effects of temporal variations during a presence experience. The model can be used to replace the complex drawings by compact numerical data for storage, comparison, and evaluation purposes. The descriptive model identifies phases – e.g., transition into VR – and parameters – e.g., intensity of a break in presence –. Further, the model provides a common language for researchers and practitioners to discuss challenges of temporal variations. The method was developed as a break in presence detector, based on the work of Slater and Garau [61, 20]. Instead of measuring a presence value, we try to improve the presence experience by identifying disturbances. In addition to the demonstrated usage as a BIP detector, it also enables detailed discussion of the cause of a particular event during the presence experience. Further, we propose to use it for comparison of multiple experiences, as the user can reflect on its own drawings to compare different experiences. In an application example ($N = 30$), we demonstrate the consistency in the users' drawings. The example shows that the method is able to safely detect a variety if BIPs, affecting different aspects of the presence concept.

1.5 Summary and Overview of the Thesis

With this thesis, I aim at improving the design and evaluation of head-mounted display based virtual reality experiences in *social everyday contexts*. I introduce a scale that divides the challenge into different environments, reaching out from private to public spaces (Figure 1.2). These environments indicate the social context and thus the corresponding problem space. My work structures the problem spaces and aims at finding specific solutions for the most critical challenges arising. Therefore, I present three objectives for this thesis. First, I present a concept to support the usage of HMDs in private everyday social contexts by the usage of a shared surface, e.g., a smartphone. By introducing a shared surface, I support the need of the HMD user to stay immersed in the virtual world and the need of the Non-HMD user to get into interaction with the HMD user. Second, I structure and explore the challenges appearing when using HMDs in a public context. I take into account the possibility that HMDs are used without supervision. Third, I propose methods to monitor and evaluate HMD based experiences. I focus on the development of tools that are feasible to use in everyday contexts.

Chapter 2 presents the included publications and puts it in the context of the higher research question of this thesis.

Chapter 3 discusses the presented publications with the research questions and the related work and points out directions for future work.

2
Publications Overview

In the following chapter I present the papers I include in the thesis. The structure follows the three main research questions I introduced in Section 1. To provide a better overview for the reader, Table 2.1 summarizes the papers and their primary contribution. It is followed by the three chapters that follow the structure of my research questions. Each chapter starts with a brief introduction of the papers included and how they link together. Each paper then is presented with a preview of the first two pages to enable a better impression of the original contribution and is summarized by a rewritten abstract. By rewriting the abstract I take the opportunity to clarify how each paper contributes to the general research question of this thesis. I do so, as abstracts of the single papers are focused on communicating the results on the level of the specific work and do not sort it into the bigger picture of the thesis.

The scientific *"We"* is used throughout this chapter, to emphasize the support of, or collaboration with my supervisor, colleagues and students. The originally published papers can be found as they are cited on the following pages. Since cooperation in scientific work is natural, I clarify the shares on each work in Table 3.1 (Appendix A).

	RQ	Title of Paper and Publication Venue	Research Method	Primary contribution
[P1]	RQ1	“Evaluating Shared Surfaces for Co-Located Mixed-Presence Collaboration” in *MUM’18*	Controlled experiment ($N = 40$)	The effects of having a shared surface in a mixed presence instructional task
[P2]	RQ1	“Defining Size Parameters for Touch Interaction in Substitutional Reality Environments” in *AVR ’18*	Controlled experiment ($N = 30$)	Design guide for button sizes in different visual feedback conditions when wearing an HMD
[P3]	RQ1	“Frontal Screens on Head-Mounted Displays to Increase Awareness of the HMD Users’ State in Mixed Presence Collaboration” in *arXiv e-prints*	Controlled experiment ($N = 25$)	Design Space & Guidelines for visually presenting the users’ state to bystanders
[P4]	RQ2	“Feeling Alone in Public – Investigating the Influence of Spatial Layout on Users’ VR Experience” in *NordiCHI ’18*	Field Study ($N = 58$)	Influence of visual and physical separation from random bystanders on the user experience
[P5]	RQ2, RQ3	“Public HMDs: Modeling and Understanding User Behavior around Public Head-Mounted Displays” in *PERDIS ’18*	Field Study, Observation, Semi-structured Interview ($N = 19$)	Introduction and testing of the Audience funnel flow model for HMDs
[P6]	RQ3	“The Usage of Presence Measurements in Research: A Review” in *Presence ’18*	Literature Review	Review on method to asses the feeling of being present in VR
[P7]	RQ3	“Estimating Visual Discomfort in Head-Mounted Displays using Electroencephalography” in *Interact ’17*	Controlled experiment ($N = 24$)	Showcasing the possibility to detect visual stress via EEG when using an HMD
[P8]	RQ3	“A Qualitative Post-Experience Method for Evaluating Changes in VR Presence Experience Over Time” in *arXiv e-prints*	Literature Review & Controlled experiment ($N = 30$)	Post-Experience Evaluation Method

Table 2.1: Overview on the contributions included in this thesis, the chosen research method and primary contribution.

[P1] received a Best Paper Award at the International Conference on Mobile and Ubiquitous Multimedia 2018

2.1 HMDs for the Living Room

RQ1: *How can we support HMD usage in private everyday social context?*

To address *RQ1* we propose the introduction of a shared surface, introduced with contribution [P1]. During the usage of shared surfaces in co-located mixed presence situations unique challenges arise. Altogether we contribute three research items that address these challenges, help to understand the possibilities and improve the application of shared surfaces.

[P1] Evaluating Shared Surfaces for Co-Located Mixed-Presence Collaboration


Evaluating Shared Surfaces for Co-Located Mixed-Presence Collaboration

Christian Mai, LMU Munich, Germany, Christian.Mai@ifi.lmu.de
Sarah Aragon Bartsch, LMU Munich, Germany, Sarah.Aragon.Bartsch@ifi.lmu.de
Lea Rieger, LMU Munich, Germany, Lea.Rieger@campus.lmu.de

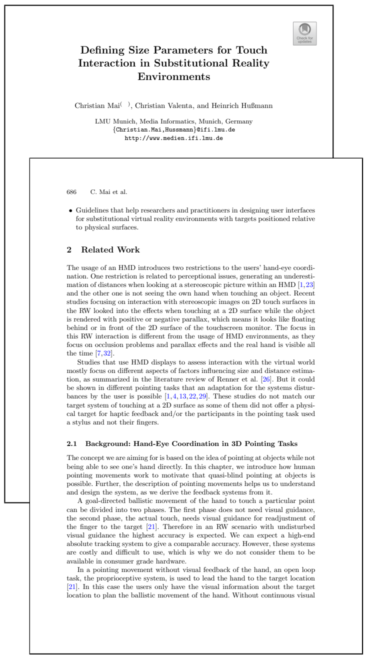
Figure 1. Collaborative task used in the study: (a) *Real_World*: shared surface without HMD (baseline), (b) *No_Avatar*: mixed-presence collaboration with a shared surface only and (c) *Avatar*: mixed-presence scenario with a rendered point-cloud avatar of the real world instructor

When wearing a head-mounted display (HMD) in everyday environments, interactions with real world bystanders often fail. A reason is the visual barrier introduced by the HMD covering the wearer's face. As a result of a failed interaction, the HMD user takes off the headset, ending the VR experience. For the Non-HMD user repeatedly failing might lead to frustration and as a result they tend to make less contact with the HMD user. This includes the risk of increasing the social exclusion of the HMD user.

