Virtual Reality Interfaces for Seamless Interaction with the Physical Reality

Dissertation

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Ceenu George

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Erstgutachter: Prof. Dr. Heinrich Hussmann
Zweitgutachter: Prof. Dr. Sidney Fels
Drittgutachter: Prof. Dr. Katrin Wolf

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ABSTRACT

In recent years head-mounted displays (HMDs) for virtual reality (VR) have made the transition from research to consumer product, and are increasingly used for productive purposes such as 3D modeling in the automotive industry and teleconferencing. VR allows users to create and experience real-world like models of products; and enables users to have an immersive social interaction with distant colleagues. These solutions are a promising alternative to physical prototypes and meetings, as they require less investment in time and material.

VR uses our visual dominance to deliver these experiences, making users believe that they are in another reality. However, while their mind is present in VR their body is in the physical reality. From the user's perspective, this brings considerable uncertainty to the interaction. Currently, they are forced to take off their HMD in order to, for example, see who is observing them and to understand whether their physical integrity is at risk. This disrupts their interaction in VR, leading to a loss of *presence* – a main quality measure for the success of VR experiences. In this thesis, I address this uncertainty by developing interfaces that enable users to stay in VR while supporting their awareness of the physical reality. They maintain this awareness without having to take off the headset – which I refer to as *seamless* interaction with the physical reality. The overarching research vision that guides this thesis is, therefore, to reduce this disconnect between the virtual and physical reality.

My research is motivated by a preliminary exploration of user uncertainty towards using VR in co-located, public places. This exploration revealed three main foci: (a) security and privacy, (b) communication with physical collaborators, and (c) managing presence in both the physical and virtual reality. Each theme represents a section in my dissertation, in which I identify central challenges and give directions towards overcoming them as have emerged from the work presented here.

First, I investigate security and privacy in co-located situations by revealing to what extent bystanders are able to observe general tasks. In this context, I explicitly investigate the security considerations of authentication mechanisms. I review how existing authentication mechanisms can be transferred to VR and present novel approaches that are more usable and secure than existing solutions from prior work.

Second, to support communication between VR users and physical collaborators, I add to the field design implications for VR interactions that enable observers to choose opportune moments to interrupt HMD users. Moreover, I contribute methods for displaying interruptions in VR and discuss their effect on presence and performance. I also found that different virtual presentations of co-located collaborators have an effect on social presence, performance and trust.

Third, I close my thesis by investigating methods to manage presence in both the physical and virtual realities. I propose systems and interfaces for transitioning between them that empower users to decide how much they want to be aware of the *other* reality. Finally, I discuss the opportunity to systematically allocate senses to these two realities: the visual one for VR and the auditory and haptic one for the physical reality. Moreover, I provide specific design guidelines on how to use these findings to alert VR users about physical borders and obstacles.

Zusammenfassung

In den letzten Jahren haben Head-Mounted-Displays (HMDs) für virtuelle Realität (VR) den Übergang von der Forschung zum Konsumprodukt vollzogen und werden zunehmend für produktive Zwecke, wie 3D-Modellierung in der Automobilindustrie oder Telekonferenzen, eingesetzt. VR ermöglicht es den Benutzern, schnell und kostengünstig, Prototypen zu erstellen und erlaubt eine immersive soziale Interaktion mit entfernten Kollegen. VR nutzt unsere visuelle Dominanz, um diese Erfahrungen zu vermitteln und gibt Benutzern das Gefühl sich in einer anderen Realität zu befinden.

Während der Nutzer jedoch in der virtuellen Realität mental präsent ist, befindet sich der Körper weiterhin in der physischen Realität. Aus der Perspektive des Benutzers bringt dies erhebliche Unsicherheit in die Nutzung von HMDs. Aktuell sind Nutzer gezwungen, ihr HMD abzunehmen, um zu sehen, wer sie beobachtet und zu verstehen, ob ihr körperliches Wohlbefinden gefährdet ist. Dadurch wird ihre Interaktion in der VR gestört, was zu einem Verlust der *Präsenz* führt - ein Hauptqualitätsmaß für den Erfolg von VR-Erfahrungen. In dieser Arbeit befasse ich mich mit dieser Unsicherheit, indem ich Schnittstellen entwickle, die es den Nutzern ermöglichen, in VR zu bleiben und gleichzeitig unterstützen sie die Wahrnehmung für die physische Realität. Sie behalten diese Wahrnehmung für die physische Realität bei, ohne das Headset abnehmen zu müssen - was ich als *nahtlose* Interaktion mit der physischen Realität bezeichne. Daher ist eine übergeordenete Vision von meiner Forschung diese Trennung von virtueller und physicher Realität zu reduzieren.

Meine Forschung basiert auf einer einleitenden Untersuchung, die sich mit der Unsicherheit der Nutzer gegenüber der Verwendung von VR an öffentlichen, *geteilten Orten* befasst. Im Kontext meiner Arbeit werden Räume oder Flächen, die mit anderen ortsgleichen Menschen geteilt werden, als *geteilte Orte* bezeichnet. Diese Untersuchung ergab drei Hauptschwerpunkte: (1) Sicherheit und Privatsphäre, (2) Kommunikation mit physischen Kollaborateuren, und (3) Umgang mit der Präsenz, sowohl in der physischen als auch in der virtuellen Realität. Jedes Thema stellt einen Fokus in meiner Dissertation dar, in dem ich zentrale Herausforderungen identifiziere und Lösungsansätze vorstelle.

Erstens, untersuche ich Sicherheit und Privatsphäre an öffentlichen, geteilten Orten, indem ich aufdecke, inwieweit Umstehende in der Lage sind, allgemeine Aufgaben zu beobachten. In diesem Zusammenhang untersuche ich explizit die Gestaltung von Authentifizierungsmechanismen. Ich untersuche, wie bestehende Authentifizierungsmechanismen auf VR übertragen werden können, und stelle neue Ansätze vor, die nutzbar und sicher sind.

Zweitens, um die Kommunikation zwischen HMD-Nutzern und Umstehenden zu unterstützen, erweitere ich das Forschungsfeld um VR-Interaktionen, die es Beobachtern ermöglichen, günstige Momente für die Unterbrechung von HMD-Nutzern zu wählen. Darüber hinaus steuere ich Methoden zur Darstellung von Unterbrechungen in VR bei und diskutiere ihre Auswirkungen auf Präsenz und Leistung von Nutzern. Meine Arbeit brachte auch hervor, dass verschiedene virtuelle Präsentationen von ortsgleichen Kollaborateuren einen Effekt auf die soziale Präsenz, Leistung und Vertrauen haben.

Drittens, schließe ich meine Dissertation mit der Untersuchung von Methoden zur Verwaltung der Präsenz, sowohl in der physischen als auch in der virtuellen Realität ab. Ich schlage Systeme und Schnittstellen für den Übergang zwischen den Realitäten vor, die die Benutzer in die Lage versetzen zu entscheiden, inwieweit sie sich der *anderen* Realität bewusst sein wollen. Schließlich diskutiere ich die Möglichkeit, diesen beiden Realitäten systematisch Sinne zuzuordnen: die visuelle für VR und die auditive und haptische für die physische Realität. Darüber hinaus stelle ich spezifische Design-Richtlinien zur Verfügung, wie diese Erkenntnisse genutzt werden können, um VR-Anwender auf physische Grenzen und Hindernisse aufmerksam zu machen.

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1
Introduction

Research on head-mounted displays (HMDs) for virtual reality (VR) has seen a rise in interest since the launch of affordable HMDs for consumers in 2016 by Oculus and HTC. Although the concept of HMDs has been around since Sutherland's introduction of the "The Sword of Damocles" in 1968 [54], until recently, it was predominantly used in research labs. With this shift from lab to consumer product has come the opportunity to use HMDs in novel ways: Museums have implemented VR experiences that enable users to experience situated artifacts more immersively or visit from the comfort of their home; industries use it as a cheap and quick alternative for prototyping designs; and marketers can create a more realistic understanding of products they are promoting (e.g. tourism, cars). In any of these and similar situations, VR serves as an extension to existing physical screens – PC or mobile phone – providing a more immersive experience with a wider field of view.

As VR-enabled HMDs are becoming wireless, they face similar challenges to established ubiquitous devices such as mobile phones. One such challenge is the disconnect between the virtual and the physical reality [2], which is heightened with VR-enabled HMDs as users are separated from the real world mentally as well as visually. In fact, the degree of perceived separation has established itself as a success measure for VR applications – commonly referred to as *presence* [72].

Although switching back and forth between the physical and virtual reality remains a challenge for established ubiquitous systems (e.g. texting or driving [76]), their limited screen space enables users to be at least visually aware of both realities. For example, a mobile phone screen affords users the ability to continuously look up to see when someone is approaching or to check an unexpected noise. With HMDs, however, this is only possible by forcing the user to take off their headset, which diminishes *presence* [72].

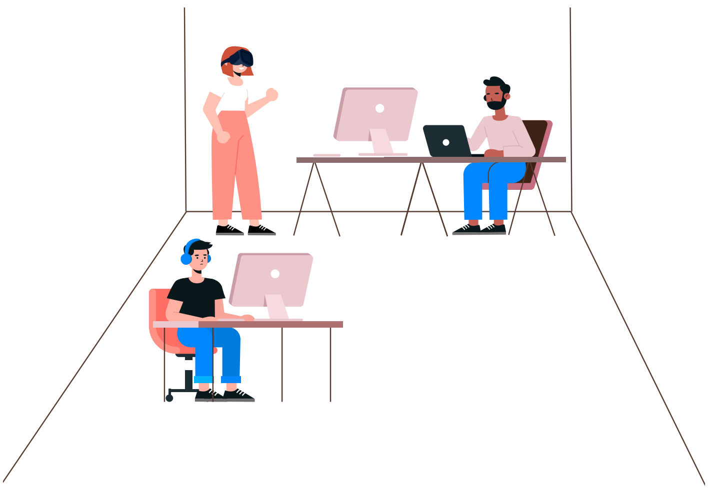


Figure 1.1: One of the challenges for HCI research with ubiquitous devices was defined as the enforced disconnection between the virtual and physical reality [2]. This is heightened with HMDs due to the visual seperation from the physical reality. Users have to take the headset off in order to respond to incidents in the physical reality, which I aim to overcome by introducing virtual reality interfaces for seamless interaction with the physical reality.

To address this challenge, I have created interfaces that enable interaction with the physical reality without having to take off the headset – which I refer to as *seamless* interaction with the physical reality. Rather than disconnecting from one reality to immerse into the other, the interface's aim is to support users in being present in VR, while remaining aware of the physical reality. The overarching research vision that guides this thesis is, therefore, to reduce this disconnect between the virtual and physical reality.

My research is guided by preliminary exploratory work that I completed to gain deeper knowledge of users' understanding of VR in co-located public places. The preliminary exploration revealed three main foci that form the structure of my thesis: (1) security and privacy, (2) communication with physical collaborators, and (3) managing presence in both the physical and virtual reality. Each focus represents a section in my dissertation for which I identify central challenges and give directions towards overcoming them.

Below I define common terms as used in this thesis, and describe my preliminary exploratory work in more detail.

1.1 Definitions

In the previous section I introduced the concept of *presence*, as a subjective measure for the success of virtual reality experiences. The counterpart to this subjective measure is *immersion*, which evaluates the technological capability. As both concepts are variables that occur throughout my projects, I review them and define the term immersive virtual reality in the context of this thesis.

Immersion and Presence

Although there are many definitions for both terms, *Immersion* is generally known as the objective evaluation of the technological capabilities (e.g. display size; accuracy of head tracking) [67]. Similarly, *presence* is a subjective measure of 'the level of realism' [85]. Questionnaires have established themselves as the main method to measure presence, although there exist alternatives. An overview of definitions and methods for measurement of presence can be found in [48].

Immersion and presence summarize the quality of a VR experience and therefore contribute towards users' mental models of the technology. My research has mostly been with high-end HMDs, such as the HTC Vive [63] and Oculus [19] headsets. They provide a highly immersive virtual reality experience compared to low-immersion ones, such as a mobile VR experience. Although I have also worked with the latter, in the case studies where *presence* was a dependent variable, I chose high-end solutions. Despite less immersive devices being able to induce high presence states, this design choice allowed me to reduce immersion as an influencing factor and compare overarching results in the discussion section of my thesis.

Virtual Reality - Many Terms for the Same Concept

Previous work has investigated the meaning of virtual reality and there exist a number of well-established definitions. In this section I review the most prominent definitions (as they capture the understanding of VR systems in the scientific community) and define VR in the context of this thesis.

The terms *virtual*, *virtual reality*, *virtual world*, and *virtual environment* have been used to describe similar concepts in and outside of academia.

Originally, the term *virtual* was used to refer to something that was imaginable but did not exist in reality, “almost or nearly as described, but not completely or according to strict definition” [73]. Outside of the research community the term has seen a rise and a shift in usage in the last decade, presumably due to its usage in context with computers to describe something that is “not physically existing but made by software to appear so” [73].

Virtual World: Conversely, a *virtual world* is “a synchronous, persistent network of people, represented as avatars, facilitated by networked computers,” putting the focus on avatars and a virtual ecology that continues after the user has already signed out [7]. A well established example is the virtual world of Second Life [44].

Virtual Reality (VR): The term “reality” is defined as “The state of things as they actually exist, as opposed to an idealistic or notional idea of them” [73]. From this standpoint, a *virtual reality* describes something that is both “not physically existing” and on the other hand “actually exists,” alluding to the notion that whatever is created in virtual reality may be perceived as actual reality. Although systems enabling virtual reality had been subject of research previously, Lanier [49] coined the term *virtual reality*, typically describing “three-dimensional realities implemented with stereo viewing goggles and reality gloves”.

Biocca et al. [8] used the term VR to describe a set of *virtual reality systems*, such as a window system (e.g. [computer] screen/portal to another world). They referred to the HMD-based usage as *immersive virtual reality*. Sherman et al. [71] provide a more recent definition that combines the above mentioned ideas by calling out four key elements that define VR, namely “virtual world, immersion, sensory feedback and interactivity.”

Virtual Environment: Ellis et al. [17] used the more conservative term *virtual environment* to define the same concept, claiming that by exchanging *reality* with the more conservative word *environment*, user expectations would be better managed. At the point of their publication, HMDs were not yet able to provide the immersive experience that is possible today. Milgram et. al [56] proposed the reality-virtuality continuum, where they defined interactions with HMDs to be in virtual environments, with the other side of the continuum defined as the real environment, or physical reality.

Today the term *virtual reality* is applied to a number of concepts, often overlapping with the words *world* and *environment*, conceptually as well as in nomenclature. This is also prominent in my publications, as each paper focuses on an individual subset of prior work, where one term may be favored over the other.

