# Designing Passenger Experiences for In-Car Mixed Reality

## Dissertation

an der Fakultät für Mathematik, Informatik und Statistik
der Ludwig-Maximilians-Universität München

vorgelegt von

**Jingyi Li**

M.A. Design & M.F.A. Media Art and Design

München, den 25.01.2023

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|---|---|
| Erstgutachter: | Prof. Dr. Andreas Butz |
| Zweitgutachter: | Prof. Dr. Orit Shaer |
| Drittgutachter: | Prof. Dr. Bastian Pfleging |

Tag der mündlichen Prüfung: 27.03.2023

# Abstract

In day-to-day life, people spend a considerable amount of their time on the road. People seek to invest travel time for work and well-being through interaction with mobile and multimedia applications on personal devices such as smartphones and tablets. However, for new computing paradigms, such as mobile mixed reality (MR), their usefulness in this everyday transport context, in-car MR remains challenging. When future passengers immerse in three-dimensional virtual environments, they become increasingly disconnected from the cabin space, vehicle motion, and other people around them. This degraded awareness of the real environment endangers the passenger experience on the road, which initially motivates this thesis to question: can immersive technology become useful in the everyday transport context, such as for in-car scenarios? If so, how should we design in-car MR technology to foster passenger access and connectedness to both physical and virtual worlds, ensuring ride safety, comfort, and joy? To this aim, this thesis contributes via three aspects:

1) *Understanding passenger use of in-car MR* —first, I present a model for in-car MR interaction through user research. As interviews with daily commuters reveal, passengers are concerned with their physical integrity when facing spatial conflicts between borderless virtual environments and the confined cabin space. From this, the model aims to help researchers spatially organize information and how user interfaces vary in the proximity of the user. Additionally, a field experiment reveals contextual feedback about motion sickness when using immersive technology on the road. This helps refine the model and instruct the following experiments.

2) *Mixing realities in car rides* —second, this thesis explores a series of prototypes and experiments to examine how in-car MR technology can enable passengers to feel present in virtual environments while maintaining awareness of the real environment. The results demonstrate technical solutions for physical integrity and situational awareness by incorporating essential elements of the RE into virtual reality. Empirical evidence provides a set of dimensions into the in-car MR model, guiding the design decisions of mixing realities.

3) *Transcending the transport context* —third, I extend the model to other everyday contexts beyond transport that share spatial and social constraints, such as the confined and shared living space at home. A literature review consolidates leveraging daily physical objects as haptic feedback for MR interaction across spatial scales. A laboratory experiment discovers how context-aware MR systems that consider physical configurations can support social interaction with copresent others in close shared spaces. These results substantiate the scalability of the in-car MR model to other contexts.

Finally, I conclude with a holistic model for mobile MR interaction across everyday contexts, from home to on the road. With my user research, prototypes, empirical evaluation, and model, this thesis paves the way for understanding the future passenger use of immersive technology, addressing today's technical limitations of MR in mobile interaction, and ultimately fostering mobile users' ubiquitous access and close connectedness to MR anytime and anywhere in their daily lives.

# Zusammenfassung

Im modernen Leben verbringen die Menschen einen beträchtlichen Teil ihrer Zeit mit dem täglichen Pendeln. Die Menschen versuchen, die Reisezeit für ihre Arbeit und ihr Wohlbefinden durch die Interaktion mit mobilen und multimedialen Anwendungen auf persönlichen Geräten wie Smartphones und Tablets zu nutzen. Doch für neue Computing-Paradigmen, wie der mobilen Mixed Reality (MR), bleibt ihre Nützlichkeit in diesem alltäglichen Verkehrskontext, der MR im Auto, eine Herausforderung. Wenn künftige Passagiere in dreidimensionale virtuelle Umgebungen eintauchen, werden sie zunehmend von der Kabine, der Fahrzeugbewegung und den Menschen in ihrer Umgebung abgekoppelt. Diese verminderte Wahrnehmung der realen Umgebung gefährdet das Fahrverhalten der Passagiere im Straßenverkehr, was diese Arbeit zunächst zu der Frage motiviert: Können immersive Systeme im alltäglichen Verkehrskontext, z.B. in Fahrzeugszenarien, nützlich werden? Wenn ja, wie sollten wir die MR-Technologie im Auto gestalten, um den Zugang und die Verbindung der Passagiere mit der physischen und der virtuellen Welt zu fördern und dabei Sicherheit, Komfort und Freude an der Fahrt zu gewährleisten? Zu diesem Zweck trägt diese Arbeit zu drei Aspekten bei:

1) Verständnis der Nutzung von MR im Auto durch die Passagiere - Zunächst wird ein Modell für die MR-Interaktion im Auto durch user research vorgestellt. Wie aus Interviews mit täglichen Pendlern hervorgeht, sind die Passagiere um ihre körperliche Unversehrtheit besorgt, wenn sie mit räumlichen Konflikten zwischen grenzenlosen virtuellen Umgebungen und dem begrenzten Kabinenraum konfrontiert werden. Das Modell soll Forschern dabei helfen, Informationen und Benutzerschnittstellen räumlich zu organisieren, die in der Nähe des Benutzers variieren. Darüber hinaus zeigt ein Feldexperiment kontextbezogenes Feedback zur Reisekrankheit bei der Nutzung immersiver Technologien auf der Straße. Dies hilft, das Modell zu verfeinern und die folgenden Experimente zu instruieren.

2) Vermischung von Realitäten bei Autofahrten - Zweitens wird in dieser Arbeit anhand einer Reihe von Prototypen und Experimenten untersucht, wie die MR-Technologie im Auto es den Passagieren ermöglichen kann, sich in virtuellen Umgebungen präsent zu fühlen und gleichzeitig das Bewusstsein für die reale Umgebung zu behalten. Die Ergebnisse zeigen technische Lösungen für räumliche Beschränkungen und Situationsbewusstsein, indem wesentliche Elemente der realen Umgebung in VR integriert werden. Die empirischen Erkenntnisse bringen eine Reihe von Dimensionen in das Modell der MR im Auto ein, die die Designentscheidungen für gemischte Realitäten leiten.

3) Über den Verkehrskontext hinaus - Drittens erweitere ich das Modell auf andere Alltagskontexte jenseits des Verkehrs, in denen räumliche und soziale Zwänge herrschen, wie z.B. in einem begrenzten und gemeinsam genutzten Wohnbereich zu Hause. Eine Literaturrecherche konsolidiert die Nutzung von Alltagsgegenständen als haptisches Feedback für MR-Interaktion über räumliche Skalen hinweg. Ein Laborexperiment zeigt, wie kontextbewusste MR-Systeme, die physische Konfigurationen berücksichtigen, soziale Interaktion mit anderen Personen in engen gemeinsamen Räumen ermöglichen. Diese Ergebnisse belegen

die Übertragbarkeit des MR-Modells im Auto auf andere Kontexte.

Schließlich schließe ich mit einem ganzheitlichen Modell für mobile MR-Interaktion in alltäglichen Kontexten, von zu Hause bis unterwegs. Mit meiner user research, meinen Prototypen und Evaluierungsexperimenten sowie meinem Modell ebnet diese Dissertation den Weg für das Verständnis der zukünftigen Nutzung immersiver Technologien durch Passagiere, für die Überwindung der heutigen technischen Beschränkungen von MR in der mobilen Interaktion und schließlich für die Förderung des allgegenwärtigen Zugangs und der engen Verbindung der mobilen Nutzer zu MR jederzeit und überall in ihrem täglichen Leben.

# Acknowledgements

*One day, in retrospect, the years of struggle will strike you as the most beautiful.*

*– Sigmund Freud*

Without all the support and collaboration I was so lucky to have during these 4.5 years, I would not have made it to the end. First, I would like to thank my supervisor **Andreas** Butz for taking me on board at the beginning and for supportive supervision along the way. I would also like to thank my external committee members, **Orit** Shaer and **Bastian** Pfleging, for insightful feedback and discussion when reviewing this thesis.

Furthermore, I want to thank the great team members I have collaborated with or accompanied me during the ride. Thank you **Linda** Hirsch for sharing the office and leisure time with me, which truly and absolutely supports and encourages my work and life. **Kai** Holländer, thank you for co-supervising the thesis and sharing research experiences when I was new to the group. Thank you **Ceenu** George for the excellent collaboration and deep discussions that inspire my work and motivate me as a woman of color in science. Thank you **Michael** Braun for bringing me on board the joint project with the BMW Group in Munich and Shanghai; it was an insane amount of fun. **Fiona** Draxler, thank you for leading our paper writing and for wonderful times together in the hut, next to the sewing machine, and on the road. Thank you **Sarah** Theres Völkel for organizing numerous cool events that enlighted this ride. Thank you **Sarah** Aragon-Hahner, I love our recharging bubble tea time and will miss it so much. Thank you **Nađa** Terzimehić for cheering me up and organizing our Max Beef lunch summit. **Robin** Welsch, thank you for your great input on improving our study design. **Florian** Müller, thank you for always providing down-to-earth and on-point feedback. Thank you **Yong** Ma for helping me with the paperwork for the scholarship and visa before I came to Munich. Thank you **Changkun** Ou for the philosophical discussion and technical support in multiple projects. Thank you **Amy** Yanhong Li for organizing Chinese New Year together and awesome house parties. Thank you **Beat** Rossmy for showing me great HCI work with a design background. Thank you **Sylvia** Rothe for our engaging chat about immersive media and for showing me around the HFF. Thank you **Henrike** Weingärtner for your caring nature and fantastic taste in music. **Yannick** Weiss, thank you for your genuine kindness, which makes me feel warm from time to time. Thank you **Steeven** Villa for your cheerful words and wonderful electronic talents. Thank you **Francesco** Chiossi for our sincere exchanges and for being the wonderful Venice guide for the group. Thank you **Dennis** Dietz for the always light-hearted conversations. Thank you **Rifat** Mehreen Amin for introducing amazing Bangladeshi food and culture to me. Thank you **Svenja** Schött for your continuous efforts in improving our website. Thank you **Florian** Bemmann for our nice lunch roulette. Thank you **Bettina** Eska for our spontaneous lovely tea breaks. Thanks go to another teamate, **Jakob** Karolus. Thank you **Jesse** Grootjen for taking care of the coffee and supporting the group so much. Thank you **Julian** Rasch for organizing great events with VR artists and within the CHI community. Thank you **Carl** Oechsner for implementing the cool chatbot for our study. **Luke** Haliburton, thank you for the antistress Secret Santa gift. Thank you **Jan** Leusmann, for your lively energy. Thank you **Maximiliane** Windl for being my wonderful skiing buddy during the winter school. Thank you **Sophia** Sakel for our funny movie nights. Thank you **Sebastian** Feger for our yummy pizza evenings. Thank you **Matthias** Hoppe for our meaningful discussion on mixed reality. Thank you **Florian** Lang for our nice conference evenings in Warsaw. Thank you **Thomas** Weber for organizing the Open Lab Day together. Thank you **Matthias** Schmidmaier for organizing our Starkbierfest. Thank you **Tony** Zhang, for our lovely chats during IDCs. Thank you **Sören** Klingner for your incredible support for our study setup in the wild. Thank you **Heiko** Drewes for sharing fascinating stories about your trips to China.

Thanks to all the Ph.D. students who have spent their time across mine in the lab: **Christian** Mai, **Malin** Eiband, **Daniel** Buschek, **Christina** Schneegaß, **Thomas** Kosch, **Pascal** Knierim, **Lewis** Chuang, **Tonja** Machulla, **Lauren** Thevin, **Ville** Mäkelä, **David** Englmeier, **Michael** Chromik, **Gesa** Wiegand, **Sarah** Prange, **Yasmeen** Abdrabou Mahmoud, **Mariam** Hassib, **Mohamed** Khamis, **Jue** Li, **Markus** Wieland, and **Annika** Kaltenhauser, to name a few.

Also, thanks go to external coworkers who inspired my work, **Andrii** Matviienko, **Mark** McGill, **Stephen** Brewster, **Chao** Wang, **Andreas** Löcken, **Stella** Clarke, **Myounghoon** "Philart" Jeon, and **Michael** Gerber. Thank you for bringing your profession and insights during our encounters.

Thanks to the amazing students that I have the pleasure to work with: **Agnes** Reda, **Luca** Woik, **Hyerim** Park, **Andrea** Ngao, **Filippe** Frulli, **Alexandra** Mayer, **Tianyang** Lu, and **Puzhen** Li, to name a few.

Further, I would like to thank **Heinrich** Hußmann, **Albrecht** Schmidt, **Florian** Alt, **Alexander** Wiethoff, **Johanna** Pirker, and especially **Sven** Mayer, for their support, feedback, and valuable suggestions. A big thank you to **Franziska** Schwamb, **Christa** Feulner, **Anja** Mebus, and especially **Rainer** Fink for keeping the lab running.

Finally, I would like to thank my friends in Germany and China, who shared my ups and downs during this ride out of my comfort zone, despite the physical and cultural distances between us, particularly during the years of Covid. Furthermore, I would like to thank my family for their love and support. Without the education and love from my mother, **Beizhen** Tan, I would not have been able to achieve the level of personal growth that I have today. Without the unconditional support from my father, **Baoguo** Li, I would not have been able to pursue my education this far. Without the company of my husband, **Haicheng** Bai, I would not have been able to reach the end of this ride alone.

## 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 25. Januar 2023

Jingyi Li

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# 1
# INTRODUCTION

Mobility is an essential part of modern life, as people spend considerable time on the road every day. The average one-way commute from home to work is, for example, about 20 minutes in Europe,[1] 26 minutes in the US,[2] and 36 minutes in China[3]. Even after the hardest hit during the Covid-19 pandemic, the automotive and mobility industries have recently recovered to precrisis levels in many regions of the world. In turn, the crisis drove industries and academia to rethink future mobility for modern societies, e.g., reinventing the cabin space as a ubiquitous working and living space on the move.

### Passenger-centered Experience of Mobile and Multimedia Applications

One promising trend, *AutoWork* [1], is to digitalize the in-vehicle space and time for work and well-being through advancing interaction with mobile and multimedia applications. With self-driving vehicles on the horizon, automotive human–computer interaction (HCI) research has experienced an ongoing shift from driver-centered task performance to passenger-centered activity experience [2]. A myriad of non-driving-related activities (NDRAs) [3] has been explored, including diverse applications for productivity, relaxation, and entertainment across a wide range of devices, from integrated car displays to brought-in personal devices.

In academia, for example, researchers have reconfigured the steering wheel to support text entry on the move [4], augmented the side-window display to provide infotainment information about the upcoming point of interest [5], and added ambient visualization cues on the periphery area of e-book screens to ease motion sickness while reading in moving cars [6]. Likewise, the automotive industry strives to enhance the ride safety, comfort, and joy of the passenger experience. BMW launched i Interaction EASE,[4] which offers three basic modes—explore, entertain, and ease—with the in-vehicle Panorama Head-Up Display changing according to the passenger's needs. Audi presented a health use case for the Urbansphere concept vehicle,[5] which transforms the cabin space into an immersive environment conducive to relaxation and meditation, e.g., by adjusting the in-vehicle lighting, soundscapes, and displays in the backrest of the front seat.

Unlike these interactions on a conventional two-dimensional display, another digitalization approach adopts emerging computing paradigms, namely mobile virtual reality (VR) and mixed reality (MR) [7]. Wearing portable VR/MR headsets, passengers can fully immerse in

[1] https://www.eurofound.europa.eu/data/european-working-conditions-survey

[2] https://www.ridester.com/average-us-commute/

[3] https://huiyan.baidu.com/reports/landing?id=123

[4] https://www.bmwgroupdesignworks.com/case_studies/beyond-mobility/

[5] https://www.progress.audi/progress/en/the-audi-urbansphere-concept-a-relaxation-programme.html

three-dimensional virtual environments with ubiquitous access and close connectedness to the digital information displayed in that space. However, this novel automotive interaction faces challenges from conflicts between the two three-dimensional spaces around the passenger: the virtual multimedia world and the physical transport world. To understand these challenges, I will first revisit the theoretical concepts of immersive VR/MR technology and its ability to simulate and create virtual spaces, which is also one of the problem's origins.

### Mobile VR/MR

Sensorama [8], invented by Heilig in 1962, is considered one of the earliest VR systems. Its setup consists of a stereoscopic color display, fans, odor emitters, a stereo sound system, and a motional chair, covering almost all human senses to provide immersive multimedia experiences. In 1968, Sutherland invented the Ultimate Display [9], the first see-through head-mounted display (HMD) that renders three-dimensional computer graphics and sound to surround the user's visual and auditory senses. This hardware upgrade fosters lightweight immersive experiences and spurs the advent of augmented reality (AR) that displays digital information overlaid on the user's physical surroundings. Finally, Milgram united the existing spectrum of multiform technologies into a common framework, the Reality–Virtuality (RV) continuum [10], spanning from the real environment (RE) to the virtual environment (VE).

On the left end, the RE and physical environment are interchangeable terms in this thesis. They describe any matter elements or spatiotemporal information perceived and processed through *consciousness* (referring to the definition by Sanchez-Vives and Slater [11, 12]) in the physical world surrounding the user. On the right end, VE and VR are interchangeable. Both refer to the highest immersion level the technology can offer that is perceived and processed through *presence*, the sense of being there or a counterpart of consciousness [13, 14], in the virtual world. Blending these two ends, the overarching concept of MR includes any mixed form of RE and VE. For example, augmented virtuality (AV) denotes a mixed form of MR by adding the elements of RE into VE. AR represents an opposite mixed form of MR by adding the elements of VE into RE. The more we shift toward the RE end, the less immersion the technology supports. Interaction becomes primarily based on two-dimensional screens, like pressing a virtual button *on* a large display. In contrast, when shifting toward the VE end, technology offers higher levels of immersion, resulting in a mix of RE and VE with greater spatial degrees, like navigating a virtual landscape *in* a VR HMD [15]. Consequently, the interaction challenges gradually evolve from *on the screen* to *in the space*.

The RV continuum is a powerful theoretical tool that, independent of technologies, synthesizes diverse *mixed* forms or outcomes of both the physical and virtual worlds into a simplified unidimensional continuum. However, it flattens the spatial nature of these two research objects and ignores the process or action of *mixing*. As a result, a critical link is missing between transferring the knowledge of knowing *what* a proper MR form is to practicing *how* to design the right way of mixing two spaces. Inspired by this design challenge for interaction in space, I transformed Milgram's RV continuum into a spatial RV continuum (see Figure 1.1)

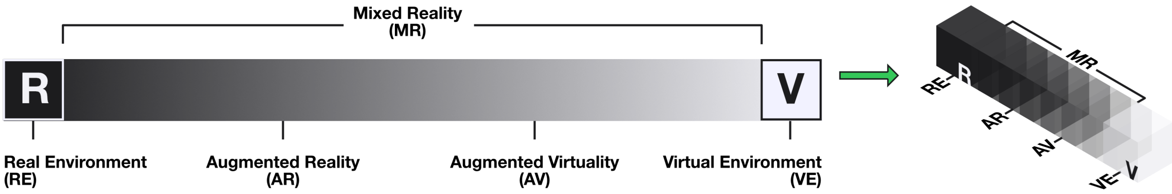



**Figure 1.1:** Adapted from Milgram's theoretical RV continuum [10] with additional gradient visualization (left), transformed to a conceptualized spatial RV continuum (right).

to emphasize the spatial nature of RE and VE that MR interaction faces. This notion serves as the basis for the following research and discussion.

As yet immersive technology has become increasingly affordable and accessible outside of labs, mobile VR/MR interaction permeates people's daily life. Fully mobile VR systems enable people to immerse in VEs anytime and anywhere from home to work [16, 17, 18]. Such a state of involvement during the immersive virtual experience involves a considerable amount of cognitive processes [19]. It entails temporal and spatial dissociation of mobile VR users from their physical world, e.g., losing track of time and self-location, surrounding objects, nearby people [20], and fearing disengagement from their REs [21].

To bridge the gap between the physical and virtual worlds, avoiding disconnection and ensuring access and connectedness to both spaces, the tech industries target the mobile MR market. While Microsoft Hololens[6] targets AR-driven MR systems, Meta Quest,[7] HTC VIVE,[8] and Varjo,[9] for example, position themselves as VR-driven MR systems. These two trends of mobile MR systems represent the AR-AV and AV-VE subsets of the continuum, respectively [22]. In this thesis, I use VR-driven MR headsets (referred to as MR in the following text) to examine the AV-VE subset of the spatial RV continuum. From this, I focus on mobile MR for future mobility in the everyday transport context. I envision mobile in-car MR systems as primarily offering a sense of presence in immersive VEs for the joy of the ride and which additionally support the mobile user's (referred to as the "passenger" below) awareness of their REs for ride safety and comfort.

### Mobile In-car MR Challenges

When using immersive technology on the road, losing awareness of the real environment can deteriorate the passenger experience. This challenge initially motivates this thesis to question: Can immersive technology become useful in the everyday transport context, such as for in-car scenarios? If so, how should we design in-car MR technology to foster passenger access and connectedness to both the physical and virtual worlds, ensuring ride safety, comfort, and joy?

[6] https://www.microsoft.com/hololens

[7] https://www.meta.com

[8] https://www.vive.com

[9] https://varjo.com/

A number of use cases have been recently explored to digitalize the in-car space and time for the immersive experiences of work and well-being. Often these mobile in-car MR systems selectively incorporate the elements of the passenger's surrounding RE into the specific VE. For example, Audi and Porsche have partnered with Holoride[10] to support passenger activities in a motion-synced virtual world enabled by the lightweight HTC VIVE Flow headset. Likewise, prior research has examined the impact of motion congruency between RE and VE on calming and entertainment experiences [23, 24] and the impact of physical seating layouts on virtual workspace layouts [25]. In a literature review, McGill et al. [7] identified three major challenges to overcome during the passenger use of mobile MR: 1) confined space, 2) motion sickness, and 3) social acceptability. These issues occur when passengers miss the information they want or need to learn about their situated RE, such as interactive in-cabin objects, vehicle motion, passing-by sceneries, and nearby people. Within this transport context, the passenger is simultaneously exposed to multicharacteristic RE spaces in cars, such as an always-confined seated space, a frequently moving space, and a sometimes-shared space. The wide variety of information condensed in these RE spaces, in turn, challenges the mobile in-car MR system to inform the passenger of them all, finding "what is needed when it is needed" in RE without breaking the sense of presence in VE [26, 27].

The rich and dynamic context plays an important role in the research of mobile interaction and user experience [28]. The previous review of mobile HCI research methods by Kjeldskov and Graham [29] outlined a limited focus on contextual issues, including not understanding what is useful or problematic from a user perspective in the context and how the real-world context matters for the mobile systems we build and use. Informed by past works, this thesis contributes to filling the gap of the underexplored real-world contexts in the nascent research area of mobile in-car MR. In particular, to address the uncertainty and lack of clarity in this future mobility scenario, I follow three steps: 1) the *user-centered* approach [30] is applied to understand passenger use of in-car MR through survey research on user needs and a field experiment to observe user behaviors; 2) the *technology-driven* prototyping of mixing realities in car rides is evaluated through field and laboratory experiments; and 3) *cross-context* thinking is used to transfer the knowledge of the transport context to other mobile contexts beyond transport, resulting in a conceptualization model for mobile MR interaction. In the following three subsections, I will elaborate on each step by explaining its theoretical motivation, research question, and contribution.

## 1.1 Understanding Passenger Use of In-car MR

During the last decade, the automotive HCI research community has faced the shift from manual to automated driving [31]. With increasing automation, the user's role of in-car interaction shifts from the driver to the passenger [32]. However, our knowledge about the

[10] https://www.holoride.com

user of automotive interactions remains more on the needs of the driver than those of the passenger, with a ratio of about 6:1, as shown in a previous literature review [33].

Understanding passenger needs and behaviors during the ride is essential to inform future automotive interactions. Prior research adopted contextual design methods [34, 35] to understand the driver's activities when balancing driving and their use of integrated in-car displays and brought-in devices in daily commutes. In comparison, limited passenger research on their needs, behaviors, and experiences has been investigated in context. For example, Krome et al. [36] demonstrated a context-based design process, from in-car brainstorming to integrating contextual features about automated driving into the ride experience. By observing passengers in public transport and combining web and in-situ surveys, Pfleging et al. [37] identified passenger needs for interacting with mobile and multimedia applications in future self-driving car rides. Furthermore, presenting real-world insights, Detjen et al. [38] used a Wizard of Oz automated vehicle and found real-world insights into the passenger's attitude towards activities. In recent repertory grid interviews about convenient passenger experiences, Berger et al. [39] identified the three key factors of well-being, physical comfort, and safety, emphasizing important contextual information of both the internal and external vehicle environments, such as sufficient physical space and the ability to view the landscape.