From this a trade off arises. On the one hand the HMD user wants to concentrate on the VR environment without being disturbed. On the other hand there is the constant need for interaction with the people in the physical world surrounding the HMD user. Previous work reminds the HMD user of the real world by integrating the Non-HMD user in the VR. In contrast, we suggest to present a shared surface in the VR that creates a common ground to talk about. The shared surface shows the same content for both users, which is located at the same physical position in the real and the virtual world. By doing so there is no need for a direct connection between the collaborators, as they both act in their world with a display presented in their world. In a between-subject user study ($N = 40$), we investigate the effects of using a shared surface on collaboration in co-located mixed-presence scenarios. We compare the following conditions: (a) real-world collaboration (Baseline) and mixed presence conditions (b) having a shared surface only and (c) combining the shared surface with an avatar representation of the real world user in VR. We show that shared surfaces enabled the users to fulfill all tasks. The success shows that there is no need to take off the HMD as collaboration is possible. However people needed some time to adapt to the limitations of the system. For example they were not able to see each other gesturing, like pointing at objects in condition (b). Further we found significant drawbacks for condition (b) in terms of qualitative measures task-completion time, error rate and number of clarifying questions. We argue that the drawbacks might affect long term collaboration, but their effect might be limited in short term interactions. Quantitative insights into the user experience show that users did experience the drawbacks in the pragmatic quality, compared to condition (a). However participants did not report a difference in the hedonic quality of the system. Adding a 3D avatar as proposed by McGill [47] in VR improves performance measures and the experienced pragmatic quality of the system.

Mai, C., Aragon Bartsch, S., and Rieger, L. (2018a). Evaluating Shared Surfaces for Co-Located Mixed-Presence Collaboration. In *7th International Conference on Mobile and Ubiquitous Multimedia*, MUM '18, New York, NY, USA. ACM, doi:10.1145/3282894.3282910

[P2] Defining Size Parameters for Touch Interaction in Substitutional Reality Environments



Defining Size Parameters for Touch Interaction in Substitutional Reality Environments

Christian Mai, Christian Valenta, and Heinrich Hußmann

LMU Munich, Media Informatics, Munich, Germany
{Christian.Mai,Hussmann}@ifi.lmu.de
http://www.medien.ifi.lmu.de

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- Guidelines that help researchers and practitioners in designing user interfaces for substitutional virtual reality environments with targets positioned relative to physical surfaces.

2 Related Work

The usage of an HMD introduces two restrictions to the users' hand-eye coordination. One restriction is related to perceptional issues, generating an underestimation of distances when looking at a stereoscopic picture within an HMD [1,23] and the other one is not seeing the own hand when touching an object. Recent studies focusing on interaction with stereoscopic images on 2D touch surfaces in the RW looked into the effects when touching at a 2D surface while the object is rendered with positive or negative parallax, which means it looks like floating behind or in front of the 2D surface of the touchscreen monitor. The focus in this RW interaction is different from the usage of HMD environments, as they focus on occlusion problems and parallax effects and the real hand is visible all the time [7,32].

Studies that use HMD displays to assess interaction with the virtual world mostly focus on different aspects of factors influencing size and distance estimation, as summarized in the literature review of Renner et al. [26]. But it could be shown in different pointing tasks that an adaptation for the systems disturbances by the user is possible [1,4,13,22,29]. These studies do not match our target system of touching at a 2D surface as some of them did not offer a physical target for haptic feedback and/or the participants in the pointing task used a stylus and not their fingers.

2.1 Background: Hand-Eye Coordination in 3D Pointing Tasks

The concept we are aiming for is based on the idea of pointing at objects while not being able to see one's hand directly. In this chapter, we introduce how human pointing movements work to motivate that quasi-blind pointing at objects is possible. Further, the description of pointing movements helps us to understand and design the system, as we derive the feedback systems from it.

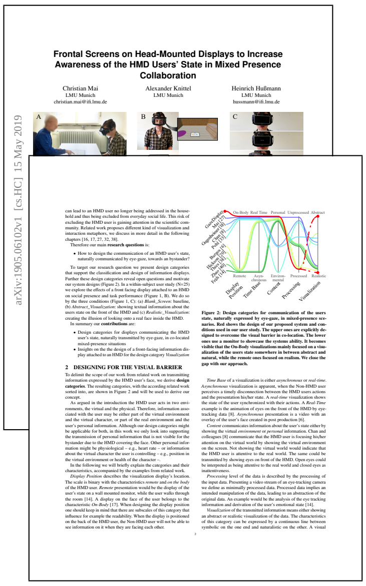
A goal-directed ballistic movement of the hand to touch a particular point can be divided into two phases. The first phase does not need visual guidance, the second phase, the actual touch, needs visual guidance for readjustment of the finger to the target [21]. Therefore in an RW scenario with undisturbed visual guidance the highest accuracy is expected. We can expect a high-end absolute tracking system to give a comparable accuracy. However, these systems are costly and difficult to use, which is why we do not consider them to be available in consumer grade hardware.

In a pointing movement without visual feedback of the hand, an open loop task, the proprioceptive system, is used to lead the hand to the target location [21]. In this case the users only have the visual information about the target location to plan the ballistic movement of the hand. Without continuous visual

The physical support of touch interaction on a 2D interface improves touch accuracy compared to mid-air pointing. When wearing a fully immersive head-mounted display (HMD) the interaction with a 2D surface can be supported by passive haptic feedback. In the particular case of this thesis, the 2D surface is the shared surface between the Non-HMD user and the HMD user used for collaboration (i.e. symmetric interaction). We assume that the physical touch surface and the visual representation in the HMD are aligned. However, HMD users can not see their hands when wearing a state of the art HMD. These HMDs usually come with hand held controllers and do not support natural pointing, e.g., by finger tracking. Therefore the HMD users' ability ot interact with the surface should be considered for the user interface design to enable the targeted symmetric interaction. To define interface parameters such as button sizes with regard to possible incorrect entries and learning abilities, we conducted a user study. In two experiments with 30 participants in total, we compared the ability of the HMD users' pointing accuracy on a 2D surface. Participants saw the surface and targets in all conditions. We compared the conditions (a) touch without visual feedback, (b) with visual feedback of the touched position, (c) a state of the art head-mounted finger tracker and (d) a real-world baseline. As a result, we give estimates for button dimensions and describe the adaptation process of the users for each feedback condition. We found that not showing feedback can be used if there is a large enough display that can be separated into two areas, but there is a drift of the touch location over time. Feedback of the touched position helps to improve precision, while accuracy is very high from the beginning. The head-mounted finger tracker provides high precision from the start, but accuracy may be limited due to calibration errors. Further the relative position of the touch surface to the user influences accuracy of the finger tracker. With our work we provide guidance for the interface design of substitutional environments, in particular for the idea of shared surfaces.

Mai, C., Valenta, C., and Hußmann, H. (2018b). Defining Size Parameters for Touch Interaction in Substitutional Reality Environments. In De Paolis, L. and Bourdot, P., editors, *Augmented Reality, Virtual Reality, and Computer Graphics*, pages 683–701, Cham. Springer International Publishing

[P3] Frontal Screens on Head-Mounted Displays to Increase Awareness of the HMD Users' State in Mixed Presence Collaboration


Frontal Screens on Head-Mounted Displays to Increase Awareness of the HMD Users' State in Mixed Presence Collaboration

Christian Mai
LMU Munich

Alexander Knittel
LMU Munich

Heinrich Hußmann
LMU Munich

arXiv:1905.06102v1 [cs.HC] 15 May 2019

2 DESIGNING FOR THE VISUAL BARRIER

The goal of a shared surface is to overcome the need for seeing the other, as the surface is shared between them. In contrast to related work, we want to foster the separation of the HMD user. It is the purpose of a virtual reality system to immerse the HMD users completely and we want to enable them to do so. Nevertheless, we found challenges in synchronizing between collaborators. Additionally not seeing the face of the HMD might affect social presence towards the HMD user. One reason is the HMD covering the wearer's face, which hinders communication during co-located mixed-presence collaboration. Therefore users take off the HMD when collaboration fails in order to restore fluid communication.