For the purpose of this thesis, I adopt Sherman et al.'s definition [8] for virtual reality (VR), which proposes that the virtual world continuously exists without the user being there. However, this definition lacks a discussion of the physical reality, whereby the real world also continues without the HMD user being mentally there. Despite being in conceptual agreement with Milgram's reality-virtuality continuum [56], I will be referring to the real environment as physical reality, to enable a differentiation between the physical vs virtual reality.

Observers and Bystanders

Prior work uses different terms when referring to a person that is part of a user experience but not the user themselves. Observers and bystanders are the most common terms in the publications that I reference throughout my work. An observer is often someone who has a negative aim in the scenario [15], so is also referred to as an attacker, because they pose a threat to the security of the user. Observers have a clear goal of observing the user. In prior work on ubiquitous computing this same goal applies, however, their intentions are not harmful to the user. Instead, they are in a social scenario with the user, whereby they comment on the HMD user's performance [20] or are affected by the HMD interaction due to the close proximity [4].

A bystander is someone who does not have an active part in the user experience of the HMD user. However, bystanders might become involved by accidentally stepping into close proximity of the HMD user's VR play area. This may, for example, be other people in a public space [74, 86] or co-workers in an open office.

As the definitions from prior work overlap, I differentiate them further by defining that observers are part of the user experience by the end of a user journey; for example, a physical co-worker who interrupts the HMD user. In contrast, a bystander enters a user journey accidentally but is not part of it [13]; for example, a co-worker who accidentally steps into the play area and bumps into the HMD user. In the context of my thesis, neither the observer or the bystander wear an HMD, and both are co-located in the physical reality.

General Reading Guideline As research is a collaborative effort, the majority of my projects were completed in close partnership with other researchers and students. Throughout the rest of my thesis, I will be using the scientific "we" when I refer to projects and publications. This is a common approach for scientific publications.

1.2 Preliminary Exploration

In the previous section I highlighted the need to investigate virtual reality interfaces for seamless interaction with the physical reality. I motivated this by prior work; however, in a user-centered approach, it is vital to explore the details of such a need in form of a field study with possible users.

> **RQ0:** *What is a non-expert's understanding of virtual reality in co-located settings and what expectations does a non-expert have towards it?*

Contribution. To explore RQ0, we conducted a preliminary exploratory study (N=34) published in [P1]. We chose public, outdoor spaces (e.g. park, museum front yard) to investigate users' mental models, expectations and acceptance of VR with mobile head-mounted displays (HMDs).

A mental model is a form of belief by users in regard to how a system works, based on previous experiences and technical background [59, 61]. While mental models of the internet have been largely discovered and leveraged [43, 59, 75], VR still remains unexplored. Building upon previous work, we chose the following tools to investigate mental models:

First, sketching, which may be used when people have difficulty verbalizing their opinion and a high variance in technical background is assumed [43, 60]. Poole et al. [64] proposed to use sketching to uncover mental models of complex technologies, which applies to our exploration of VR.

Second, the story completion method (SCM) [9]. This tool allows us to capture users' feelings towards a technology and leave way for imagination and creativity in regards to usage. Our aim was to explore participants' desires and experiences beyond popular use cases, such as gaming. This can only be achieved if a deeper understanding can be gained of what non-experts are expecting from the technology rather than solely evaluating present technical understanding. In our story, we used a fictional character named *ALEX* who had recently acquired a wireless head-mounted display.

Third, the technology acceptance model (TAM) and adapted social awareness questionnaire [66]. As the adoption rate for VR technology has staggered, not meeting expectations set by industry leaders, there is a need to evaluate the acceptance of the technology among non-experts. Davis et al. [77] developed a questionnaire, namely the technology acceptance model (TAM), that analyses what causes people to accept or reject a technology. Although there exist a number of variations of the TAM [77, 78], we adopted the original one by Davis et al. [77] to investigate VR acceptance.

As HMDs are detached devices, envisaged to be used in any social context (e.g. at home with family and in public with strangers) and due to our assumption that being secluded from the real world when fully immersed may influence a person's willingness to use HMDs, we customized Rico et al.'s [66] social awareness questionnaire. They reviewed social acceptability of gestures for mobile interfaces, comparing gestures in different audiences and locations. As VR usage is also context-dependent and predominantly interacted through gestures, we customized the questionnaire to investigate perception towards VR usage.

To summarize, building on previous work, we used the following tools: A drawing task [43, 60], the story completion method [9], the technology acceptance model (TAM) [77] and an adapted social awareness questionnaire [66]. By using different sets of tools, we were able to obtain a variety of responses. By using the thematic analysis approach for analyzing the results, we were able to identify a number of themes, beyond technological capability, that affect a ubiquitous virtual reality user experience. The results of the thematic analysis and discussion are published in [P1].

Three rephrased themes from [P1] form the basis of my research and inform the structure of this thesis:

Focus 1 Usable Security and Privacy for VR: Observability of HMD User Interactions

Focus 2 Communication with Co-located Collaborators

Focus 3 Managing Presence in the Physical and Virtual Reality

For each of the foci that were derived from this preliminary exploration, I created research questions (RQs) that guided my research on seamless interfaces for virtual reality interaction. In the next sections I will discuss the individual foci as a result of the preliminary exploration, describe them in the context of prior work, introduce research questions and provide details on my contribution for addressing each of them.

1.3 Usable Security and Privacy for VR: Observability of HMD User Interactions

> “ALEX is in a completely empty room without anything and anyone”
>
> *(Participant 26)*
> Preliminary Exploration [33]

Privacy was found to be an unvoiced concern in our preliminary exploration [P1]. As part of the story completion method, the majority of participants placed their fictional character *ALEX* alone in a room, specifically mentioning the door being locked. We found that they were worried about co-located people and being observed by them. However, observability through bystanders was not exclusively mentioned in a negative context. The relationship to the observer paid a role in determining whether it was positive or negative. A close relationship, for example, in the form of a mother taking off the headset when the user was scared, resulted in a scary experience turning into a positive one.

As expected, in the majority of stories, *ALEX* took the HMD off to be aware of the real world. Although there was no immediate threat in the physical reality, Alex was forced to do it as the HMD interaction did not afford another option. Note that the see-through option was not available at the point of the study and thus we could not include it in our exploration. To enable a seamless interaction in this context, users have to (i) be aware of the physical reality and (ii) understand what possible [negative or positive] effects observability of HMD interactions have on them.

In this section I want to introduce our work on the negative aspects of observability, which is situated within the HCI research area of usable security and privacy. How awareness of the physical reality may be improved for seamless interactions with HMDs is discussed in 1.5. Positive aspects of observability are covered in section 1.4.

Observability is popularly referred to as shoulder surfing, which refers to a situation when an attacker observes the screen of a laptop or smartphone user without them knowing. Of course, the easiest way to do so is outside of the user's immediate field of view; often from behind and over their shoulder – see image 1.2.

Prior work has revealed varying types of data that observers are able to retrieve from mobile devices [15]. Although not always malicious, it leaves the victims feeling uncomfortable and harassed. Specifically, personal data leakage causes concern. HMDs introduce two new changes that can exacerbate this: Firstly, they blind the user from the physical reality, empowering the observer to choose their attack location without limiting themselves to the back of the HMD user. Secondly, the user interacts by using multiple modalities, such as gestures, controller clicks and gaze. Thus, the attacker can observe these modalities; instead of shoulder surfing a physical screen, with keyboard input. So independent of the device, the goal of research on usable security and privacy is twofold: (a) design usable interactions that empower the user to take action against possible threats, and simultaneously (b) develop secure systems to minimize these [23]. To date, there exist limited recommendations for HMD interactions in this context.

Hence, the first goal of this thesis is to understand what interactions/gestures of an HMD user can be observed by a bystander.

RQ1 A: *Which tasks of an HMD user can be observed by a bystander?*

Eiband et al. found that 9% of attacks were on users' credentials [15]. Stealing login details through shoulder surfing is predominantly investigated on ubiquitous devices, as users are able to use them in public places with unknown bystanders. On mobile phones results highlighted that shoulder surfing risk is perceived to be low, independent of how high it actually is [39]. Thus, the risk has to mitigated by the system rather than relying on the user to take action.

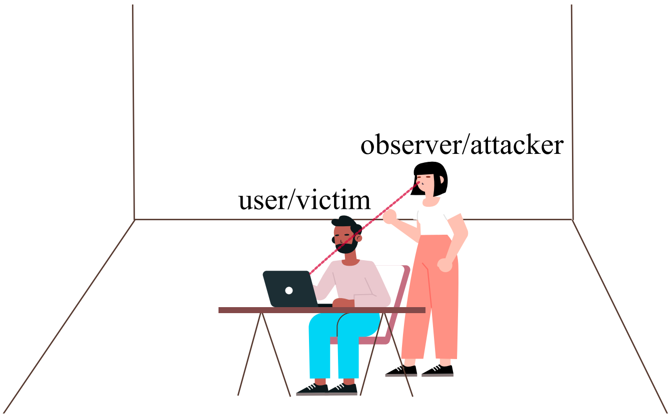


Figure 1.2: The term shoulder surfing is coined by usable security and privacy research to refer to situations whereby an attacker observes the screen and input of a user. To increase the success of their attack this is done behind the back/shoulder of a laptop or a smartphone user, as it is outside of the user's field of view. HMD users are blinded from the reality, thus attacking is possible from anywhere and rather than the physical screen attackers observe gestures, body and head movements.

This may be done by letting users know when someone is observing them [5] so that they can take action such as turning the screen away or hiding it with body parts (e.g. hands over phone screen during pin entry.) It can also be resolved by adapting user input by providing alternative input modalities such as gaze [1] or novel methods that are difficult to observe, such as authentication with patterns [83]. However, in the context of HMDs it is unclear whether prior work on ubiquitous devices can be transferred to VR and whether novel authentication concepts need to be designed from a usable security perspective.

> **RQ1 B:** *How to create and test authentication mechanisms for VR users that are both usable and secure?*

Contribution. To explore RQ1a, this thesis presents a user study that investigated which tasks and task switches can be observed by bystanders [P5]. Tasks were based on common tasks that are currently completed on ubiquitous devices, as derived from a preliminary diary study we completed [P5] where participants had to keep a diary about their digital media usage and respond to pre-defined questions. Based on these results we included five tasks in our study: Watching a video, typing a text, authenticating, reading a text and 3D manipulation. Eiband et al. [15] found a similar set of tasks as a result of their shoulder surfing risk study on mobile phones. Instead of 3D manipulation their list included gaming, which we excluded, as our setup/story was an office environment with architects. We found bystanders were able to successfully identify both task switches (83%) and tasks (77%) within only a few seconds of the task switch. We also provide design recommendations (e.g. pointer vs tapping to increase security) for implementing less observable VR interactions and suggest concepts that enable privacy in co-located work spaces with HMDs.

To explore RQ1b, this thesis investigated whether existing authentication methods from ubiquitous devices, such as PIN and pattern from mobile phones, can be transferred to VR [P2]. We found that they are comparably usable while being more secure. This is due to the fact that the attacker has no view of the visual channel within the HMD and observing the interaction itself was less successful than prior studies on shoulder surfing of mobile phones. Additional factors that are particular to HMDs were also investigated: a 2D mobile screen only affords prominent interactions with gestures, whereas the HMD provides additional input modalities, such as a laser pointer. Similarly, VR is not limited by the physical screen space and thus gives way to explore varying sizes/distances of interfaces for PIN/pattern input and feedback. To investigate the 3D space for authentication, we iteratively designed a novel authentication mechanism for VR – named *RoomLock* [P3]. Within this system, participants have to select virtual objects that are placed in a three dimensional virtual space as a password. We found *RoomLock* to be comparably usable while being more secure than the transferred solutions from [P2]. Finally, as head and gaze interaction is available on the the majority of HMDs, we investigated whether we can improve security by implementing it as an additional input modality within our novel authentication mechanism *RoomLock* [P4]. We found that although it improves security, it was less usable than the previously tested input modalities.

1.4 Communication with Co-located Collaborators

> "When ALEX took off his headset, he saw that the [newly seated] neighbour [in his train compartment] was laughing out loud."
>
> *(Participant 2)*
> Preliminary Exploration [P1]

In our preliminary exploration, co-located bystanders were frequently mentioned as part of the story completion method [P1]. In the stories, these co-located bystanders unexpectedly appeared *during* the HMD usage, as in the quote from one of our participants mentioned above. If the bystanders were strangers, this was perceived as a negative surprise. The results from the social awareness questionnaire, which we also used in [P1], reinforced the preference for familiar co-located bystanders rather than strangers.

Technology has not only disrupted the way we communicate with distant people, whether it is colleagues, family or friends, but it has also changed co-located communication. Video conferencing, short messages and emails allow us to bridge distances, however, they also make it easier to stay seated in our work chairs instead of walking over to a colleague. Diefenbach et al. [14] found that placing a smartphone on the table changes the way the user pays attention and communicates with their social partner. There is extensive research into how technology has changed the way people interrupt and communicate [55], independent of who the owner of the device is vs the bystander. However, in the context of HMDs it is unclear how bystanders interrupt an HMD user and how to visualize the interruption in VR. To explore this gap, the second focus of my thesis investigates seamless interruption and communication between HMD users and bystanders.

RQ2 A: *How to support interruptions between HMD users and bystanders?*

In a collaborative setting, interruptions occur in order to establish a communication channel between the interrupter and the interruptee; in our case, the bystander and the HMD user. In contrast to prior work where both co-located collaborators are in the same reality after an interruption, here the HMD user is still in the virtual reality unless they take off their headset. To enable a seamless communication and maintain presence in VR, the HMD user may leave the headset on to communicate. However, this was found to be disturbing and made bystanders feel left out [69]. The alternative is for both collaborators to be in virtual reality, whether with an HMD or with less immersive devices such as a tablet or smartphone.

Gugenheimer et al. created asymmetric VR experiences with co-located players in the physical reality to foster communication. The latter was equipped with a tablet that acted as a window to the virtual reality. They found that this solution improved overall enjoyment of the VR experience for users with and without the HMD [38]. Outside the gaming context, interaction between co-located collaborators where one is an HMD user has been applied for training purposes, for example in military or surgery scenarios where it is difficult to practice in real conditions. However, in these scenarios, the performance and presence of the HMD user are in the focus rather than the bystander. There exists limited research on the virtual representation of a co-located physical collaborator/bystander in a mixed reality setting with VR users. To close this gap, I investigate a number of factors that influence collaboration, such as trust, performance and social presence.