The literature suggests the emerging user adoption of mobile headsets for transferring passenger activities from screen-based to immersive in-the-space interaction. However, this comes with concerns about disconnection from the physical world. Williamson et al. [40] confirmed a lower acceptance of VR headsets than existing in-flight infotainment systems, as airplane passengers feared losing awareness of their events or surroundings and extensive head or hand movements that can cause unintentional contact with nearby people. Passengers share this concern about losing awareness of their physical surroundings in other public transport modes such as bus rides [41]. In contrast, an online survey showed that mobile users had significantly reduced acceptance of using mobile headsets in cafes or living rooms when surrounded by others but found headsets are only slightly inappropriate in cars [42]. However, it is underexplored in car rides what elements of RE the passenger needs to be aware of during in-car MR interaction and what is a useful in-car MR system from the passenger's perspective. Therefore, the first objective of this thesis is to understand the passenger's use of in-car MR, including their needs and behaviors, following the user-centered design (UCD) approach [30]. This goal is summarized in the first research question:

> **RQ1. User-centered:** *What are the passenger's needs and behaviors during the use of in-car MR?*

**Contribution.** To understand the passenger's use of mobile in-car MR systems, this thesis contributes to identifying the passenger's needs to maintain physical integrity [P01] and examining the passenger's head movements in VE and its side effect on motion sickness during the ride [P02]. For this, two methods are applied: survey research (static setup) and field experiments (moving setup). Finally, I contribute to an initial model for in-car MR interaction to conceptualize how the demanded information about both the physical and virtual worlds can be spatially organized in user interfaces (see Figure 1.2).

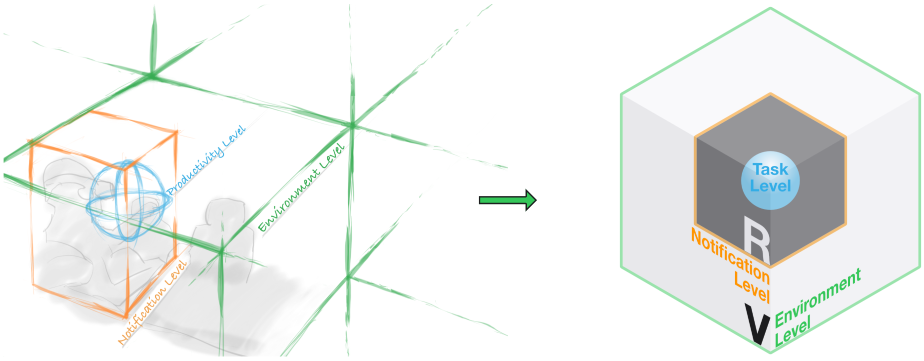



**Figure 1.2:** Three information levels for in-car MR applications varying in proximity to the passenger: from the innermost Productivity or Task Level (in blue), Notification Level (in orange), to the outermost Environment Level (in green). The visualization on the right is a revision based on the sketch (left) published in the original paper [P01].

To concretize the futuristic scenario of using nonexisting in-car MR systems and facilitate passenger anticipation, I narrowed down the initial explorative study to a productivity use case in line with the notion of *AutoWork* [1]. Therefore, today's car commuters were recruited and introduced to video clips, questionnaires, and interviews about the hypothetical use case of in-car MR for mobile working [P01]. Overall, they expressed willingness to use MR headsets for mobile working in an immersive workspace. However, given the spatial conflicts between the confined in-car space and borderless virtual working scenes, they were mainly concerned with their physical integrity. As a result, while immersed in working VEs, passengers want to receive notifications about the RE around them, such as the most critical information about the physical borders of their surroundings. Individual differences account for VE preferences: some prefer a single office for concentration, while others prefer an open-place office or library for external motivation. Additionally, when exposed to real-time interaction using HMDs in a moving car, passengers provided contextual feedback about the risk of motion sickness induced by frequent head movements when exploring VEs [P02]. With highway travel, they achieved the best tradeoff between engagement and motion sickness in VEs when the primary interaction area was controlled with a head movement range between -50° and 50° along the yaw axis (looking left and right).

These findings guided the interaction design for in-car MR systems in the following series of studies. In particular, the identified passenger needs for physical integrity informed the subsequent studies of the type of essential information about the passenger's surrounding RE and the corresponding placement of notifications. Meanwhile, the suggested head-movement range instructed the placement of primary interaction areas in the VE. Moreover, these applied methods demonstrate the advantages of an economic static setup to explore specific passenger needs, such as their thoughts about the confined in-car space. In contrast, a realistic moving setup helps generate fruitful contextual feedback stimulated only in on-road tests.

The comparison between distinct research methods concerning costs and validity will be discussed in Chapter 3.

Finally, I present a conceptualization model to synthesize the findings of passenger research. This initial model involves three information levels, conveying different information content that varies in proximity to the passenger, from the innermost Productivity or Task Level, the middle Notification Level, to the outermost Environment Level (see Figure 1.2). The innermost Task Level targets the passenger's primary activities, such as productivity tasks, consuming most cognitive processes. The middle Notification Level includes the demanded information about the surrounding RE of the passenger, such as physical border cues, spatially mapped to the physical space of passenger seats. Finally, the outermost Environment Level is tailored to individual preferences about the degree of VE engagement, including limited or unlimited scene setups. Additionally, the identified head movement range denotes the comfort placement range of the user interfaces across these three information levels. More details about the development of the model extensions will be discussed in Chapter 3. The model provides a basic three-dimensional structure to facilitate spatial thinking about the interaction context and guide the design practice of *mixing* RE and VE around the passenger in the following studies.

## 1.2 Mixing Realities in Car Rides

The identified passenger needs for keeping awareness of the real environment align with the prior research, bridging the gap between RE and VE using reality-aware MR systems in everyday contexts [18]. From a technical perspective of a useful MR system, emerging approaches comprise Substitutional Reality [43] and RealityCheck [44]. The former pairs every physical object around a user with a virtual counterpart. The latter blends the user's RE into VE through a real-time three-dimensional geometric analysis of the physical environment. On the other hand, from a user's perspective of a useful MR system, current research achieved a consensus on incorporating RE elements into VE, yet diverged on *when*, *why*, and *how* awareness should be increased [45]. A wide range of studies analyzed RE elements in different contexts, such as the **Amount** of reality views during typing [46], the visual **Fidelity** of passersby representations when they invade the tracking area [47], and the **Placement** of in-VR notifications that show incoming messages or bystander indications [48, 49]. This thesis focuses on the latter research paradigm of developing and evaluating a useful MR system from the user's perspective. In particular, I deploy quick prototyping of in-car MR systems to understand how passengers use and experience different mixed forms of MR that incorporate various RE elements into VE.

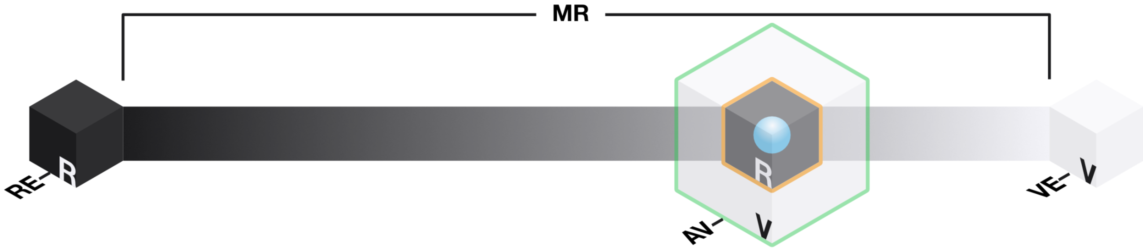
In passenger use of mobile MR systems, research mainly focuses on three major challenges: 1) confined space, 2) motion sickness, and 3) social acceptability [7, 50]. Various design decisions were proposed to enable the passenger to glimpse the outside world and maintain awareness of the real environment without taking off the headset and breaking their presence. For example, to support awareness of the confined in-vehicle space around the passenger, previous work incorporated a camera view of the surrounding cabin environment, such as integrated furniture, into a virtual home theatre [40] or incorporated a three-dimensional cabin model as an overlay on VE [51]. Concerning the motion sickness induced by the mismatch between visual and vestibular senses, prior research incorporated visual motion cues into VE. One approach paired real-time vehicle motion and path with the virtual movement and path of the player in first-person shooter and racing games [52, 53]. An alternative approach used abstract visualizations of vehicle motion, such as live street-view videos or simulated motion flows, embedded into transparent backgrounds in the user's field of view or only peripheral areas in the headset [24, 54]. Increasing awareness of nearby people, existing systems focus on rendering the action of other passengers using avatars and conveying their intentions to interrupt using notifications such as a visual prompt in VE or a complete switch from VR to reality view [40, 51]. In addition, recent work has addressed the new challenge of losing situational awareness by incorporating vehicle and traffic signs into VE, enabling passengers to know about the ego vehicle's actions and intentions on the road [55].

Informed by these various mixed forms of RE and VE, this thesis adopts the incorporation approach as a promising solution to address the identified challenges during passenger use of HMDs. Based on the identified passenger needs for physical integrity and passenger behaviors influenced by motion, the second objective of this thesis is to explore *technology-driven* solutions to address the challenge of confined spaces and the challenge of mobile reality. This goal is summarized in the second research question:

> **RQ2. Technology-driven:** *How can we design in-car MR technology that empowers passengers with access and connectedness to information in both the physical and virtual worlds during the ride?*

**Contribution.** This thesis contributes to prototyping and evaluating a series of mobile in-car MR systems, addressing targeted challenges of the confined in-car space and the on-road environment in motion. In particular, these systems provide a design strategy for incorporating RE into VE (see Figure 1.3). The strategy considers four aspects: 1) User in RE, 2) User Presentation in VE, 3) Elements in RE, and 4) Element Presentation in VE. As the basis for mixing RE and VE, the first two aspects regarding the user share three dimensions: **Dynamics**, **Posture**, and **User Mode**. The other two aspects consider distinct dimensions for mixing. Regarding the element in RE, the strategy is to extract *what* information about RE is essential from a user's perspective to be mixed into VE, including two dimensions: **Objects** and **Content**. When adding the selected elements into VE, the aspect of element presentation in VE targets *where*, *when*, and *how* to mix. They involve seven dimensions: **Information Level**, **Placement**, **Availability**, **Modality**, **Modality Mode**, **Fidelity**, and **Amount**.

For the first two steps, the design strategy suggests that in-car MR systems should analyze the passenger's **Dynamics**, **Posture**, and **User Mode** in RE and design their resulting representations in VE. These two steps can be congruent or incongruent setups. For example, the




**1) User in RE:**

| | |
|---|---|
| **Dynamics:** | Static, Moving |
| **Posture:** | Seated |
| **User Mode:** | Single User |

**3) Elements in RE:**

| | |
|---|---|
| **Objects:** | Noninteractive Object, Interactive Object, Interactive Input Device |
| **Content:** | Location, Speed, Progress |

**2) User Presentation in VE:**

| | |
|---|---|
| **Dynamics:** | Static, Moving |
| **Posture:** | Seated, Walking |
| **User Mode:** | Single User, Multi User |

**4) Element Presentation in VE:**

| | |
|---|---|
| **Information Level:** | Task Level, Notification Level, Environment Level |
| **Placement:** | Separated, Situated |
| **Availability:** | Continuous, System-triggered, User-triggered |
| **Modality:** | Visual, Haptic |
| **Modality Mode:** | Single Modality, Multi Modality |
| **Fidelity:** | Abstract, Realistic |
| **Amount:** | Minimum, Full |

**Figure 1.3:** Design strategy for incorporating RE into VE based on the publications [P03–P08]. The strategy considers four aspects in sequence: 1) user in RE, 2) user presentation in VE, 3) elements in RE, and 4) element presentation in VE. Within each aspect, multiple design dimensions are revealed to instruct the hands-on practice of mixing realities during in-car MR interaction.

majority of the implemented experiments used *static*, *seated*, and *single-user* setups, representing a typical scenario of a single passenger seated in the backseat consuming media when the car is parked [P3–P7]. Meanwhile, their presentations in VE differed. Some completely mirrored this setup, creating a static, seated, and single representation of the passenger in VE, such as a mobile worker typing and reading in a virtual office for concentration [P05], or a player relaxing on a virtual beach for well-being [P07]. Others changed to a *multiuser* setup in VE, enabling the passenger to work in a virtual open-plan office with simulated coworkers to keep motivation [P03] or invite other players into the calming virtual landscape for sharing their moments in VR [P06]. In contrast, [P04] kept the single-user setup in VE while changing to a *moving* and *walking* presentation to enable a first-person shooter game experience. Finally, [P08] used congruent setups of the passenger in real car rides and the player in first-person shooter games, with the coupled *moving*, seated, and single-user setups in both RE and VE to diminish motion sickness.

The third step suggests that in-car MR systems should consider *what* elements of RE, such as **Objects** and **Content**, need to be incorporated into VE, depending on the target challenge. To increase awareness of the physical in-car space around the passenger during MR interaction, the system can incorporate physical objects from the surrounding cabin space. These include *noninteractive objects*, such as the approaching car interior [P03] that invades the player's space, *interactive objects*, such as mounted in-car buttons [P04, P06], and *interactive input devices*, such as portable keyboards [P05]. In addition, the system can incorporate the content in space and time, such as self-*location*, vehicle *speed*, and travel *progress* [P07, P08], to support situational awareness and allow the passenger to know what is going on around them.

The fourth step suggests that in-car MR systems should consider *where* (**Information Level** and **Placement**), *when* (**Availability**), and *how* (**Modality**, **Modality Mode**, **Fidelity**, and **Amount**) to incorporate these selected RE elements into VE. Regarding *where* to mix the selected RE in VE, I refer to the proposed three information levels (see Figure 1.2). For example, the system can assign selected task-related information, such as keyboard camera views [P05], to the innermost *Task Level* for the primary activities the passengers aim to complete. Meanwhile, the system can indicate information about the physical in-car surroundings of the passenger [P03, P04, P06] or the spatiotemporal variations of the on-road environment [P08] on the middle *Notification Level*. Lastly, the system can assign less-critical traffic information to the outermost *Environment Level* as ambient information in VE without interfering with the primary interaction area [P07]. After selecting the information level, the system needs to consider the method of information placement within the level, i.e., *separated* or *situated*. The placement of information is decisive for how seamless the gap between RE representation and VE can be perceived by the user. Therefore, aiming for unobtrusive incorporation, such as calming VE experiences, the system can present RE elements by situating three-dimensional artifacts into the three-dimensional virtual world [P06, P07]. In contrast, for intentional quick interruptions or alerts, the system can present RE elements using pop-up or floating windows separate from the virtual world [P03, P04, P05, P08].

In addition, in-car MR systems need to consider *when* these presentations of RE elements should be available in VE. For example, the system can display these presentations *continuously* in VE for constant user input or system output [P06, P07]. Alternatively, these presentations can be *triggered by the user* when they want or need to interact with their physical surroundings, such as quickly grabbing a drink from the cup-holder during the game [P04] or customizing their virtual displays closer or further in VE [P05]. Additionally, they can be *triggered by the system* through diverse context-aware incorporation. In particular, a proximity-aware system [P03] blends indications of physical borders into VE when the user approaches them to support awareness of the confined in-car space during the interaction. Likewise, a location-aware system [P08] can add spatiotemporal information about the ride into VE for situational awareness of the on-road environment in motion.

Finally, in-car MR systems should consider *how* to present RE elements in VE. Regarding the modality and its mode, most of the implemented experiments used a *single modality* setup of *visual* cues, given the dominant visual sense in consumer VR experiences. Exceptionally, [P06] compared a visual display, a haptic display, and a combination of both by (un)pairing a car-interior-based haptic display with its counterpart in the situated VE. The results showed that the *multimodality* MR experience lowered the passenger's awareness of the confined space and fostered a feeling of connectedness to the virtual world. After selecting the modality and its mode, the system should finally consider the fidelity and amount of presentation when incorporating RE elements into VE. Often these two dimensions change hand in hand. For example, to increase awareness of the physical in-car space, visualization cues about the surrounding cabin environment range from *abstract* and *minimum* two-dimensional virtual grids [P03] or images of car regions to a *realistic* and *fully* three-dimensional model of the car interior [P04], or shifting from a selective camera view of the physical keyboard to a broader view of the keyboard and its situated car interior [P05]. Likewise, to increase situational awareness of on-road environments in motion, visualization cues about mobile reality range from abstract metaphors using digital artifacts in VE for indicating vehicle speed and travel progress [P07] to minimum text only or fully combined with live street-view video feeds [P08].

In summary, these prototypes demonstrated a systematic set of design dimensions when incorporating RE elements into VE. These strategies were shown to support the passenger's awareness of spatial constraints of their physical surroundings and situational awareness of ride environments in response to the challenges of confined space and mobile reality. In particular, the implemented experiments mainly used a static, seated, single-user setup, focused on the middle Notification Level as a "bridge" between RE and VE, and explored a number of design alternatives for presenting the selected objects and content of RE in VE. Meanwhile, two methods were applied, field and laboratory experiments. I will compare these methods in Chapter 3.

## 1.3 Transcending the Transport Context

After the ride ends, the passenger tends to continue interacting with mobile devices outside of the car in daily life. Today, they keep using, for example, their smartphones or smartwatches in living and working spaces. When envisioning future mobile interaction with VR headsets, Gugenheimer [56] coined the new interaction concept as "nomadic VR", where users can bring their headsets and immerse themselves in any place. However, during such ubiquitous immersive interaction from one place to another, the mobile MR system is challenged to support user awareness of distinct REs from one context to another [21]. Here, the question arises if the proposed design strategy for mixing RE and VE applies independently of the context, e.g., from the car to living spaces, ensuring the system's scalability and usefulness across everyday application scenarios.

Focusing on the spatial scale of distinct REs, this thesis continues the proposed research direction [P06], switching from taking the confined space as the challenge to the opportunity of providing haptic displays for a multimodal immersive experience. Besides visual and auditory feedback, prior work explored leveraging everyday physical objects in the user's surroundings as tangible proxies to provide haptic sensations, enhancing immersive MR experiences [57, 58, 59]. However, it is underexplored how these physical objects can be utilized across the spatial scales of everyday REs, such as from seated to walking scales.

Moreover, the physical arrangement of REs influences social interaction between MR users and other people in their surroundings. For example, users in public environments felt more confident interacting in VR when physical separations were present in their surroundings, with less likelihood of hitting another person [60]. Sometimes, VR users and bystanders may negotiate physical boundaries using nearby tangible objects in their households, such as a carpet, to avoid invading the other person's space [61]. Nonetheless, the social acceptability of MR headsets in shared and social spaces is challenged today. Particularly in places where people are supposed to spend time together and share the same experience, such as living rooms, users largely reduced their willingness to use headsets [42]. It is unclear if the proposed design strategy applies to incorporating this new dimension of RE elements, other people, and how such bystander-aware systems can address the challenge of social acceptability.

Taken together, as the context of mobile MR interaction changes, would the proposed design strategy for incorporation still apply in other everyday contexts, such as living spaces, supporting user awareness of the real environment? The third objective of this thesis is to examine the scalability of the incorporation dimensions from transport to other contexts, addressing the common challenges of spatial constraints and social acceptability in everyday mobile MR interaction. This goal is summarized in the third research question:

> **RQ3. Cross-context:** *What implications does in-car MR research have on mobile MR interaction in other everyday contexts beyond transport?*

**Contribution.** This thesis contributes to two implications on mobile MR interaction in other contexts beyond transport regarding the spatial scale and social scale of incorporating REs. Based on a literature review, a design space for VR haptics across three spatial scales (seated, standing, and walking) [P09] is presented. A previous laboratory experiment examined the incorporation approach of close-space bystanders in a multiuser environment [P10]. Based on these findings, I complemented the model for mobile MR interaction across everyday contexts with these new dimensions and items (see Figure 1.4).

To provide an overview of how haptic representations in VE differ across the spatial scales of REs, 20 papers containing the original keywords "virtual reality," "haptic feedback," and "confined space" were reviewed using the PRISMA approach [62]. The results identified a new dimension for mixing realities when presenting haptic sensations in VE: **Haptic Display**. Further, the review showed that in the most confined seated-scale REs, it is promising to design the haptic displays within reach of the user's arm, such as *wearables* on the hand and arm [63, 64, 65], *physical proxies* worn on the palm [66], or a *grounded device* which is always attached to the seated user—such as a chair [67]. When expanding the interaction area to standing- and walking-scale REs, the chance to induce other haptic sensations increases. In addition to conventional *handheld* controllers [68], the system can induce kinesthetic sensations from interaction with specialized grounded devices tailored to the situated household [69, 70] and multiple force forms from encountering an *autonomous* consumer-grade robot [71].

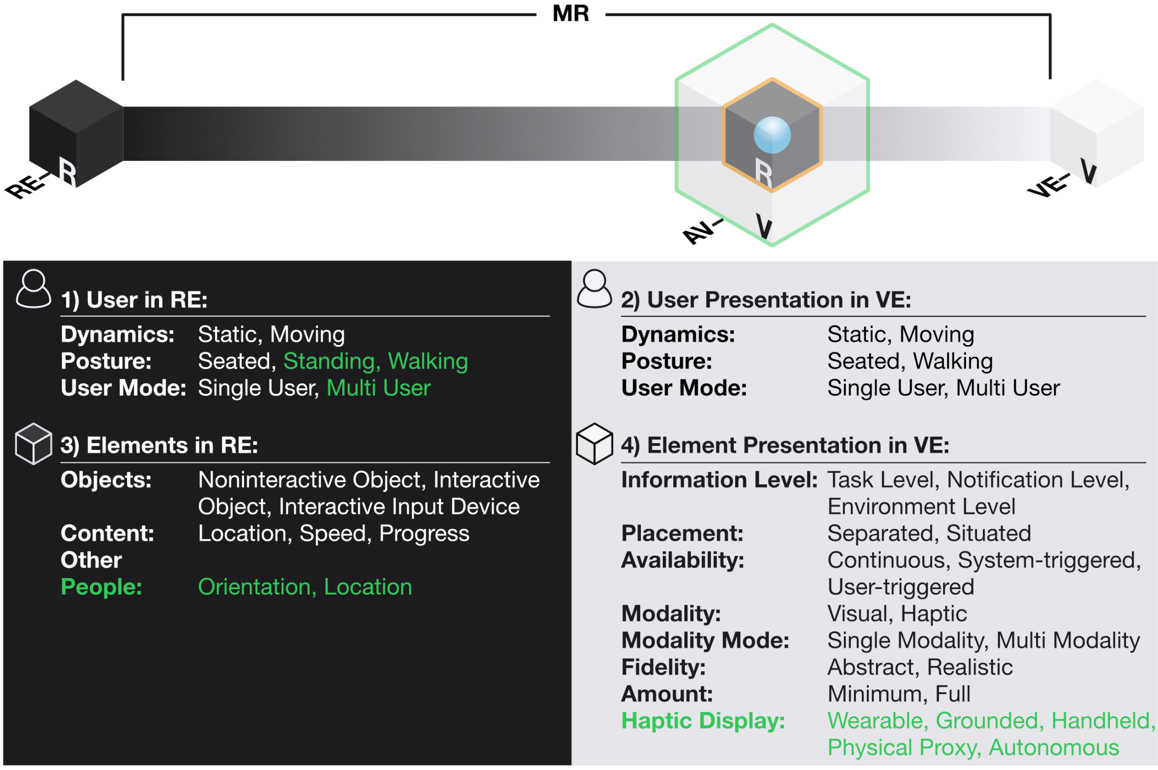



**Figure 1.4:** Extension of the design strategy for incorporating RE into VE based on the publications [P09–P10], with the newly added dimensions marked in green.