We introduce design categories based on related work that help us to identify alternatives for designing the communication of the user's state via information displays. We explore the visualization type by the three visualization conditions (a) a blank screen, (b) abstract visualization – text – vs (c) realistic visualization – displaying an imitation of the wearer's face on the front of the HMD. The results of a within-subject user study ($N = 25$) showed significant effects of abstract information visualization on collaborative performance. However there is the risk of increasing the influence on social presence with the abstract visualization perceived as robotic interaction. Additionally we found indications for a positive effect of the realistic condition (c) on social presence. However the realistic condition (c) still suffers from an uncanny valley effect, an experience of seeing a human face that looks almost real but might be not. The uncanny valley might either be introduced by the implementation or the fact that it is just not possible to look through an HMD. Based on our findings, we stress the importance of providing cues to support natural communication to facilitate successful mixed-presence collaboration.

Mai, C., Knittel, A., and Hußmann, H. (2019). Frontal Screens on Head-Mounted Displays to Increase Awareness of the HMD Users' State in Mixed Presence Collaboration. *arXiv e-prints*, arXiv:1905.06102v1

2.2 Exploring the Public

The research on using HMDs in public environments is in an early stage. Therefore, the contribution of this section aims to provide a structure to tackle the challenges.

> **RQ2:** *What are the challenges in the public usage of HMDs and how should we approach them?*

We contribute two research items to *RQ2*, to better understand and structure current challenges.

[P4] Feeling Alone in Public – Investigating the Influence of Spatial Layout on Users' VR Experience

As argued in Chapter 1, the main difference between using HMDs in traditional laboratory environments and public environments is people surrounding the user. We explain the problem space we need to take into account when designing HMD systems for public deployments. From the categories in the problem space we decided to investigate the influence of the spatial layout. Current public deployments show different concepts which can be distinguished by the visual and physical separation of the HMD user and bystanders. In contrast to lab environments, users in public environments are affected by physical threats – e.g., other people in the space running into them – but also cognitive threats – e.g., not knowing, what happens in the real world. We contribute an extensive discussion of the factors influencing a user's VR experience in public. Based on this we conducted a between-subject design user study ($N = 58$). In particular, we compared environments in which an HMD user is (a) surrounded by other people, (b) physically separated by a barrier, or (c) in a separate room. We could not show an effect in the objective measures on movement area, movement speed or acceleration. Qualitative data, igroup presence questionnaire [58] and PANAS [70], did not show a difference. We think the results are surprising, as one might expect a feeling of insecurity when acting in public while being blindfolded. The interviews revealed that the overall very positive experience might be explained by the positive attitude towards the examiner and the people in the real world.

Mai, C., Wiltzius, T., Alt, F., and Hußmann, H. (2018c). 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, New York, NY, USA. ACM, doi:10.1145/3240167.3240200

[P5] Public HMDs: Modeling and Understanding User Behavior around Public Head-Mounted Displays

Head-Mounted Displays (HMDs) are becoming ubiquitous; we are starting to see them deployed in public for different purposes. Museums, car companies and travel agencies use HMDs to promote their products. As result, HMDs lay around and are, thus, being used in public without an expert's supervision. The situation arises as not having the need for a supervising person can increase the number of public deployments and reduce the cost for running the system. However, our previous research [P5] [46] shows that the presence of an expert has a positive effect on the participants' feeling of security, and thus the whole VR experience. Previous research has shown that public display installations face similar challenges and opportunities. For example, as with public displays, public HMDs struggle to attract the passer-by's attention, but benefit from the honeypot effect that draws attention to them. In this work, we discuss how public HMDs can benefit from research in public displays. In particular, we propose an adaptation of the audience funnel flow model of public display users to fit the context of public HMD usage. In an observational field study ($N = 19$), we could show that the *Audience Funnel Flow Model for HMDs* is consistent with the process that users go through. In particular we found that most people are reluctant to use the system because they do not understand the purpose of it. Also an official person was missing that allowed the usage. Finally we found that people stopped the interaction, as they did not understand how to operate in VR. These findings are similar to findings from research on public displays and it motivates to use the knowledge. However, due to the form factor of an HMD, the need to put on and the inherent separation from others, the requirements will lead to different solutions for HMDs than those known for public displays.

Public HMDs: Modeling and Understanding User Behavior around Public Head-Mounted Displays

Christian Mai
LMU Munich
Munich, Germany
Christian.Mai@ifi.lmu.de

Mohamed Khamis
LMU Munich
Munich, Germany
Mohamed.Khamis@ifi.lmu.de

of public displays research concepts. This includes (1) mental models and (2) frameworks like the audience funnel flow model [3]. However, designing systems that attract attention and motivate users to move from one phase in the audience funnel to another one can be different in case of public HMDs compared to public displays. This might be due to HMDs having different design needs – being small, light and wearable on the user's head – to mostly big public displays that predominantly need to be visible from a long distance.

Thus in this work, we bridge the gap between research in public displays and public HMDs. We do so by reporting on a field study in which we studied the audience behavior when interacting with public HMDs. We then map this behavior to the "audience funnel" [3], which describes the phases that lead to interaction with public displays and the underlying models of attention and motivation. This allowed us to (1) adapt the model to public HMDs, with the aim to support designers of unsupervised public HMDs, (2) identify intersections between the fields of public displays and public HMDs, and (3) gain insights about the possible barriers preventing people from progressing from one stage of the audience funnel model to the following one. Based on our findings, we present novel research opportunities that are relevant to researchers and practitioners who (1) work in public displays and want to bring in their experiences to the novel area of public HMDs, as well as to those who (2) want to leverage the use of HMDs in public space. Our findings indicate that similar mental models exist for the public usage of HMDs across the phases of the audience funnel, but there are differences in the design needs for public HMDs. We discuss the novel research opportunities and challenges of public HMDs, and how existing research in public displays can be leveraged in this area.

BACKGROUND AND RELATED WORK

In this section we give a brief introduction to the audience funnel concept and introduce the terms *attention* and *motivation*, as defined in the research on public displays.

Modeling the Behavior of Public Display Users

Many models were proposed to model the behavior of public display users. Researchers proposed spatial models [42, 45] and temporal models [3, 30, 32] for the behavior of public display users. One of the most commonly used models is the audience funnel [3], which describes the different phases of interaction in front of public displays. It was first presented by Brignull and Rogers [3]. They investigated how people gather around a large public display and how they change from "onlookers" to "interaction with the display" and back again. This concept was adapted by the work of Michelis et al. [30], focusing on the observable behavior. They contributed to the model by introducing additional phases, as well as a mechanism to evaluate the conversion rate of a display, i.e., a threshold after which passers-by move from one phase to another. At the outset of interaction, a challenge for public displays is to draw attention. In a second step, the challenge is to motivate and maintain the user's motivation to interact (Figure 2). The conversation rate is determined by counting the people changing from one phase to the next. With this number, the quality of different systems can be compared [30].

In this work, we focus on the audience funnel; we study its applicability on public HMD users, and adapt it accordingly.