RQ2 B: *How does the virtual representation of a collaborator affect factors that influence collaboration, such as trust, performance, social presence?*

Contribution. To investigate RQ2a our approach was twofold: First, we explored how bystanders interrupt an HMD user and whether they are capable of observing the HMD user's task switches, solely through interpreting their gestures [P5]. We found that bystanders tended to use voice interruptions during task completion and that repetition improved interruption behavior, thus showing the capability of interrupting in opportune moments upon training. Based on these results, we propose interaction concepts that enable bystanders to choose opportune moments for interruption, for example, the need for prominent vs. subtle gestures. We also propose concepts that include the layout of the physical reality, whereby the user is guided to stand facing a specific direction. For example, the user could be positioned to face the bystander to indicate openness for interruption, or with their back to the bystander to show that they do not want to be disturbed. This does not affect their VR experience but provides subtle cues to the bystander. Second, we conducted a detection response task study to understand how interruptions may be displayed in VR and to what extent they affect presence and performance of the VR user [P6].

To explore RQ2b this thesis presents three publications that investigate varying variables affecting communication between collaborators, such as social presence, spatial presence, performance and trust. We investigated the effect of collaborator representation in VR on social presence and performance [P7]. In [P8], we explored how we can measure trust in VR through a trust game while changing the representation of the players between a robot and a human. Finally, we explored whether displaying the real-time heart rate of the co-located collaborators improves presence and performance [P9].

For more details on corresponding publications see Chapter 2 and for an in-depth discussion on learnings and directions for future work in this area see Chapter 3.

1.5 Managing Presence in the Physical and Virtual Reality

> "being physically present in the real world but mentally present in the virtual one is a struggle"
>
> *(Participant 9)*
> Preliminary Exploration [33]

Our preliminary exploration confirmed that users struggle to balance their presence in both realities and fear for their physical integrity/safety [P1]. In the stories, this was verbalized in the form an unknown bystander but tripping over physical objects was also found to be worrisome. Similarly, Adams et al. [3] revealed that users' concerns are "focused on the physical" rather than on online threats.

The time we spend with digital media has been increasing steadily over the last few years. In Germany, for example, adults spend nearly four hours per day online [81] and in the USA it is six hours [45]. Assuming the average person rests or sleeps eight hours a day, we spend approximately a third of our waking time in some form of virtual reality. Currently, this is dominated by smartphones and PCs where immersion is influenced by the physical size of the screen. Other sensory channels, such as audio, may increase the sense of immersion; however, the visual sense was found to overpower these [84]. HMDs make use of the visual sense by filling the user's field of view with a display and providing a more immersive experience than the ubiquitous systems, and in this way, create unexplored challenges, which we summarize below.

First, in contrast to HMDs, smartphones afford the user the ability to remain aware of the physical reality while immersed in the virtual one. For example, a user can look up directions on Google Maps while navigating the physical street. Users seem to have learned to balance their presence between the virtual and physical reality, yet independent of how well they might perceive they are managing the transition between different realities, it has been found to have negative effects. Users tend to overestimate their ability to balance their presence in both realities, which negatively affects the physical integrity and safety of themselves and bystanders. While many users in the real world overestimate their ability to interact on their phone whilst driving [6, 65] or walking, leading to accidents and confrontations with physical objects, [12] this challenge is heightened with HMDs due to the fact that the user is fully surrounded by a screen and therefore by virtual reality.

Second, blinding the HMD user from the physical reality has a negative effect on social interactions, as mentioned in section 1.4. Bystanders feel excluded and the introduction of the HMD was perceived to create a negative social context, where communication is not warranted [69, 14].

Third, presence is a main measure for the quality of a VR experience. A VR experience is found to be successful/good if a high level of presence is achieved, to the extent that a measure of how unaware the user is of the physical reality is often included in common questionnaires that determine the level of presence [68, 72, 85]. To summarize, we want to investigate the following research question:

> **RQ3:** *How can we support users to be aware of the physical reality while maintaining their presence in VR?*

Contribution. We contribute four studies to investigate this research question [P10-12]. To explore RQ3 we first completed a round of expert interviews to explore what positive and negative factors affect co-located interaction with HMDs, and how to support or overcome them. As part of these interviews, we also asked interviewees to identify solutions that already cater to or have the potential to enable HMD users to seamlessly interact with co-located bystanders, and what possible novel solutions may look like. Our analysis of factors and novel vs existing solutions resulted in the *seamless transition* (SeaT) design space. The design space acts as a starting point for researchers and practitioners who want to create systems that enable users to seamlessly transition between realities and in-between states of realities according to Milgram's reality-virtuality continuum [56], for example from VR to augmented virtuality and from physical reality to augmented reality.

In a second study, we iteratively created two exemplary solutions based on novel solutions and gaps identified in the SeaT design space; namely the sky portal and the virtual phone. Both are windows to the other reality. The aim was to create solutions that consider all dimensions of the SeaT design space rather than focusing on particular dimensions. Our results showed that the sky portal performed worse than the baseline; the see-through capability of the HTC Vive [11]. However, for the virtual phone condition, performance and presence was comparable to the baseline, and participants perceived it to be an upgrade to the baseline. Thus, we argue that participants favor a solution that would enable them to have a peek/window into the other reality without completely leaving the one they are currently in. The first two studies are published in [P10].

In a third study, we explored the inclusion of audio/haptic signals to notify/warn/inform users about physical borders [P11]. This was motivated by the gap we found in the SeaT design space of solutions that leverage the audio and haptic channels. Currently, users are warned about physical borders through their visual channel, such as the built-in grid/mesh solution in common HMDs [80]. Based on Wicken's cube which suggests that allocating senses to varying tasks is possible without a significant increase in cognitive demand, we explored whether senses can be allocated to specific realities. Thus, while the visual sense is focused on the virtual reality, the auditory and haptic senses act as indicators for physical borders. We found sense allocation to be comparable to visual indicators for physical boundaries. Due to the lack of significance in the results with regards to presence, we can only suggest that presence is better when senses are allocated. This has to be discussed in future work and will be discussed further in section 3.

In the fourth and most recent study, we investigated the necessity to display physical borders in a confined, seated setting, such as the back seat of a car [P12]. Similar to the previous studies, we wanted to understand whether users wanted to be aware of the real world in a closed setting with co-located people, such as the driver.

1.6 Summary and Overview of the Thesis

The aim of this thesis is to explore the design interfaces that empower HMD users to seamlessly interact with physical reality. Based on preliminary exploratory work on co-located interaction with HMDs, I present three objectives of this thesis: First, investigating how interactions for HMD users can be designed to be usable, secure and private; second, investigating how communication between HMD users and bystanders can be supported; and third, introducing a design space to conceptualize existing and novel solutions on seamless transition interfaces and carrying out subsequent studies that supplement gaps in this design space.

Chapter 2 briefly introduces the publications included in this thesis and clarifies how they contribute to the overall research aims.

Chapter 3 positions and discusses the results of this thesis with respect to the outlined research questions and highlights areas for future work.

2
Publications

Having introduced the main research questions of this dissertation, I will now introduce the papers included. For a snapshot of these publications and their primary contribution, refer to table 2.1. This table is meant to support readers in identifying papers relevant to their interest or topic.

The following sections provide a more detailed overview of the individual papers, structured by the research questions they were guided by. Each paper is introduced with a short summary and a preview of the first page(s) of the original publication. In the summary, I rewrote the paper abstract to detail how it fits with each section's research question[s].

The original publications and a table that clarifies the contributions of all authors (Table A.1) are available in the Appendix A.

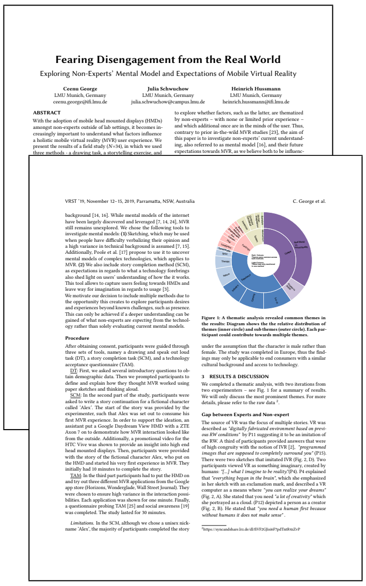
2.1 Preliminary Exploration

The first publication [P1] influenced the individual foci and acts as basis for this thesis. We explored HMD users uncertainties in the context of co-located HMD usage in public places. It has to be noted here that it was submitted for publication at a later date, although the study itself was completed at the beginning of my research.

> **RQ0:** *What is a non-expert's understanding of virtual reality in co-located settings and what expectations does a non-expert have towards it?*

[P1] Fearing Disengagement from the Real World

Summary. With the adoption of mobile head-mounted displays amongst non-experts outside of lab settings, it becomes increasingly important to understand what factors influence a co-located VR user experience in public places. We present the results of a field study (N=34), in which we used three methods - a drawing task, a storytelling exercise, and the technology acceptance questionnaire (TAM) - to explore factors, beyond technical capability, that influence the user experience of HMDs. Our analysis highlights 4 themes that are in non-expert users' minds with regards the usage of HMDs in co-located, public places.



The first theme is the discrepancy between non-experts' understanding and expectations towards virtual reality vs what the industry is offering. Prior work highlights that methods, such as training, can improve acceptability and understanding [22]. Although necessary, I did not focus on this part in my thesis, as I believe that prior work on ubiquitous systems is transferable and due to the fact that this theme is highly influenced by the capability of the hardware at the time of the study. This will be discussed further in section 3.

The other themes form the base for my thesis and are also reflected in the structure of the sections: (i) privacy as an unvoiced concern, (ii) social interactions with bystanders, and (iii) managing presence between realities.

George, C., Schwuchow, J., and Hussmann, H. (2019). Fearing Disengagement from the Real World. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3359996.3364273

	RQ		Title of Paper and Publication Venue	Research Method	Primary contribution
[P1]	RQ0		"Fearing Disengagement from the Real World" in *VRST '19*	Field study with Story Completion Method and Structured Interviews (N=54)	Qualitative study that explores how HMD usage for virtual reality is perceived in co-located public places
[P2]	RQ1	B	"Seamless and Secure VR: Adapting and Evaluating Established Authentication Systems for Virtual Reality" in *Proc. USEC, NDSS '17*	Controlled experiment (N=27)	Evaluating usability and security of PIN/pattern authentication for virtual reality
[P3]	RQ1	B	"Investigating the Third Dimension for Authentication in Immersive Virtual Reality and in the Real World" in *IEEE VR '19*	Controlled experiment (N=36)	Development and evaluation of novel authentication mechanism *RoomLock* for VR
[P4]	RQ1	B	"Using Gaze and Head-pose to improve the Usability and Observation Resistance of 3D Passwords in Virtual Reality" in *AVR 20*	Controlled experiment (N=36)	Evaluation of eye tracking as an alternative input modality for *RoomLock* to improve security/observation resistance
[P5]	RQ1 + 2	A	"Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings" in *DIS '19*	Observations, Controlled experiment and structured interviews (N=40)	Analysis of users' interruption behavior and their capability to recognize HMD users tasks through observation from the physical world
[P6]	RQ2	A	"Intelligent Interruptions for IVR: Investigating the Interplay between Presence, Workload and Attention" in *CHI '18*	Adaption of Detection response task in VR (N=20)	Evaluation of interruption designs for VR and their effect on presence, workload and attention
[P7]	RQ2	B	"Training in IVR: Investigating the Effect of Instructor Design on Social Presence and Performance of the VR User" in *VRST '19*	Controlled experiment (N=16)	Analysis of the effect that social presence has on performance and how to influence this through avatar design
[P8]	RQ2	B	"Trusting Strangers in Immersive Virtual Reality" in *IUI '18*	Adaption of Trust Game and standartized Trust Questionnaire for VR (N=30)	Discussion on the appropriate method to measure trust in VR
[P9]	RQ2	B	"Towards Augmenting IVR Communication with Physiological Sensing Data" in *CHI '18*	Controlled lab study (N=30)	Development and evaluation of real-time heart rate visualisations for VR for co-located collaborators
[P10]	RQ3		"Seamless, Bi-directional Transitions along the Mixed Reality Continuum: A Conceptualization and Prototype Exploration" in *ISMAR '20*	Interviews (N=20), prototype creation and evaluation (N=36)	Analysis of interviews and solutions to create design space *SeaT* for seamless transition concepts. Development and evaluation of exemplary prototypes based on design space.
[P11]	RQ3		"Invisible Boundaries for VR: Auditory and Haptic Signals as Indicators for Real World Boundaries" in *TVCG '20*	Prototype creation and evaluation (N=33)	Development and evaluation of audio/haptic boundary system for VR
[P12]	RQ3		"An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality" in *AutoUI'20*	Interviews with rear-seat users (N=11)	Discussion on future research directions

Table 2.1: Overview of publications included in this thesis abbreviated [P1] - [P12] and their methods and primary contributions.

2.2 Usable Security and Privacy of VR: Observability of HMD User Interactions

Our preliminary work highlighted that users were concerned about their security and privacy when using head-mounted display, due to their secluded vision from the physical reality [P1]. On the one side they were worried about bumping into physical objects, such as wires. On the other side, their concern was with regards to [unwanted] observers. This section discusses papers that contribute towards increasing the understanding of risks associated with being observed during HMD usage. Specifically, we investigated (i) which tasks can be observed by a bystander and (ii) how authentication mechanisms can be designed in such a context.

The first question is summarized in RQ1A and the second question is summarized in RQ1B.

RQ1 A: *Which tasks of an HMD user can be observed by a bystander?*

Despite observability of HMD users being disadvantageous from a security and privacy perspective, it can also be leveraged to support co-located collaborators in identifying opportune moments to interrupt. Thus, observability can have positive and negative implications from a user's perspective. Firstly, from a positive perspective, we hypothesized that similar to the physical reality, co-located bystanders may be able to interpret whether an HMD user is available for social interactions or not. For example, in the physical reality we know through observation whether someone is focused in a specific task or in-between tasks [40, 58] and thus, we can decide whether to interrupt them or not. Secondly, a negative implication is when users feel observed during an intimate or private task. Especially, without being able to see who is observing, as is the case with HMDs for VR. To understand whether observability is possible with HMDs, we investigated 5 different tasks (read, write, authenticate, watch a video, 3D manipulation) in the context of interruptions. In [P5] we investigated whether they are capable of identifying individual tasks solely through observation from the physical reality. The negative aspects discussed in this publication contribute towards RQ1A and the positive ones towards RQ2A. Thus, the image of the paper will only be displayed below, however, within the summary for RQ2A [P5] will be mentioned again without an image.