To support user awareness of nearby people in close and shared spaces, such as a seatmate on a couch, the MR system was designed to incorporate visualization cues of the seatmate, revealing their changes in *orientation* and *location*. This incorporation of **Other People** was triggered by the context-aware system, leveraging the seatmate's head movements as indicators of conversation interest. In a laboratory experiment, users preferred the mixed visualization cues using a combination of *separated* animojis and *situated* avatars, which grabbed the user's attention faster and guided them to the exact location of the seatmate in the physical world. The findings exemplified that the proposed design strategy for incorporating RE into VE remains applicable and needs context-aware extensions when addressing the user's awareness of distinct RE elements in a new context.

The moving RE of the transport context is not represented often in other everyday environments, considering today's mobile users use mobile technology mostly in static indoor environments. Therefore this thesis does not investigate moving REs beyond the transport context, such as using VR in water slides.[11] However, I will discuss a holistic model for everyday mobile MR interaction across contexts, including potential future research directions, in Chapter 3. Likewise, I will discuss the applied methods of literature reviews there.

[11] `https://www.therme-erding.de/en/tropical-spa-sauna/tropical-spa-water-park/virtual-reality/virtual-reality-slides/`

## 1.4 Summary and Overview of the Thesis

The aim of this thesis is to design user experiences for everyday mobile MR interaction with a focus on passenger experiences for in-car MR. In particular, I have presented three objectives of this thesis: first, understanding passenger needs and behaviors during their use of in-car MR; second, exploring the design strategy for mixing realities in car rides and evaluating the system's usefulness from the user's perspective in series of field and laboratory experiments; and third, transferring the presented design strategy from transport to other everyday contexts and investigating the model for mobile MR interaction across contexts.

Chapter 2 briefly introduces the publications included in this thesis and clarifies their primary contributions addressing the overall research aims.

Chapter 3 discusses the results of this thesis in response to the literature and research questions, compares the implemented research methods, and highlights potential directions for future research.

# 2
# PUBLICATIONS

Having introduced the thesis structure and main research questions, I will now introduce more details of the papers included. Table 2.1 presents an overview of the publications included in this thesis, with the relevant research question, method, and primary contributions. Following the table, I will summarize each publication that comprises this cumulative thesis, including its original title, revised abstract, and a preview of the first pages of the original publication. With this more-detailed impression of the content in each publication, readers can decide to extend their reading according to the relevant topics. I have rewritten the original abstracts to clarify how they contribute to the overall research aims of this thesis. As most publications were conducted in collaboration with my supervisor, colleagues, and students, I use the scientific "*We*" throughout this chapter. Table 3.1 lists the original publications and clarifies my contributions and the contributions of other authors.

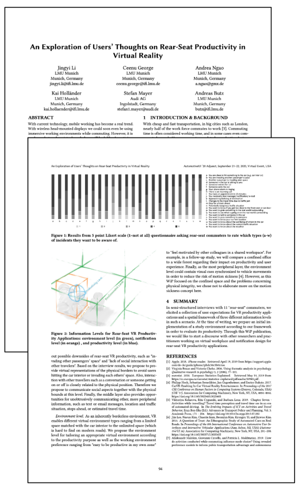
## 2.1 Understanding Passenger Use of In-car MR

The first two publications [P01–P02] provide insights into understanding what a useful in-car MR system is from the user's perspective, following the UCD approach [30]. They address research question RQ1:

> **RQ1. User-centered:** *What are the passenger's needs and behaviors during the use of in-car MR?*

#### [P01] An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality

**Summary.** To concretize the hypothetical application scenario of in-car MR and facilitate users' anticipation, we narrowed it down to a productivity use case in this initial user research. With wireless HMDs, 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 HMDs 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 eleven commuters, they generally could imagine using HMDs in cars for working, but were concerned with their physical integrity while in VR. Two types of preferred working environments stuck


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

Jingyi Li, LMU Munich, Munich, Germany, jingyi.li@ifi.lmu.de
Ceenu George, LMU Munich, Munich, Germany, ceenu.george@ifi.lmu.de
Andrea Ngao, LMU Munich, Munich, Germany, a.ngao@gmx.de
Kai Holländer, LMU Munich, Munich, Germany, kai.hollaender@ifi.lmu.de
Stefan Mayer, Audi AG, Ingolstadt, Germany, stefan1.mayer@audi.de
Andreas Butz, LMU Munich, Munich, Germany, butz@ifi.lmu.de

ABSTRACT
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

1 INTRODUCTION & BACKGROUND
With cheap and fast transportation, in big cities such as London, nearly half of the work force commutes to work [3]. Commuting time is often considered working time, and in some cases even com-

An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality — AutomotiveUI '20 Adjunct, September 21–22, 2020, Virtual Event, USA

Figure 1: Results from 5 point Likert scale (1=not at all) questionnaire asking rear-seat commuters to rate which types (a-w) of incidents they want to be aware of.

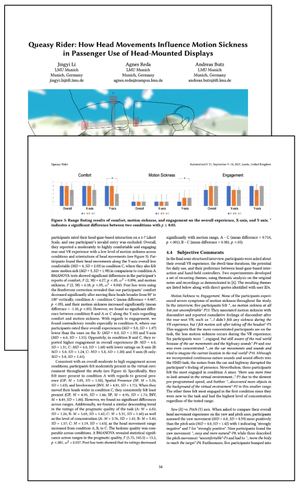
**Table 2.1:** Overview of the publications included in the thesis, abbreviated as [P01–P10], with their relevant research question (RQ), method, and primary contributions.

| ID | RQ | Publication Title and Venue | Research Method | Primary Contributions |
|---|---|---|---|---|
| [P01] | RQ1 | "An Exploration of Users' Thoughts on Rear-Seat Productivity in Virtual Reality" in *AutoUI'20* | Interview Survey ($N = 11$) | Analysis of users' attitudes to future in-car VR interactions, initial information architecture for productivity applications |
| [P02] | RQ1 | "Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of HMDs" in *AutoUI'21* | Field experiment – moving ($N = 21$) | Analysis of head movements on motion sickness, quantification of an upper-threshold head range during in-car VR |
| [P03] | RQ2 | "Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car" in *MTI'21* | Field experiment – parked ($N = 33$) | Prototype and evaluation of in-car VR workspaces |
| [P04] | RQ2 | "Towards Balancing Real-World Awareness and VR Immersion in Mobile VR" in *CHI'22* | Field experiment – parked ($N = 19$) | Analysis of car interior visualizations during MR interactions with the surrounding in-car space and VR games |
| [P05] | RQ2 | "Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs" in *MobileHCI'22* | Field experiment – parked ($N = 19$) | Prototype and evaluation of in-car MR workspaces |
| [P06] | RQ2 | "A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions" in *MuC'22* | Laboratory experiment ($N = 30$) | Prototype and evaluation of car-interior-based haptic displays for multi-modal MR experiences |
| [P07] | RQ2 | "A Journey Through Nature: Exploring Virtual Restorative Environments as a Means to Relax in Confined Spaces" in *C&C'21* | Laboratory experiment ($N = 21$) | Analysis of automotive ambient visualizations cues for providing travel information during in-car calming VR |
| [P08] | RQ2 | "Location-Aware Virtual Reality for Situational Awareness On the Road" submitted to *MobileHCI'23* | Field experiment – moving ($N = 17$) | Analysis of situational awareness during the in-car MR ride |
| [P09] | RQ3 | "Towards a Design Space of Haptics in Everyday Virtual Reality across Different Spatial Scales" in *MTI'21* | Literature review ($N = 20$) | A design space for haptic VR across three spatial scales |
| [P10] | RQ3 | "SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality" submitted to *DIS'23* | Laboratory experiment ($N = 22$) | Analysis of close-bystander awareness during mobile MR in confined social settings |

out and three information levels for rear-seat VR productivity emerged from our interviews: (productivity) task, notification, and environment. The proposed information levels function as the basis for the conceptualization model of mobile MR interaction, guiding the spatial structure of organizing user interfaces.

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. Virtual Event, DC, USA: Association for Computing Machinery, pp. 92–95. DOI: 10.1145/3409251.3411732

#### [P02] Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of Head-Mounted Displays


Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of Head-Mounted Displays

**Summary.** To gather users' contextual feedback and behaviors for an in-depth understanding of this future in-car interaction, we simulated a VR game. We tested the passenger experience of playing in HMDs on a real highway ride. In autonomous cars, drivers will spend more time on NDRAs. Getting their hands off the wheel and eyes off the road, the driver, similar to a rear-seat passenger today, can use multiple built-in displays for such activities or even in mobile VR headsets. A wider motion range is known to increase engagement but might also amplify the risk of motion sickness while switching between displays. In a field study ($N = 21$) on a city highway, we found a head movement range of $\pm 50°$ with a speed of $1.95$ m/s to provide the best tradeoff between motion sickness and engagement. Compared to the pitch ($y$) axis, movement around the yaw ($x$) axis induced more engagement with less motion sickness. The proposed head movement range guided the following series of prototype designs, trying to diminish motion sickness during the passenger's use of in-car MR.

Li, J., Reda, A., and Butz, A. [2021a]. Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of Head-Mounted Displays. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '21. Leeds, United Kingdom: Association for Computing Machinery, pp. 28–38. DOI: 10.1145/3409118.3475137

## 2.2 Mixing Realities in Car Rides

Based on the identified passenger needs and behaviors, we brought these insights into a series of prototype designs of in-car MR systems [P03–P08]. In particular, the passenger's concern about physical integrity reflected the impaired awareness of their close surroundings in the car. Therefore, [P03–P06] aimed to address the challenge of confined space [7, 50]. Meanwhile, the passenger's sensory conflicts induced by the moving interaction space emphasized the importance of knowing what was going on in their ride environment. As a result, [P07-P08] targeted the challenge of mobile reality [55]. Both aiming to bridge the information gap between RE and VE with technical solutions of mixing realities, they address research question RQ2:

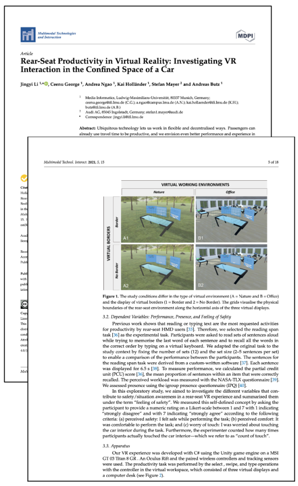
> **RQ2. Technology-driven:** *How can we design in-car MR technology that empowers passengers with access and connectedness to information in both the physical and virtual worlds during the ride?*

### 2.2.1 Challenge of Confined Space

To support passenger awareness of their close in-car surroundings in HMDs, [P03–P06] explored the designs of incorporating the essential **Objects** of the confined RE with various element presentations in VE, such as **Fidelity** and **Amount**.

#### [P03] Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car

**Summary.** As a follow-up work of our interview-based study [P01], this research also focused on the productivity use case. Ubiquitous technology lets us work in flexible and decentralized ways. Passengers can already use travel time to be productive, and we envision even better performance and experience in vehicles with emerging technologies, such as VR headsets. However, the confined physical space constrains interactions, while the virtual space may be conceptually borderless. Therefore, we conducted a study ($N = 33$) to examine the influence of physical restraints and virtual working environments on performance, presence, and the feeling of safety. Our findings show that virtual borders make passengers touch the car interior less, while performance and presence are comparable across conditions. Although passengers prefer a secluded and unlimited VE (Nature), they are more productive in a shared and limited one (Office). We further discussed choices for virtual borders and environments, social experience, and safety responsiveness. Our work highlights opportunities and challenges for future research and the design of in-car MR interaction.


Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car

VIRTUAL WORKING ENVIRONMENTS

Nature | Office

Li, J., George, C., Ngao, A., Holländer, K., Mayer, S., and Butz, A. [2021b]. Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car. In *Multimodal Technologies and Interaction* 5.4. MDPI, pp. 1–18. DOI: 10.3390/mti5040015

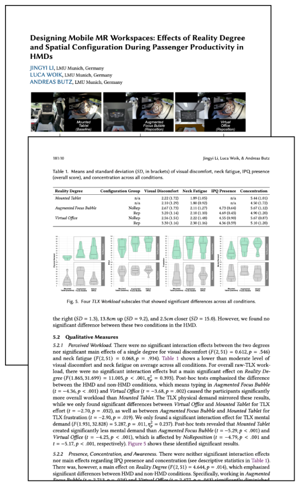
### [P04] Towards Balancing Real-World Awareness and VR Immersion in Mobile VR


Towards Balancing Real-World Awareness and VR Immersion in Mobile VR

**Summary.** In this work, we explored further design alternatives of incorporating the essential surroundings of the passenger into VE for balancing immersion and awareness of the real environment. We examined two-dimensional and three-dimensional visual cues of the rear-seat space to notify passengers about different real-world tasks (*lower armrest*, *take cup*, *close window*, and *hold handle*) during a first-person VR game. The results from our pilot study ($N = 19$) show that users perceive a lower workload in the task *hold handle* than all other tasks. They also feel more immersed in VR after completing this task, compared to *take cup* and *close window*. Based on our findings, we proposed real-world task types, synchronous visual cues, and various input and transition approaches as promising directions for future research. In terms of this thesis, this work demonstrated the potential of interacting with the user's surroundings during virtual experiences in HMDs. Moreover, this revealed that the research agenda shifted by transferring the spatial constraints of RE from a challenge to an opportunity of providing multimodal immersive experiences.

Li, J., Frulli, F., Clarke, S., and Butz, A. [2022a]. Towards Balancing Real-World Awareness and VR Immersion in Mobile VR. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. New Orleans, LA, USA: Association for Computing Machinery, pp. 1–6. DOI: 10.1145/3491101.3519824

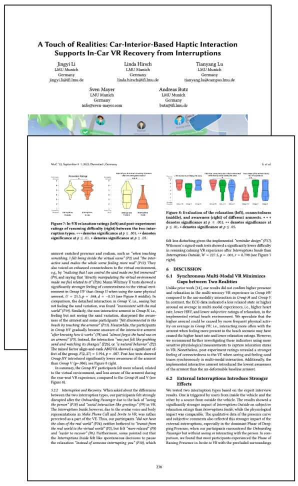
### [P05] Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs


Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs

**Summary.** As a follow-up study of the proposed mobile VR workspace [P03], we implemented three different types of MR workspaces along the RV continuum for a comprehensive evaluation. Likewise, we envisioned that HMDs could complement the prevalent use of mobile devices for work. In a field study ($N = 19$), we tested three mobile workspace setups along the RV continuum (*Mounted Tablet*, *Augmented Focus Bubble*, and *Virtual Office*) and let users reposition the virtual keyboard and display while typing on a physical keyboard in a parked car. The results revealed that using HMDs lowered the users' awareness of their real surroundings but increased their perceived workload with a performance impairment of text entry rate compared to just using a tablet. Letting users customize their workspace layout improved their perceived performance and decreased their pitch-axis head movements when switching between the virtual display and keyboard. Further, we discussed the potential future work regarding the dynamic incorporation of productivity tools, adaptive MR work environment designs, and optimizing upper thresholds of physical discomfort in mobile MR workspaces.

Li, J., Woik, L., and Butz, A. [2022b]. Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs. In *Proc. ACM Hum.-Comput. Interact.* 6.MHCI. Association for Computing Machinery, pp. 1–17. DOI: 10.1145/3546716

#### [P06] A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions




**Summary.** In this last study on the challenge of confined in-car space, we incorporated the spatial constraints of RE into VE and evaluated the conceptual idea of reshaping the car interior for immersive automotive interaction. In such application scenarios of future mobility, real-world interruptions will challenge HMD users. For example, while passengers are immersed at a virtual beach, an incoming phone call might interrupt their presence in the virtual calming experience. We investigated how to help users recover from such interruptions by exploring haptic and visual cues that help them recall their prior presence in VR. We approached this by developing a passive haptic display for rear-seat passengers using an interactive armrest. In a laboratory experiment ($N = 30$), participants played with virtual sand to relax, feeling the changes in the real armrest and seeing them on the virtual beach. We compared this multisensory experience to single modalities (just visuals or just haptics). The results showed that the multimodal experience lowered the user's awareness of the armrest more and fostered a feeling of connectedness to the virtual world after real-world interruptions. We proposed using car-interior-based haptic displays to support immersion and recovery from interruption during in-car MR interaction.

Li, J., Hirsch, L., Lu, T., Mayer, S., and Butz, A. [2022c]. A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions. In *Proceedings of Mensch Und Computer 2022*. MuC '22. Darmstadt, Germany: Association for Computing Machinery, pp. 229–239. DOI: 10.1145/3543758.3543768

### 2.2.2 Challenge of Mobile Reality

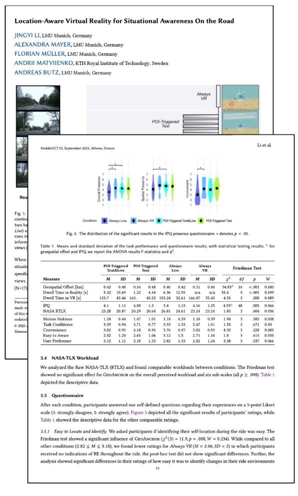
To support passenger awareness of the ever-changing on-road environment in HMDs, [P07–P08] explored the designs of incorporating the essential **Content** of the moving RE with various element presentations in VE, such as **Placement** and **Availability**.

### [P07] A Journey Through Nature: Exploring Virtual Restorative Environments as a Means to Relax in Confined Spaces

**Summary.** Unlike incorporating those tangible **Objects** of confined RE, the nonphysical **Content** of moving RE requires different presentations in VE. In this initial exploration, we focused on a well-being use case, aiming to add visual cues of vehicle information without interrupting the presence. VR technologies can counteract stress or fatigue and restore attention, e.g., by recreating the beauty of nature in a Virtual Restorative Environment (VRE). This has gained additional relevance in the Covid-19 global pandemic: when facing the stress of physical restrictions and limited activity space, how can VR technologies provide the individual experience of being away? We created a VRE that can be used during trips in automated cars using a captured natural environment and simulated artifacts that communicate vehicle information during VR relaxation. In a user study ($N = 21$), we compared the proposed in-car VRE to the user simply closing their eyes. We found that the VRE strongly improved the subjective ratings of mood and slightly increased attentional capacity, and objectively measured performance in a working memory test. Our results provided a concrete starting point for exploring calming VR experiences for future passengers but also users at home.

Li, J., Ma, Y., Li, P., and Butz, A. [2021c]. A Journey Through Nature: Exploring Virtual Restorative Environments as a Means to Relax in Confined Spaces. In *Creativity and Cognition*. C&C '21. Virtual Event, Italy: Association for Computing Machinery, pp. 1–9. DOI: 10.1145/3450741.3465248

### [P08] Location-Aware Virtual Reality for Situational Awareness On the Road



**Summary.** To examine the spatiotemporal changes of moving RE and its impact on the passenger's sense of presence in VE, we prototyped and evaluated location-aware incorporation designs in real car rides. When future passengers immerse themselves in VR, disconnected from the physical world, it can lead to degraded situational awareness, e.g., losing track of self-location. Although previous research investigated indications of surroundings in static setups, they remain unexplored in the mobile transport context with dynamic environments. In this paper, we introduced three location references based on real-world points of interest (POIs), using text, live video streaming, and their combination. We conducted a field study ($N = 17$) where participants estimated their physical location while exposed to in-car VR entertainment. Our results show that constant

live video feeds efficiently guides users' attention to their physical surroundings but it negatively impacts VR presence. POI-triggered text does not degrade presence but participants spend less time looking at them. In contrast, the location-aware combination of text and live video ensures VR presence and increases attention to surroundings. We discussed the challenge of situational awareness for immersive mobile and multimedia applications using different incorporation approaches depending on users' spatiotemporal association changing across transport modes.

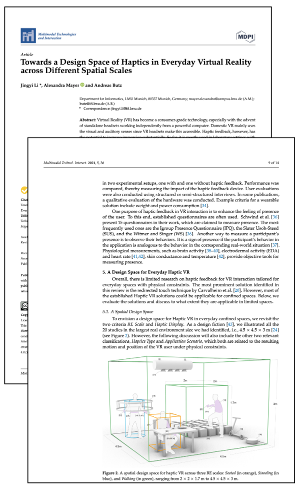
Li, J., Mayer, A., Müller, F., Matviienko, A., and Butz, A. [2023a]. Location-Aware Virtual Reality for Situational Awareness On the Road. In *Proc. ACM Hum.-Comput. Interact.* MHCI. Association for Computing Machinery, pp. 1–17. DOI: SUBMITTED

## 2.3 Transcending the Transport Context

Mobile users interact with their smart devices in everyday contexts beyond transport, such as in their living spaces. In turn, [P09–P10] aimed to examine how the implemented design strategy for incorporation used in the previous in-car prototypes can apply or adapt to different mobile contexts. They address research question RQ3:

> **RQ3. Cross-context:** *What implications does in-car MR research have on mobile MR interaction in other everyday contexts beyond transport?*

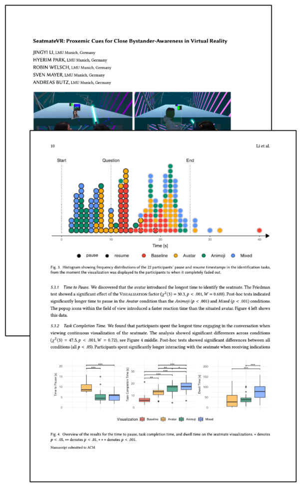
#### [P09] Towards a Design Space of Haptics in Everyday Virtual Reality across Different Spatial Scales


Towards a Design Space of Haptics in Everyday Virtual Reality across Different Spatial Scales

**Summary.** Following the concept of car-interior-based haptic display [P06], this work reviewed the potential of utilizing the surrounding physical objects in domestic VR. Consumer-grade standalone headsets mainly use the visual and auditory senses for creating immersive multimedia experiences. Haptic feedback, however, has the potential to increase immersion substantially. So far, it is mostly used in laboratory settings with specialized haptic devices. Especially for domestic VR, there is underexplored potential in exploiting physical elements of the daily confined settings. In a literature review ($N = 20$), we analyzed VR interaction using haptic feedback with or without physical limitations. From this, we derived a design space for VR haptics across three spatial scales (seated, standing, and walking). Using the design space, we demonstrated two exemplary scenarios of a household VR gym and passenger VR relaxation. The results provide insights into incorporating haptic sensations of **Objects** into VE, such as considering the **Haptic Display** dimension of presenting RE in VE.

Li, J., Mayer, A., and Butz, A. [2021d]. Towards a Design Space of Haptics in Everyday Virtual Reality across Different Spatial Scales. In *Multimodal Technologies and Interaction* 5.7. MDPI, pp. 1–14. DOI: 10.3390/mti5070036

#### [P10] SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality



**Summary.** Finally, this work focused on the challenge of social acceptability [7, 50]. Prior research explored ways to alert VR users of bystanders entering the play area from afar. However, in confined social settings like sharing a couch with seatmates, bystanders' proxemic cues, such as distance, are limited during interruptions, posing challenges for proxemic-aware systems. To address this, we investigated three visualizations, using a two-dimensional *animoji*, a fully-rendered *avatar*, and their combination, to share the bystanders' orientation and location gradually during interruptions. In a user study ($N = 22$), participants played VR games while responding to questions from their seatmates. We found that the *avatar* preserved game experiences yet did not support the fast identification of seatmates as the *animoji* did. Instead, users preferred the *mixed* visualization, where they found the seatmate's orientation cues instantly in their view and were gradually guided to the person's actual location. We discussed the implications for fine-grained proxemic-aware VR systems to support interaction in constrained social spaces. This work revealed one direction for future research, such as balancing awareness of **Other People** in confined social settings and the sense of presence in VE during everyday mobile MR interaction.

Li, J., Park, H., Welsch, R., Mayer, S., and Butz, A. [2023b]. SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Association for Computing Machinery, pp. 1–18. DOI: SUBMITTED

# 3
# DISCUSSION AND FUTURE WORK

This thesis aimed to design user experiences for everyday mobile MR interaction, starting with a focus on passenger experiences for in-car MR. At the time of writing, this research area, in-car MR, is fast-growing yet remains at an early stage. With respect to the three HCI waves [72], the first and second waves of mobile MR interaction are gathering momentum. The community still lacks the necessary understanding of different user groups, as well as systematic prototypes and empirical evaluations that can be generalized to other interaction contexts. This thesis followed the UCD approach [30] to address these objectives. In particular, I first presented insights based on user research, then brought these insights into prototyping and evaluating system solutions, and finally iterated on the learned design strategies by applying them in multiple interaction contexts. In this final chapter, I discuss the results of this thesis in response to the relevant research questions, reflect on the selected research methods, and highlight potential directions for future work. Figure 3.1 shows a holistic overview of the design strategy for incorporating RE into VE during mobile MR interaction based on the findings from this thesis and potential directions for future research.