Audience Attention

In public environments a display is not necessarily the central point of interest for humans. People have their own intrinsic goals, like getting to an appointment in time or looking for a certain shop. The challenge for designers is to find a balance between drawing the attention of the users [37] and not overexerting them by integrating into the surrounding environment [48]. A possible approach to attract attention is by behavioral urgency – signaling the need for immediate action [11] – and surprise. Also social effects take place, such as the so called Honeypot effect, which was observed and studied in a myriad of previous works [2, 3, 20, 27, 33, 49]. The honeypot effect refers to situations where the interaction/attention of one or more user motivates others to interact/attend to with the display [3]. A further effect is the landing effect, which describes situations where people pass by a public display, stop, and then return to the display [33]. A structured way of designing and reporting studies on display blindness in the wild is introduced by Memarovic and colleagues [28]. Compared to these works, our work is the first to investigate attention to public HMDs.

Motivation to Interact

As previously mentioned, people in public environments are very likely not searching for a display to use, but will rather come across a display in a public place. Since the HMD does not have any meaning or function when not resting on a user's head, people need to be motivated to put the HMD on. Similarly, Michelis describes several building blocks that can be used to motivate people to interact with public displays. These are *Challenge and Control*, *Curiosity and Exploration*, *Choice*, *Fantasy and Metaphor* and *Collaboration* [29]. Similar to how the honeypot effect can influence attention to the display, it could also motivate users to interact with the public display. Another social aspect is the staging effect, which on one hand, some users interact solely to be noticed by others [7], while others resist interaction to avoid social embarrassment [6]. Motivation to interact with public HMDs was never studied before, our work attempts to close this gap in research.

Interaction in Public

There is a large body of research that looks into how the presence of others influences a single persons actions. People have a certain role like being an instructor or security officer which implies a certain expected behavior and will foster or prevent certain types of actions. Furthermore, people in public environments might be related to each other, e.g., they might be friends or complete strangers [14]. Models that describe these effects are, to name but few, proxemics [17] – the study of how humans physical position to each other – or social facilitation – behavior change due to the mere presence of others – (see [43] for an overview). According to Mueller et al. [32], the important factors for motivating interaction in front of public displays are *The Presentation of Self*, *The Selective Control of Access to the Self*, *The Control over one's Personal Data*, *Social Behavior*, *The Public Nature of the Space*. In contrast to the use of public displays *The Selective*

Mai, C. and Khamis, M. (2018). 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, New York, NY, USA. ACM, doi:10.1145/3205873.3205879

2.3 Methods for Monitoring and Evaluation of HMD usage

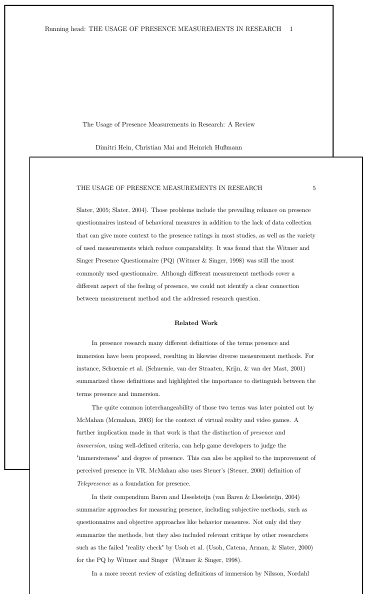
The change in contexts, from the laboratory to everyday environments, creates new demands on methods to monitor and evaluate HMD based experiences.

> **RQ3:** *What kind of methods for monitoring and evaluation fit the needs of the everyday contexts?*

To contribute to *RQ3* we provide three publications. A literature review on the tools used for the evaluation of presence [P6], one of the core measurements of a VR experience. A method for real time monitoring [P7] and for the detection of temporal variations in the presence experience [P8]. Our target is to provide tools that are suitable in the everyday context and easy to use by non professionals.

[P6] The Usage of Presence Measurements in Research: A Review

The research on presence in recent years resulted in a number of definitions and methods to measure it. Due to the variety of concepts, it is difficult to compare and interpret presence ratings of individual studies. We conducted a literature review in order to gain insight into the usage of presence measurements, including the new evolving contexts. Therefore we looked at studies using head-mounted displays and presence measurements in the years 2016 and 2017. We show that 93% of the 41 reviewed studies rely on eight presence questionnaires with the criticized Witmer and Singer Presence Questionnaire being utilized the most. Behavioral or physiological measures were only used in 3% of the studies. With our work, we aim to foster the discussion about guidelines of presence measurements that help practitioners and researchers to evaluate their work in a sustainable manner. The findings motivate our attempts to provide tools that are easy enough to use in everyday scenario.


Running head: THE USAGE OF PRESENCE MEASUREMENTS IN RESEARCH 1

The Usage of Presence Measurements in Research: A Review

Dimitri Hein, Christian Mai and Heinrich Hußmann

THE USAGE OF PRESENCE MEASUREMENTS IN RESEARCH 5

Slater, 2005; Slater, 2004). Those problems include the prevailing reliance on presence questionnaires instead of behavioral measures in addition to the lack of data collection that can give more context to the presence ratings in most studies, as well as the variety of used measurements which reduce comparability. It was found that the Witmer and Singer Presence Questionnaire (PQ) (Witmer & Singer, 1998) was still the most commonly used questionnaire. Although different measurement methods cover a different aspect of the feeling of presence, we could not identify a clear connection between measurement method and the addressed research question.

Related Work

In presence research many different definitions of the terms presence and immersion have been proposed, resulting in likewise diverse measurement methods. For instance, Schuemie et al. (Schuemie, van der Straaten, Krijn, & van der Mast, 2001) summarized these definitions and highlighted the importance to distinguish between the terms presence and immersion.

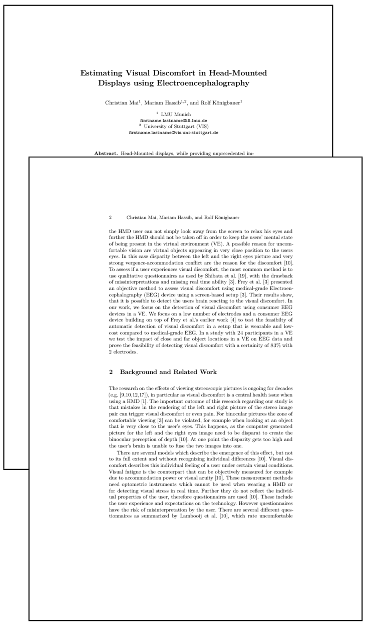
The quite common interchangeability of those two terms was later pointed out by McMahan (Mcmahan, 2003) for the context of virtual reality and video games. A further implication made in that work is that the distinction of *presence* and *immersion*, using well-defined criteria, can help game developers to judge the "immersiveness" and degree of presence. This can also be applied to the improvement of perceived presence in VR. McMahan also uses Steuer's (Steuer, 2000) definition of *Telepresence* as a foundation for presence.

In their compendium Baren and IJsselsteijn (van Baren & IJsselsteijn, 2004) summarize approaches for measuring presence, including subjective methods, such as questionnaires and objective approaches like behavior measures. Not only did they summarize the methods, but they also included relevant critique by other researchers such as the failed "reality check" by Usoh et al. (Usoh, Catena, Arman, & Slater, 2000) for the PQ by Witmer and Singer (Witmer & Singer, 1998).