[P5] Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings

Summary. Head-mounted displays (HMDs) are being used for VR and AR applications and increasingly permeate our everyday life. We investigate (a) whether bystanders are capable of identifying HMD users tasks by observing their gestures, and (b) which strategies they employ. In a lab study (N=64) we found that bystanders are able to successfully identify both task switches (83%) and tasks (77%) within only a few seconds of the task switch. One of the observable tasks was *authentication*, which had a 69% success rate. Although, less successful than the average success rate, it highlights a need to investigate how observable authentication mechanisms are. This motivated the previously mentioned investigations into authentication mechanisms [P2-P4]. Additionally, we discuss how designers and practitioners can design non-observable HMD interactions within a co-located work space.


Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings

Ceenu George[1], Philipp Janssen[1], David Heuss[1], Florian Alt[2]
[1]LMU Munich, Germany,{firstname.lastname}@ifi.lmu.de
[2]Bundeswehr University Munich, Germany, florian.alt@unibw.de

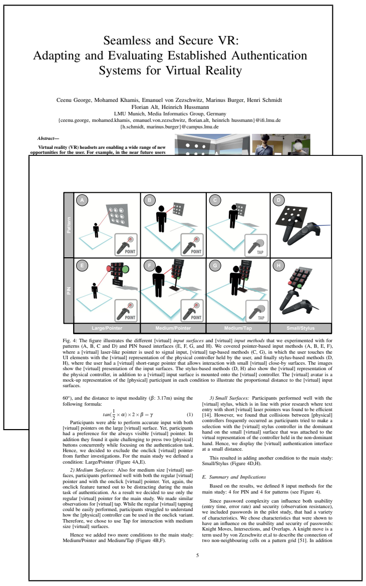
George, C., Janssen, P., Heuss, D., and Alt, F. (2019). Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, DIS '19, pages 497–510, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3322276.3322363

In [P5] we found that authentication tasks are observable and we discussed the need to investigate this further. This motivated RQ1B, which [P2-P4] contribute towards.

> **RQ1 B:** *How to create and test authentication mechanisms for VR users that are both usable and secure?*

We contribute three publications to this question. Firstly, we investigated whether existing 2D authentication mechanisms for ubiquitous systems can be transferred to virtual reality interactions with HMDs. Secondly, we created a novel authentication mechanism that makes use of the 3D environment to authenticate, namely *RoomLock*. Finally, we investigated whether multi-modal interaction with gaze further improves security.

[P2] Seamless and Secure VR: Adapting and Evaluating Established Authentication Systems for Virtual Reality


Seamless and Secure VR:
Adapting and Evaluating Established Authentication Systems for Virtual Reality

Ceenu George, Mohamed Khamis, Emanuel von Zezschwitz, Marinus Burger, Henri Schmidt
Florian Alt, Heinrich Hussmann
LMU Munich, Media Informatics Group, Germany
{ceenu.george, mohamed.khamis, emanuel.von.zezschwitz, florian.alt, heinrich hussmann}@ifi.lmu.de
{h.schmidt, marinus.burger}@campus.lmu.de

Abstract—

Virtual reality (VR) headsets are enabling a wide range of new opportunities for the user. For example, in the near future users

Summary. Virtual reality (VR) headsets are enabling a wide range of new opportunities for the user. For example, in the near future users may be able to visit virtual shopping malls and virtually join international conferences. These and many other scenarios pose new questions with regards to privacy and security, in particular authentication of users within the virtual environment. As a first step towards seamless VR authentication, this paper investigates the direct transfer of well-established concepts (PIN, Android unlock patterns) into VR. In a pilot study (N = 5) and a lab study (N = 25), we adapted existing mechanisms and evaluated their usability and security for VR. The results indicate that both PINs and patterns are well suited for authentication in VR. We found that the usability of both methods matched the performance known from the physical world. In addition, the private visual channel makes authentication harder to observe, indicating that authentication in VR using traditional concepts already achieves a good balance in the trade-off between usability and security. The paper contributes to a better understanding of authentication within VR environments, by providing the first investigation of established authentication methods within VR, and presents the base layer for the design of future authentication schemes, which are used in VR environments only.

George, C., Khamis, M., von Zezschwitz, E., Burger, M., Schmidt, H., Alt, F., and Hussmann, H. (2017). Seamless and Secure VR: Adapting and Evaluating Established Authentication Systems for Virtual Reality. In *Proceedings of the Network and Distributed System Security Symposium (NDSS 2017)*, USEC '17. Internet Society, doi:10.14722/usec.2017.23028

[P3] Investigating the Third Dimension for Authentication in Immersive Virtual Reality and in the Real World


Investigating the Third Dimension for Authentication in Immersive Virtual Reality and in the Real World

Summary. Immersive Virtual Reality (IVR) is a growing 3D environment, where social and commercial applications will require user authentication. Similarly, smart homes in the real world (RW), offer an opportunity to authenticate in the third dimension. For both environments, there is a gap in understanding which elements of the third dimension can be leveraged to improve usability and security of authentication. In particular, investigating transferability of findings between these environments would help towards understanding how rapid prototyping of authentication concepts can be achieved in this context.

We identify key elements from prior research that are promising for authentication in the third dimension and merge them with out results from [P2]. Based on these, we propose a concept in which users authenticate by selecting a series of 3D objects in a room using a pointer. We created a virtual 3D replica of a real world room, which we leverage to evaluate and compare the factors that impact the usability and security of authentication in IVR and RW. In particular, we investigate the influence of randomized user and object positions, in a series of user studies (N=48). We also evaluate shoulder surfing by real world bystanders for IVR (N=75).

Our results show that 3D passwords within our concept are more resistant against shoulder surfing attacks compared to 2D mechanism, such as PIN and pattern from [P1]. However, participants took slightly longer for password creation and entry in *RoomLock* than the 2D counterpart. We also found interactions to be generally faster in RW compared to IVR, yet workload is comparable.

George, C., Khamis, M., Buschek, D., and Hussmann, H. (2019). Investigating the Third Dimension for Authentication in Immersive Virtual Reality and in the Real World. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 277–285. doi:10.1109/VR.2019.8797862

[P4] Using Gaze and Head-pose to improve the Usability and Observation Resistance of 3D Passwords in virtual Reality


GazeRoomLock: Using Gaze and Head-pose to Improve the Usability and Observation Resistance of 3D Passwords in Virtual Reality

Summary. Authentication has become an important component of Immersive Virtual Reality (IVR) applications, such as virtual shopping stores, social networks, and games. We showed in [P2] and [P3] that compared to traditional graphical (pattern) and alphanumeric (PIN) passwords, a more promising form of passwords for IVR are 3D passwords with *RoomLock*. This work evaluates four multimodal techniques for entering 3D passwords in IVR that consist of multiple virtual objects selected in succession. Namely, we compare eye gaze and head pose for pointing, and dwell time and tactile input for selection. A comparison of a) usability in terms of entry time, error rate, and memorability, and b) resistance to real world and offline observations, reveals that: multimodal authentication in IVR by pointing at targets using gaze, and selecting them using a handheld controller significantly improves usability and security compared to the other methods and to prior work from [P3]. We discuss how the choice of pointing and selection methods impacts the usability and security of 3D passwords in IVR.

George, C., Buschek, D., Ngao, A., and Khamis, M. (2020). GazeRoomLock: Using Gaze and Head-Pose to Improve the Usability and Observation Resistance of 3D Passwords in Virtual Reality. In De Paolis, L. T. and Bourdot, P., editors, *Augmented Reality, Virtual Reality, and Computer Graphics*, pages 61–81, Cham. Springer International Publishing

2.3 Communication with Co-located Collaborators

In a co-located context, social interactions with collaborators are unavoidable. The communication channel may be instigated by the HMD user to enquire about events in the physical reality they cannot see, such as unexpected noises, or by the bystander to ask about a common project. Independent of who starts the communication, the HMD user is forced to take their HMD off in order to engage in the conversation. In order to enable a seamless interaction, our approach was twofold: In RQ1A, we investigated how we can support interruptions. We review this from the point of the bystander as well as the HMD user. After discussing how communication can be initiated through seamless interruptions, we explore in RQ2 B how the bystander can be represented in VR and what effects the design choice has on collaboration factors, such as trust, performance and social presence.

RQ2 A: *How to support interruptions between HMD users and bystanders?*

I contribute two papers to this research question, namely [P5] and [P6]. [P5] was introduced at the beginning of section 1, due to it discussing positive as well as negative aspects of observability. The negative aspect contributes to RQ1A, whereas the positive one contributes to RQ2A. As such, I will provide a summary of the positive aspects of observability that support interruption between co-located collaborators and HMD users in the summary below.

[P5] Should I Interrupt or Not? Understanding Interruptions in Head-Mounted Display Settings

Summary. Interruptions are known to affect performance and workload of the person being interrupted [55]. In the context of head-mounted displays an additional variable is affected, namely presence. Considering the novelty of this setup, a detailed understanding of interruptions in settings where people wearing an HMD (HMD user) and people not wearing an HMD (bystander) is missing. We investigate whether bystanders are capable of identifying when HMD users switch tasks by observing their gestures, and hence exploit opportune moments for interruptions. In a lab study (N=64) we found that bystanders are able to successfully identify both task switches (83%) and tasks (77%) within only a few seconds of the task switch. Furthermore, we identified interruption strategies of bystanders. Based on these findings, we discuss how to design HMD interactions, which can be easily recognized from the physical reality.

[P6] Intelligent Interruptions for IVR: Investigating the Interplay between Presence, Workload and Attention


Intelligent Interruptions for IVR: Investigating the Interplay between Presence, Workload and Attention

Ceenu George
LMU
Munich, Germany
ceenu.george@ifi.lmu.de

Manuel Demmler
LMU
Munich, Germany
demmler@cip.ifi.lmu.de

Heinrich Hussmann
LMU
Munich, Germany
hussmann@ifi.lmu.de

Abstract
Whereas interruptions is a very active subfield of research within HCI, as of today interruptions in immersive virtual reality (IVR) have received only little attention. We conducted a lab study (N=20) with a head mounted display (HMD) to understand the relationship between presence, workload and attention in IVR when measuring three virtual interruption designs. The answer to this question is interesting because prior research has revealed a positive effect on performance when providing intelligent interruptions, for example based on users' level of attention. Our work launches

Introduction
Interruptions have been found to disrupt the task at hand, leading to a loss of overall performance [1, 12]. In the context of IVR there is the added negative effect on the users' perception of presence and immersion. Although there exist varying definitions, both terms measure the quality of any virtual reality (VR) experience. Presence describes a subjective evaluation of how the virtual world is perceived [9] and immersion is an objective evaluation of the technological capabilities (e.g. display size, tracking accuracy).

Past work has revealed that there exist opportune moments, in which the cost of an interruption is reduced [18]. They provide evidence that there are advantages of designing intelligent interruptions by targeting moments with low workload and attention [4]. Although there exist well established methods to measure these human variables in other domains, such as NASA TLX [6] and iGroupPresence questionnaire [16], they have not been sufficiently analysed in the context of IVR with HMD's. Additionally, correlations and causalities between these variables, although highly discussed in real world (RW) literature [7], often remain unexplored for IVR. Prior work on the interplay between presence, workload and attention has focused on virtual environments [19, 16], however there exists no current evidence for their appropriateness in IVR with HMDs.

We iteratively designed and developed a prototype that allows the measurement of attention (through detection response tasks (DRT)), presence and workload (through questionnaires) in IVR, while exposed to three virtual interruption designs across two different scenes (Fig. 1).

We conducted an exploratory lab study ($N = 20$) with our prototype, which revealed that a trade-off between presence and attention (acceptance of VR vs. fast reaction time) is required when designing interruptions for IVR.

Figure 1: We measure attention, presence and workload on three interruption designs within two different scenes.

Related Work
Presence and Immersion in IVR
Witmer and Singer [19] define presence as a tool to measure the "level of realism" compared to the RW. If presence is high, their so called 'looming effect' becomes apparent, whereby users react in the physical world to actions that are perceived in the virtual world. For example, placing physical controllers on a virtual table or avoiding moving virtual cars by stepping aside in the RW [17]. The original list of factors affecting presence also includes 'immeadiacy of control', 'multimodal presentation' [17] and 'broad focus' [5]. These factors were used as requirements for the creation of the scenes for the study prototype.

The most adopted way to measure presence is through subjective evaluations. In prior work presence was found to be "something that people can be consciously aware of" and therefore report on in a post-study questionnaire or through verbal feedback [10]. Oftentimes, these questionnaires probe the awareness of the RW [19], acknowledging that RW interruptions decrease presence. Contrary to prior work, we focus on virtual interruptions, displayed in VR. A summary of alternative measurements can be found in [10]. The most relevant alternative measure for the purpose of this paper include findings from [2] who found a negative correlation between secondary reaction time and immersion. We don't explicitly measure immersion, as the latest HMDs (e.g. HTC Vive) already offer a high level of immersion, but rather focus on the subjective measure of presence by using a post-study (IPQ) questionnaire [16].

Attention and Workload in Relation to Presence
A high level of attention results in a high level of presence [19]. Fontaine [5] also highlights the importance for a 'broad focus', thus increased levels of presence are achieved when the VR scene is perceived as a whole rather than

Summary. In [P5] we found that co-located bystanders naturally interrupt the HMD user by physically tapping the HMD user on their body or by calling them. This would force the HMD user to take off their headset, as their physical integrity is obstructed and presence in VR is weakened. To enable a seamless interruption in this context (i) the bystander has to be provided with an alternative way to interrupt, which I discuss in chapter 3, (ii) and the interruption has to be visualized in VR. The latter had received only little attention in HCI research at the point of publication of this paper. With this, we take a first step to close this gap by investigating the interplay between presence, workload and attention to inform intelligent interruptions. We conducted a lab study (N=20) with a head-mounted display (HMD) to understand the relationship between these variables in IVR when measuring three virtual interruption designs. The answer to this question is interesting, because prior research has revealed a positive effect on performance when providing intelligent interruptions, for example based on users' workload. Our work launches research on interruptibility in IVR by investigating (1) the relationship between attention, presence and workload and (2) the feasibility of measuring them. Our analysis suggests that a trade-off between presence and attention is required when designing interruptions for IVR. Our findings are valuable for researchers and practitioners who want to collect data on attention, presence and workload in IVR, to inform interruptability.

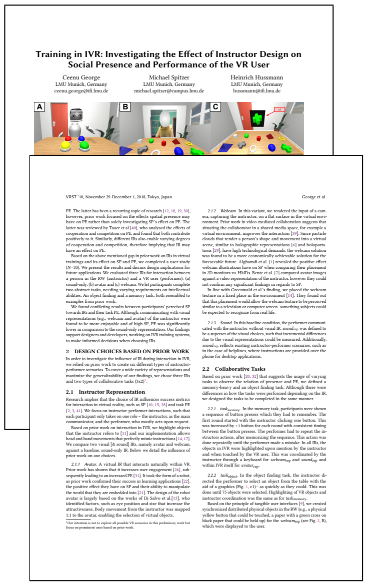
George, C., Demmler, M., and Hussmann, H. (2018a). Intelligent Interruptions for IVR: Investigating the Interplay between Presence, Workload and Attention. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA '18, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3170427.3188686

Once a communication channel has been established, it becomes necessary to review how the bystander can be represented in VR to maintain seamless communication between the HMD user and the physical collaborator. In addition, varying visualizations may have an effect on factors, such as trust and social presence, that contribute towards collaboration. We explore these visualizations and factors in RQ2 B and contribute [P7-P9] towards it.