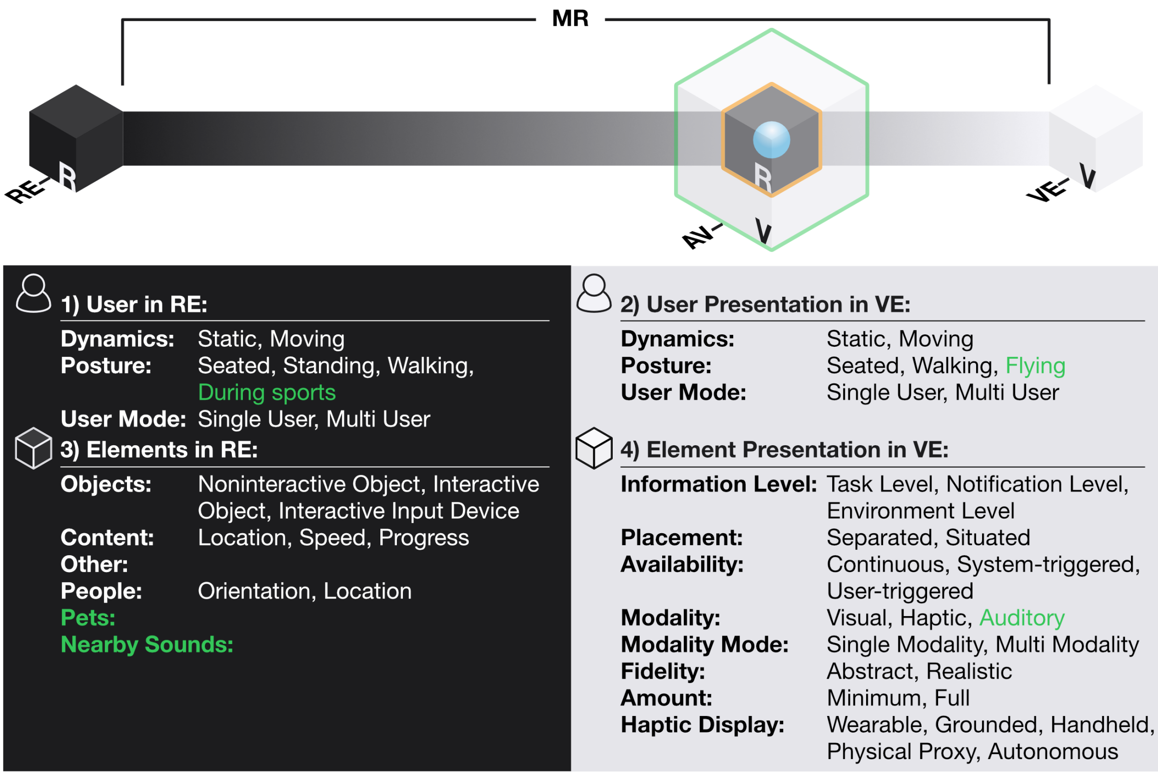



**Figure 3.1:** Design strategy for incorporating RE into VE during mobile MR interaction, with exemplary directions for future research marked in green.

## 3.1 Understanding Passenger Use of In-car MR

In modern life, people spend a considerable amount of their time in daily commutes. As a passenger, they tend to spend this travel time for work and well-being with mobile and multimedia applications [1, 37, 38]. Unlike today's conventional interaction on two-dimensional screens, the new computing paradigm of mobile MR creates an in-space interaction where the user can immerse themselves in a three-dimensional virtual world, achieving a sense of presence [13, 14] yet being disconnected from their situated physical world. As a result, passengers expressed their fear of losing awareness of the real environment while using headsets during bus rides and flights, such as missing events, personal items, and other people in their surroundings [40, 41]. In comparison, wearing headsets on the metro or train was found to be socially acceptable, while wearing them in a car was only slightly inappropriate [42]. Taken together, three main challenges of passenger use of HMDs were identified: 1) confined space, 2) motion sickness, and 3) social acceptability [50]. However, when it comes to the in-car application scenario, it is still unclear which specific elements of the passenger's surroundings must be present in which ways in headsets and what constitutes a useful in-car MR system from the passenger's perspective.

The first objective of this thesis was to explore further the needs and desires of the passengers during mobile MR interaction in car rides. To this end, this thesis contributed to identifying the passenger's need to maintain physical integrity when encountering spatial conflicts between RE and VE [P01]. In addition, this thesis introduced an optimal head movement range between -50° and 50° along the yaw axis as the best tradeoff between engagement and motion sickness when passengers encounter sensory conflicts between RE and VE [P02]. These findings brought insights into what constitutes a "good" design for an in-car MR system. The system needs to address the challenge of confined space induced by the impaired awareness of the close in-car surroundings of the passenger. Moreover, three information levels were proposed to guide the spatial organization of user interfaces and serve as a basic model for mobile MR interaction (see Figure 1.2). Additionally, the system needs to tackle the challenge of mobile reality, supporting awareness of the on-road environment in motion. These insights further guided the following series of system prototype and evaluation designs.

Regarding the research methods, I have used an interview survey [P01] and a field experiment [P02]. The techniques of involving users in the design and development of a product/system change at different stages of the design cycle [73]. At the early stage of the design cycle, background interviews and questionnaires are widely used for collecting data related to the needs and expectations of users. Likewise, to understand the passenger's needs in mobile MR interaction, online or face-to-face interview surveys [37, 40, 42, P01] often use photos and videos to depict the envisioned application scenarios of the passenger using HMDs as stimuli, followed by a set of Likert-scale or open-ended questions to gather subjective ratings and thoughts of the given topic. This common technique is easy and quick to set up and capable of covering large user samples, yet at the cost of ecological validity. Without actively experiencing the targeted product/system, the formed opinions about hypothetical scenarios are vulnerable to changes once the real experience is provided [74]. As a result, prior work has commonly used the simulation technique already at an early stage of the design cycle. For example, Wizard of OZ autonomous rides on real roads [38] provided passengers with a high-fidelity simulation to facilitate their anticipation of futuristic applications for collecting real-world insights.

However, the drawback of using the simulation technique at an early stage is that it is time- and cost-consuming to set up compared to conventional interviews and questionnaires. Moreover, the entire research process involves careful considerations like road safety and ethics. For example, addressing the challenge of mobile reality, our field experiment on a highway [P02] revealed the challenge of inducing the right amount of motion sickness to quantify the upper threshold of an interaction range without imposing severe symptoms and danger on the participants. In turn, online surveys or interviews may fail to investigate this moving feature of the target interaction space but succeed in probing other questions, such as static features of the confined interaction space. In summary, in-car MR user research needs to combine the methods of surveys, interviews, and simulation techniques flexibly, tailored to the relevant research question, considering the required cost and sample size, and including protocols of safety and ethics when needed.

Future work should further explore users' needs and behaviors during mobile MR interaction and validate the findings using different methods in the relevant contexts. For example, regarding the user in RE, the unexplored **Posture** in everyday context include common ones used *during sports* [75], such as accessing digital information through HMDs while biking for daily transport [76]. Likewise, user presentation in VE can analyze the **Posture** of *flying*, as widely used for entertainment experiences [77, 78]. Finally, with regard to elements in RE, unexplored items include **Pets** and **Nearby Sounds**, which were previously found to be essential to maintain user awareness of their surroundings during interaction in HMDs [45]. I added these examples into the final model for mobile MR interaction (see Figure 3.1).

## 3.2 Mixing Realities in Car Rides

Following the UCD approach [30], designers need to translate the identified user needs into the design language for system development. To build a useful MR system from a user's perspective, prior work revealed promising solutions by incorporating RE into VE [45]. In particular, some high-granularity design dimensions, such as the **Amount**, **Fidelity**, and **Placement** of incorporating RE, finely adjust the balance between supporting user awareness of the real environment and their sense of presence in VR [46, 47, 48, 49]. Compared to these study contexts limited to living or working REs, new problems occur in the transport context. The in-vehicle interaction space faces the challenge of confined space, motion sickness, and social acceptability [7, 50]. To address these, new design dimensions were proposed, such as the sensory congruence between RE and VE [23, 24, 52], to support the passenger's awareness of their surroundings without inducing motion sickness and breaking the presence in HMDs.

Informed by these design dimensions, the second objective of this thesis was to create a systematic design strategy for context-aware incorporation. To this end, I synthesized the findings from a series of prototyping and evaluation systems that were designed to address the identified challenges of confined space and mobile reality during the passenger's use of in-car MR. The resulting design strategy involved four aspects and twelve dimensions (see Figure 1.3), helping instruct the hands-on design practice of mixing realities during in-car MR interaction. In particular, the four aspects revealed a sequential approach for designing the two ends of the spatial RV continuum, namely the user and elements in RE and their presentations in VE. Researchers and practitioners can approach the design space of mobile MR interaction following four steps. First, the MR system needs to consider the dynamics, posture, and mode of the user in RE, given their situated contexts. Second, it should decide on the relevant user presentation in VE, paired or unpaired with the user in RE, dependent on the given interaction purpose. Third, the system needs to select the essential element in RE based on the user's needs. Fourth, it should explore and evaluate design alternatives of the element presentation in VE for building a useful system. Regarding the final step, this thesis contributed to seven design dimensions that have considered *where*, *when*, and *how* to incorporate the selected RE elements into VE. While most dimensions use categorical design options, the **Fidelity** and **Amount** contain continuous ones. In other words, there are no fixed or discrete levels between *abstract* and *realistic* nor between *minimum* and *full*.

At this latter phase of the design cycle, I conducted laboratory and field experiments to involve the user's feedback on their experiences for evaluating and improving the system's usefulness [73]. Referring to the framework for in-vehicle interaction [79], I positioned the implemented experiments in Figure 3.2. As I focused on involving real users in the design cycle, [P03–P08] all addressed the human *Agent* who perceives and acts upon the in-vehicle and on-road environments. However, they utilized different types of testing scenarios and environments in response to the relevant research question. In particular, the field experiment in real car rides [P08] contributed to the system solutions for incorporating spatiotemporal information into virtual experiences. Testing in unconstrained scenarios on real roads induced more realistic on-road situational awareness than static laboratory experiments. Likewise, [P05] tested the prototypes of MR workspaces in a real car parked in specific residential areas. The testing environment and scenarios still involved uncontrolled yet more predictable traffic flows and distractions than rides on the highway. This ensured certain real-world influences without too much cost for the study setup that targeted the in-vehicle interaction space.

In contrast, the laboratory experiments used prototype vehicles [P03–P04] and driving simulators [P06–P07] at an earlier stage of prototyping. While both used constrained scenarios, sitting inside full-size mock-ups of car interiors comprised a higher degree of fidelity of the passenger's physical surroundings, such as the three-dimensional physical borders [P03] and multiple car regions, including door handles, windows, cup holders, and armrests [P04]. In comparison, using driving simulators usually only covers certain regions, such as the armrest area [P06]. However, it allows for quick and dirty prototypes that can iterate the designs of car-interior-based haptic displays. With regard to the challenge of mobile reality, a simulator

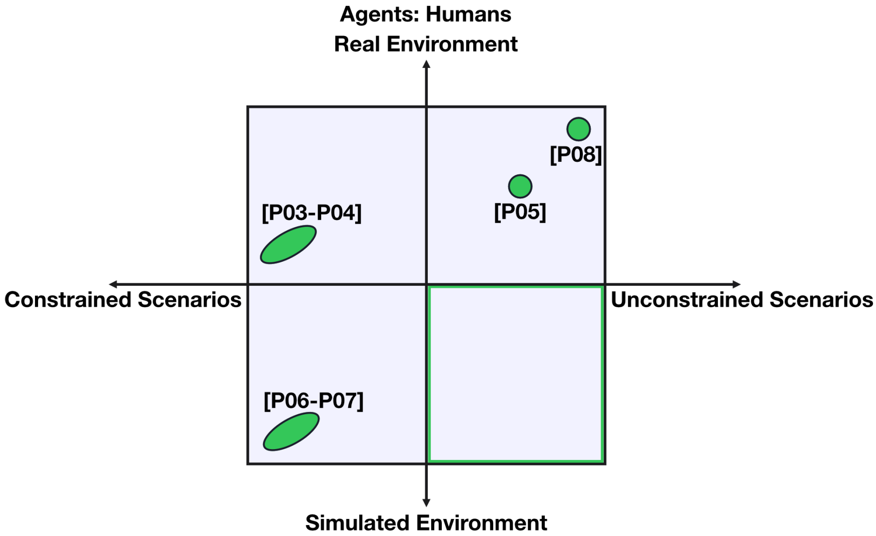



**Figure 3.2:** Comparing the laboratory and field experiments [P03–P08] (marked in green dots) based on the framework for in-vehicle interaction [79]. The underexplored methods in this thesis, using simulated environments and unconstrained scenarios (highlighted in the green bounding box), have revealed new opportunities and avenues for future research.

study lacks ecological validity yet can benefit from an efficient and valuable collection of user feedback on early design prototypes of the element presentation in VE [P07]. As a result, this leads to the unexplored area of using the simulated environment and unconstrained scenarios for future work (see Figure 3.2), such as the open-ended Wizard of Oz in the simulator [80, 81] for MR passenger experiences.

The proposed design strategy was dependent on the implemented prototypes in this thesis, which have covered a number of use cases yet remain limited. Future research should be open to identifying new design dimensions and continue to improve the granularity of each design dimension. For example, an in-car MR system can be used to investigate incorporating the unexplored **Modality** of *auditory* presentation of RE elements [82, 83] into virtual experiences and analyze the resulting cognitive workload compared to visual and haptic modalities. I added this example to the final model for mobile MR interaction (see Figure 3.1).

## 3.3 Transcending the Transport Context

Anticipating nomadic VR [56], users can bring their headsets and immerse themselves anytime and anywhere [18]. These rich and dynamic interaction contexts challenge mobile MR systems to support user awareness of distinct REs from one place to another [21]. Here the question arises, would the design strategy still apply and support awareness of the real environment in other everyday contexts beyond transport, such as in living spaces? The third objective of this thesis was to examine the scalability of the proposed design dimensions from transport to other everyday contexts that share the challenges of spatial constraints and social acceptability during mobile MR interaction.

To answer RQ3, this thesis contributed two implications on mobile MR interaction regarding the spatial scale and social scale of incorporating REs. Particularly, the literature review consolidated the proposed concept of leveraging everyday physical objects in the surroundings of the user beyond the seated spatial scale as haptic feedback for a multimodal immersive experience [P09]. The resulting new *standing* and *walking* **Posture** and additional design dimension of **Haptic Display** complemented the proposed design strategy. In addition, a laboratory experiment discovered that the granular design of incorporating the *orientation* and *location* of copresent others enacted social interaction between the user and their seatmate in confined social settings during MR interaction [P10]. Likewise, the resulting new design dimension of **Other People** and the additional *multiuser* mode complemented the design strategy. Furthermore, the design alternatives of this new element in RE were presented in VE with the proposed **Placement** using *separated* and/or *situated* visualizations of the seatmate. These results substantiated the scalability of the proposed design strategy from transport to other contexts and expanded the type of design dimensions for more context-aware mixing realities (see Figure 1.3).

Regarding the methods, I have used a literature review [P09] and laboratory experiment [P10] when approaching the new research areas, haptic MR and social MR, respectively. In particular, [P09] functioned as a scoping review [84], which has been found to be useful when the body of literature shows a complex or heterogeneous nature amenable to a more precise systematic review. By mapping the existing literature in terms of its nature, features, and volume, a scoping review aims to clarify the working definitions and conceptual boundaries of the given research area. In comparison, when studying an area with a more well-established research paradigm, such as social presence in VR [85], hands-on prototyping and tests advance system innovation. Taken together, when extending research to new fields, researchers need to embrace systematic literature reviews and experiments, depending on the maturity of the given research field.

Future research should further explore other mobile interaction contexts, including different transport means and other public and shared spaces [18]. For example, the market for passenger use of HMDs is thriving with emerging services, such as FlixVR[1] and InflightVR.[2] Unlike car rides, these public transport modes potentially involve more colocated people in the user's surroundings. As a result, increasing events of passengers getting on and off during bus rides or airline onboard services may easily break the user's presence in virtual experiences [25, 40, 86]. In addition, the user is concerned about invading others' spaces during interaction in HMDs, decreasing the social acceptability of using HMDs in public [42, 87]. Future research need to further validate the proposed design strategy in daily public and shared settings.

[1] `https://www.flixbus.com/virtual-reality`

[2] `https://www.inflight-vr.com/`

## 3.4 Outlook and Closing Remarks

This thesis aimed to design user experiences for everyday mobile MR interaction, with an initial focus on passenger experiences for in-car MR. Starting from the nascent research area, in-car MR, I followed the UCD approach [30]. In particular, my work developed along three steps: first, understanding the passenger's needs and behaviors during their use of HMDs; second, prototyping and evaluating technical solutions for building a useful system based on the identified user insights; and third, applying the identified design strategy in other contexts and finalizing the conceptual model for future research and the design of mobile MR interaction.

By comprising an entire design cycle, this thesis has paved the way for understanding the future passenger use of immersive technology, addressing today's MR technical limitations in mobile interaction. The ultimate vision of this thesis is to foster mobile users' ubiquitous access and close connectedness to MR anytime and anywhere in their daily lives. To enable connection anywhere, it is worth investigating cross-device mobile MR interaction from HMDs to mobile phones, tablets, and PCs for future work. Therefore, any comprehensive in-vehicle MR system should support cross-reality transition when accessing digital information from augmented reality windshield displays to HMDs [5, 88, 89].

Concerning the three HCI waves, mobile MR research seems still to be undergoing the first and second HCI waves, with emerging explorations of interaction in professional and personal life [90]. Anticipating the third wave, future work should investigate mobile MR interaction in people's social life with the design goal shifting from performance and interaction context to cultural, social, and ethical values [72]. When mobile devices permeate people's daily life, the implicit data sensation and collection endanger the privacy of the user as well as nearby people in public [91]. Recent work has emphasized the potential malicious use of manipulating the user's perception in VR, which can manipulate their movements in the physical world, resulting in them potentially hurting themselves or others nearby [92]. More speculative research on mobile MR interaction will be needed to clarify the boundaries of this new computing paradigm before its wide adoption in the future society fueled by mobility and digitalization.

# List of Figures



# List of Tables

# Glossary

**Awareness of the Real Environment** Awareness of the self and the external world constitutes consciousness in the real world [11]. While immersed in the virtual environment, people gradually become disconnected from the physical world. They lose track of physical objects, self-locations, and other people in the real environment, which I refer to as degraded awareness of the real environment in this thesis.

**Context** Dey et al. [28] defined context as "any information that can be used to characterize the situation of entities (i.e., whether a person, place or object) that are considered relevant to the interaction between a user and an application, including the user and the application themselves." Context gains importance in ubiquitous computing, as its geometric and semantical properties have been leveraged to design HCI embedded in the user's everyday life, supporting their daily activities at home, at work, in town, and on the road [93]. In this thesis, I first focus on the everyday transport context, especially in-car scenarios, and then extend the findings to everyday living spaces, involving dynamic spatial scales and multiuser scenarios.

**In-Car MR** An emerging research field in HCI, in-car MR aims to investigate passenger use of VR and MR headsets in car rides [7, 50]. In this thesis, I refer to the term "in-car MR" as the target scenario, a specific transport context of passengers performing daily activities such as work, entertainment, and well-being through mixed reality simulated in the VR headset.

**Mixed Reality (MR)** Mixed Reality (MR) was coined by Milgram et al. [10], referring to the immersive technology that supports interaction with different types of Real Environments (REs), Virtual Environments (VEs), and a mix of both, along the Reality-Virtuality (RV) continuum. In this thesis, I refer to MR, with a focus on the right subset of the continuum, namely from the complete VE to incorporating the essential parts of RE into VE.

**Passenger** A passenger is traditionally defined in transport research as a human riding a transport means driven by a driver. In this thesis, I refer to the term passenger as the user of mobile MR headsets in future transport means independent of the presence of a driver.

**Passenger Experience** Today's passenger experience is a criterion used to reflect the travel quality of the transport means measured by its users. As the transport industry increasingly innovates and digitalizes its cabins to provide passengers access to all types of information, content, and services, the passenger experience extends to the qualities of their access to digital spaces on the move, including safety, comfort, and joy of the ride. In this thesis, I use the term passenger experience focusing on the user experience of mobile VR and MR headsets in cars, concerning safety, effectiveness, efficiency, errors, and satisfaction.

**Virtual Reality (VR)** Lanier [94] coined the term Virtual Reality (VR) as "three-dimensional realities implemented with stereo viewing goggles and reality gloves." This technical term can be seen as comparable to the right-end VE along the RV continuum, leveraging immersive technology to create all types of VEs where users are empowered to feel being there, creating a sense of presence [95].

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# Original Publications

None of the work included in this thesis would have been possible without my supervisor, colleagues, and the students I supervised. Table 3.1 clarifies my own and others' contributions to the included projects.

| | My Contribution | Contributions of Others |
|---|---|---|
| [P01] | I came up with the original model and visualization. I cosupervised the study with C. George, K. Holländer, and our industrial partner S.Mayer. I codeveloped the main research idea and validated the data analysis with C.George. I was the lead author of the resulting publication. | C.George helped with the development of the research idea and writing. A. Ngao conducted the study. K.Holländer contributed to the initial conceptualization. A. Butz and S. Mayer advised the research project and contributed to reviewing and editing the paper. |
| [P02] | I developed the main research idea and supervised the study. I contributed to the study design and data analysis. I was the lead author of the resulting publication. | A. Reda developed the prototype and conducted the study. A. Butz advised the research project and edited the final version of the paper. |
| [P03] | I cosupervised the study with C. George and K. Holländer. I codeveloped the main research idea and validated the data analysis with C. George. I was the lead author of the resulting publication. | C. George helped with the development of the research idea and writing. A. Ngao developed the prototype and conducted the study. K. Holländer contributed to the initial conceptualization. A. Butz and S. Mayer advised the research project and contributed to reviewing and editing the paper. |
| [P04] | I developed the main research idea and study design and analyzed the data. I cosupervised the study and was the lead author of the resulting publication. | F. Frulli developed the prototype and conducted the study. S. Clarke helped with the conceptualization. A. Butz advised the research project and edited the final version of the paper. |
| [P05] | I came up with the main research concept and study design. I supervised the study. I developed the data analysis and was the lead author of the resulting publication. | L. Woik developed the prototype and conducted the study. A. Butz advised the research project and edited the final version of the paper. |
| [P06] | I cosupervised the study and codeveloped the main research idea with L. Hirsch. I was the lead author of the resulting publication. | L. Hirsch contributed to the development of the research idea and writing. T. Lu implemented the prototype and conducted the study. S. Mayer and A. Butz edited the final version of the paper. |

| | | |
|---|---|---|
| [P07] | I supervised the study and developed the main research idea. I developed the data analysis and was the lead author of the resulting publication. | Y. Ma codeveloped the study design. P. Li implemented the prototype and conducted the study. A. Butz advised the research project and edited the final version of the paper. |
| [P08] | I came up with the main research idea and supervised the study. I analyzed the data and was the lead author of the resulting publication. | A. Mayer implemented the prototype and conducted the study. F. Müller and A. Matviienko helped with the study design and paper writing. A. Butz edited the final version of the paper. |
| [P09] | I supervised the study and developed the main research idea. I was the lead author of the resulting publication. | A. Mayer conducted the study. A. Butz advised the research project and edited the final version of the paper. |
| [P10] | I developed the main research idea and supervised the study. I was the lead author of the resulting publication. | H. Park implemented the prototype and conducted the study. R. Welsch and S. Mayer helped with the study design, data analysis, and paper writing. A. Butz advised the research project and edited the final version of the paper. |

Table 3.1: Clarification of my own and others' contributions to the projects included in this thesis.

[P01] 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. Association for Computing Machinery, pp. 92–95. DOI: 10.1145/3409251.3411732.

[P02] Li, J., Reda, A., and Butz, A. (2021a). Queasy Rider: How Head Movements Influence Motion Sickness in Passenger Use of Head-Mounted Displays. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '21. Association for Computing Machinery, pp. 28–38. DOI: 10.1145/3409118.3475137.