In a more recent review of existing definitions of immersion by Nilsson, Nordahl

Hein, D. and Mai, C. (2018). The Usage of Presence Measurements in Research: A Review. In *Proceedings of the International Society for Presence Research Annual Conference*, Presence. ISBN: 978-0-9792217-6-7

[P7] Estimating Visual Discomfort in Head-Mounted Displays using Electroencephalography



Estimating Visual Discomfort in Head-Mounted Displays using Electroencephalography

Christian Mai[1], Mariam Hassib[1,2], and Rolf Königbauer[1]

[1] LMU Munich
firstname.lastname@ifi.lmu.de
[2] University of Stuttgart (VIS)
firstname.lastname@vis.uni-stuttgart.de

Abstract. Head-Mounted displays, while providing unprecedented im-

2 Christian Mai, Mariam Hassib, and Rolf Königbauer

the HMD user can not simply look away from the screen to relax his eyes and further the HMD should not be taken off in order to keep the users' mental state of being present in the virtual environment (VE). A possible reason for uncomfortable vision are virtual objects appearing in very close position to the users eyes. In this case disparity between the left and the right eyes picture and very strong vergence-accommodation conflict are the reason for the discomfort [10]. To assess if a user experiences visual discomfort, the most common method is to use qualitative questionnaires as used by Shibata et al. [19], with the drawback of missinterpretations and missing real time ability [3]. Frey et al. [3] presented an objective method to assess visual discomfort using medical-grade Electroencephalography (EEG) device using a screen-based setup [3]. Their results show, that it is possible to detect the users brain reacting to the visual discomfort. In our work, we focus on the detection of visual discomfort using consumer EEG devices in a VE. We focus on a low number of electrodes and a consumer EEG device building on top of Frey et al.'s earlier work [4] to test the feasibilty of automatic detection of visual discomfort in a setup that is wearable and low-cost compared to medical-grade EEG. In a study with 24 participants in a VE we test the impact of close and far object locations in a VE on EEG data and prove the feasibility of detecting visual discomfort with a certainity of 83% with 2 electrodes.

2 Background and Related Work

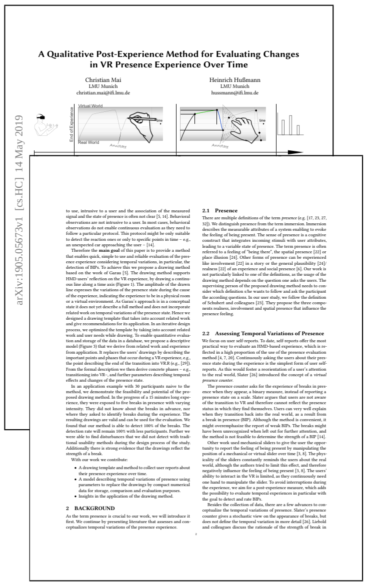
The research on the effects of viewing stereoscopic pictures is ongoing for decades (e.g. [9,10,12,17]), in particular as visual discomfort is a central health issue when using a HMD [1]. The important outcome of this research regarding our study is that mistakes in the rendering of the left and right picture of the stereo image pair can trigger visual discomfort or even pain. For binocular pictures the zone of comfortable viewing [3] can be violated, for example when looking at an object that is very close to the user's eyes. This happens, as the computer generated picture for the left and the right eyes image need to be disparat to create the binocular perception of depth [10]. At one point the disparity gets too high and the user's brain is unable to fuse the two images into one.

There are several models which describe the emergence of this effect, but not to its full extent and without recognizing individual differences [10]. Visual discomfort describes this individual feeling of a user under certain visual conditions. Visual fatigue is the counterpart that can be objectively measured for example due to accommodation power or visual acuity [10]. These measurement methods need optometric instruments which cannot be used when wearing a HMD or for detecting visual stress in real time. Further they do not reflect the individual properties of the user, therefore questionnaires are used [10]. These include the user experience and expectations on the technology. However questionnaires have the risk of misinterpretation by the user. There are several different questionnaires as summarized by Lambooij et al. [10], which rate uncomfortable

Head-Mounted displays can substantially add mental workload and visual strain on users. Both effects can limit the ability to feel present in the virtual world and even worse have negative impact on the user's health. Everyday contexts have a number of challenges that lead to these effects. In private households, users are very likely to use the HMD without professional supervision. Current approaches for these environments limit the time an HMD might be used, which only takes long-term effects into account. In addition, novice users often do not know what to expect and as a result accept visual stress as being state of the art. Therefore, the work with these new user groups also comprises a risk in semi-public and public environments. Participants not reporting about stress makes it difficult for system operators to detect negative impact on the user. Hence, the only indication for possible visual stress is the duration of usage. Assessing visual discomfort is currently possible through questionnaires and interviews that interrupt the interaction, do not enable real time monitoring and provide only subjective feedback. We suggest to use Electroencephalography (EEG) to gain insights about the visual discomfort of HMDs. We evaluate the use of a consumer-grade EEG for estimating visual discomfort during HMD usage in a study with 24 participants. Our results show that the usage of a BCI in combination with an HMD, to detect uncomfortable viewing conditions is possible. We gained a accuracy of 83% with a binary classifier in our study. Further, our results indicate that only two to four electrodes are necessary, which can easily be integrated into the head mount of an HMD. This can pave the way for designing adaptive virtual reality experiences that consider user visual fatigue without disrupting immersiveness.

Mai, C., Hassib, M., and Königbauer, R. (2017). Estimating Visual Discomfort in Head-Mounted Displays using Electroencephalography. In *Proceedings of the 16th IFIP TC13 International Conference on Human-Computer Interaction*, INTERACT '17, pages 243–252, Cham. Springer International Publishing, doi:10.1007/978-3-319-68059-0_15

[P8] A Qualitative Post-Experience Method for Evaluating Changes in VR Presence Experience Over Time



A particular measure to evaluate an HMD based experience is the state of feeling present in virtual reality. Existing methods either lack in taking breaks in presence (BIP) into account – questionnaires – or are complex in their application and evaluation – physiological and behavioral measures –. Inspired by Slater and Steeds virtual presence counter, we aim at a method that identifies single disruptive events, the BIPs. We argue that consumer-grade HMD systems are generally able to provoke a high sense of presence in VR for the user. However, singular events during the experience – e.g., noise from the real world – or temporal events – a boring experience – can have negative short-term effects on presence. To provide a practical approach, we propose a post-experience method based on user drawings. After ending the VR experience, we ask the user to draw a line expressing the course of the presence state during the experience. The template we provide for the drawing shows the time along the horizontal axis with the state of presence orthogonal to it. Markings along the time axis indicate the moment when taking the HMD on and off to provide some reference for the user. The amplitude of the line drawn by the user expresses the feeling of being present, either in the virtual – above the time axis – or in the real world – below the time axis –. Users are asked to comment on their drawings to enable the connection between experience and cause for later evaluation. Further, we provide application instructions and discuss alternatives for the template design serving different scenarios.

The resulting drawings can vary in two ways. First, the time axis does not reflect the absolute time of the experience's cause and is used by each participant differently. Second, the users express the strength of a BIP differently along the vertical axis. To make the drawings comparable, we propose a descriptive model that objectively describes the drawing. Deriving compact numerical data from the drawings enables storage, comparison, and evaluation. The descriptive model for temporal variations of presence includes points, phases, and parameters derived from related work on the research of the presence experience. With this data, one does not need to work with the absolute drawings, but can use mathematics approaches to analyze the data. In particular, a drawn BIP caused by the same event does not have to be in the same position within the drawing template as the points of the model describe it with numbers.

An example for a relevant point is the moment one puts on the HMD. A phase during the cause of experience is the transition into VR and an exemplary parameter the strength of a BIP. Besides enabling the automated analysis of user drawings, the model supports practitioners in understanding the effects of temporal variations. Further, the model provides the opportunity for a common language within the research and commercial community for challenges, which still is lacking. In an exploratory user study ($N = 30$) participants went through a gamified experience that did not include any BIPs by default. We introduced certain BIPs with varying strength and addressing different factors loading on the overall presence experience. The result shows that the drawings are remarkably consistent across the participants and that the method can detect all BIPs. There is also evidence that participants use the drawings to express the strength of BIPs. With our method practitioners and researchers can accelerate the evaluation and optimization of experiences by detecting BIPs. The ability to store objective parameters paves the way for automated evaluation methods and big data approaches.