> **RQ2 B:** *How does the virtual representation of a collaborator affect factors that influence collaboration, such as trust, performance, social presence?*

[P7] Training in IVR: Investigating the Effect of Instructor Design on Social Presence and Performance of the VR User

Summary. We investigate instructor representations (IRs) in the context of virtual training with head-mounted displays. Despite the recently increased industry and research focus on virtual training in immersive virtual reality , the effect of IRs on the performer (VR user) has received little attention. We present the results of a study (N=33), evaluating the effect of three IRs - webcam, avatar and sound-only - on social presence (SP) and performance (PE) of the VR user during task completion. Contrary to our assumption based on prior work, our results show that representing the instructor visually has a negative effect on performance. Instead, for high-performance scenarios we propose to only include the sound of the instructor. We also found significant effects on social presence depending on instructor representation. Our results are valuable for practitioners and designers who are building VR applications for synchronous teaching between HMD users and physical collaborators without an HMD.


Training in IVR: Investigating the Effect of Instructor Design on Social Presence and Performance of the VR User

Ceenu George, LMU Munich, Germany, ceenu.george@ifi.lmu.de
Michael Spitzer, LMU Munich, Germany, michael.spitzer@campus.lmu.de
Heinrich Hussmann, LMU Munich, Germany, hussmann@ifi.lmu.de

VRST '18, November 29-December 1, 2018, Tokyo, Japan — George et al.

George, C., Spitzer, M., and Hussmann, H. (2018c). Training in IVR: Investigating the Effect of Instructor Design on Social Presence and Performance of the VR User. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3281505.3281543

[P8] Trusting Strangers in Immersive Virtual Reality

Summary. Social interactions in immersive virtual reality (IVR) benefit from more realistically designed avatars whilst head-mounted displays are simultaneously offering virtual reality experiences with improving levels of immersion and presence. The combination of these developments creates a need to understand how users remit trust towards avatars in IVR. We evaluated trust towards two categories of avatars (robot vs. human-like) in VR by conducting a lab study (N=21) where participants had to play a trust game (TG) with each avatar. Our findings highlight that although the trust game revealed equal trust levels towards both categories of avatars, participants felt a significant sense of "togetherness" with the human-like avatar compared to the robot.

Trusting Strangers in Immersive Virtual Reality

Ceenu George[1], Malin Eiband[1], Michael Hufnagel[2], Heinrich Hussmann[1]
[1] {ceenu.george, malin.eiband, hussmann}@ifi.lmu.de, [2] {michael.hufnagel}@campus.lmu.de
[1,2]LMU Munich, Germany

Figure 1. (A) Robot avatar (B) Human-like avatar (C) VR room for trust game (D) Machine, to send money to trust game partner.

and are therefore only measuring the initial money sent by the trustor.

Secondly, trust questionnaires, such as the interpersonal trust scale [6] – measuring propensity to trust – and the SOEP [5] – specifically measuring trust in strangers.

Thridly, we also measured social presence [1] to understand whether people perceived a togetherness in the virtual scene.

This paper presents preliminary results of a lab study that used *quantitative* - in form of a TG -, and *qualitative* - in form of questionnaires - tools, to measure trust towards categories of avatars (RvsH) in VR.

STUDY

We conducted a within-subjects lab study (*N*=21, 6 female, Age: Mean=23.6/SD=3.5) to investigate whether *categories of avatars* (RvsH, counterbalanced) influence trust in strangers in IVR. We measured the *amount of money sent* during the TG and completed pre- and post game questionnaires, such as interpersonal trust, SOEP and social presence.

Apparatus

We built a virtual scene (Fig.1) in Unity that was accessible with an Oculus Rift and controllers. Two virtual avatars, human-like and robot, were developed to depict the trustee. The trustor was always a human-like avatar, however participants could only see their avatar's hands during the entity of the VR experience. Money was sent through an ATM-like machine (Fig.1, D) to avoid body movement in VR and only rely on hand gestures.

Procedure

Participants were first asked to sign a consent form and were then presented with Rotter's Interpersonal Trust Scale. An introductory task to the HMD (Oculus Rift) consisting of picking up and putting down items was used to prepare participants for the TG. Participants were given 2.5 EUR for each round, they had to play two rounds (RvsH) of the game and were told that they were matched with a different random [real world human] player in another room in each round. However, the second player was in fact always controlled by an assistant during the TG who simply returned the amount of money a participant had sent to maintain a neutral experience for all participants. Rounds were counterbalanced and introductions were provided on a screen in VR and verbally prior to entering the virtual world. After the TG, participants answered the SOEP and the social presence questionnaire. We additionally asked them if they believed that they had really played with another human player or not and whether their behaviour in the second round had been influenced by the first on a seven-point Likert Scale. In addition to the money received for playing the TG, participants were compensated with 5 EUR.

RESULTS AND DISCUSSION

We could not confirm a significant difference between the amount sent to the human-like ($Mean = 6.8$, $SD = 3.5$) vs robot ($Mean = 6.3$, $SD = 3.4$) avatar. This indicates that there may not be a difference in trust towards these categories of avatars. A dependent t-test showed a significant difference ($p < 0.05$) in the social presence scores between the two categories, such that human-like ($Mean = 4.1$, $SD = 2.8$) was perceived to create a more intimate level of togetherness in the virtual world than robot ($Mean = 3.1$, $SD = 4.1$). The variance in scores for robot was high, which reduces the effect of these results, however this suggests that although participants sent the same amount of money to both categories, they felt more comfortable when in the presence of the human-like avatar.

We found no relationship between the trust in strangers, that the TG measured, and the propensity to trust, which was measured by the 'Interpersonal Trust Questionnaire'.

CONCLUSION AND FUTURE WORK

This paper presented preliminary results on the perception of trust between categories of avatars (human like vs. robot) in IVR. Trust was evaluated by questionnaires as well as in form of a trust game, whereby participants had to play against both categories of avatars. Our preliminary quantitative results could not confirm a difference in trust between the categories, however, qualitative findings revealed participant felt more comfortable in presence of the human-like avatar.

Future work may look into how these results are comparable to the real world differences between the described categories (e.g. real world robot vs. human). We argue that there is a need to obtain an understanding on trust in IVR prior to releasing connected social and collaborative apps for HMD devices.

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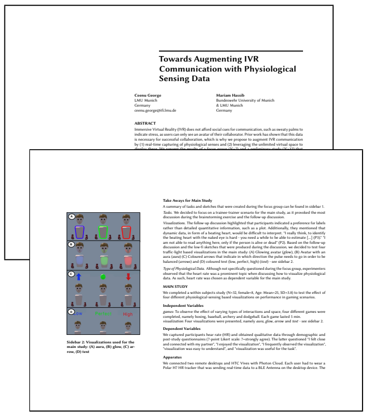
George, C., Eiband, M., Hufnagel, M., and Hussmann, H. (2018b). Trusting Strangers in Immersive Virtual Reality. In *Proceedings of the 23rd International Conference on Intelligent User Interfaces Companion*, IUI '18 Companion, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3180308.3180355

[P9] Towards Augmenting IVR Communication with Physiological Sensing Data

Summary. Immersive Virtual Reality does not afford social cues for communication, such as sweaty palms to indicate stress, as users can only see an avatar of their collaborator. Prior work has shown that this data is necessary for successful collaboration. Thus, we propose to augment IVR communication by (1) real-time capturing of physiological senses and (2) leveraging the unlimited virtual space to display these. We present the results of a focus group (N=7) and a preliminary study (N=32) that investigate how this data may be visualized in a playful interaction and the effects the visualisations have on the performances of the collaborators.


Towards Augmenting IVR Communication with Physiological Sensing Data

George, C. and Hassib, M. (2019). Towards Augmenting IVR Communication with Physiological Sensing Data. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI EA '19, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3290607.3313082

2.4 Managing Presence in the Physical and Virtual Reality

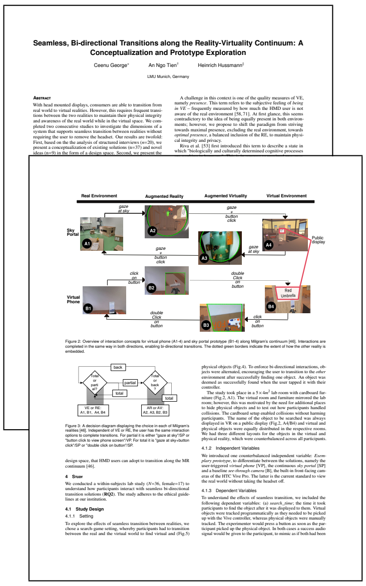
In our preliminary work we found that users struggle to balance virtual and physical reality [P1], because they cannot see one reality while they are in the other. To overcome this challenge, we propose to include parts of the physical reality in VR.

In their reality-virtuality continuum Milgram et al. [56] define the latter state as augmented virtuality – an in-between state. In his continuum both ends represent extremes. On one side is virtual and on the other side physical reality. Inclusion of physical elements into VR is referred to as augmented virtuality and embedding virtual objects in the physical reality is named augmented reality.

In this section I present publications [P10-P12] that are concerned with creating and testing applications that enable HMD users to transition from one state to the other while maintaining their presence.

> **RQ3:** *How can we support users to be aware of the physical reality while maintaining their presence in VR?*

[P10] Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration


Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration

Ceenu George, An Ngo Tien, Heinrich Hussmann

LMU Munich, Germany

Summary. With head-mounted displays for consumers, users are able to transition from real world to virtual realities. Due to the visual overpowerment users are mentally immersed in virtual reality and encouraged to believe that they are in another reality. However, their physical body continues to be exposed in the physical reality without HMD users being able to see it. To maintain physical integrity and awareness of the physical reality in this split state, users are required to frequently transition between the virtual and physical reality. To investigate the dimensions of a system that supports users in seamlessly transitioning between realities, without taking the headset off, we completed two consecutive studies. Our results are twofold: Firstly, based on the the analysis of structured interviews (N=20), we present a conceptualization of existing solutions (N=37) and novel ideas (N=9) in form of a design space. Secondly, we present the results of a user study (N=36), in which we tested two exemplary prototypes that evolved from the design space, called "Sky Portal" and "Virtual Phone" . Our exploration shows that our Virtual Phone metaphor has the potential to support HMD users in transitioning to in-between states along Milgram's reality-virtuality continuum [38] without leaving the reality they are currently in. They are

also enabled to complete micro-interactions across the realities, even without performance loss. To our knowledge, this is the first publication that investigates bi-directional transition solutions between realities. Our findings are valuable for researchers and practitioners who want to create VR solutions that enable users to treat both realities equally.

George, C., Ngao, A., and Hussmann, H. (2020a). Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration. In *2020 IEEE Symposium on Mixed and Augmented Reality*. IEEE Computer Society, doi:10.1109/ISMAR50242.2020.00067. "Preprint: http://www.medien.ifi.lmu.de/forschung/publikationen/detail?pub=george2020seamless"

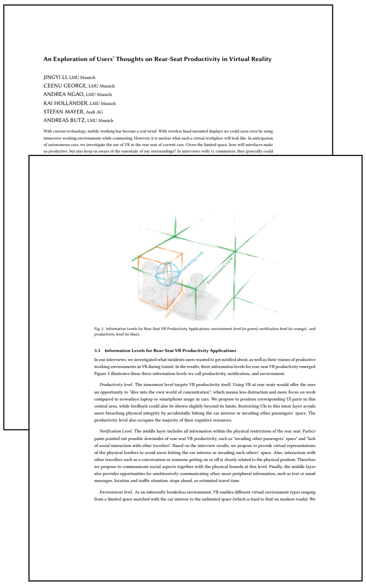
[P11] Invisible Boundaries for VR: Auditory and Haptic Signals as Indicators for Real World Boundaries

Invisible Boundaries for VR: Auditory and Haptic Signals as Indicators for Real World Boundaries

Summary. Maintaining awareness of real world boundaries whilst being immersed in virtual reality (VR) with head-mounted displays (HMDs), is a necessity for the physical integrity of the user. In this context, this paper investigates whether human senses can be allocated specifically to the real and the virtual world and what effect this has on workload, presence, performance and perceived safety. We present the results of an exploratory lab study (N=33) where the auditory sense of participants was trained to be an indicator for real world boundaries, while their visual sense was bound to a VR experience with an HMD. The choice of senses, namely auditory and haptic, are derived from our analysis in [P10], where we highlight in form of the SeaT - design space that there is limited prior work that reviews how they may be used to indicate real world events. Our results suggests that the allocation of senses increases workload. However, while performance is comparable to purely visual indications of boundaries, allocation seems to improve presence. Participants prefer the signals to be separate or combined subsequently, depending on the priority and proximity to the boundary. Our findings are a first step towards to explore the inclusion of audio and haptic signals to increase awareness of the real world. However, the variance in the data also sheds light on the need for further investigation on the methodology, specifically which variables act as success measures for a VR application.

George, C., Tamunjoh, P., and Hussmann, H. (2020b). Invisible Boundaries for VR: Auditory and Haptic Signals as Indicators for Real World Boundaries. *IEEE Transactions on Visualization and Computer Graphics*, pages 1–1, doi:10.1109/TVCG.2020.3023607

[P12] An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality


An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality

JINGYI LI, LMU Munich
CEENU GEORGE, LMU Munich
ANDREA NGAO, LMU Munich
KAI HOLLÄNDER, LMU Munich
STEFAN MAYER, Audi AG
ANDREAS BUTZ, LMU Munich

With current technology, mobile working has become a real trend. With wireless head-mounted displays we could soon even be using immersive working environments while commuting. However, it is unclear what such a virtual workplace will look like. In anticipation of autonomous cars, we investigate the use of VR in the rear seat of current cars. Given the limited space, how will interfaces make us productive, but also keep us aware of the essentials of our surroundings? In interviews with 11 commuters, they generally could

Fig. 2. Information Levels for Rear-Seat VR Productivity Applications: environment level (in green), notification level (in orange) , and productivity level (in blue).

3.3 Information Levels for Rear-Seat VR Productivity Applications

In our interviews, we investigated what incidents users wanted to get notified about, as well as their visions of productive working environments in VR during transit. In the results, three information levels for rear-seat VR productivity emerged. Figure 2 illustrates these three information levels we call productivity, notification, and environment.