[P03] Li, J., George, C., Ngao, A., Holländer, K., Mayer, S., and Butz, A. (2021b). Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car. In *Multimodal Technologies and Interaction* 5.4. MDPI, pp. 1–18. DOI: 10.3390/mti5040015.

[P04] Li, J., Frulli, F., Clarke, S., and Butz, A. (2022a). Towards Balancing Real-World Awareness and VR Immersion in Mobile VR. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. Association for Computing Machinery, pp. 1–6. DOI: 10.1145/3491101.3519824.

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[P08] Li, J., Mayer, A., Müller, F., Matviienko, A., and Butz, A. (2023a). Location-Aware Virtual Reality for Situational Awareness On the Road. In *Proc. ACM Hum.-Comput. Interact.* MHCI. Association for Computing Machinery, pp. 1–17. DOI: SUBMITTED.

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[P10] Li, J., Park, H., Welsch, R., Mayer, S., and Butz, A. (2023b). SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality. In *Proceedings of the 2023 ACM Designing Interactive Systems Conference*. DIS '23. Association for Computing Machinery, pp. 1–18. DOI: SUBMITTED.

# Location-Aware Virtual Reality for Situational Awareness On the Road

JINGYI LI, LMU Munich, Germany
ALEXANDRA MAYER, LMU Munich, Germany
FLORIAN MÜLLER, LMU Munich, Germany
ANDRII MATVIIENKO, KTH Royal Institute of Technology, Sweden
ANDREAS BUTZ, LMU Munich, Germany

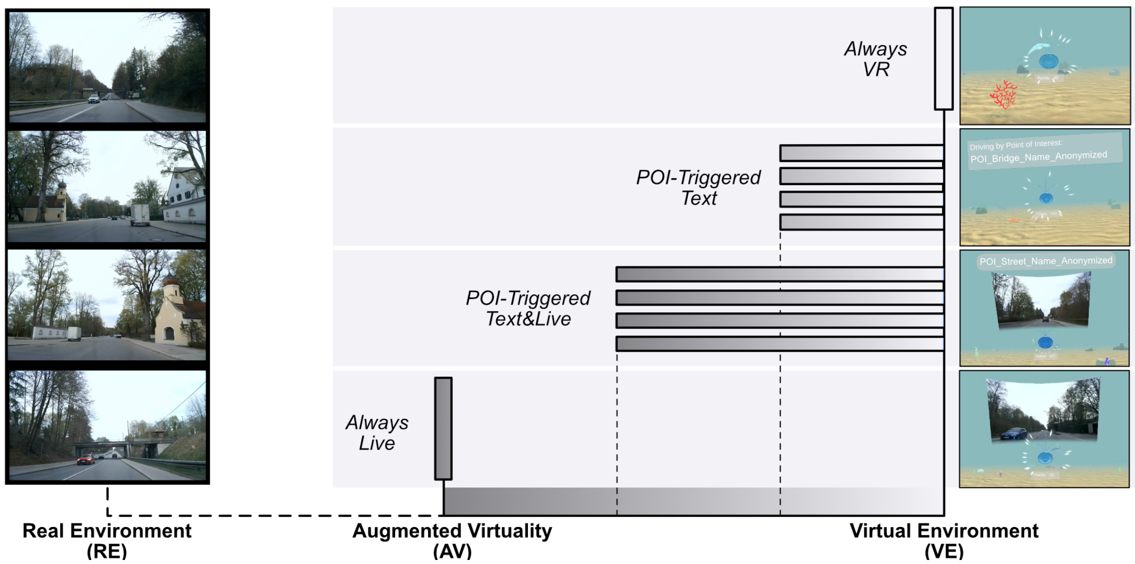


Fig. 1. We investigated situational awareness during mobile virtual reality (VR) interaction on the road, along the Reality-Virtuality (RV) continuum [42] focusing on the subset between augmented virtuality (AV) and virtual environment (VE). These endpoints represent two baselines that persistently incorporate live street views of the user's situated real environment (RE) into target VE (*Always Live*) or persistently no indications of RE at all (*Always VR*). In between, we proposed location-aware systems, incorporating RE cues into VE only when passing specific locations. In particular, we designed two visualizations that revealed different amounts and fidelity levels of information about points of interest (POIs) along the way, using street names alone (*POI-Triggered Text*) or combined with live street views (*POI-Triggered Text&Live*).

When future passengers are immersed in Virtual Reality (VR), the resulting disconnection from the physical world may degrade their situational awareness on the road. To address this, we propose incorporating real-world cues into virtual experiences when passing specific locations. We designed two visualizations using points of interest (POIs), street names alone or combined with live street views. We compared them to two baselines, persistently displaying live cues (*Always Live*) or no cues (*Always VR*). In a field study (N=17), participants estimated their locations while exposed to VR entertainment during car rides. The results show that adding any



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environmental cues inevitably degrades VR presence compared to *Always VR*. However, *POI-triggered Text&Live* preserves VR presence better than *Always Live* and attracts user attention to the road more than *POI-triggered Text*. We discuss the challenges of situational awareness for using mobile VR on the road and potential incorporation strategies across transport contexts.

CCS Concepts: • **Human-centered computing → Virtual reality**; **Field studies**.

Additional Key Words and Phrases: in-vehicle virtual reality, situational awareness, location-aware system, POI

**ACM Reference Format:**
Jingyi Li, Alexandra Mayer, Florian Müller, Andrii Matviienko, and Andreas Butz. 2023. Location-Aware Virtual Reality for Situational Awareness On the Road. In *MobileHCI'23: The ACM International Conference on Mobile Human-Computer Interaction, September 2023, Athens, Greece*. ACM, New York, NY, USA, 19 pages. https://doi.org/XXXXXXX.XXXXXXX

## 1 INTRODUCTION

With self-driving vehicles on the horizon, future passengers can invest their travel time alone for work and well-being through mobile and multimedia applications [14, 15, 46]. The automotive industry and research strive to reinvent the in-car space into mobile offices and living rooms by integrating large-scale displays and augmented reality windshield displays into the cabin for realizing passenger-centered infotainment systems [3, 28, 48]. Unlike conventional mobile interactions on flat screens, a promising approach to enhance in-vehicle experiences is through the use of virtual reality (VR) [49]. VR allows for fully immersive in-vehicle experiences in diverse three-dimensional virtual environments, promoting relaxation [32, 45], productivity [31, 43], and entertainment [23, 28, 37] while reducing real-world distractions from traffic environments. Furthermore, VR can enhance user engagement and satisfaction by allowing users to interact with the virtual world that transcends the physical boundaries of passenger seats, which is inaccessible with traditional flat-screen interfaces mounted and restricted to the cabin space [35, 59]. While feeling present and secluded in the virtual world, mobile VR users are disconnected from their situated physical world, leading to real-world disengagement involving spatial and temporal disassociation [16, 25]. This impaired reality awareness gains importance when using mobile VR headsets in transport contexts, as it endangers mobile users' on-road situational awareness [12], such as losing track of fast-changing self-location during the ride.

To support reality awareness [44] while preserving VR presence or "the feeling of being there" [53, 54], today's mobile VR headsets are often equipped with mixed reality (MR) features, such as the Oculus Passthrough[1] or Space Sense[2]. Likewise, prior research adopted this MR approach, incorporating the visualization cues of users' real environments (REs), such as nearby objects and other people, into the target virtual environments (VEs) [40, 44]. When extending the interaction context from indoor households to outdoor ride environments, new challenges arise in the fast-moving interaction space [35, 38]. As a result, new types of RE information and design dimensions were required to re-calibrate the balance. For example, prior in-car VR studies incorporated indications of real-time vehicle motion into virtual environments, with varying levels of Fidelity, Amount, and Congruence, for fine-tuned balances between VR presence and reality awareness during the ride [23, 37, 45]. However, losing track of what is going on in fast-changing ride environments, such as not knowing self-location over time, challenges the existing solutions limited to incorporating real-world stimuli from the indoor cabin space rather than those from dynamic outdoor environments [12]. Today's mobile users habitually maintain their situational awareness by perceiving contextual changes in their ride environments by simply diverting their attention from primary activities (e.g., surfing on smartphones) out of windows back and

[1] https://developer.oculus.com/blog/mixed-reality-with-passthrough/, last accessed April 19, 2023
[2] https://vrscout.com/news/oculus-quests-space-sense-feature-detects-people-and-pets/, last accessed April 19, 2023

forth. Yet it is unclear how this quick and repetitive cognitive switch can be supported in mobile VR headsets, how it would influence the balance between VR presence and reality awareness on the road, and its further impact on the usefulness of in-vehicle VR systems from a user's perspective.

In this paper, we contributed to the research of mobile VR interaction in everyday transport contexts, focusing on the challenge of situational awareness while using immersive technology on the road. In particular, we proposed location-aware systems, incorporating ride environments into VR only when passing specific locations. We designed two visualizations using points of interest (POIs) along the way, street names alone (*POI-Triggered Text*) or combined with live street views (*POI-Triggered Text&Live*), as real-world location references. Additionally, we created two baselines for comparison, persistently displaying live street views (*Always Live*) or persistently no indications at all throughout VR experiences (*Always VR*). In a field study (N=17), participants experienced VR entertainment inside headsets and were asked to estimate their self-location during car rides. Our results showed that *Always Live* efficiently guided users' attention to the incorporated ride views but disrupted their sense of presence in VR. *POI-Triggered Text* did not degrade the presence but was less noticeable. In contrast, *POI-Triggered Text&Live* raised users' attention to outdoor ride environments, at the same time, preserved VR presence. Based on these results, we highlight implications for future research on the challenge of situational awareness during mobile VR interaction on the road and potential incorporation strategies in different transport contexts.

The main contributions of our work are: "Firstly, we addressed the research gap in situational awareness during mobile VR by providing empirical evidence with higher ecological validity through field experiments, as opposed to prior simulator-based studies. Secondly, we extended incorporation strategies from indoor to outdoor interaction contexts by proposing to reveal real-world cues depending on users' spatio-temporal association with their on-road environments. Finally, we identified the research challenge of temporal factors in field experiments aimed at sufficiently eliciting degraded situational awareness and ensuring the effective incorporation of real-world location cues that extend beyond the current moment.

## 2 RELATED WORK

We first reviewed the literature regarding in-vehicle MR challenges, examined the proposed solutions for supporting reality awareness in balance with VR presence across everyday mobile interaction contexts, and finally highlighted the research gap concerning the challenge of situational awareness during mobile VR interaction on the road.

### 2.1 In-Vehicle Mixed Reality Challenges

The nascent research area of in-vehicle MR focused on the new computing paradigm of mobile interaction, using immersive technology in cars and other means of transportation for ubiquitous access and connectedness to digital information anytime and anywhere. Anticipating future self-driving cars, today's commuters already expect to spend their travel time for work and well-being through mobile and multimedia applications [8, 14, 47]. Meanwhile, recent research on in-vehicle mobile interaction extends from driver-centered task performance to passenger-centered activity experiences [13]. Prior work explored considerable ways of digitalizing the cabin space for the comfort and joy of rides. From the large-scale display mounted to car ceilings as a Theatre Screen[3] for rear-seat entertainment, to the augmented car doors for infotainment information about nearby sightseeing spots [3], to augmented reality windshield displays with location information about nearby vehicles for cross-car game experiences [28]. With the increasing amount, scale,

[3]https://www.bmw.com/en/events/ces2022/theaterscreen.html, last accessed April 19, 2023

and fidelity of displays integrated into the cabin, the emerging paradigm of in-vehicle mobile interaction evolves from *on the screen* to *in the space* [48, 49]. Another digitalization approach uses standalone VR headsets as end products to empower mobile interaction with the highest level of immersion that today's technology can afford. On the market, the Holoride[4] company launched the concept of in-car entertainment where passengers can play first-person shooter games in a virtual space motion-synced to real-time vehicle movements. Likewise, FlixBus[5] introduced the use case of using VR in long-distance bus rides for filling monotonous travel time in various three-dimensional virtual environments. For example, simulated workspace and calming underwater landscapes, were found to help passengers escape from real-world distractions and immerse themselves in virtual experiences for better concentration and relaxation [33, 45].

Along with increasing presence in the virtual world, users become concerned about disengaging from the physical world when using mobile VR headsets in their daily lives [16]. When users' VR presence overtakes their reality awareness, it endangers their physical integrity and causes unintentional invasion into physical borders or others' personal spaces [30, 43]. To support reality awareness during in-vehicle VR interaction, prior work incorporated indications of real-world stimuli from the cabin space, including car boundaries, other passengers, and vehicle motion, into virtual experiences. In particular, *when* (Availability) [31] and *how* (Fidelity, Amount, and Congruence) [1, 23, 29, 37] to incorporate were found to be critical design dimensions. In summary, prior work mainly focused on the real-world stimuli from the indoor cabin space when addressing the challenges of confined space, social acceptability, and motion sickness [35, 38].

In comparison, reality awareness of on-road environments remains under-explored yet is essential for maintaining situational awareness during mobile VR interaction in transport contexts [11]. Recent research started to investigate incorporating situational awareness cues using a series of traffic signs and text descriptions that proactively revealed approaching events along the way, which lowered cognitive workload compared to no cues during VR entertainment in the driving simulator experiment [12]. However, higher-granularity design dimensions are still lacking for a fine-tuned balance between VR presence and situation awareness during immersive mobile interaction in real car rides [25].

### 2.2 Incorporation Strategies for Reality Awareness in Mobile VR Interaction

In a broader sense of mobile interaction contexts, prior research explored considerable design dimensions for incorporating reality into virtual experiences, supporting mobile VR users' reality awareness on the road, at home, and at work. For example, regarding what to be incorporated, various Types of real-world information were found essential in the given task, e.g., incoming messages [24, 50], surrounding physical boundaries [17], interactive objects [34], the self-like avatar hands [26], and other people, such as bystanders [27, 57]. When presenting the selected real-world information in virtual scenes, multiple interaction Modalities were found effective in raising users' reality awareness, using auditory and haptic feedback [17, 36]. Meanwhile, the majority focused on visual cues of reality, given the dominant impact of the visual sense in the immersive medium. In particular, prior work compared multiple levels of visualization Fidelity for fine-grained incorporation. For example, passersby were presented with 2D images, 3D scans, and avatars in room-scale VR games to facilitate awareness of other people when they approach users [57]. Users' hands were visualized with realistic, abstract, and fingertips-only representations to let users see their own hands and support typing tasks in VR [26]. Furthermore, prior studies investigated the system usability concerning different levels of Amount and Availability for incorporating reality into VR [18, 34]. Finally, regarding where to display these

[4] https://www.holoride.com/en, last accessed April 19, 2023
[5] https://www.flixbus.com/virtual-reality, last accessed April 19, 2023

visualizations, many design alternatives of Placements, such as through a head-up display, on-body, floating, and in-situ, were analyzed across different use cases [50].

During everyday mobile VR from one place to another, rich and dynamic contexts challenge the system to understand *what* and *when* users need to learn about their situated real environments and *how* this real-world information should be presented in virtual environments. As a result, specific design dimensions and levels for an optimal balance between reality awareness and VR presence are context-dependent during mobile VR interaction.

## 3 CONCEPT

Informed by the existing incorporation strategies, we applied the proposed design dimensions for incorporating real-world stimuli from dynamic outdoor environments to address the challenge of situational awareness during in-vehicle VR interaction. To concretize the application scenario, we focused on in-car VR entertainment as a representative use case of future mobility, where passengers spend travel time relaxing in a calming virtual world simulated through VR headsets. We referred to Milgram's Reality-Virtuality (RV) continuum [42] for the ideation of our system concepts. In particular, we envision useful in-car VR entertainment systems should primarily ensure passengers' presence and engagement in VE, secondarily supporting reality awareness of their situated RE. To this end, our systems focused on the right half of the continuum, with a dominant part of user experience in VE. Additionally, the objective of in-car VR systems is to identify an optimal balance between VR presence and reality awareness on the road by comparing the higher granularity of design dimensions. Therefore, we targeted our concepts within a precise subset of the continuum, between Augmented Virtuality (AV) and Virtual Environment (VE) (see Figure 1).

Among this subset, we developed a VE-driven balance and a RE-driven balance by incorporating different levels of RE into VE for fine-tuning the balance between these two parts. Furthermore, informed by today's passengers' quick and repetitive cognitive switch between mobile screens and outside ride views, we brought this insight into our location-aware in-vehicle VR systems. They were designed to incorporate on-road RE into VE, only when passing specific locations. With this, the location-aware system was expected to help users form continuous spatio-temporal associations with dynamic outdoor environments by displaying just enough location cues, supporting on-road situational awareness without breaking the presence in VR.

Regarding *what* information about on-road RE to incorporate, we used POIs, such as nearby streets or landmarks, which function as real-world location references to increase situational awareness (e.g., seeing the bridge means arriving at the destination at the next cross) [19]. Recent survey research also highlighted important contextual information about external vehicle environments, namely the ability to view the landscape and POIs, for convenient passenger experiences [4]. Concerning *how* this RE information needs to be incorporated into VE, we designed two POI-triggered visualizations, considering the Fidelity and Amount. Regarding the dimension of Fidelity, we designed two levels using *symbolic* text presentation of POIs displaying street names and *literal* real-time representation of POIs showing live street views [20]. Concerning the dimension of Amount [34], we expected showing a *minimum* amount of POIs through text notifications (*POI-Triggered Text*) for a VE-driven balance, maximizing VR presence with just enough on-road situational awareness. In comparison, we expected showing a *partial* amount of POIs through text and live street views (*POI-Triggered Text&Live*) for a RE-driven balance, supporting simultaneous engagement with RE and VE. We adopted the idea of glimpses towards the outside world, referring to the Mirror concept, earlier found supporting periodically checking what's going on around users in the air cabin without disrupting or forcing them to leave the virtual environment during PlaneVR [59]. We note other unobtrusive design alternatives, e.g., mapping a detected gust of wind in the physical world into animated wind effects in virtual gaming environments to avoid real-world distractions and breaks in the presence [56]. Similar metaphoric ambient visualizations have been explored for representing vehicle dynamics during in-car VR. Li et al. [32] explored embedding seagull movements representing vehicle speed and sailboat position representing the journey progress into calming VR experiences. However, such metaphoric notifications were found unrealistic when viewing these computer-animated artifacts in captured 360-degree videos, which are difficult to generalize across different virtual environments. Finally, concerning *where* to place these visualizations, we displayed them on a virtual display in front and slightly above the user's horizontal view, as suggested for alleviating passenger carsickness in the prior work [45].

## 4 METHODOLOGY

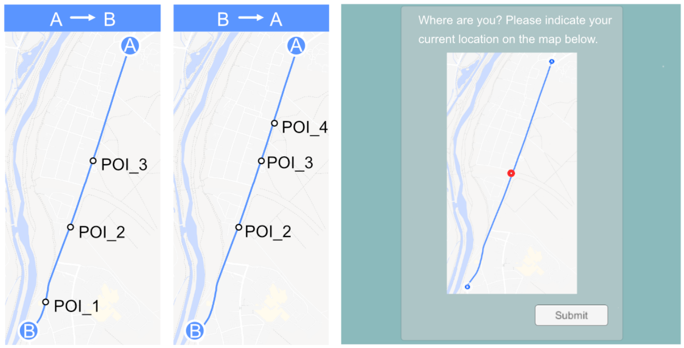
We evaluated our concepts to answer the research question: *"How can we preserve in-car VR users' sense of presence in virtual entertainment environments while maintaining their on-road situational awareness during the ride?"*

### 4.1 Study Design and Task

We designed a within-subject experiment where we compared our concepts and two non-location-aware baselines that represent the endpoints of the targeted AV-VE subset. As the VE baseline, *Always VR* persistently revealed no indications of RE. In contrast, as the AV baseline, *Always Live* persistently incorporated real-time indications of on-road RE (live street views) into VE. During the experiment, users interacted with an in-car VR entertainment system supported by different levels incorporating real-world location references. As the independent variable, we varied this real-world GeoAnchor with four levels along the AV-VE subset (see Figure 1): (a) *Always Live*, (b) *POI-Triggered Text&Live*, (c) *POI-Triggered Text*, and (d) *Always VR*.

To investigate users' situational awareness in real rides, we drove participants in a suburban area with flowing traffic. In particular, the selected ride between A and B (anonymized for review) was about 3 kilometers and 5 minutes. The driving route and the virtual pathway were comparable, given the close-to-straight route configurations in both virtual and physical environments. This also allowed us to use both directions and thus conserve energy for transporting while not sacrificing comparability between rides. We counterbalanced the order of four conditions and two rides (from A to B, from B to A) using a Balanced Latin Square design. Along these two rides, we defined three POIs per ride (see Figure 2 a). We selected a nearby main street and three well-known landmarks, including a bridge, a chapel, and a restaurant. We used two identical POIs (the street and the bridge) in the middle of both rides but a different POI at the end of each ride. With this, we aimed to avoid displaying POIs close to the start of the ride, inducing VR presence at the beginning of each entertainment experience.

The participant's task was to interact with virtual entertainment content and, upon request, estimate their self-location in the ride. For this, we asked participants to indicate their location twice during each condition by asking them: "Where are you? Please indicate your current location on the map below." This question appeared as a pop-up (with the VR entertainment scene paused) first around one-third and then around two-thirds of each ride. Participants were asked to input their estimation via gaze interaction (see Figure 2 b): First, they had to create a red dot on the map by looking at the position they thought they were at and then press a button to confirm their selection, with a dwell time of 0.5 seconds for each step. After completing this task, they resumed interaction with the virtual entertainment scene.




(a) Selected POIs and routes (b) In-VR map task

Fig. 2. (a) The layout of the pre-defined POIs, with three per ride tested in the experiment; (b) The user interface for in-VR map task via gaze interaction.

### 4.2 Apparatus

To realize the POI-triggered mechanism of location-aware in-vehicle VR systems, we implemented a pre-programmed Global Positioning System (GPS) that tracked the vehicle's real-time geospatial location compared to the pre-logged POIs. The exact GPS coordinates and names of the selected POIs were anonymized for review. We used the iOS App GPS2IP[6] to track the vehicle's GPS data, stored in the widely used NMEA GGA format[7]. Then we sent the collected data from the iPhone to the laptop through the client program PuTTY[8] to ensure stable connections. In Unity scripts, the system read the decimal degrees of the real-time vehicle GPS data and compared it to the pre-stored GPS coordinates of the selected POIs. After pilot testing, we defined the threshold of entering a nearby-POI range as 0.0008 degrees in both latitude and longitude (around 80 meters). Therefore, the system triggered the relevant POI notification when the vehicle approached one of the selected POIs. Likewise, we defined the threshold of leaving the nearby POI. When the relative difference was larger than 0.0001 degrees (around 10 meters), the visualizations disappeared, as the vehicle had just passed the given location point.

For the entertainment application, we developed a calming VR experience using the underwater landscape [45], including a variety of low-poly-style sea animals and plants. The borderless virtual scene allows the virtual pathway to be mapped to an arbitrary real-time vehicle direction on diverse driving routes in the future, counteracting motion sickness caused by sensory conflicts [7, 23, 37]. In the center of the interaction area, we used a jellyfish model with a 10-second animation loop to encourage a slow breathing pattern while navigating through the scene [2, 55]. The animation is triggered when the user's gaze follows the jellyfish, with changes in color saturation and emitting particles around. For engagement in VR, we awarded 10 points and added sound effects for completing each 10-second gaze interaction. The collected points were shown in the game view. To simulate this in-vehicle VR entertainment, we set up a Dell G5 laptop (GTX 2070) in the car and ran Unity3D in a Meta Quest 2 (a singular fast-switch LCD display with an 1832 x 1920 per eye resolution, 120 Hz refresh rate, 104° horizontal and 98° vertical field of view), connected to the laptop via a USB cable in link mode. For the audio, we used the headset's built-in speakers. We used one hand-held

[6] http://www.capsicumdreams.com/gps2ip/, last visited April 19, 2023
[7] https://www.nmea.org/content/STANDARDS/NMEA_0183_Standard, last visited April 19, 2023
[8] https://www.chiark.greenend.org.uk/~sgtatham/putty/, last visited April 19, 2023

controller mounted to the car interior to track the vehicle motion and then subtracted these position and rotation changes from the headset. By this, we aim to stabilize the VR scene independent of car movements on the road.