Mai, C. and Hußmann, H. (2019). A Qualitative Post-Experience Method for Evaluating Changes in VR Presence Experience Over Time. *arXiv e-prints*, arXiv:1905.05673v1

3 Discussion and Future Work

This thesis contributes to solving the challenges arising from the application of HMDs in everyday social contexts. In previous decades, HMDs were primarily used in laboratory environments under professional supervision. The tools and methods developed in related research form the foundation for today's advance of consumer-grade HMDs. Everyday contexts, however, demand a critical discussion and a rethinking the usage of existing practices from the laboratory context.

This thesis, therefore, reached out to structure unknown challenges existing in everyday contexts. I presented concrete solutions for the private context. In particular, I introduced the concept of a shared surface to support co-located mixed presence collaboration (see Section 2.1; [P1]-[P3]). My research was targeted on a better understanding of the challenges when using a shared surface as a proxy between a Non-HMD and an HMD user. To further investigate the novel contexts, I analyzed and structured the challenges arising in a public environment (see Section 2.2; [P4],[P5]). I showed that the social context plays an important role in these environments and found that a major challenge is the applicability of existing research methods. To support future research, I provided a problem space and a method to understand and analyze user behavior around HMDs deployed in public. The third thematic block of my work, the development of new methods for the public context, was based on the realization that there are only a few methods feasible for the everyday context. I introduced two methods to monitor and evaluate HMD-based experiences, in particular, to find breaks in presence (see Section 2.3; [P5]-[P8]). Although my research focused on methods for everyday contexts, the presented methods can also be applied to a laboratory context.

In this last chapter, I discuss my contribution to the original research questions. From the discussion, I derive questions that can inform future work on the topics.

3.1 Integration of HMDs in Private Environments

The usage of an HMD in a private context makes an HMD user a social actor [24]. Therefore I asked RQ1: *"How can we support HMD usage in private everyday social contexts?"*. Interruptions by others are a central challenge in the social context [47]. Methods known from the work on distributed environments can be used to support the mixed presence situation. However, the use of these methods leads to an artificial separation between a Non-HMD user and an HMD user (e.g., in [29, 51, 65]). Another solution is to make use of the co-location in a home environment by integrating the Non-HMD user's action into the VR experience. Other work proposes an explicit integration of the Non-HMD user via a video stream [47]. Both approaches have in common that they create an asymmetry of information and interaction possibilities between a Non-HMD and an HMD user. Leveraging the asymmetry [24] is a valuable approach in a mixed presence gaming scenario. However, an asymmetric system design does not provide sufficient awareness of the workspace to support successful collaboration. Therefore I aimed at a symmetric system design. Further, an explicit integration of a Non-HMD user is distracting an HMD user in several ways. First, it is reminding an HMD user about the real world, which interferes with the illusion to be at another place. Secondly, a visualization can conflict with the virtual environment, for example through interferences. Thirdly, the integration of a 2D or 3D abstraction of the person outside the virtual environment is challenging in terms of technology. It is also difficult to embed the Non-HMD user's stream into the virtual world.

With contribution [P1] I showed that a shared surface is sufficient to support collaboration. The shared surface creates a symmetric system design in a co-located mixed-presence situation. A proxy, like a smartphone that exists in every household, would be used to communicate between the collaborators. The HMD user can take the physical smartphone and act with it like in reality, while the attention stays in the virtual world. Additionally, representing the Non-HMD user in VR helps to decrease errors and task completion time, which reinforces McGill's approach [47]. However, the avatar representation cannot fully simulate a real-world-scenario, yet. In our study, people experienced the shared surface with a lower pragmatic quality compared to seeing the real world user. In contrast the hedonic quality was the same with and without an avatar present. At the same time participants adapted to the restrictions influencing the pragmatic quality of the system. By getting used to the system, the subjective perception and objective quality in using the system could improve over time. Therefore, the simplicity of a shared surface and its adoption by users should be researched in real-world situations. Today it is difficult to make such a comparison, as there are too few users that integrated these technologies into their lives. Hence, with the further success of HMDs in everyday contexts, comparison of my approach and the related work in the field will be necessary.

To this point, I can only speculate on the outcome of the comparison, with slight favor for the shared surface. As argued above, there are drawbacks in the quality of collaboration when using a shared surface, which could diminish over time. Still, I do not think that most collaborations in an everyday context require seeing the other person in VR. An exemplary situation is an HMD user laying in bed or sitting on a couch next to a Non-HMD user. Both might be focused on their tasks while talking and therefore naturally not look at each other. A smartphone could easily be handed over from a Non-HMD user to an HMD user and serve the communication. The HMD would receive the content visible on the smartphone screen and display it in the virtual world. By this action of sharing the smartphone as a haptic proxy the social presence is created by the joint action [6], without the reported negative impacts of a video stream of the surrounding in VR. In addition, the shared surface overcomes the practical issue of integrating an HMD user in VR, by filming or tracking the Non-HMD user.

Although, I argued above for the shared surface as a superior solutions, this might only hold for particular situations during the day in a household. There may be other situations that require less or even more support from a system in mixed presence interaction than our concept can provide. An example for less needed interaction is the notification of an HMD user about the presence of another person. As a notification, a beep may be sufficient to inform the HMD user of the presence of the non-HMD user. More interaction possibilities by a mixed presence system are needed for instance in the mixed-presence gaming scenario by Gugenheimer [24]. Future research should aim on field research in order to classify the use cases and needs on the tools better than it is possible from a research laboratory. Our solution might cover a certain range of these tasks, but more tools are needed to cover the full bandwidth of possible situations.

To enrich the interaction possibilities of the shared surface, I provide design recommendations for its interface, in particular for button dimensions. As shown in [P2], an HMD user's interaction possibilities are limited when interacting with a physical surface due to the coverage of the user's eyes. The users cannot see their hands anymore and therefore pointing accuracy towards a physical target on the surface is limited. In [P2] I addressed the interface design of a table top surface. In the future, when a smartphone is used as a shared surface, the need for interface design will depend on how people hold the device. If a Non-HMD user holds the smartphone, an HMD user faces the same situation as in our study in [P2]. However, when an HMD user holds the smartphone, interaction possibilities might improve. By holding the smartphone, HMD users are supported by the haptics of the smartphone, which they can use as a reference during the pointing task. Related work on the research on mobile offices in VR [21] addresses similar issues. For example the question of how visual feedback influences the interaction with a physical keyboard [22, 33, 47]. Still the research on using smartphones as input devices while being in VR is limited.

[P1] and [P2] mainly focused on connecting an HMD user with the outside world. In contrast [P3] was intended to explore the integration of an HMD user in the social context in the real world. By introducing the idea of a front-facing display, I aimed to enhance the awareness of a Non-HMD user about an HMD user's state [P3]. I found that current research looks into tracking a user's face and expressions under the HMD. They then overlay the tracking result with high visual fidelity onto a video stream, making the HMD disappear, leading to the illusion of being able to see the HMD user. However, the result is presented on a remote screen. Another branch of research suggested mounting displays on an HMD to provide non-HMD users with information about the virtual world. Since they used abstract visualizations, the possibilities of creating social proximity may be limited. I combined these approaches because I suspected that, regarding social presence, an abstract visualization would create a different experience for the Non-HMD user than a realistic one. To investigate this field of tension, I compared the communication of the user status through an abstract and realistic representation on a front-facing screen on an HMD. We demonstrated the benefits that are introduced when there is information available about an HMD user's state in general. However, we could not find clear indications that showing a realistic face on an HMD improves social presence for a Non-HMD user or the quality of collaboration. When abstract information about the HMD users state was shown, we found that there could be negative effects on social presence. Users described it to be robotic. That means instead of bringing the co-locaties closer together by improving the awareness there is the risk of increasing the separation.