Productivity level. The innermost level targets VR productivity itself. Using VR at rear seats would offer the user an opportunity to "dive into the own world of concentration", which means less distraction and more focus on work compared to nowadays laptop or smartphone usage in cars. We propose to position corresponding UI parts in this central area, while feedback could also be shown slightly beyond its limits. Restricting UIs to this inner layer avoids users breaching physical integrity by accidentally hitting the car interior or invading other passengers' space. The productivity level also occupies the majority of their cognitive resources.

Notification Level. The middle layer includes all information within the physical restrictions of the rear seat. Participants pointed out possible downsides of rear-seat VR productivity, such as "invading other passengers' space" and "lack of social interaction with other travelers". Based on the interview results, we propose to provide virtual representations of the physical borders to avoid users hitting the car interior or invading each others' space. Also, interaction with other travellers such as a conversation or someone getting on or off is closely related to the physical position. Therefore we propose to communicate social aspects together with the physical bounds at this level. Finally, the middle layer also provides opportunities for unobtrusively communicating other, more peripheral information, such as text or email messages, location and traffic situation, stops ahead, or estimated travel time.

Environment level. As an inherently borderless environment, VR enables different virtual environment types ranging from a limited space matched with the car interior to the unlimited space (which is hard to find on modern roads). We

Summary. Ubiquitous technologies have enabled mobile working for everyone. As head-mounted displays are becoming wireless, they can also be used to increase productivity during transit. However, it is unclear how such an immersive virtual workplace would look like. In anticipation of autonomous cars, we investigate the use of VR in the rear seat of current cars. Given the limited space, how will interfaces make us productive, but also keep us aware of the essentials of our surroundings? In interviews with 11 commuters, participants reported that they could imagine using VR in cars for productivity, but were concerned with their physical integrity/safety while in VR. Similar results were found in my early exploration on co-located usage of HMDs [P1]. Additionally, we discuss varying types of working environments that may be used to support focused productivity in rear-seat VR. Finally, our analysis reveals three information levels for rear-seat VR productivity, which have emerged from our interviews: productivity, notification, and environment. These preliminary results highlight the opportunity to transfer results from my thesis (e.g. interruption display) to unexplored situations, such as the rear-seat of a car.

Li, J., George, C., Ngao, A., Holländer, K., Mayer, S., and Butz, A. (2020). An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, AutomotiveUI '20, page 92–95, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3409251.3411732

2.5 Constraints and Limitations

Although each of my publications has a dedicated limitations section, there are three overarching constraints that I deem noteworthy.

Firstly, the preliminary exploration [P1] that motivated the foci in my thesis, can only be seen as a snapshot of the current state. Such a study needs to be replicated, as soon as influencing factors change. Technological improvements, such as the availability of *wireless* HMD devices, such as the Oculus Quest, call for the preliminary study to be repeated in order to understand whether our findings are still applicable and to what extent users perception has shifted.

Secondly, due to the lack of human and monetary resources, the majority of my studies (10/12) have been lab-based. Research shows that immersive workspaces are not going to be established for another 5-10 years [62]. However, as this change is progressing and HMDs are penetrating the productivity landscape, rather than solely being used for gaming, I hope to collaborate with users that are already working in co-located settings with HMDs or seeking to do so. The last publication is an example of one these ongoing efforts.

Thirdly, my studies have mainly had a task-centric approach, which Abowd and Mynatt [2] assess to be inappropriate for evaluating ubiquitous devices. They state that such an approach is not suitable, as tasks that users complete in everyday settings greatly vary. Although I agree that it is difficult to generalise findings from task-centric usability techniques, we have taken two measures to overcome this critique: Firstly, our work is grounded on a user-centric field exploration [P1]; focused on the interaction rather than common tasks. Secondly, each research question has at least one publication where the focus was on user behavior in a specific scenario [P5] – or on conceptualizing the research area – e.g. SeaT design space [P10].

3 Discussion and Future Work

The main objective of this thesis is to enable seamless interactions with the physical reality. I presented a preliminary exploration that highlighted themes that were in HMD users' minds during co-located VR usage with physical bystanders. These themes translated into three foci that form the structure of my thesis. For each focus, I developed interfaces and concepts that allow HMD users to be aware of the physical reality without taking their headset off.

Firstly, I introduced the concept of seamless authentication, whereby users authenticate in VR without relying on additional devices such as a mobile phone or a PC. After reviewing the transferrability of existing 2D authentication systems, we developed a novel 3D concept that we tested with multiple interaction modalities.

Secondly, I investigated seamless communication, which enables bystanders to communicate with VR users within the 3D environment. I proposed design guidelines for VR interactions that enable (i) bystanders to choose opportune moments for interruptions and (ii) VR users to decide how much they want to reveal through their gestures. I provided interruption designs in VR and discussed their effect on presence and performance. I conducted several case studies to explore the relationship between virtual representations of co-located collaborators and collaboration variables, such as presence, performance, trust and social presence.

Thirdly, I presented a design space on seamless transitions [SeaT] to conceptualize existing and novel solutions that enable HMD users to navigate along the reality-virtuality continuum without taking their headset off. I developed and tested three interfaces derived from gaps within the [SeaT] design space. Finally, I investigated the transferrability of my concept on seamless transitions to a chauffeur-driven car setting with the aim to enable productivity in VR during transit.

In this final chapter I reflect on my contribution for each focus and discuss it in relation to prior work. I end the discussion by proposing future research directions for each focus section.

3.1 Preliminary Exploration

As technology is advancing and high-end head-mounted displays are becoming ubiquitous, there is a need to evaluate users' mental models, expectations and acceptance of VR in co-located settings (**RQ0**).

To investigate RQ0, we completed an exploratory field study that revealed common themes in the minds of potential VR users [P1]. These themes directly translate to the structure of my thesis.

Focus 1: Usable Security and Privacy of VR: Observability of HMD User Interactions. Users are concerned about privacy when wearing head-mounted displays, specifically the fear of being observed.

Focus 2: Communication with Co-located Collaborators. Users found it challenging to communicate with bystanders due to the inability of VR-enabled HMDs to enable a view of the real world.

Focus 3: Managing Presence in the Physical and Virtual Reality. Users struggle with managing presence between the real and virtual reality; especially in regard to their physical integrity.

The following sections discuss each focus in relation to related work and provide directions for future work.

3.2 Usable Security and Privacy of VR: Observability of HMD User Interactions

Prior work on usable security and privacy for VR-enabled HMDs is limited. Although there is extensive research on authentication and shoulder surfing on ubiquitous devices, the transferrability of the findings to HMDs is unclear; firstly, because HMDs afford a limited or no view of the physical reality and are thus more prone to shoulder surfing attacks, and secondly, because interaction in VR is within a 3D environment rather than a 2D environment it requires varying levels of workload, potentially affecting entry times and error rates.

Table 3.1 provides an overview of my contribution on authentication in VR – see P2-P4. To give a comprehensive view of the research area, I have added the most prominent related work that I built upon, in the first row of the table, and follow-up projects by other researchers in the last row.

Table 3.1: Overview of authentication mechanisms developed for VR in this thesis [P2-4]. To my knowledge, my work was the first investigation on usable security in VR. For ease of comparison, the first two rows are prior work on popular authentication mechanisms from mobile phone authentication. Similarly, the last three rows highlight recent related work.

Paper	**Type**	**Modality**	**Details**	**Entry Time (s)**	**Error (%)**	**SSS* (%)**	**Memorability (%)**	**Password Length**
[83, 46]	PIN PR	tap		1.50	0.8	97	70	4/10
[82, 83]	pattern PR	tap		3.14	15	71.4	41	5/9
P2	PIN	pointer	L** surface	2.57	1.13	18		4/10
	PIN	pointer	M surface	2.38				
	PIN	tap	M surface	3.36				
		Stylus	S surface	2.67				
	pattern	pointer	L surface	3.0	5.18			
	pattern	pointer	M surface	3.18				
	pattern	tap	M surface	3.84				
	pattern	stylus	S surface	2.87				5/9
P3	RoomLock VR	pointer	baseline	6.39	2.7	18.5	77.7	4/9
	RoomLock VR	pointer	user random	7.25		12.5		
	RoomLock VR	pointer	object random	14.53				
	RoomLock PR	pointer	baseline	4.84				
	RoomLock PR	pointer	user random	5.26				
	RoomLock PR	pointer	object random	8.87				
P4	RoomLock VR	gaze	baseline	9.15		15-18		
	RoomLock VR	gaze	multi-modal	5.94		10-18		
	RoomLock VR	head	baseline	9.56		58		
	RoomLock VR	head	multi-modal	5.51		18 -56		
[53]	PIN 2D cube	tap		1.69	8.1	2.22	n/a	4/9
[53]	PIN 2D cube	gaze		2.39	11.8	0	n/a	4/9
[21]***	*LookUnlock* PR	gaze		min. 6.0	n/a	5.9	n/a	4/n/a

*Shoulder Surfing Success
**L, M, S stands for the size of the interface. Details can be found in [P2]
***The usability is based on assumptions, as the paper does not include a usability study.

Tasks and Task Switches are Observable from the Physical Reality (RQ1A)

This thesis revealed that observers are able to guess tasks (77%), such as PIN and pattern entry, and task switches (83%), solely through observing HMD users' gestures [P5]. From a usable security perspective, this means that co-located observers are able to identify when an HMD user starts to enter a password, even without a view of the virtual reality. Subsequently, the question arises of whether bystanders are able to guess a password solely through observing the user. In recent work by Adam's et al. [3] observability was not found to be a concern. However, this outcome can be warranted to the study design. Contrary to our preliminary study, where participants were interviewed in public places about future usage of detached devices, Adams et al. asked them about their own experience. At the point of their study, HMDs predominantly required a high-end PC-setup which is also reflected in their demographics data [3].

Transferring Known Authentication Mechanisms to VR Increases Security While Maintaining Usability (RQ1B)

We know from prior work on smartphones that shoulder surfing success rate is high – 90% for PINs and 71% for patterns (see Figure 3.1). HMDs naturally hide the virtual display from bystanders, and thus provide an opportunity to decrease the risk of shoulder surfing. We conceptualize this affordance and propose seamless authentication, whereby the user does not need to take off the headset in order to enter their password. At the time of the study, users had to enter their credentials on the smartphone or an external display in order to authenticate. This thesis adds an investigation on the transferrability of PIN and pattern authentication to VR [P2]. Our results highlight that the shoulder surfing success rate is reduced to 18% by introducing seamless authentication. Additionally, we found pattern entry to be more usable in VR than in the physical reality. We also provide design guidelines on input size and interaction modality to balance security and usability.

Using the 3D Environment for Authentication Increases Security (RQ1B)

This thesis adds multiple studies investigating authentication in the 3D environment to increase usability and security, conceptualized in the form of a novel authentication mechanism named *RoomLock* [P3, P4]. At first glance, the studies show that authenticating using the 3D environment increases security while decreasing usability. Similarly, in [P4] we found that multi-modal interaction with gaze increases security further but it also has a negative effect on usability. However, usability is commonly measured by combining the variables' entry times, error rate and memorability. A closer look at these individual data points, see table 3.1, reveals that although entry times were higher, error rates were lower than for pattern input and memorability was better than for PIN and pattern input. Entry times were also influenced by the amount of previous experience that participants had had with the device and the choice of modality. Considering that smartphones have been part of humans' everyday life for more than a decade, it can be assumed that entry times are higher just because participants are more familiar with it. Future work may review long term learning effects on entry times for *RoomLock*. Follow up studies by other researchers investigated alternative interaction concepts, such as a Rubik's cube to enter PINs [53] and *RoomLock* for AR [21], called *LookUnlock*. *LookUnlock* resulted in higher entry times than in the physical reality, see Table 3.1, which I attribute to the higher workload associated with mixed reality usage and the longer dwell times (800ms in RoomLock vs 1500 in *LookUnlock* ms). The user has to differentiate physical and virtual objects from each other in order to authenticate. Although entries within the Rubick cube system performed better in regard to entry time, the password space was smaller than in our study on 2D PIN entry. Additionally, the error rate was higher than in our concepts.

Transferring Findings on Authentication Mechanisms from the Physical Reality to VR (RQ1B)

The authentication mechanisms investigated in [P2] and [P3] had higher entry times in VR than their counterparts in the physical reality – see table 3.1 entry times in authentication types (column "Type") in VR vs PR. I argue that the higher entry times, compared to PIN and pattern entry, are the results of the increased workload required to complete interactions in VR. This is manifested by the imitation study we completed in the physical reality where participants were significantly quicker than in VR and perceived a lower workload [P3]. Thus, based on the results of my thesis, transferring findings from studies in the physical reality cannot be directly transferred to VR. We propose to re-test suitable authentication mechanisms in VR instead of assuming transferrability.

This thesis has highlighted that designing with observability from PR in mind is vital for usable, secure and privacy aware VR applications. Although I have given specific design guidelines in regard to size and input modality for authentication mechanisms, further research needs to explore where the exact balance lies between how much of the 3D space can be leveraged for interaction to decrease observability – security, vs the increase in workload it requires to make sense of the virtual environment and its effects on entry time/error rate – usability.

The Right Timing for Usable Security Research for VR

In prior work on usable security for VR Adams et al. [3] interviewed developers and VR users on the topic of privacy. In contrast to our findings from interviews with non-experts, their expert users were less concerned about it. Adams found that participants were willing to give up their privacy for the exclusivity of the VR experience. This phenomenon may be due to the age range of the participants that took part in that study. Prior work found that a lower age correlated with the willingness to give up privacy for the exclusivity to be part of a new tech/app community [50]. Adams' study showed that developers were concerned about privacy and saw it as a priority; however, they also felt that VR was not sufficiently established to be worrying about it yet. This discrepancy is an ongoing challenge for usable security and privacy research for VR: When is a good time to start research on usable security for VR? After it has established itself in everyday, co-located situations when we know the contexts and tasks that HMDs will be used for, or before, when we have to make assumptions based on established ubiquitous devices? I argue for the latter, as the industry is pushing for headsets to become more ubiquitous and used in co-located settings, and thus, research into usable security needs to occur now. Of course, maintaining ecological validity is challenging when working with assumptions in regard to future usage. This challenge may be overcome by regularly repeating the preliminary exploration to investigate whether mental models and expectations have shifted.

Observable vs Hidden Interactions for Co-located VR Interaction

Although focus 1 in my thesis started by exploring general advantages and disadvantages of observability, the primary contribution is on authentication mechanisms. Now that we have revealed what interactions during authentication are observable and what methods bystanders employ to recognize them, it would be interesting to generalize these findings in the form of a design space for observable vs hidden interactions. For example, hidden interactions may be subtle, such as pointing to a distant object, or involve minute movements with the fingers, such as rotating a cube. In contrast, observable gestures may be more visible and grand, such as tapping on a public screen in VR.