We used a standard four-seater passenger car, Ford Fiesta. To broadcast a live video feed of ride environments, we used a HAMA c600 Pro full HD webcam (1920 x 1080 resolution) and mounted it above the middle dashboard. The webcam's perspective was chosen so that the middle of the frame was pointing toward the front street view. Thus, the frame blended the view out of the front windshield into the virtual scene, offering a broad street view congruent with the driving direction. With this customized implementation of Passthrough, we ensured controllability of the size and position of incorporated ride views across conditions, without unwanted distractions like car interiors and drivers blocking the views.

### 4.3 Dependent Variables

To assess the usability of proposed location-aware in-vehicle VR systems, we measured the following dependent variables: **Geospatial offset**: As a measure of on-road situational awareness, namely how accurately participants knew where they were in the ride, we logged the GPS data of the participant's input and the vehicle's real-time location when each in-VR map task was triggered and displayed. Based on these two GPS coordinates saved in a Unity log file, we then took the great circle distance using the haversine method as the geospatial distance between them, which we refer to as geospatial offset. **Dwell time in reality**: This was the total time users spent on an area of interest in the incorporated on-road RE. In Unity, we logged the dwell time when participants looked at the interfaces of text and/or live video feed when they were present. Therefore, this measurement did not apply in the *Always VR* condition. **Dwell time in VR**: The total time users spent on the interaction area during VR entertainment. Likewise, we logged the dwell time in each condition when participants looked at the interactive area around the jellyfish. **Perceived workload**: After each condition, we used the NASA-Task Load Index (TLX) as a measure of mental demand, physical demand, temporal demand, performance, effort, and frustration [21]. **Presence**: We used the IPQ presence questionnaire as a measure of general presence, spatial presence, experienced realism, and involvement in VR [51]. **Situational awareness, VR experience, and user preference**: Finally, we defined nine questions using a 5-point Likert scale to ask participants about their experiences regarding how easy it was to locate themselves in the ride, how easy they could focus in VR, and how useful the system was in each condition.

### 4.4 Procedure

Before the study, we pre-screened participants based on the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-S [6]) and only invited those with a MSSQ raw score lower than 30.4, the 95% percentile, who are less prone to motion sickness. On-site, the experimenter explained the study goal of testing passengers' situational awareness. After giving their consent, participants were helped to sit in the car back-row, behind the co-driver seat. After filling out a demographic questionnaire, participants were driven by the experimenter in a test round, including both rides, without wearing headsets, to familiarize themselves with the selected streets and POIs. During this test round, the experimenter introduced the route information with explicit reminders of the selected POIs and the map task interface via printouts (see Figure 2) in both directions. When the car was parked, participants were instructed to wear the VR headset and interact with the underwater scene via gaze. Participants were given the opportunity to try the gaze interaction in the headset and ask questions concerning the study task.

Next, the study started with the assigned order of GeoAnchor conditions. After each ride, when the car was parked, we asked participants to take off the headset and fill out the questionnaires about the experience condition. Finally, after experiencing four conditions, participants were interviewed about their overall thoughts and suggestions for mobile VR interaction on the road. Each participant was compensated 25 € for the 2.5-hour study, six rides in total. The study setup and procedure were approved by the local ethics review board (anonymized for review).

### 4.5 Participants

Through online advertisements, we recruited 17 participants (10 female, 7 male) aged between 21 to 59 years ($M = 28, SD = 9.5$). Four participants had no prior VR experiences. Eleven used VR headsets less than once per year, one person used the headset weekly, and one used it daily. Their commonly used headsets were Meta Quest and HTC Vive. More than half traveled as car passengers daily (n=3) or weekly (n=7), with each ride lasting from 30 minutes to 2 hours (n=14).

### 4.6 Analysis

For parametric data, we used a one-way repeated measures ANOVA. We tested the data for normality using Shapiro-Wilk's test. The analysis showed that all measures violated normality (all $p \leq .016$) except the measures of IPQ presence ($p = .165$) and its sub-scales of spatial presence ($p = .101$) and involvement ($p = .081$). In cases where Mauchly's test indicated a violation of the assumption of sphericity, we corrected the test with Huynh-Feldt epsilon corrections (when $\epsilon > 0.75$) or Greenhouse-Geißer correction (when $\epsilon < 0.75$). For post-hoc tests, we used Bonferroni correction. For non-parametric data, we performed an Aligned Rank Transformation as proposed by Wobbrock et al. [10, 60] with Holm post-hoc tests for the measure of geospatial offset concerning the two influencing factors of the conditions and the temporal order of the map tasks in each ride. For all other measures, we applied non-parametric test procedures; we used Friedman tests with Wilcoxon signed-rank test. We further reported the eta-squared $\eta^2$ as an estimate of the effect size. Statistical significance is reported for $p < .05$.

## 5 RESULTS

### 5.1 Geospatial Offset

We discovered that the temporal order of in-VR map tasks influences participants' accuracy in their estimation of self-location during each ride, independent of the GeoAnchor condition. The mixed factor align-and-rank ANOVA showed a significant ($F(1, 16) = 34.83, p < .001, \eta^2 = 0.685$) main effect for the temporal order of map tasks with a large effect size. Post-hoc tests confirmed a significantly larger geospatial offset in the second map task than the ones in the first map task ($p < .001$). Figure 3 (left) depicts the distribution of these two trials. However, we found no significant effect for GeoAnchor ($F(3, 96) = 0.685, p = .564, \eta^2 = 0.021$) and neither interaction effects ($F(3, 96) = 0.403, p = 0.751, \eta^2 = 0.012$).

### 5.2 Dwell Time

We found that participants spent more time looking at on-road RE when the live video feed was provided during the virtual experience. The Friedman test showed a significant ($\chi^2(3) = 35.6, p < .001, W = 0.699$) influence of GeoAnchor on how long participants focused on the real-world location references with a large effect size. Post-hoc tests confirmed that participants looked at the incorporated RE significantly longer when the live video feed was presented in the *Always Live* ($p = .003$) and *POI-Triggered Text&Live* ($p = .01$) conditions, as compared to the *POI-Triggered Text* only. Figure 3 (right) shows the distribution of the three conditions incorporating RE into VE. Meanwhile, we found no

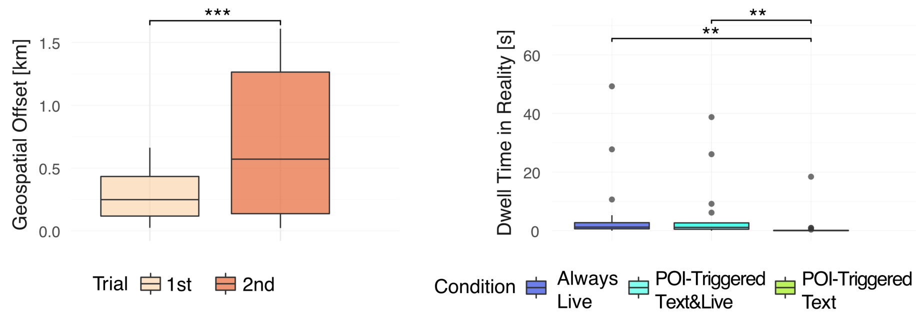



Fig. 3. The significant differences in the geospatial offset between the temporal order of in-VR map tasks (left) and the dwell time on transit visual cues across conditions (right). $*$ denotes $p \leq .05$, $**$ denotes $p \leq .01$, $***$ denotes $p \leq .001$.

significant differences regarding the dwell time in VR between all four conditions ($\chi^2(3) = 4.55, p = .208, \eta^2 = 0.893$). Table 1 shows the descriptive statistics.

### 5.3 IPQ Presence

The results showed that having constant live video feeds of on-road RE in the view degraded the VR presence. The one-way repeated measures ANOVA showed a significant influence of GeoAnchor on the overall presence ($F(3, 48) = 4.93, p = .005, \eta^2 = 0.066$). Participants felt significantly less immersed in VR entertainment when having a constant view of live street views in the *Always Live* condition, compared to having no RE indications in *Always VR* ($p = .027$) or viewing live street views only when passing specific locations in *POI-Triggered Text&Live* ($p = .034$), as indicated by post-hoc tests. The sub-scale of spatial presence mirrored the results ($F(3, 48) = 2.81, p = .049, \eta^2 = 0.046$). Post-hoc tests indicated that participants felt a significantly heightened sense of being physically present in the virtual entertainment scene when receiving location-aware text descriptions and live street views in the *POI-Triggered Text&Live* condition compared to the *Always Live* condition ($p = .043$). Likewise, the analysis confirmed significant differences in the sub-scale of involvement ($F(3, 48) = 5.12, p = .004, \eta^2 = 0.101$). Post-hoc tests showed significantly reduced involvement in VR entertainment when participants received constant live indications of RE in *Always Live*, compared to no indications at all in the *Always VR* condition ($p = .036$). Figure 4 depicts the distribution of significant results. The Friedman test showed no significant differences in other sub-scales (all $p \geq .059$).

### 5.4 NASA-TLX Workload

We analyzed the Raw NASA-TLX (RTLX) and found comparable workloads between conditions. The Friedman test showed no significant effect for GeoAnchor on the overall perceived workload and six sub-scales (all $p \geq .098$). Table 1 depicts the descriptive data.

### 5.5 Questionnaire

After each condition, participants answered our self-defined questions regarding their experiences on a 5-point Likert scale (1: strongly disagree, 5: strongly agree). Figure 5 depicts all the significant results of participants' ratings, while Table 1 shows the descriptive data for the other comparable ratings.

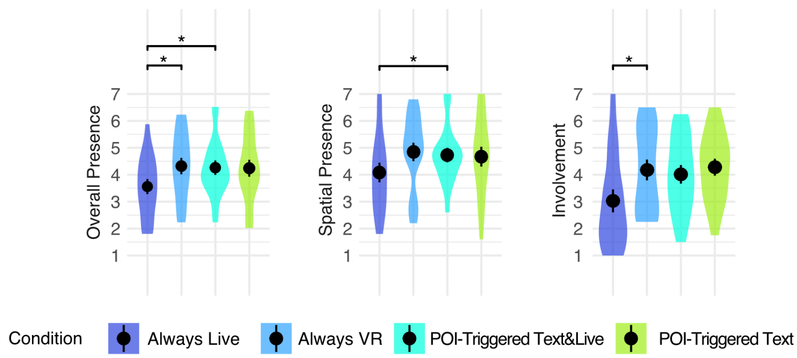



Fig. 4. The distribution of the significant results in the IPQ presence questionnaire. $*$ denotes $p \leq .05$.

Table 1. Means and standard deviation of the task performance and questionnaire results, with statistical testing results. $^{\triangle}$ for geospatial offset and IPQ, we report the ANOVA results F-statistics and $\eta^2$.

| | **POI-Triggered Text&Live** | | **POI-Triggered Text** | | **Always Live** | | **Always VR** | | **Friedman Test** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measure** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | $\chi^2$ | $df$ | $p$ | $W$ |
| Geospatial Offset [km] | 0.42 | 0.48 | 0.54 | 0.48 | 0.46 | 0.42 | 0.51 | 0.46 | 34.83$^{\triangle}$ | 16 | <.001 | 0.685 |
| Dwell Time in Reality [s] | 5.42 | 10.69 | 1.22 | 4.44 | 6.36 | 12.95 | n/a | n/a | 35.6 | 3 | <.001 | 0.699 |
| Dwell Time in VR [s] | 153.7 | 43.44 | 163. | 45.23 | 155.24 | 32.61 | 166.87 | 35.45 | 4.55 | 3 | .208 | 0.089 |
| IPQ | 4.1 | 1.11 | 4.08 | 1.3 | 3.4 | 1.15 | 4.16 | 1.25 | 4.93$^{\triangle}$ | 48 | .005 | 0.066 |
| NASA RTLX | 23.28 | 20.87 | 20.29 | 20.64 | 26.81 | 24.61 | 23.24 | 23.24 | 1.85 | 3 | .604 | 0.036 |
| Motion Sickness | 1.24 | 0.44 | 1.47 | 1.01 | 1.18 | 0.39 | 1.18 | 0.39 | 1.94 | 3 | .585 | 0.038 |
| Task Confidence | 3.59 | 0.94 | 3.71 | 0.77 | 3.53 | 1.33 | 3.47 | 1.01 | 1.55 | 3 | .671 | 0.03 |
| Convenience | 3.82 | 0.95 | 4.18 | 0.95 | 3.76 | 0.97 | 3.82 | 0.95 | 4.33 | 3 | .228 | 0.085 |
| Easy to Aware | 2.82 | 1.24 | 2.65 | 1.06 | 3.12 | 1.5 | 2.71 | 1.16 | 1.8 | 3 | .615 | 0.035 |
| User Preference | 3.12 | 1.11 | 3.18 | 1.33 | 2.82 | 1.33 | 2.82 | 1.24 | 3.38 | 3 | .337 | 0.066 |

*5.5.1 Easy to Locate and Identify.* We asked participants if identifying their self-location during the ride was easy. The Friedman test showed a significant influence of GeoAnchor ($\chi^2(3) = 11.9, p = .008, W = 0.234$). While compared to all other conditions ($2.82 \leq M \leq 3.18$), we found lower ratings for *Always VR* ($M = 2.06, SD = 2$) in which participants received no indications of RE throughout the ride, the post-hoc test did not show significant differences. Further, the analysis showed significant differences in their ratings of how easy it was to identify changes in their ride environments ($\chi^2(3) = 13.2, p = .004, W = 0.259$). Post-hoc tests confirmed significantly higher approval for keeping a continuous window to the outside fast-changing environments in the *Always Live* condition as compared to *Always VR* ($p = .034$). Figure 5 (left two) depicts these results.

*5.5.2 Focus and Confidence in VR Entertainment.* We asked participants if they were able to focus on the virtual entertainment environment. The analysis indicated a significant effect for the GeoAnchor factor ($\chi^2(3) = 13.3, p = .004, W = 0.261$). While compared to all other conditions ($4.18 \leq M \leq 4.35$), we found lower ratings for the *Always Live* ($M = 3.35, SD = 1.17$) in which live street views were continuously visible in the primary interaction area, post-hoc tests did not confirm significant differences. The significance was mirrored in the participants' ratings of how confident they

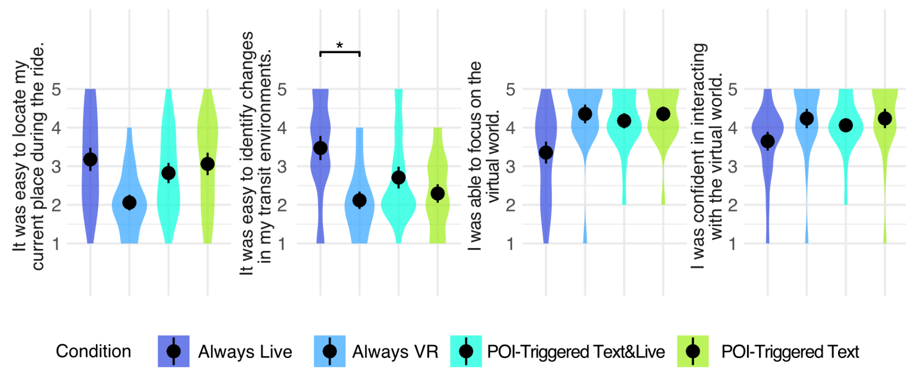



Fig. 5. The participants' answers to our self-defined questions using a 5-point Likert Scale (1: strongly disagree, 5: strongly agree). ∗ denotes $p \leq .05$.

were while interacting with the virtual entertainment scene ($\chi^2(3) = 10.5, p = .015, W = 0.206$). Likewise, compared to all other conditions ($4.06 \leq M \leq 4.24$), while we found lower ratings for *Always Live* ($M = 3.65, SD = 1$), post-hoc tests did not show significant differences (see Figure 5 right two).

*5.5.3 Motion Sickness, Task Confidence, Convenience, Easy to Aware, and Preference.* We asked if participants felt motion sickness while using the in-car VR systems, and they reported comparable disapproval in all conditions ($p = .585$). On average, participants self-reported a moderate level of confidence in the map tasks without significant differences between conditions ($p = .671$). Likewise, they hold neutral opinions when evaluating if the system was convenient to use, with comparable ratings in all conditions ($p = .228$). Additionally, they reported limited approval when asked if staying aware of their ride environments was easy, with comparable differences between conditions ($p = .615$). Finally, while participants' rankings on average indicated a slightly higher preference for the *POI-Triggered Text* and *POI-Triggered Text&Live* conditions than the non-location-aware baselines, we found no significant differences between conditions ($p = .337$). Table 1 depicts the descriptive statistics.

### 5.6 Interview Feedback

In the final interview, we asked participants to describe why they liked or disliked a RE cue. We followed a thematic analysis [5] to code the participant's subjective comments. The identified themes are illustrated below with participants' representative quotes under their IDs. The authors translated all quotes from the participant's mother tongue to English.

When receiving no indications in the *Always VR* condition, participants could better focus and immerse themselves in VR but lacked on-road situational awareness, e.g., *"I did not have a feeling about how far on the route we had already driven"* (P2) and *"really did not know what was going on"* (P10). *POI-Triggered Text* seems to be our participants' most preferred in-car VR system, as it conveyed succinct yet informative messages of the real-world location. Particularly in familiar rides, the text message offered enough information as *"if it's the way to work, there aren't any exciting things happening"* (P22). Likewise, in new rides where street views are unfamiliar to passengers, the text description is more self-explanatory than the video, e.g., *"I don't get a better orientation despite the picture"* (P1). This just enough amount of information also enabled better concentration in VR for some participants, e.g., *"I could play very well, and I knew approximately where I was"* (P12).

However, participants had different opinions when both text and video cues were present in VR. Regarding new rides, some participants found the *POI-Triggered Text&Live* system easier to orient in unfamiliar places when they *"did not know the streets so well"* (P4). Furthermore, the video presentation was favored over text as *"it did not need to be read"* (P8, P11, P17). Overall, *POI-Triggered Text&Live* introduced few interruptions during VR entertainment but still provided *"some of the surroundings"* (P2, P10). Finally, in the *Always Live* condition, more than half of the participants (9/17) found the constant live video feed of street views in the underwater scene *"confusing"* (P1) and made them feel *"lost"* (P10) or even *"irritating"* (P13). Further, they *"could not concentrate on the game"* (P5) as they *"watched the video for half of the time"* (P12) and *"felt disconnected from the virtual scene"* (P14). Still, some participants liked this continuous window to the outside fast-changing ride environments, which *"could mentally prepare me for breaks"* (P15) and *"ease the hard time when I do not know where I am"* (P17).

## 6 DISCUSSION

Our results suggest that the mobile use of immersive VR applications on the road progressively reduces users' situational awareness over time. To address this, incorporating constant live video feeds of street views can efficiently re-direct user attention back to the road but reduce their VR presence simultaneously. In contrast, the location-aware incorporation of ride environments only *when* passing specific locations preserves VR presence. Meanwhile, how much VR users' attention is redirected to reality depends on the granularity design of visualization Fidelity and Amount.

### 6.1 Incorporating Live Indications Into VR Ensures User Attention to the Road

We discovered that adding the live-video presentation of users' situated on-road environments into the virtual experience helps maintain their attention on the road, independent of its Availability, either provided persistently or only when passing by specific locations during the ride. Moreover, participants' ratings indicate that having such a constant live window towards outside ride environments in headsets facilitates identifying their self-location and especially changes in their situated transport context during VR entertainment. In line with prior research for domestic VR [57], we suggest incorporating live video feeds of RE into VR, revealing full details of the user's surrounding area of interest and physical environment, for an efficient cognitive switch from VR to the physical world. Notably, this high-Fidelity incorporation only applies in scenarios when the in-vehicle VR system needs to prioritize reality awareness immediately over VR presence, like emergent transport events, for a RE-driven balance.

### 6.2 Constantly Revealing Full Details of On-Road Environments Is a Deal-Breaker for VR Presence

While persistently adding the live video of on-road RE increases users' perceived situational awareness, it largely breaks their sense of presence in VR. Our participants reported that seeing fast-changing street views constantly in the virtual scene hinders their focus and confidence in VR interactions (cf. Figure 5). Further, participants' ratings indicate unpleasant interactions when having *Always Live* indications of RE constantly visible in the primary interaction area in VR. It is unexpected as prior work found that users favor such high Fidelity indications to increase reality awareness of nearby interactive objects without negative impacts on their feeling of presence in domestic VR contexts [22]. We attribute this discrepancy to the distinct nature of real-world stimuli from outdoor environments compared to indoors. In particular, the live video feed of room-scale REs often incorporates static and personal objects in users' close surroundings [1, 29]. In contrast, live video feeds of on-road REs involve an unpredictable and considerable amount of variation and information carried along the way. While revealing users' surrounding live street views in VR, these live video feeds also incorporate frequently moving and less related elements on the road, such as other passing-by vehicles.

These distinct and complex RE stimuli in transport contexts challenge conventional incorporation strategies' sensitivity to spatio-temporal context awareness previously limited to detecting small-scale changes during VR interaction indoors.

### 6.3 Gradual Incorporation of Real-World Cues Depending on Spatio-Temporal Association

When comparing two implemented ways of incorporating live videos, we discovered that showing them only when passing by specific locations ensures users' sense of presence in VR while maintaining attention to their reality. Moreover, such location-aware systems allow pleasant interactions, as indicated by participants' preference ratings. These findings imply that the optimal availability, or *when* to incorporate on-road environments into VR, depends on the given transport state [34]. For example, constantly showing live videos of on-road environments when approaching arrivals can help users mentally prepare to get off by diverting their attention efficiently to their situated ride environments. However, the same live video incorporation halfway through the ride without any spatio-temporal association with users' surroundings can disturb the sense of presence and lead to uncomfortable VR experiences. Underlining the concept of seamless transitions between realities [18], we envision in-vehicle VR systems to embrace dynamic incorporation strategies varying along the ride, depending on users' spatio-temporal association with the physical world. For example, indications of on-road REs can evolve from *Always VR* halfway in the ride to *POI-Triggered Text&Live* notifications a couple of minutes before the arrival to a constant *Always Live* streaming shortly before the ride end, gradually transitioning users' presence from the virtual world and guiding their attention back to the road. Incorporating real-world cues from dynamic outdoor environments into VR requires considering users' spatio-temporal association with the physical world to maximize VR presence as long as possible while supporting situational awareness at the right moment.

### 6.4 Temporal Factors Challenge Research on Situational Awareness during Mobile VR on the Road

Over time in VR, our participants lost track of where they were and performed worse at identifying accurate self-location along the way (cf. Figure 3 Geospatial Offset). Their rankings also support this finding. Staying aware of transit environments during VR interactions in all conditions was challenging (cf. Table 1 Easy to Aware). From this, we emphasize that the challenge of situational awareness of real-world stimuli from dynamic outdoor environments is an essential supplement to the previously identified challenges limited to the indoor cabin space [35, 38], empowering mobile users to know what is going on around them inside the vehicle, as well as on the road.

When addressing this issue, however, our results indicated that adding POI cues into VR did not provide sufficient support for situational awareness. This contradicts the prior work that successfully enhanced awareness of surrounding objects and people in close surroundings following this incorporation approach [27, 31, 34]. From this, we speculate that revealing full details of the "current" POI does not suffice for successive situational awareness of fast-moving outdoor environments. In line with situational awareness in transportation research [9, 11], we suspect revealing additional intention information, e.g., displaying both "current" (perception and/or comprehension) and "following" (prediction) POIs, might improve on-road situational awareness with accurate self-location. Besides, in our field experiment, each ride only lasted around five minutes, which could limit the elicitation of VR presence. We speculate that our experiment had a ceiling effect; namely, participants' situational awareness was impaired yet not as sufficient as to disclose any significant impacts of the implemented POI cues. Future research is needed to test these assumptions considering temporal factors in experiment setups, including the sequential incorporation of multiple on-road views and the effective elicitation of degraded situational awareness.

## 7 LIMITATIONS AND FUTURE WORK

We are convinced that our results offer an important contribution to the future development of awareness support for in-vehicle VR experiences. However, our study design and results imply limitations and directions for future work, which we discuss below.