In summary, in line with related work, I found that there is a benefit of designing for the visual and cognitive separation of Non-HMD and HMD users [P1, P3]. As I argued above, none of the solutions available today might fit all use cases in the everyday context. The reasons are technological challenges and complexity of the system design. Also design decisions, like providing asymmetric or symmetric interfaces fulfill different needs of the users. The limitation of all existing studies is their laboratory-based approach. However, I argued in the Introduction (Chapter 1) that the interplay between consumers and their adoption of technology often leads to a reconsideration of design concepts. My work helps to understand possible design alternatives for the everyday practice. Future work will have to revisit the proposed concepts by related work and me, for their applicability and effects in the field.

As a final remark for this chapter, I would like to stress that HMDs can have an even stronger impact on the separation between people in a household than smartphones do today. As developers of immersive systems, we must be aware that our design considerations should not focus solely on the user experience of an HMD user. As I wrote in the introduction for research question one (Section 1.2), Nintendo did not continue to invest in VR because it was not social. Based on the experience I made throughout the studies, I argue that VR is not social because we do not design for that. I believe that there is a strong need for future research to find solutions to the social barrier problem, to make HMDs a success in private context.

3.2 Usage of HMDs in Public Environments

The second part of this thesis explored HMD usage in public spaces based on the question RQ2: *"What are the challenges in the public usage of HMDs and how should we approach them?"*. I found that there is a gap in understanding the problem space leading to design challenges in these environments. Therefore, I aimed at understanding the problem space better, with a focus on the social context. There is a long history of research on the impact of others on a single human's behavior, e.g., proxemics or social facilitation (see [P4] for a detailed discussion). Surprisingly we could not observe significant changes in user experience or behavior similar to the known effects presented in [P4] and [P5]. This is caused by the effect that existing methods to evaluate HMD experiences do not fit the need of everyday contexts. Finding that the methods had shortcomings, resulted in the work on new methods and tools I ask for in RQ3 (Section 1.4). Another reason not to detect an effect could be the presence of a supervising person. People reported that this supervising gave them the feeling of security during their experience in public. We expected such effects caused by the supervising person in [P4] and tried to limit the effects while keeping in mind the safety of participants in public. Our findings underline the assumption that the social context plays an important role in the use of HMDs. Future research should further analyze these effects, in particular when designing HMD systems that are intended to be deployed without supervision. If the effect of a supervisor being present during the development phase is not taken into account, the final system design might be biased.

With the contribution of [P5] I investigated the potential of research on public displays for the unsupervised public deployment of HMDs. I found that the research on public displays has an overlapping problem space with public usage of HMDs. Therefore, in [P5] I propose the *audience funnel flow model for HMDs*, based on the related work. The *audience funnel flow model* adds a time component to the problem space that divides the user story into six single stages. The stages range from the moment when potential users could detect the HMD to the follow-up actions when they inform others about the experience. The combination of contribution [P4] and [P5] can serve as the base of an evaluation process. In particular, [P4] provided an understanding of factors influencing the user experience concerning the environment. These properties of the problem space from [P4] can be analyzed separately in each stage of [P5]. For future research, I recommend following the stages of the *audience funnel flow model for HMDs* to challenge the problem space. For example, a future research project could investigate on the role and integration of the person accompanying an HMD user.

The consequent analysis of the problem space and adaption from related work can lead to new research opportunities and the creation of guidelines and methods. An exemplary conflict showcasing the varying needs of using HMDs in public is that public displays should work without touching them. In contrast, HMDs need to be touched and even be put on the head. Regarding the social context, I found differences between related work from other fields and the usage of HMDs. Users passing by in a social group tend to explore a public exhibit as a community. For example, the experience *WorldBeat* offered two drumsticks [7], that were intended to be used by a single user. During the deployment, the sticks were shared by handing them over between users to integrate the group into the experience. The action of sharing was inherent in the system design and could, therefore, be easily adapted by users themselves. Current consumer grade HMDs are not designed for such behavior, although it is recommended to support collaboration [7]. A possible re-design might be to remove an HMD's head-strap and mount it on a stick like a stereoscope. However, such a device would limit the possible interaction with the VR environment. The examples above indicate that there are additional opportunities to improve a public HMD-based experience, by consequently taking into account the knowledge from related fields.

In summary, I found that the impact of the social context in public exhibitions using HMDs is currently an underestimated challenge. To address this challenge, I propose to use findings from related research areas for the use of devices in public. My work contributes to this by providing insights into the challenges in public scenarios and a methodological framework to address them.

3.3 Methods for Design and Evaluation of HMD usage in Everyday Social Contexts

In the third part of this thesis, I asked the question RQ4: *"How do we monitor and evaluate HMD experiences in the everyday contexts?"*.

Existing methods to monitor and evaluate VR experiences do not fulfill the requirements of everyday contexts and needs of practitioners. They are difficult to apply and not accurate enough to detect differences in alternative system designs. Additionally, practical methods do not offer the possibility to detect breaks in presence that disturb the VR experience. I see the later as an issue, given that the general quality of modern HMDs is very high. Hence, the overall presence experience to be in VR will be excellent. However, single events can have a negative impact on the user experience and hence disturb the feeling of being present in VR.

We conducted a literature review providing an overview of existing methods to evaluate HMD experiences, in particular, the measurement of presence. The results give insights into the tools currently used to evaluate the presence experience of an HMD user [P6]. We found a heavy reliance on questionnaires and show that mostly the controversially discussed Witmer and Singer presence questionnaire is used. The dependence on questionnaires shows the need of researchers and practitioners for practical tools. Therefore, I want to underline with my work that it is necessary to develop more precise methods that are easily applicable to overcome the limitations of questionnaires. In my work I argued that instead of measuring a single overall presence value, one might focus on the detection of events that disturb the presence experience. Slater [61] already introduced the idea of looking for breaks in presence. He argued that people have difficulty recognizing and expressing when something is positive for them, but they can express how much something bothers them. This argumentation is in line with the idea of measuring discomfort instead of comfort established in the field of ergonomics. Hence, for future work I suggest to proceed with the research on evaluation methods. Further, we need to gain a better understanding on the users' experience during a break in presence. A particular example could be a combination of physiological measurements and subjective assessments. A more precise tool could be developed by combining a heart rate measurement and the drawing method I presented in [P8]. The heart rate could give clues to the exact occurrence of a break in presence during an experience, and the drawing method would allow the user to evaluate the break. Furthermore, the detection of a break in the heart rate signal could be used to save a screenshot of the virtual scene at that moment. When drawing the experience, the screenshot could be used on the drawing sheet's timeline to remind the user that the disturbance occurred. This reminder would be especially interesting if the experience is very long. In a more broader sense we need to better understand how a BIP evolves over time. E.g., users might be able to recover very fast from a very strong break and reestablish a strong feeling of being present. However, a boring experience with limit interaction possibilities at first would not show a real break, but users might do hard to feel present in the experience.