3.3 Communication with Co-located Collaborators

This thesis introduced the concept of seamless communication, which entails interaction concepts and interfaces that support the HMD user to continue to wear the headset during communication with bystanders. This thesis contributes towards meeting this challenge by investigating interruptions and communication channels in co-located settings with HMD users.

McFarlane and Latorella [55] compiled a taxonomy of human interruption, which I have adapted to visualize the research agenda for communication with HMD users in co-located settings – see Figure 3.1. Although there are more recent conceptualizations of interruptions, I chose McFarlane and Latorella's taxonomy as (i) it discusses interruptions in general rather than for a specific device, and (ii) many of the more recent publications are built on their work.

Figure 3.1 provides a visual overview of the taxonomy from A-F. It highlights in green the sections that I have contributed towards, and the ones that may be investigated as part of future work are highlighted in grey. I have included research questions from my publications in dotted borders, as these are not part of the original taxonomy. I have also excluded the dimension that conceptualizes human differences, such as age, as I believe that prior results can be transferred to the context of HMD interruptions. Lastly, I have changed (F) to be the effect of the "channel of communication" rather than the overall interruption.

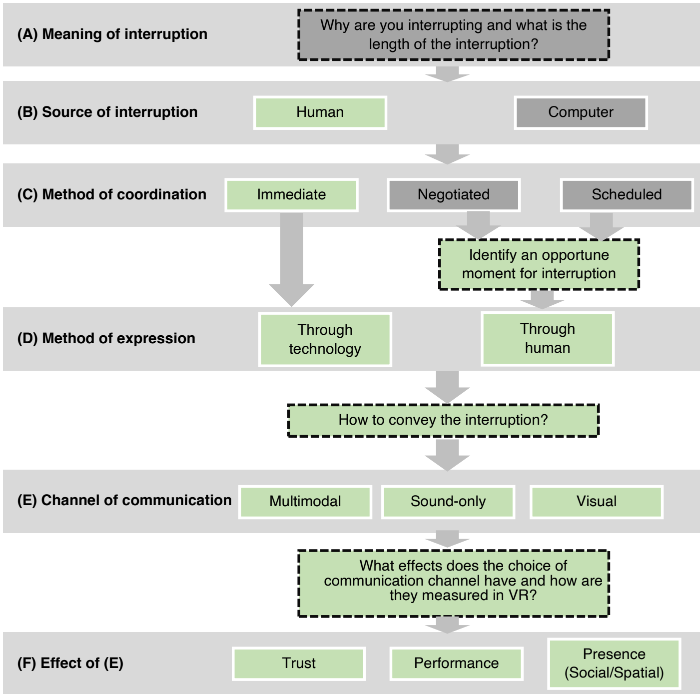


Figure 3.1: McFarlane and Latorella [55] conceived a taxonomy of human interruption, which I have adapted to visualize the research agenda for communication with HMD users in co-located settings. The dimensions that I have contributed towards are highlighted in green vs the ones that may be investigated in future work in grey. Research questions that are part of this thesis and are added to the original taxonomy are denoted with dotted borders.

HMDs Introduce Three Challenges for Co-located Interruptions (RQ2A)

In [P5] we focused on the (B) human as source of interruption. We investigated which (E) channels of communication they use if they themselves are the (D) method of expression. We found that bystanders use different methods to convey interruptions: 62.5% speak, 18.8% speak & touch, 9.4% touch, 3.1% wave (AR only), and 6.3% did not interrupt (VR only). The last subset claimed to have felt uncomfortable about interrupting someone who was clearly deeply engaged with another device. Notably, they chose these methods, despite knowing that the HMD user was wearing headphones. The challenges these approaches create are threefold: First, in this context the bystander feels unheard, depending on the volume of the headphones. Second, they force the bystander to get into close proximity of the user to touch and interrupt. Third, the HMD creates a setting in which bystanders do not feel like they can interrupt at all. To overcome these challenges this thesis introduced multiple concepts and interfaces for seamless communication, whereby the user is not forced to take off the headset but is given the choice to do so.

Empowering the Bystander to Choose Opportune Moments for Interruptions (RQ2A)

First, I investigated whether humans are able to negotiate or schedule ((C) method of coordination) their interruption by observing gestures and user movements [P4]. Thus, if the interruption is not immediate, users may determine through observation when an opportune moment is to interrupt. Bystanders may schedule their interruption when the HMD user is completing a task switch. Additionally, I propose interaction concepts that empower the HMD user to signal (negotiate) when they do not want to be disturbed, e.g. by providing the option to move the virtual focus to work with their back to the co-located user.

An overarching question that remains unresolved is the effect of observable or hidden gestures on the collaboration between an HMD user and bystander. This may be evaluated with qualitative data, such as observations and interviews. However, they may also be quantified by counting the number of times an HMD user is interrupted over a certain period of time and how that it is perceived by both parties. It is unclear whether including an HMD user in a co-located setting decreases overall willingness to communicate with each other. Finally, similar to prior work on AR interactions [4, 47], social acceptability of these devices needs to be explored in co-located settings.

My aim was to investigate how the (human) bystanders can be empowered to be a (D) method of expression themselves; without introducing additional technology. Although we highlighted that this has a clear advantage in terms of interruptability, it is unclear what effects such a non-technological solution has and how it performs in comparison to a technical solution, such as a traffic-light system that informs bystanders about the HMD user's state. We explored such systems in participatory focus group sessions [24]. For example, the HMD user could sense (e.g. through the camera feed) when a bystander was in close proximity. Alternatively, the bystander may be equipped with an interface/technology which can be used to signal interruptions in VR. However, future work needs to evaluate how such methods compare to a human-only solution.

Trade off between Response Time and Presence as a Determinant for Interruption Design (RQ2A)

Second, I investigated how to convey an interruption when the (D) method of expression is through technology. In [P6] I explored varying interfaces for displaying virtual interruptions and the effects they had on performance and presence. We found that the textual interruption, compared to an ambient light and a spot-light, had the most negative impact on presence; however, participants were also quicker to respond to it. This suggests a trade-off between the urgency of the interruption and the negative impact on presence.

Once the HMD user has been interrupted by the bystander, the question arises of how to continue the communication between these two parties and which channel to use. Of course, the question on how to continue the communication is dependent on multiple factors; most importantly, the amount of time they are planning to uphold the communication channel and the type of task to be completed. The extent to which time and task have an effect on type of channel for communication may be explored in future work. Although McFarlane and Latorella [55] created the taxonomy for interruptions, I refer to it mainly to organize my work on communication. I do not claim that the taxonomy applies to communication in general, but did find that their dimensions are equally relevant for my contributions on co-located communication with HMDs.

Third, this thesis adds multiple studies that investigate varying channels for continuous communication in which the (D) method of expression is technology; specifically, virtual representations of co-located physical collaborators. This thesis therefore focuses on the (F) effect the choice of (E) communication channel has on the [other] VR collaborator rather than exploring how the varying representations such as as their embodiment and performance affect the represented user.

Trade-off Between Performance and Social Presence as a Determinant for the Virtual Representation of Collaborators (RQ2B)

In [P5] we found that performance of the HMD user increases when the (E) channel of communication is sound-only from the collaborator. However, we also found that social presence is the highest when a virtual representation such as an avatar is present. This suggests that there is a trade-off between performance and social presence. Thus, in situations where performance is vital, such as during surgical training, sound-only may be preferred, whereas in business meetings, such as sales pitches, social presence may be prioritized.

Augmenting Avatars through Text-Based Visualizations of the Heart Rate Improves Performance (RQ2B)

Next, we explored how to transfer concepts that we know from communication in the physical reality to the virtual reality. Communication is multi-faceted, and interpreting changes in the appearance of the collaborator is part of it. For example, parents can judge whether children are lying by observing where they are looking at and whether they start sweating. Physiological responses such as this enrich communication, independent of whether we can control them or not. An increased heart rate may, for example, lead to sweaty palms, which are not visible during VR communication. In [P9], we explored how to transfer and augment this concept to VR by developing an interface in which both collaborators saw visualizations of each other's real-time heart rate. Thus, in our trainer vs trainee scenario the visualization was displayed to the other collaborator, and the aim was to adjust one's own game play to stabilize the other player's heart rate. If the heart rate of the trainee was going down, the trainer had to intensify the game. Similar to [P6], where participants reacted to text quickly, the text-based design was perceived to be easier to understand than the alternative visualizations. However, the other visualizations, specifically the color changing avatar, were found to be more enjoyable and intuitive. The combined results suggest that a text format provokes high performance due to easier understanding, but alternative visualizations that are embedded in the scene result in a better experience. In a recent study Gosh et al. [36] evaluated interruption designs and confirmed that text based interruptions resulted in faster reaction times. Future work may investigate whether long-term usage of VR increases the susceptibility to embedded visualizations for interruptions and communication and therefore leads to similar performance as the text alternative. Although visualizations were perceived to be enjoyable and useful, controlling the other player's heart beat by adjusting one's own game play was found to be difficult. I attribute this to the motoric effort that was required to play the games while focusing on the heart rate visualization. I propose to transfer this concept to scenarios where the motoric effort is limited, such as a seated job interview experience. Villani et al. [79] have highlighted that virtual reality can serve as a training platform for job interviews. They measured heart rate to evaluate how participants manage anxiety, as this was found to be a determinant for the success of the hiring decision. Future work may investigate how heart rate may be displayed in such a context and how it can support applicants to manage their anxiety.

Trust is Difficult to Measure in VR Due to the Realness of the Virtual Avatar vs the Ambiguity of who is controlling it (RQ2B)

Finally, we explored the concept of trust (F) between the virtual representation of a co-located physical collaborator and the HMD user. Taking the headset off and confirming the identity of the collaborator in the physical reality upon visual inspection disrupts the VR experience and breaks presence. To enable a seamless interaction, the user has to trust the virtual representation. Before exploring how trust can be established in such a context, I first wanted to understand how trust can be measured in VR. This thesis adds an investigation into methods to measure trust in VR [P8]. Similar to [P7] we found differences in social presence between the different avatar designs, whereby the human avatar provoked a higher perception of social presence. Due to the insignificant results, we cannot confirm whether trust was also higher; however, the trust game suggests that more money was sent to the human avatar than the robot one. The methods used to measure trust did not lead to results that were significantly correlated with each other, which we attribute to the high variance in the data. We believe that this is due to the unclear notion of who the counterpart exactly was – human or AI. Although we had informed participants at the start of the study that the avatar was controlled by a human, they voiced confusion about this topic, and it was unclear whether trust was established with the avatar, and whether or not the human was controlling the avatar. Throughout my work on RQ1 and RQ2, I have imitated studies across both realities, as I believe that transferring familiar concepts from the physical reality into VR facilitates trust in VR. For future work, I propose to imitate the study on trust in robots vs in humans in the physical reality to understand how the results compare between between both realities. Although in VR it may be possible to control a human avatar, translating this mental model of control over avatars to the physical reality would mean that a human is controlling another human. This would be interesting as it is unclear how the notion of trust is translated to a robot in the physical reality and – more complex – a human who is controlled by another human.

3.4 Managing Presence in the Physical and Virtual Reality

Managing presence between realities is something humans already do. Ubiquitous systems have forced us to continuously navigate our attention from the virtual to the physical. When the virtual reality is limited to a physical screen, this management task seems doable and users seem to be successfully managing it. HMDs, however, create a new setting, whereby using one reality forces the user to completely visually give up the other reality. Users are anxious about giving up virtual reality [16] but how do they handle not seeing the physical reality? Our preliminary exploration highlighted a discomfort that users experienced about not being aware of physical threats, such as objects (e.g. cable, chair) or people (unwanted intruder) [P1]. Popular ubiquitous devices, such as a laptop or mobile phone, allow users to transition between realities, as the VR only takes up a small part of our visual field. This is possible through the human visual perception that enables users to focus on the virtual reality (e.g. smartphone), while remaining aware of the physical reality. However, this is impossible with HMDs that blind the user from the physical reality – they cannot transfer their usage patterns from existing ubiquitous devices to HMDs. To overcome this challenge, I investigated seamless transition concepts that allow users to navigate along the reality-virtuality continuum without taking their headset off.

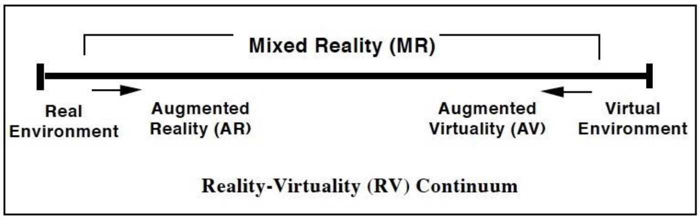


Figure 3.2: The reality-virtuality continuum from Milgram et al.'s [56] publication on "merging real and virtual worlds". In my thesis, managing presence between the outer states (RE vs VE or virtual reality vs physical reality), involves transitions to in-between states (AR vs AV). Our concept of seamless bi-directional transitions envisions the transitions themselves to be completed in the same way, treating both environments equally.

Fig. 3.2 shows the reality-virtuality continuum, where Milgram differentiates between outer states and in-between ones [56]. Outer states are virtual environment (VE or in the context of this paper VR) and real environment (RE or in the context of this paper PR). In-between states are augmented reality and real virtuality, where one of the outer states is augmented with parts of the other outer state. In the context of my thesis, transitions are possible from the outer state to the immediate in-between state – which we refer to as partial transitions – and from the outer state to the other outer state – which we refer to as total transition. Most importantly, transitions are performed in the same way in both directions, making them bi-directional.

Design Space for Seamless Transitions (SeaT) to Conceptualize Existing Work and Foster Novel Ideas (RQ3)

This thesis adds a design space [P10] that conceptualizes seamless transition concepts in co-located settings, namely the SeaT design space. The design space is a result of (a) interviews with expert (researchers and developers) and novice (gamer) users of VR, and (b) an in-depth analysis of solutions from prior work. It draws attention to the fact that (i) existing solutions satisfy one to two dimensions rather than considering all of them equally, and (ii) that the auditory and haptic senses have been neglected in this context. These two findings form the direction for the rest of the projects in this section.

Virtual Phone Metaphor Enables Seamless Transitions While Maintaining Presence (RQ3)

First, it is unclear whether an overarching solution that satisfies all dimensions within the design space is better than existing solutions. Based on novel ideas from the SeaT design space, I took a first step towards resolving this uncertainty by iteratively developing two prototypes for bi-directional transitions. Thus, user transitions could be completed in one direction (VR to PR), in the same way as in the other direction (PR to VR) [P10]. We completed a user study with the two prototypes to understand the value of the transition concepts and how presence is affected. Due to the scope of this thesis, we are only presenting the most prominent solution from [P10], namely the Virtual Phone metaphor. Metaphors support users in transferring existing mental models to new contexts. Jamar et al. [42] define it as "[...] tools we use to link highly technical, complex software with the user's everyday environment."