### 7.1 Other Transportation

In our experiment, we focused on providing situational awareness for in-car settings. However, other contexts of use in other means of transport such as trains and airplanes [52, 59] impose other requirements. Regarding the controllability of traffic environments, an airline or a train railway is more controlled than a car ride. Therefore, the POIs along the way can be standardized and fixed according to the given public transport route, using in-between station names. Thus, we assume displaying location in the text (a nearby city name) can suffice in public transit, while a video (passing by an in-between train station) can be unnecessary and even degrade VR presence. More critically, in these public transit, awareness of other people in shared spaces [1, 41] changes user preference regarding how external transit environments are incorporated and positioned in virtual environments. Prior work exemplifies how VR users adjust their virtual content layout to avoid colliding with the personal space of other passengers [43]. Future research needs to test multiple presentations and multi-user environments, extending location-aware VR systems from cars to other everyday transportation.

### 7.2 Other Triggers

In the presented experiment, we focused on POI-triggered incorporation as support for situational awareness. While we found promising results, future studies need to compare this to different trigger mechanisms of transitional interfaces between realities. For example, let users snooze all notifications until a specific location [58] or intermix reality based on their engagement needs [34], e.g., remind me to save and stop the game when approaching the final 100 meters.

### 7.3 Other Visualizations and Technical Improvements

We systematically considered, e.g., the presentation [20] with double encoding in symbolic text and literal video, the placement closely above the horizon [45] (cf. Section 3). Future studies can explore other visualizations, such as providing discrete 2D snapshots of POIs in a given time interval instead of constant live videos, as well as other placements, e.g., attached to the headset, which can influence the system's efficiency and effectiveness [29, 50, 57]. Besides, we only tested the fixed camera perspective from the front windshield. Future studies can investigate how other perspectives, e.g., side window views, panorama views, and 360-degree live street views, impact situational awareness and VR presence. Although our participants reported limited motion sickness, future studies can improve the technical setup for minimum latency between the physical and virtual environments [39].

## 8 CONCLUSION

In this paper, we investigated how location-aware in-vehicle systems can support users' on-road situational awareness and preserve VR presence. We designed two visualizations using POIs along the ride, street names alone or combined with live street views. In a field study (N=17), we comparing them to two baselines that persistently show live indications of RE or no indications at all during in-car VR entertainment. We discovered that adding any indications of on-road RE into virtual entertainment experiences decreases users' presence in VR. In particular, the *Always Live* indications revealing full details of areas of interest and surrounding environments guide users' attention to reality but degrade VR presence. *POI-Triggered Text* preserves the presence, but users spend less time on the incorporated ride views. In contrast, *POI-Triggered Text&Live* attracts user attention to outdoor environments and preserves VR presence at the same time. With our work, we contribute the first step toward realizing and addressing the challenge of on-road situational awareness during mobile VR interaction in everyday transport contexts. In particular, we propose considering mobile users' spatio-temporal association with dynamic outdoor environments when incorporating real-world cues into VR. Furthermore, we emphasize the research challenge concerning temporal factors in field experiments for future research on mobile VR interaction on the road.

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# SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality

JINGYI LI, LMU Munich, Germany
HYERIM PARK, LMU Munich, Germany
ROBIN WELSCH, LMU Munich, Germany
SVEN MAYER, LMU Munich, Germany
ANDREAS BUTZ, LMU Munich, Germany

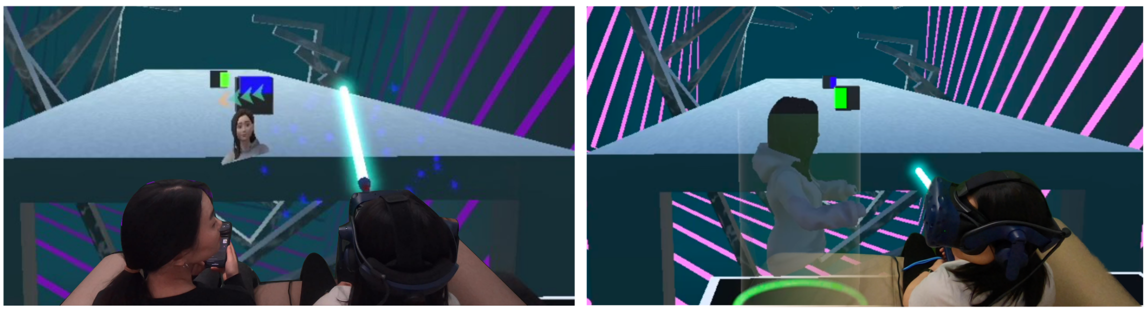

Fig. 1. During seated VR games, the *Mixed* visualization prepares users for fast communication with close-space bystanders: first showing an *Animoji* (left) in the player's view when the seatmate starts turning toward the player to initiate a conversation, and then transitioning to an *Avatar* (right) that shows the physical location of the seatmate who is looking toward the player.

While prior work investigated how virtual reality users can be alerted to bystanders entering their physical space, it is unclear how to foster awareness of people in close proximity, such as a seatmate on a sofa or in a car. We introduce three visualizations using a 2D animoji, a fully-rendered avatar, and their combination, allowing virtual reality users to communicate with their seatmates. We conducted an experiment (N=22) where participants played a virtual reality game while responding to questions of a seatmate. Our results show that the *Avatar* is unobtrusive, not covering the primary view, yet does not support fast identification of the seatmate's orientation as the *Animoji* does. Instead, users prefer our *Mixed* design, where they find orientation cues in their view and are guided to the seatmate's location. We discuss our results in terms of proxemics and highlight implications for interactions across everyday social spaces, including multi-user environments.

CCS Concepts: • **Human-centered computing → Virtual reality**.

Additional Key Words and Phrases: bystander awareness, proxemics, close space, seated virtual reality

Authors' addresses: Jingyi Li, LMU Munich, Munich, 80337, Germany, jingyi.li@ifi.lmu.de; Hyerim Park, LMU Munich, Munich, 80337, Germany, hyerim.park@campus.lmu.de; Robin Welsch, LMU Munich, Munich, 80337, Germany, robin.welsch@um.ifi.lmu.de; Sven Mayer, LMU Munich, Munich, 80337, Germany, sven.mayer@ifi.lmu.de; Andreas Butz, LMU Munich, Munich, 80337, Germany, butz@ifi.lmu.de.


Manuscript submitted to ACM

**ACM Reference Format:**
Jingyi Li, Hyerim Park, Robin Welsch, Sven Mayer, and Andreas Butz. 2023. SeatmateVR: Proxemic Cues for Close Bystander-Awareness in Virtual Reality. 1, 1 (January 2023), 18 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

## 1 INTRODUCTION

Virtual Reality (VR) technology empowers users to immerse themselves in virtual environments and thus, disconnect them from the physical world [36]. To keep users aware of their physical surroundings, advanced VR systems can detect and incorporate proxemic cues [12] of surrounding areas of interest into the virtual world, e.g., showing the position and orientation of bystanders in a top-down radar view [18]. Today's solutions focus on situations where bystanders enter or leave the room or game space and depict a change in distance from far (4 m) to close space (1 m) around users [18, 28]. However, as VR headsets permeate into contexts with limited space, such as at home [6] or on the go [35, 42], interactions with bystanders occur in close space, often without physically repositioning. Thus, the question arises, how can we can foster awareness of the close-space bystander while keeping users engaged in the VR environment?

For supporting bystander awareness in far-space interactions, several solutions have been evaluated, leveraging the proxemic changes in surrounding people, e.g., distance [38], location and orientation [18], and body movements [28]. However, in interactions with bystanders in close proximity, such as a seatmate sitting next to users, where *Distance* [8] does not change substantially, other proxemic cues, especially orientation, gain importance as a social signal [1]. Moreover, research in psychology and neuroscience showed that social interactions in close-space (often referred to as personal space or peri-personal space) entail different neuronal and psychological mechanisms than interactions in far-space (i.e., extrapersonal space) [4, 19, 27]. Therefore, it is unclear how the existing proxemic cues in far-space interactions will hold true to provide enough information about a seatmate's behavior and intention without disturbing VR experiences.

With this, our work focuses on close-space interactions between the VR user and bystander. In more detail, this paper first proposes three visualizations to overcome the drawbacks of far-space interactions concerning the limited visualization and interpersonal spatial scales, which we evaluate in a second step. Building upon the success of prior work, we added proxemic cues of close-space bystanders' orientation and location, and incorporated these as seatmates' social signals into VR. We designed and evaluated three Visualization concepts: (1) a 2D *Animoji* appears in a head-up display, attached to the headset, (2) a fully-rendered *Avatar* pops up at the edge of the players' field-of-view and then guides them to the side, the seatmate's actual location, and (3) a *Mixed* version of both, which first shows an animoji within the player's view and then leads them to the seatmate side. In a lab study (N=22), we investigated their usability and compared them to a *Baseline* that showed no indications. In the evaluation, participants played a VR game on a couch while sitting next to another person (seatmate). During the game, the seatmate tried to grab the VR player's attention and asked questions.

Our results show that an *Avatar* did not support fast identification of the seatmate. A constantly in-view *Animoji* grabbed the user's attention but did not support locating the seatmate in physical space. In contrast, a *Mixed* visualization allowed for pleasant interactions where users efficiently noticed the seatmate's presence and were directed to the actual location, fostering communication. Based on the results, we further discuss the usage of close-space bystanders' proxemic cues. We highlight implications for VR interactions in everyday social contexts across spatial scales and the number of users. The main contributions of our work are 1) extending the single representation of bystanders from far-to close-space interactions, 2) exploring continuous visualizations of bystanders' changes in proxemic dimensions, and 3) closing the research gap of close bystander awareness, fostering VR interactions in dynamic social spaces.

## 2 RELATED WORK

Below, we review literature grouped into two categories: bystander awareness and proxemic interaction in VR research. We highlight two research gaps that guide our work, the lack of continuous bystander visualizations and the lack of study context in close-space interactions.

### 2.1 Bystander Awareness in VR Systems

VR is increasingly used in a wide range of contexts from mental health [17, 29, 37] to entertainment [5, 14, 30]. Immersive virtual environments offer the sense of presence, the feeling of "being there" [36], and even social presence, the "sense of being together with another" [31]. However, VR often disconnects users from their physical surroundings, which challenges their awareness of surrounding objects and other people. Recent experimental feature Space Sense[1] of Meta detects any object, person, or pet that enters the guardian space and visualizes them with ghostly figures shown at their actual locations throughout the game. However, it can disturb VR presence when the surroundings keep moving into the player's view or become difficult to notice when the changes happen outside the view.

Prior studies investigated the awareness of other people in shared and social spaces. For example, von Willich et al. [38] found an avatar visualization of passersby positions was the fastest and the most accurate representation compared to a more literal 3D-scan and a more abstract 2D-image representation. Likewise, Kudo et al. [18] found an avatar situated in the 3D virtual environment was easy to identify when the bystander changed their location and orientation to chat with VR users. In contrast, a symbolic icon separated from the virtual environment but always displayed in the player's view prioritized VR presence when a bystander was there but showed no interest in users. Recently, Rettinger et al. [28] developed an avatar that visualized the bystander's positions and movements of the arm, finger, and head, which increased awareness but introduced more cognitive workload that disturbed VR experiences. Most bystander visualizations use a single representation, either 2D icons or 3D avatars [18, 38], at the cost of either slow and inaccurate bystander awareness or degraded engagement in VR. A continuous visualization [18] with multiple representations has the potential to balance both yet remains under-explored, e.g., how to gradually adapt the detail level of visualizations according to the amount of bystanders' interest in VR users.

### 2.2 Proxemic Interaction in Virtual Environments

Proxemics, the science of how humans use space [11], is important to social VR. In anthropology, Hall et al. [11] defined *proxemics* with four main zones of interpersonal distance: 1) intimate distance (touching - 0.46 m), 2) personal distance (0.46 m - 1.22 m), 3) social distance (1.22 m - 2.40 m), and 4) public distance (>2.40 m) from observing human-human interactions. Based on the work of Bailenson et al. [1] on proxemics in virtual spaces, the concept of personal space has been further refined by Hecht et al. [13] to be a circular region with a radius of 1 m, in which humans maintain invisible boundaries to other people, avoiding intrusion and consequent discomfort [40]. Note that while interactions outside of this personal space, also referred to as far space, especially gaze and location are particularly important for both virtual and physical spaces [12, 13, 40], close-space interactions use other proxemic cues, such as the orientation of the head, arms, and torso as social signals [12]. Therefore, it becomes apparent that proxemic cues are differently used for close

[1] https://vrscout.com/news/oculus-quests-space-sense-feature-detects-people-and-pets/, last accessed January 23, 2023

and far interactions between humans. The concept of proxemics has also been used to design human-machine interfaces. Ballendat et al. [2] proposed using proxemics as a means of input for devices in ubiquitous environments under the term *proxemic interaction*. Greenberg et al. [8] have refined this concept and put forth five dimensions of proxemic relationships including *Position*, *Orientation*, *Movement*, *Identity*, and *Location* for proxemic interactions. Others put this concept to use by utilizing *F-formations* which combine distance and relative body orientation among multiple users, such as *side-to-side* to enable co-located collaboration [21, 32].

Lately, various researchers have applied proxemic interaction in VR when studying bystander-aware systems. O'Hagan and Williamson [25] explored different reality-aware behaviors of VR HMDs and found that automatic communication of bystanders' co-existence in a shared physical room through notifications but without the position information caused uncomfortable user experiences. Further, Medeiros et al. [24] identified a strong user preference for maintaining VR presence while keeping receiving notifications that evolve dynamically according to the changing distance between users and bystanders in the room. These solutions mainly examined the proxemic relationship between VR users and the bystanders in far-space interactions beyond users' personal space (>1m) [13], such as a bystander walks up to a user to initiate an interaction [13, 15, 40]. However, it is unclear which proxemic cues are relevant for visualizing bystanders in close-space interactions (<1m). Here, proxemic cues of *Distance*, *Location*, *Movement* and *Identity* between VR users and non-VR users remain unchanged as the interaction between them unfolds. Other cues, such as the user's orientation, are focal in close-space interactions [11, 12]. When a seated bystander wants to interact with the user sitting side-to-side, they will shift their upper body towards the other person, effectively changing their body *Orientation* to indicate interest and start a conversation [21, 32]. As exemplified by the work of Williamson et al. [42], which showed how users and close bystanders react to using VR on a plane, the side-to-side physical spatial arrangement poses a particular challenge for the use and adoption of VR during close-space interactions.

### 2.3 Summary

In sum, we built our work on human-human proxemics, proxemic interaction, and visualization design for bystander awareness in VR. We extended the existing uni-representation visualizations for bystander awareness from far- to close-space interaction. We also explored the design of proxemic cues using continuous visualizations and multiple representations. Particularly, we focus on the challenging design for *side-to-side F-formations* [21, 42] to identify suitable dimensions of proxemic cues and their corresponding visualization designs to provide just enough information without degrading VR experiences.

## 3 CONCEPT

In this paper, we investigate close bystander awareness in VR with visualizations that depict proxemic cues of the seatmate. We envision a system that can display a sequence of *Orientation* cues of the seatmate, with a *side-to-side* range from looking to the side in the VR users' direction to the opposite side (i.e., from 0° to 180°, where 90° means looking straightforward), see Figure 2 top row. This information on *Orientation* should be represented in VR to show users when the seatmate wants or does not want to interact. To guide the visualization design, we divided the *side-to-side* range into four zones: (1) no interest (180-90°), e.g., the seatmate focusing on own activities; (2) slight interest, e.g., wondering what the VR user is doing (90-60°), (3) potential interest (60-30°), e.g., uncertain to interrupt or not, (4) interest (30-0°), e.g., ready to interrupt and talk to VR users based on proxemics literature [11, 12]. Next, following Kudo et al. [18], we adapted the two successful far-space visualizations, 2D icons, and 3D avatars, to our close-space context. With their combination, we created a continuous visualization, using a *Mixed* version of both animoji and avatar representations,

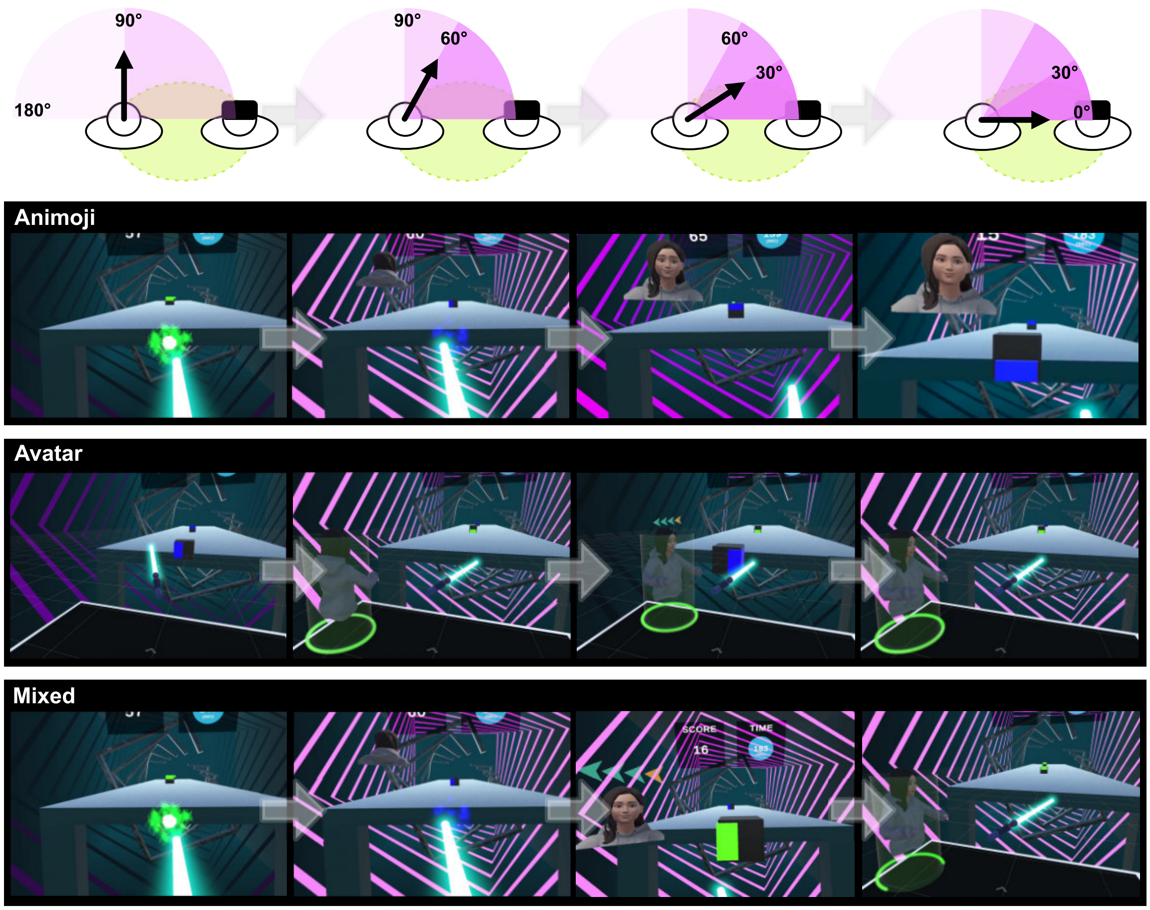


Fig. 2. From left to right, the animation design of proxemic cues follows the four orientation zones in the *side-to-side* spatial arrangement. From top to bottom, three visualization concepts, *Animoji*, *Avatar*, and *Mixed*, as tested in the experiment.

which was expected to enable fast and accurate bystander awareness while preserving VR engagement [18]. Figure 2 shows an overview of the three concepts along the four orientation zones. Below, we detail how these three concepts vary along the *side-to-side* range, following the four defined zones:

*Animoji.* This visualization is inspired by the symbolic representation using 2D icons showing the *Distance* changes of the bystander in far-space interactions [18]. They are separated from the actual location of the bystander and always displayed within the field of view to increase awareness efficiently [33]. Likewise, we designed an animated emoji to display the changes in the seatmate's *Orientation* in *side-to-side* close-space interactions. The animation follows the seatmate's orientation in four zones, showing (1) from a 100% transparent back of animoji to indicate no interest, (2) fading in the solid back of animoji to indicate slight interest, (3) turning to the front face to indicate potential interest to interrupt, and (4) smiling to users to indicate interest to interact.

*Avatar.* This visualization is based on the literal representation using 3D avatars, showing the *Distance* changes of the bystander in far-space interactions while situated in the actual location of the bystander [18]. Likewise, we adapted the concept to side-to-side setups and designed an animated 3D avatar, with a similar appearance to the animoji but higher visual fidelity. The animation again follows the four zones, showing the avatar on the side (1) from transparent, (2) fading in while looking forward, (3) starting to turn toward the user, and (4) smiling. However, in close-space interactions, the avatar would be located outside of the field of view in VR. Thus, we adjusted the placement of the avatar in (3), from the actual location of the seatmate on the side to the edge of the horizontal field of view in VR. Additionally, we added an arrow above the avatar to show VR users the direction to the actual location of the out-of-view person [9].

*Mixed.* This visualization combines the *Animoji* and *Avatar* in animation sequences. It aims to prioritize VR presence when the seatmate has limited interest by showing a separated *Animoji* and prioritize bystander awareness when interest increases, gradually changing from the icon to a situated *Avatar*. The animation proceeds (1) from transparent, (2) fading in the solid back of *Animoji*, (3) turning to the front face with an arrow above the *Animoji* to show the direction of the seatmate's actual location, and (4) transitioning into a smiling *Avatar* situated on the side.

## 4 EVALUATION

To answer our research question, we evaluated these three visualizations against a baseline condition. We designed a within-subject experiment in which participants played a seated VR game. As the independent variable, we varied the VISUALIZATION factor of the sequence of proxemic cues with four levels: (a) *Baseline*: with no proxemic indications of the seatmate throughout the VR experience, (b) *Animoji*: with visualization sequence attached to the headset, visible in a head-up display within the field of view, (c) *Avatar*: the sequence pops up situated at the edge of the field of view and directs users to the actual location of the seatmate, and (d) *Mixed*: the sequence appears in the head-up display and guides users to the actual location aside. We counterbalanced the order of the conditions using a Balanced Latin Square design [41].

### 4.1 Task

Following Kudo et al. [18], we used an identification task inside the HMD. In our scenario, we asked the participant to pause the game with a button press on the controller when they noticed that the seatmate wanted to talk to them. We tried to simulate real small talk and thus asked participants to verbally answer a question from the seatmate played by the experimenter in VR without taking off the HMD. For this, we designed four short pre-recorded questions as repeated measures in each condition: (Q1) "Do you have fun with this game?," (Q2) "What is the score now?," (Q3) "Do you like this game?," and (Q4) "How much time is left?" We counterbalanced the order of the questions using a Balanced Latin Square design in each visualization condition. The first question was designed to be asked 36 seconds after the game started, with a 45-second interval between each question's start. Finally, they were asked to resume the game by pressing the same button when they thought that the social interaction was over.

### 4.2 Apparatus

We conducted the study on a two-seater couch in the lab. The couch has a seat size of $110 \times 50$ cm, with an interpersonal distance between the left and right seats of around 30 - 50 cm, therefore, adequately representing an interaction in close space [11, 20]. Participants played the VR game on the couch while the experimenter played the seatmate on their left side, forming a *side-to-side F-formation* [21]. During each social interaction in the VR game, the experimenter followed the study protocol, turning toward the user at specific timestamps without verbal communication and then turning away from the user to look straightforward.

Next to the couch, we set up a Dell G5 laptop (GTX 2070) and ran Unity3D on an HTC VIVE Pro Eye VR headset (110° horizontal field-of-view). For the VR interaction, we used a single VIVE controller and integrated headphones. In the task, we implemented the button using the trackpad on the controller to pause and resume the game. We connected an external speaker to play the questions pre-recorded by the experimenter (seatmate).

For the game, we developed the first-person slicing cube game ourselves, mimicking the popular VR game Beat Saber[2], to ensure engagement in the virtual world. The player's goal is to hit as many cubes as possible at the right moment with a saber (controller) when cubes approach. Players can earn one point per cube if they succeed in hitting its colored sides and will lose one point if they miss it. We implemented effect sounds when participants successfully sliced the cubes. We used the same song as the rhythm background for each game and set a 240-second timer. We displayed the score and time on a top-front interface. When creating the seatmate visualizations, we resembled the experimenter's facial expressions for realistic social interactions. To create the animoji, we used Apple's ARKit face tracking[3] on an iPhone to capture the facial expressions of the experimenter (seatmate). To create the 3D avatar, we used the Ready Player Me application[4]. Then, we mapped the recorded facial expressions animations to the avatar's face using Unity Face capture package[5].