Further, I want to highlight that there is still no common understanding of the presence concept between researchers and disciplines, as it was criticized before [15, 55]. Missing standardization makes it difficult to compare different systems evaluated with different tools. Future researchers might not be able to interpret the measured values or even reusing them for meta-analysis. With the growing number of public HMD deployments, there will be a growing need to control and evaluate the capabilities of these systems. Designers of VR experiences, operators and independent institutions will need a common language and standardized measures to communicate with each other.

I proposed the usage of EEG to detect visual stress of an HMD user caused by an HMD ([P7]). I did so, as I found that people tend not to report issues that are based on the visual system. They often believe that these disturbances are normal or forget single events as time goes by. We prove the feasibility when using a consumer grade EEG in combination with an HMD and show a high detection rate for negative visual stimuli of 84%. The physiological measurement enables the real-time assessment of an HMD system based on user perception. In contrast to analyzing the VR system's output, like monitoring the scene for flickering textures, this approach reduces the risk to miss disturbing stimuli. We could identify the most promising electrodes that can easily be integrated into an HMD. In the future, conventional HMDs will be equipped with more sensors, e.g., eye-tracking. Future work should, therefore, take into account the possibilities of these sensors. They are mainly thought to improve the immersive quality of a VR system. With a growing number of unattended HMD users, these sensors might additionally help to ensure the wearer's health and well-being. There might be other opportunities like the detection of cognitive attention shifts towards the real world, breaks in presence, based on the physiological measures. The BIPs might be caused by the user being afraid of colliding with physical objects or trying to localize an approaching Non-HMD user. To detect these attention shifts, I propose to investigate the combination of information about the virtual world, behavioral measures, and physiological measures. For example, it might be possible to detect when users are afraid of hitting physical objects around them. Behavioral measures might then show slower or less accelerated movements of the HMD user. The knowledge about the virtual world would provide insights on the current task. Finally, the physiological measures could give indications for the user's stress level. By combining this kind of information, the system might be able to tell if the user currently is moving slowly because of the virtual scene or because of physical threats in the real world. As a result, the system could provide additional support to the user to overcome the particular fear. Such a tool might be used to ensure to detect and eliminate stimuli from the real world, negatively influencing the user's experience.

Finally, I presented a method that allows users to express their perception of temporal variations in the presence experience [P8]. With the drawing method, I addressed the need to detect issues in a VR experience, which have a negative influence on presence in VR. So far, HMD experiences are mainly evaluated by the use of questionnaires and interviews, which do not support the detection adequately. To enable fast and easy detection of BIPs I recommend to use the drawing method. Not only does it help HMD users to reflect on their own experience. Even more, it gives an HMD user and the interviewer a base for discussion. For example, it enables the user to compare two immersive experiences graphically. An interviewer and an HMD user can discuss the drawings in order to avoid misunderstandings. Furthermore, the discussion based on the drawing can help to gain deeper insights into the progress of the presence experience over time. In addition to the method, I provided a descriptive model of the progress of a presence experience during an HMD session. The descriptive model enables the storage of the drawings in a database for further statistical analysis. Our study in [P8] focused on demonstrating the feasibility of the method. Future work may make use of our tool and create a more in-depth understanding of the user drawings. In particular the single phases, like the transition into VR can be explored in more detail with the help of our method. I encourage researchers and practitioners to apply the method, as there is a lot of potential for the application and need to better understand how the method will perform.

In summary, I contributed to RQ3 by investigating on currently used methods to evaluate an HMD user's experience. I provided two practice-oriented tools, the detection of visual stress by EEG and the drawing method to detect BIPs that help to identify single disruptive events. From the experience, I made during my work on these approaches I found that there is a strong need for these tools. As development and research is accelerating through the proliferation of HMDs, the need to provide valid measurements to compare designs is getting even more critical. However, the given methods are not sufficient yet. With my approaches, I want to stimulate this work and encourage researchers to build upon my contributions to provide the tools that are needed in the future.

3.4 Final Remarks

At the beginning of the thesis, I cite Nintendo, which argued not to invest in VR as it is not social [14]. They argued that to make VR a success it needs to be designed to be social. During the progress of my work, I found many indications that Nintendo might be right with their claim. 2016 Oculus shipped the first consumer-grade HMD to the end consumer market. Consumers had many concerns about these systems like low resolution of the screens, a small field of view and the need for a cable connection to the computer. The industry reacted to that and started to develop systems that have high resolution, improved field of view and even work without a cable connecting them to a computer. However, until today there are no advances in the design of consumer-grade HMDs that address the social context they are used in. The quote that states that Nintendo is not doing VR in the beginning of my thesis (Section 1.2, [14]) is from 2015. To the end of working on my thesis in 2019, Nintendo announced the Labo-VR kit [50]. The core of the system is to put a Nintendo Switch into a cardboard VR headset, which is in contrast to other manufacturers aiming for high-end HMDs. Nintendo differs, as they design for social activity. They provide a system design that can be collaboratively built and explored by the users. Further, the HMD does not have a head strap, which fosters a social experience, as one can easily hand the device over. They do so, as they take into account the social context, as I and work related to my thesis argued before. I do not know yet if the specific concept of Nintendo will be a success. However, the playful concepts of Nintendo show that the consideration of the social context leads to new design decisions.

With my thesis, I want to make others aware of these challenges and motivate further work on it. I hope that my contribution to defining and understanding the challenges in everyday social contexts will serve as a starting point for others.

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Appendices

A
Original Publications

Table 3.1 shows the share of my work in the contributions included in this thesis. The according contributions can be found as cited in *"Chapter 2 Publications Overview"*.

	My Contribution	Contributions of others
[P1]	Original research idea and study design; First prototype of the apparatus for the user study; Statistical analysis; Leading author of the resulting paper	Implementation of the apparatus for the user study (Lea Rieger); Conducting the user study and coding of the videos (Lea Rieger); Writing the paper (Sarah Aragon Bartsch)
[P2]	Original research idea and study design; Supervision of the study design and implementation; Statistical analysis; Leading author of the resulting paper	Implementation of concept for user study (Christian Valenta); Conducting the user study (Christian Valenta); Writing the paper (Heinrich Hußmann)
[P3]	Original research idea; Supervision of the study design and implementation; Leading author of the resulting paper	Study design and implementation (Alexander Knittel); Writing the paper (Alexander Knittel, Heinrich Hußmann)
[P4]	Original research idea; Supervision of the study design and implementation; Analysing the data and statistics; Leading author of the resulting paper;	Study design and implementation (Tim Wiltzius); Coding of collected video, interview and drawing data (Tim Wiltzius); Supervision of the study design (Florian Alt); Study design (Heinrich Hußmann); Writing the paper (Florian Alt, Heinrich Hußmann)
[P5]	Original research idea and study design; Implementation; Conducting the user study, coding and statistics; Leading author of the paper	Writing the paper (Mohamed Khamis)
[P6]	Original research idea; Literature review; Writing the paper	Literature review (Dimitri Hein); Leading author of the paper (Dimitri Hein)
[P7]	Original research idea; Supervision of the study design and implementation; Leading author of the paper	Supervision of the study design and implementation (Mariam Hassib); Implementation and conduction of the user study (Rolf Königbauer); Statistics (Mariam Hassib; Rolf Königbauer); Writing the paper (Mariam Hassib)
[P8]	Original research idea and study design; Supervision of the study design and implementation; Concept for and supervision of Android App; Analysis and statistics of the study results; Leading author of the paper	Implementation and conduction of the user study (Niklas Thiem); Analyzing the data (Niklas Thiem); Writing the Paper (Heinrich Hußmann)

Table 3.1: Clarification of contributions on the publications included in this thesis.

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

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

München, den 15. Mai 2019

Christian Mai