The virtual phone acts as a tangible window to the other reality with which the user can partially transition to an in-between state in the reality-virtuality continuum – see Figure 3.3. We envision the user interacting with the other reality by using familiar interaction concepts on the phone, such as zooming in and tapping to direct attention. Our study showed that the Virtual Phone metaphor enables micro-interactions in the reality-virtuality continuum without performance loss. In the Virtual Phone condition participants achieved comparable presence in VR while using significantly more partial transitions than total ones.

The next step would be to determine how our overarching transition concepts can be compared to existing solutions. This is a challenging quest, as there is no common variable that is used to measure success. A majority use presence as a dependent variable but I believe that this is unsuitable, as the questionnaires that evaluate presence are constructed under the assumption that the less we know about the physical reality, the better the VR experience is. However, as we found in [P1], with HMDs users seek to be aware of the physical reality in order to maintain their physical integrity and complete micro-interactions, such as checking who is approaching when they hear a sound. In this context, I argue for separating the question about physical reality awareness from the overall presence questionnaire and evaluating them separately. A high awareness of the physical reality might be something that is perceived to be a positive trait in a ubiquitous context, as suggested by Abowd and

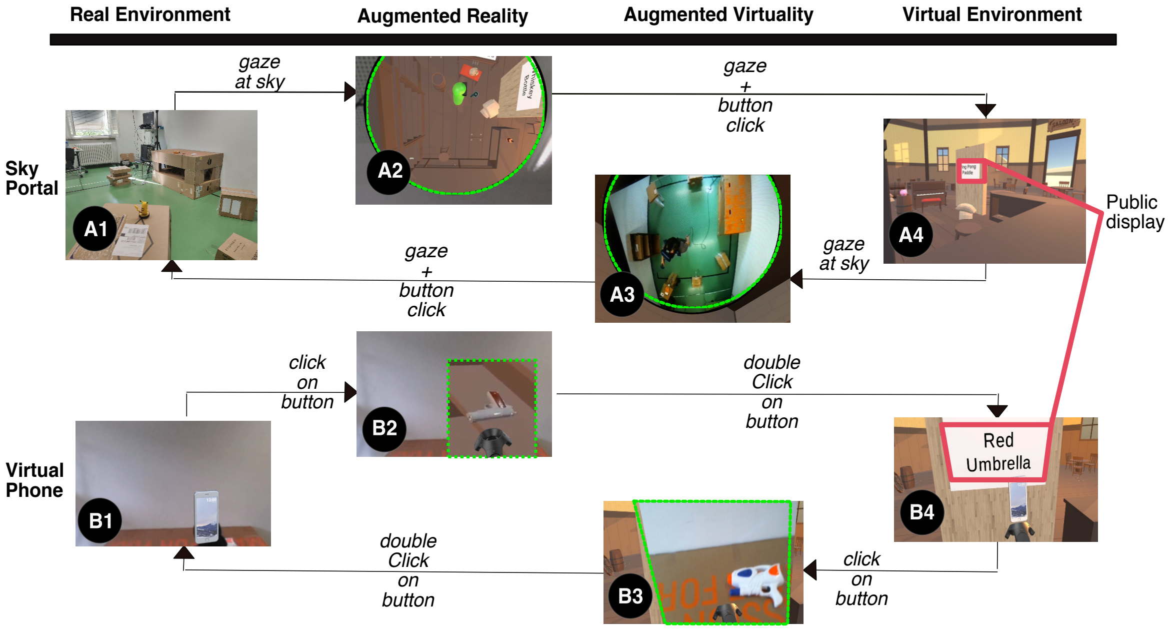


Figure 3.3: Overview of interaction concepts for virtual phone (A1-4) and sky portal prototype (B1-4) along Milgram's continuum [56]. Interactions are completed in the same way in both directions, enabling bi-directional transitions. The dotted green borders indicate the extent of how the *other* reality is embedded [P10].

Mynatt [2]. For example, being notified about changes in the physical reality may increase trust while maintaining presence in VR.

Audio/Haptic Borders Provide Omni-Directional Feedback on Real Boundaries While Increasing Workload (RQ3)

Second, motivated by the gap in existing work as revealed by the SeaT design space, this thesis adds an exploration into the inclusion of auditory and haptic senses to increase awareness of the physical reality [P11]. Of course, it is not surprising that auditory and haptic senses have been neglected, as the HMD predominantly uses our visual perception to create an illusion of a virtual reality. The effort to use auditory and haptic senses to increase awareness of the physical reality has mainly been on interruptions research [36]. However, prior work has revealed that users are capable of obtaining different degrees of information from audio and haptic feedback. Results showed that audio can be used to increase spatial understanding of the virtual [18] and physical [10] reality. Similarly, Yang et al. [37] showed that haptic feedback can be delivered in different strengths and even spacing to support navigation on handheld devices. These research efforts have in common that the visual sense is not overloaded with additional information and the user can focus on their primary task, while the other senses – haptic and audio – can focus on secondary tasks, such as spatial awareness. Allocating senses to tasks to maintain performance and workload is a well-known concept, popularly summarized by Wickens et al. [84]. Based on these insights, we developed a system that signals physical borders through auditory and haptic signals to HMD users [P11]. Our results revealed that allocating senses to different realities increases workload, performance is comparable to purely visual indications of boundaries and there is a tendency for presence to be better in VR. Participants appreciated the omnidirectional feedback that audio was able to provide which enabled them to be aware of a wall that was behind them without turning towards it visually. Although this exploration seems like a promising alternative for visual indicators for physical borders, the increase in workload needs to be investigated further. Thus, for future work I propose a twofold approach: First, split the haptic and audio feedback and only leverage one sense to indicate physical borders. Second, the primary task in VR required a high workload, which may have interfered with the overall workload data. Both of these approaches should decrease the variance in the results and result in a more definite outcome.

Transferring the Concept of Seamless Transitions to Rear-Car Settings (RQ3)

Third, in my most recent work, I have been investigating the transferrability of my research to other contexts, namely rear-car productivity with HMDs [P12]. This setting is interesting, as it is requires ubiquitous devices such as a tablets and mobile phones rather than a PC, but we can control the influencing factors. For example, the number of co-located people that can sit in the car and the space that the HMD user can occupy. This thesis adds a first exploration of rear-car productivity, in which we completed interviews with chauffeur driven commuters to understand their needs. Our results showed that similar to our preliminary exploration [P1], participants were worried about communication with co-located passengers and feared for their physical integrity. Contrary to our assumption, participants were less concerned about car-specific issues such as traffic. Interestingly, in the car setting participants favored being without distractions from the smartphone, such as text messages or email alerts. They perceived this to be a space where they could focus on one task for a short period of time, for example, when being driven to the airport. Future studies need to confirm whether their voiced needs match with their behavior. Next, I plan to transfer my work on allocating senses to indicate physical borders to the car setting. A visual solution such as a mesh may be obsolete in this confined space and may be replaced by audio or haptic boundaries.

3.5 Closing Remarks

> “The ‘real world’ is now also a legacy term. For your grandchildren, holding on to that distinction [between virtual and real] will be the thing that makes you a kind of quaint and really incomprehensible being.”
>
> *William Gibson* [51]

To date my research has been focused on supporting users to be aware of one reality while being in the other. However, this presumes a difference between the real and virtual reality. William Gibson, the author who invented the term “cyberspace", claims that there will be no difference between these two realities in the future. Although we can currently see a difference between virtual and real, research on ubiquitous, wearable devices and implants to augment humans, raises the question when this differentiation will cease to exist. Once humans wear implants that continually show them virtual reality embedded with physical reality; with an image quality that is the same for both realities, will they still be able to differentiate them? In [P10] I discussed seamless bi-directional transitions, where transitions between both realities are completed in the same way. I see this as a first step towards omnipresence – striving to be in both realities at the same time without favoring one.

Finally, although this thesis has highlighted that it is vital to be aware of one reality while being in the other, especially in co-located settings, this may not be preferred by all users. In particular situations, HMD users may want to embrace the secluding aspect of HMDs. An alternative research approach would be to strive for mindful interaction concepts, where HMDs empower the user to focus on one reality at a time without having to manage their presence between different ones. It may be better to embrace this interaction paradigm that HMDs naturally afford instead of striving to be more like popular ubiquitous systems, such as mobile phones, where users struggle with managing their presence. Alexis et al. [41] analyzed users’ motivations for wanting to disengage from the mobile phone and proposed an intervention concept to support them. Similarly, momento app provides statistics about time spent online [57] and features a forest that visualizes time spent in the physical reality by a growing vs. dying tree [70]. To investigate mindfulness in the context of HMD usage, I propose to re-evaluate the concept of presence. Understanding how users currently manage their presence, not just in the virtual and physical reality but also in their own mental reality, may support the creation of mindful concepts for HMD users. Or in simpler terms, it may support researchers and practitioners to decide how and when to design for omnipresence and when to foster focused usage.

LIST OF FIGURES

List of Tables

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Figure 1 and 2 originated from pikisuperstar / Freepik and were redesigned and edited by me for the purpose of this thesis.

Appendices

A
Original Publications

Table A.1 provides an overview of my own and collaborators' contributions in regard to the publications included in this thesis. After the table, the original papers are included in the presented order P1 - P12. Please refer to the published versions.

	My Contribution	Contributions of others
[P1]	I came up with the research idea, the study design; analyzed study data and was the leading author of the resulting publication.	Julia Schwuchow completed the study; Heinrich Hussmann edited the final version of the paper and supervised the project.
[P2]	I came up with the original research idea, study design and strategy. Further, I created the first version of the prototype; I authored the paper.	Mohamed Khamis supported in the analysis of the Levenshtein distance and discussed the study design with me; Marinus Burger and Henri Schmidt created the final version of the prototype and completed the study; Emanuel von Zezschwitz contributed a section on "Virtual Reality as a Feasible Research Tool" in the discussion; Florian Alt edited the final version of the paper; Heinrich Hussmann supervised the project.
[P3]	I came up with the original research idea and study design; I supervised the implementation of the prototype, as well as the data collection; I completed the analysis and the second security study; I authored the resulting publication.	Introducing the variable of moving users vs objects was a result of a discussion with Daniel Buschek; An Ngo Tien created the prototype and completed part of the study; Daniel Buschek and Mohamed Khamis edited the final version of the paper; Heinrich Hussmann supervised the project.
[P4]	I came up with original research idea together with Mohamed Khamis; Mohamed Khamis and I supervised the main study design and implementation; I analyzed the resulting data together with Mohamed Khamis and I was the leading author of the resulting publication.	Andrea Ngao extended the prototype from [P3] and conducted the study; Mohamed Khamis contributed towards the discussion section; Daniel Buschek edited the final version of the paper.
[P5]	I came up with the original research idea; I supervised the implementation of the prototype and the implementation of the study; I analyzed the resulting data and authored the publication.	David Heuss and Phillipp Janssen created the prototype and conducted the study. Florian Alt supervised the project and edited the paper for clarity and readability
[P6]	I came up with the original research idea; I supervised the implementation of the prototype and the implementation of the study; I analyzed the resulting data and authored the resulting publication.	Manuel Demmler created the prototype; Heinrich Hussmann supervised the project.
[P7]	I came up with the original research idea; I supervised the development and implementation of the concept and prototype; I analyzed the resulting data and authored the resulting publication.	Michael Spitzer implemented the prototype; Heinrich Hussmann edited the final version of the paper.
[P8]	I came up with the original research idea and was the leading author; I supervised the implementation and study together with Malin Eiband; Malin Eiband and I analyzed the resulting data together.	Michael Hufnagel created the prototype and conducted the study; Heinrich Hussmann supervised the project.
[P9]	I came up with the original research idea, completed the analysis and authored the paper. I supervised the implementation and study together with Mariam Hassib.	Patrick Waldner created the prototype and completed the study.
[P10]	I came up with the original research idea; I created the first version of the design space; I supervised the development and implementation of the concept and prototype; I designed the pre- and main-study; I analyzed the resulting data and authored the resulting publication.	An Ngo Tien developed the prototype and conducted the study; Heinrich Hussmann commented on earlier versions of the paper and supervised the project.
[P11]	I came up with the original research idea; I supervised the development and implementation of the concept and prototype; I analyzed the resulting data and authored the resulting publication.	Patrick Tamunjoh contributed in various brainstorming sessions that led to the idea, developed the prototype and conducted the study; Heinrich Hussmann edited the final version of the paper.
[P12]	I developed the idea together with Kai Hollaender, Jingyi Li and our industry partner Stefan Mayer; I supervised the study planning and study implementation together with Jingyi Li; I contributed significantly to the publication.	Andrea Ngao conducted the study in her MA thesis. Jingyi Li was the leading author of the publication. Andreas Butz edited the final version of the paper.

Table A.1: Overview of publications included in this thesis and clarification of contributions.

[P1] George, C., Schwuchow, J., and Hussmann, H. (2019). Fearing Disengagement from the Real World. In *25th ACM Symposium on Virtual Reality Software and Technology*, VRST '19, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3359996.3364273

[P2] George, C., Khamis, M., von Zezschwitz, E., Burger, M., Schmidt, H., Alt, F., and Hussmann, H. (2017). Seamless and Secure VR: Adapting and Evaluating Established Authentication Systems for Virtual Reality. In *Proceedings of the Network and Distributed System Security Symposium (NDSS 2017)*, USEC '17. Internet Society, doi:10.14722/usec.2017.23028

[P3] George, C., Khamis, M., Buschek, D., and Hussmann, H. (2019). Investigating the Third Dimension for Authentication in Immersive Virtual Reality and in the Real World. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 277–285. doi:10.1109/VR.2019.8797862

[P4] George, C., Buschek, D., Ngao, A., and Khamis, M. (2020). GazeRoomLock: Using Gaze and Head-Pose to Improve the Usability and Observation Resistance of 3D Passwords in Virtual Reality. In De Paolis, L. T. and Bourdot, P., editors, *Augmented Reality, Virtual Reality, and Computer Graphics*, pages 61–81, Cham. Springer International Publishing

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[P6] George, C., Demmler, M., and Hussmann, H. (2018a). Intelligent Interruptions for IVR: Investigating the Interplay between Presence, Workload and Attention. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA '18, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3170427.3188686

[P7] George, C., Spitzer, M., and Hussmann, H. (2018c). Training in IVR: Investigating the Effect of Instructor Design on Social Presence and Performance of the VR User. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18, New York, NY, USA. Association for Computing Machinery, doi:10.1145/3281505.3281543

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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 05. August 2020

Ceenu George