### 4.3 Measures

In each condition, we logged the reaction time to pause in the identification task and calculated the number of misses as a measure of system effectiveness. Additionally, we logged the task completion time, dwell time on visualizations, and head motion as measures of system efficiency. After each condition, we measured system satisfaction by self-ratings of social presence and bystander awareness, VR game experience and discomfort, and user preferences. More specifically, we measured the following dependent variables:

**Misses**: as the number and the proportion of the failed tasks, i.e., did not pause the game, in the total amount of trials across all four conditions and within each condition. **Time to pause**: as the reaction time to detecting the seatmate's interest through the visualizations. **Task completion time**: as the time interval between pressing and releasing the button in the identification tasks in each condition. **Head motion**: as the measure of VR users' head movements switching between playing the VR game and viewing seatmate cues. We first measured the maximum angular movements along the yaw-axis, looking left (**min yaw**), and the pitch-axis, looking down (**min pitch**). The data was logged every 0.2 seconds and recorded as a maximum value that changes over time. In addition, we measured the angular velocity, i.e., average angular movements along the yaw (**yaw velocity**) and pitch (**pitch velocity**) axes over the total time in each condition. **Dwell time**: as the total time the VR users spent in areas of interest, shifting their attention from the game to the seatmate visualizations. **Game experience questionnaire (GEQ)**: After each condition, we used the five flow items from the core module using a 5-point Likert scale to capture users' engagement in the implemented game [16]. **Game Score**: We measured players' performance based on the number of cubes hit by the participant divided by the number of cubes generated during the entire game in each condition. **Social presence questionnaire**: We used the five-item social presence questionnaire on a 7-point Likert scale to capture users' feelings of being with another while seeing different seatmate visualizations in VR [1]. **Seatmate awareness, user preference,**

[2]https://beatsaber.com/, last accessed January 23, 2023
[3]https://developer.apple.com/documentation/arkit/content_anchors/tracking_and_visualizing_faces, last accessed January 23, 2023
[4]https://readyplayer.me, last accessed January 23, 2023
[5]https://docs.unity3d.com/Packages/com.unity.live-capture@1.0, last accessed January 23, 2023

**and physical discomfort**: We defined eight questions ourselves using a 5-point Likert scale to ask participants about their experiences regarding how easy it was to locate the seatmate, how much visual discomfort and neck fatigue they felt in VR, and how usable each condition was.

### 4.4 Procedure

After welcoming the participants, we explained the study goal of investigating close bystander awareness. After giving their informed consent for participation in our study, participants filled out a demographic questionnaire, and we invited them to sit on the couch with the experimenter on their left. In a slide show, we informed participants of the customized Beat Saber game, the designs of the seatmate's proxemic cues, and their tasks to identify the seatmate's (lack of) interest and give verbal answers. In a tutorial (around 8 minutes), they familiarized themselves with the VR headset and how to play, pause, and resume the game with the controller. We encouraged them to ask questions concerning the study task.

Next, the study started with the assigned visualization condition. Participants played the game on the two-seater couch, slicing as many cubes as possible. In between, they completed the identification task, i.e., answering four questions per condition, in VR without taking off the HMD. After each condition, participants were asked to fill out the questionnaires outside VR. After the last condition, we interviewed participants about their opinions and suggestions for game experiences and seatmate cues. Each participant was compensated 15 € for the study duration (1.5-hour). The study setup and procedure were approved by the local ethics review board (ID anonymized).

### 4.5 Participants

We used convenience sampling to recruit 24 participants via our institutional mailing lists. We excluded data of two participants as they did not follow the instructions at the beginning of the experiment and failed to pause and resume in the first one or two conditions. The remaining 22 participants (11 female, 10 male, and 1 non-binary) were between 19 and 38 years old ($M = 24.73$, $SD = 5.37$). Five participants had no prior VR experiences, twelve use VR headsets less than once per year, four use VR weekly, and one uses it daily. Oculus and HTC VIVE were our participants' most commonly used headset models.

### 4.6 Data Processing

Our dataset consisted of recordings from 352 experimental trials (22 participants × 4 conditions × 4 questions). We processed the data and identified commission errors as the proportion of additional action, i.e., pausing the game twice. We attribute these errors to our study design's artifacts, as participants tend to react throughout the experiment when asked to complete the tasks. The mean rate of commission errors is 4.55% across all four conditions. The highest rate is 7.95% in the *Animoji* condition, when seeing the popup proxemic cues always within the view, followed by 4.55% in *Mixed*, 3.4% in *Baseline*, and the lowest 2.27% in *Avatar*. We corrected these errors by either deleting a quick 1.67-second ($SD = 1.31$) re-pause at the end or a 2.24-second ($SD = 2.26$) wrong pause at the start. In case two pauses are comparable, i.e., a 4.64-second ($SD = 2.23$) pause followed by a 4.38-second ($SD = 2.71$) re-pause, we deleted the time interval between them. Accordingly, we used the first pause to measure the time to pause and the time between the first pause and the last resume to measure task completion time.

Table 1. Means and standard deviation of the behavioral data and some questionnaire results, with statistical testing results. △ for social presence, we report the ANOVA results, F-statistics, and $\eta^2$.

| | Baseline | | Animoji | | Avatar | | Mixed | | Friedman Test | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measure** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | $\chi^2$ | $df$ | $p$ | $W$ |
| Misses [#] | 0.64 | 1.4 | 0.14 | 0.64 | 0.45 | 1.22 | 0. | 0. | 6.77 | 3 | .08 | 0.103 |
| Time to Pause [s] | n/a | n/a | 5.38 | 2.97 | 9.66 | 2.38 | 5.07 | 2.10 | 30.3 | 2 | <.001 | 0.688 |
| Task Completion Time [s] | 6.77 | 3.76 | 15.43 | 4.35 | 12.09 | 3.66 | 17.41 | 4.72 | 47.5 | 3 | <.001 | 0.72 |
| Dwell Time [s] | n/a | n/a | 42.31 | 25.02 | 33.45 | 33.38 | 76.84 | 37.1 | 25.4 | 2 | <.001 | 0.576 |
| Min Yaw (left) [deg] | 56.8 | 28.01 | 55.81 | 31.72 | 66.47 | 25.02 | 81.97 | 18.10 | 19.5 | 3 | <.001 | 0.296 |
| Min Pitch (down) [deg] | 13.07 | 8.36 | 10.34 | 8.63 | 13.54 | 9.95 | 16.58 | 9.68 | 9.82 | 3 | .02 | 0.149 |
| Yaw Velocity [deg/s] | 5.4 | 2.78 | 4.74 | 2.82 | 7.05 | 3.33 | 8.05 | 2.64 | 16.5 | 3 | <.001 | 0.25 |
| Pitch Velocity [deg/s] | 3.72 | 1.45 | 3.09 | 1.19 | 3.32 | 1.12 | 3.57 | 1.58 | 10.7 | 3 | .014 | 0.162 |
| GEQ-Flow | 3.89 | 0.76 | 3.72 | 0.78 | 3.77 | 0.75 | 3.73 | 0.71 | 5.64 | 3 | .13 | 0.086 |
| Game Score [%] | 77.48 | 18.01 | 77.69 | 17.67 | 77.06 | 15.41 | 73.77 | 18.67 | 1.36 | 3 | .714 | 0.021 |
| Social Presence | 3.62 | 0.71 | 4.34 | 0.73 | 4.48 | 0.69 | 4.54 | 0.69 | 11.01△ | 3 | <.001 | 0.222 |
| User preference | 2.27 | 0.83 | 3. | 1.15 | 3. | 1.38 | 3.45 | 1.06 | 13.8 | 3 | .003 | 0.209 |
| Visual discomfort | 1.45 | 0.8 | 1.59 | 0.96 | 1.64 | 0.95 | 1.55 | 0.8 | 2.71 | 3 | .438 | 0.041 |
| Neck fatigue | 1.41 | 0.59 | 1.41 | 0.67 | 1.41 | 0.73 | 1.45 | 0.74 | 0.529 | 3 | .912 | 0.001 |

## 5 RESULTS

We analyzed the processed data and, below, report our results regarding bystander awareness and experiences in the VR game.

### 5.1 Analysis

We used a one-way repeated measures ANOVA to analyze the effect of the VISUALIZATION factor. We tested the data for normality using Shapiro-Wilk's test. The analysis showed that all measures violated the normality (all $p \leq .033$) except the measure of social presence ($p = .338$) for simple parametric testing. Thus, for social presence, we used a $t$-test with Bonferroni correction applied. For all other measures, we applied non-parametric test procedures; we used Friedman and Wilcoxon signed-rank tests. Statistical significance is reported for $p < .05$.

### 5.2 Misses

The mean rate of misses is 7.67% across all four conditions. The highest rate is 15.9% within the *Baseline* condition, when seeing no proxemic cues, followed by 11.36% in the *Avatar*, 3.41% in the *Animoji*, and 0% in the *Mixed* condition. On average, each participant had 0.64 misses in the *Baseline*, 0.45 in the *Avatar* and 0.14 in the *Animoji* condition. The Friedman test showed no significant differences between all conditions, see Table 1. For missing data, we proceeded as follows: If the participant completed one or more trials in the given condition, we filled the missing data with the mean value of the participant's behavioral data in these completed trials. If the participant failed all four trials in the given condition, we filled the missing data with the mean value of all completed trials by the other participants.

### 5.3 Behavioral Data

Figure 3 shows the frequency distribution of the mean timestamps of pause and resume.

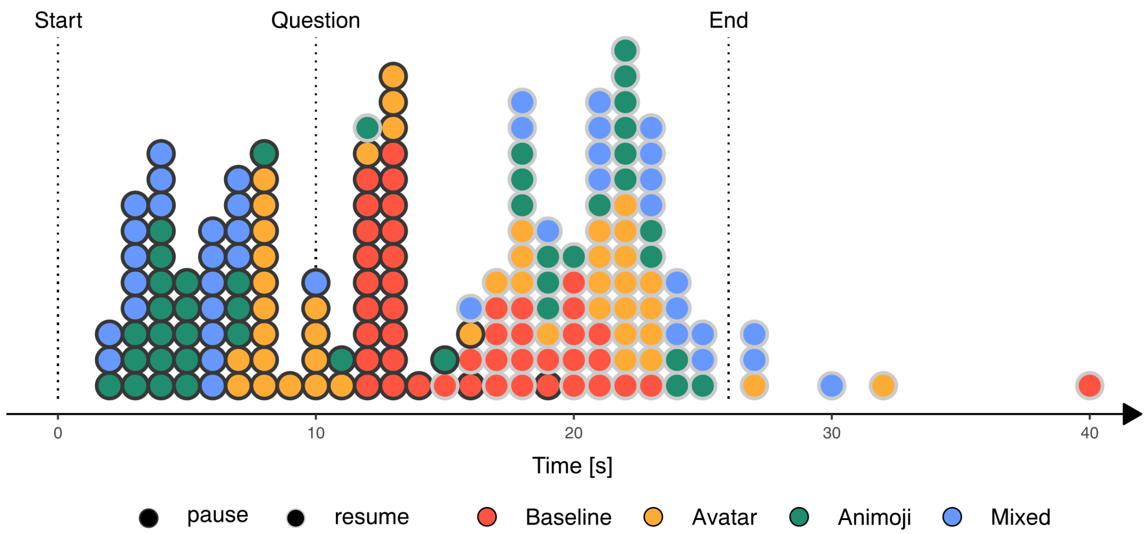


Fig. 3. Histogram showing frequency distributions of the 22 participants' pause and resume timestamps in the identification tasks, from the moment the visualization was displayed to the participants to when it completely faded out.

*5.3.1 Time to Pause.* We discovered that the avatar introduced the longest time to identify the seatmate. The Friedman test showed a significant effect of the VISUALIZATION factor ($\chi^2(3) = 30.3, p < .001, W = 0.688$). Post-hoc tests indicated significantly longer time to pause in the *Avatar* condition than the *Animoji* ($p < .001$) and *Mixed* ($p < .001$) conditions. The popup icons within the field of view introduced a faster reaction time than the situated avatar. Figure 4 left shows this data.

*5.3.2 Task Completion Time.* We found that participants spent the longest time engaging in the conversation when viewing continuous visualization of the seatmate. The analysis showed significant differences across conditions ($\chi^2(3) = 47.5, p < .001, W = 0.72$), see Figure 4 middle. Post-hoc tests showed significant differences between all conditions (all $p < .05$). Participants spent significantly longer interacting with the seatmate when receiving indications

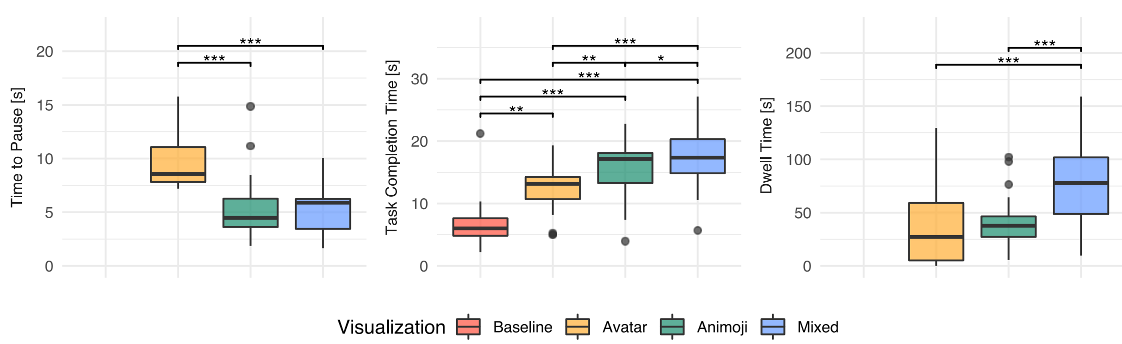


Fig. 4. Overview of the results for the time to pause, task completion time, and dwell time on the seatmate visualizations. $*$ denotes $p < .05$, $**$ denotes $p < .01$, $***$ denotes $p < .001$.

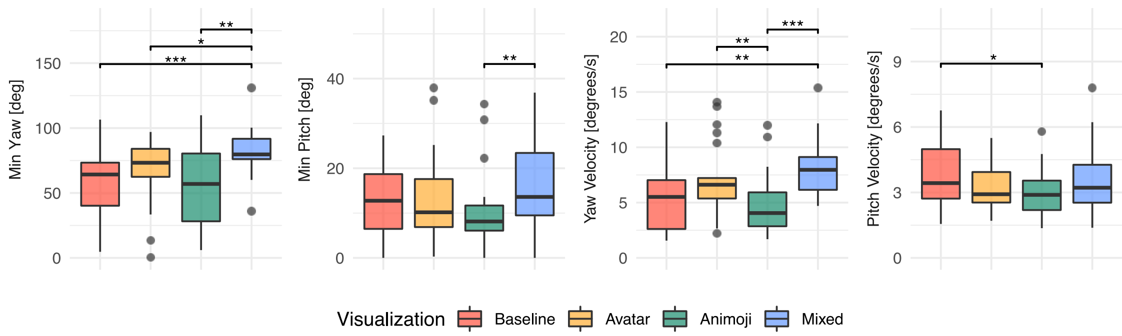


Fig. 5. Significant differences in the head motion data along the yaw axis, looking left and right, and the pitch axis looking up and down. $*$ denotes $p < .05$, $**$ denotes $p < .01$, $***$ denotes $p < .001$.

of the seatmate compared to no visual cues at all, especially viewing *Mixed* visualizations compared to the *Avatar* ($p < .001$), *Animoji* ($p = .045$), and *Baseline* ($p < .001$) conditions. Moreover, *Animoji* introduced significantly longer interaction with the seatmate than *Avatar* ($p = .003$).

*5.3.3 Dwell Time.* Likewise, the Friedman test showed a significant effect for the Visualization ($\chi^2(2) = 25.4, p < .001, W = 0.576$), see Figure 4 right. Post-hoc tests confirmed significantly longer dwell time in the *Mixed* multi-representation condition than in the *Animoji* ($p < .001$) and *Avatar* ($p < .001$) uni-representation conditions.

*5.3.4 Head Motion.* We discovered that participants turned towards their seatmates wider and faster when viewing the seatmate's continuous visualization. Visualization had a significant effect on the angle by which people turned left toward the seatmate ($\chi^2(3) = 19.5, p < .001, W = 0.296$), see Figure 5 left. Post-hoc tests revealed that in the *Mixed* condition, participants exhibited a larger maximum angular movement than in the *Animoji* ($p = .006$), *Avatar* ($p = .013$) and *Baseline* ($p < .001$) conditions. A similar pattern was found when looking at the downwards angular rotation on the pitch axis ($\chi^2(3) = 9.8, p = .02, W = 0.149$), see Figure 5 middle left. Post-hoc tests indicated that in the *Mixed* condition, participants tended to look further down than in the *Animoji* ($p = .003$) condition, in which the separated 2D icons always appeared in the top-left corner of the users' view.

Additionally, the analysis showed a significant effect of the Visualization factor on the yaw velocity ($\chi^2(3) = 16.5, p < .001, W = 0.25$), see Figure 5 middle right. The post-hoc comparisons could show that there was significantly faster angular movement, looking left and right, in the *Mixed* ($p < .001$) and *Avatar* ($p = .008$) conditions than in the *Animoji* condition. Moreover, the *Mixed* condition introduced significantly faster yaw angular movements than the *Baseline* ($p = .004$). Further, the analysis showed significant differences in the pitch axis ($\chi^2(3) = 10.7, p = .014, W = 0.162$), see Figure 5 right. Post-hoc tests confirmed significantly slower pitch velocity (looking up and down) in the *Animoji* condition than in the *Baseline* ($p = .022$).

### 5.4 Social Presence

We analyzed the aggregated mean value of the 5-item social presence questionnaire. The one-way repeated measures ANOVA test showed a significant effect of Visualization on the overall social presence ($F(3, 63) = 11.01, p < .001, \eta^2 =$

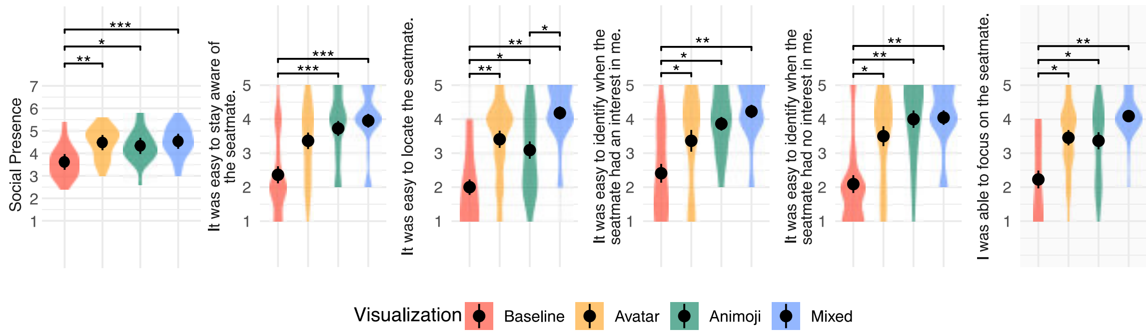


Fig. 6. The participants' answers to our self-defined questions regarding seatmate awareness and user preference in the experiment. $*$ denotes $p < .05$, $**$ denotes $p < .01$, $***$ denotes $p < .001$.

0.222). Participants experienced a relatively higher "sense of being together with another" in the *Mixed* ($p < .001$), *Avatar* ($p = .002$), and *Animoji* ($p = .013$) conditions than in the *Baseline*, as indicated by post-hoc tests (see Figure 6).

Further, we analyzed the participants' answers to each item. When asked if the participants perceived that they were in the presence of another person in the room with them, the analysis showed significant differences across conditions ($\chi^2(3) = 9.45, p = .024, W = 0.143$). Post-hoc tests showed significantly higher approval for the *Mixed* condition than the *Baseline* ($p = .026$). When asked if the participants felt that the person was watching them and was aware of their presence, the analysis showed a significant ($\chi^2(3) = 21.2, p < .001, W = 0.321$) effect of the Visualization factor. Participants felt significantly more feedback from the seatmate when viewing the proxemic cues in the *Mixed* ($p < .001$) and *Animoji* ($p = .025$) conditions than in the *Baseline*, as revealed by the post-hoc comparisons. Finally, when asked if they perceived the person as being only a computerized image, not a real person, the analysis showed significant ($\chi^2(3) = 11.9, p = .008, W = 0.18$) differences across conditions. As shown in post-hoc tests, participants felt the seatmate significantly less like a real person when seeing the flat icon separated from the actual location in the *Animoji* ($p = .015$) condition than in the *Baseline*.

### 5.5 GEQ Flow and Game Score

We analyzed the aggregated mean value of the five flow items from the GEQ core module, see Table 1. The analysis did not indicate any significant differences between conditions ($p = .13$). Likewise, we found no significant differences in each item across conditions when asking about participants' concentration and engagement in the game, all $p \geq .102$. The game score mirrored these results. The analysis showed no significant differences between conditions ($p = .714$).

### 5.6 Questionnaire

After each condition, participants answered questions regarding their awareness of the seatmate and experiences in VR on a 5-point Likert scale (1: strongly disagree, 5: strongly agree), see Figure 6.

*5.6.1 Seatmate Awareness.* We asked the participants if it was easy to stay aware of the seatmate and found a significant effect of the Visualization factor on the ease of keeping seatmate awareness ($\chi^2(3) = 21.1, p < .001, W = 0.319$). Post-hoc tests confirmed significantly higher approval for the *Mixed* ($p = .006$) and *Animoji* ($p = .005$) conditions than for the *Baseline* condition. When we asked the participants if locating the seatmate was easy, it mirrored the results, with significant differences across conditions ($\chi^2(3) = 26.8, p < .001, W = 0.406$). Participants found it significantly easier to locate the seatmate in the *Mixed* ($p = .001$), Animoji ($p = .023$) and *Avatar* ($p = .008$) conditions than in the *Baseline*. Further, participants found it significantly easier to locate the seatmate using *Mixed* multi-representations than using the single *Animoji* ($p = .032$) as indicated by post-hoc tests.

Additionally, we asked the participants if it was easy to identify when the seatmate had (no) interest in them. The analysis showed significant differences in identifying seatmate's interest ($\chi^2(3) = 19.7, p < .001, W = 0.298$) and no interest ($\chi^2(3) = 24.5, p < .001, W = 0.371$). A similar pattern was found in post-hoc tests for the three visualization conditions that were significantly easier to identify both interest (*Mixed*: $p = .005$; *Animoji*: $p = .014$; *Avatar*: $p = .024$) and no interest (*Mixed*: $p = .002$; *Animoji*: $p = .003$; *Avatar*: $p = .028$), as compared to the *Baseline*. Likewise, the analysis showed significant ($\chi^2(3) = 21.9, p < .001, W = 0.332$) differences in the participants' answers about if they were able to focus on the seatmate. Post-hoc tests depict significantly higher approval ratings for the *Mixed* ($p = .002$), *Animoji* ($p = .041$), and *Avatar* ($p = .013$) conditions than for the *Baseline*.

*5.6.2 User Preference and Physical Discomfort.* We asked the participants if they would like to use the system from day to day. The analysis showed significant differences in their ratings ($\chi^2(3) = 13.8, p = .003, W = 0.209$), see Table 1. Post-hoc tests indicated significantly higher preference for the continuous visualizations of the seatmate in the *Mixed* ($p = .02$) condition than for the *Baseline*. Finally, we asked the participants if they felt general visual discomfort and neck fatigue during the VR experience. The analysis did not indicate any significant differences across conditions in both ratings. Overall, participants reported limited to no physical discomfort using VR in the experiment.

### 5.7 Qualitative Results

In the final interview, we asked participants to describe why they liked or disliked a proxemic cue. We followed a thematic analysis [3] to code the participant's subjective comments. The identified themes are illustrated below with participants' representative quotes under their IDs. The authors translated all quotes from the participant's mother tongue to English.

For the most preferred *Mixed* condition, participants expressed that they liked that the visualization was continuous as it was *"obvious to identify whether the seatmate wanted to talk or not"* (P12) and *"easy to find the seatmate because the arrows pointed in the right direction"* (P10). With regard to following the proxemic cue of the seatmate in *Mixed*, P8 described the experience metaphorically as *"someone is knocking on the door, so you stop, listen, and turn around to see if someone is there."* However, some participants criticized such proactive guidance when they intended to immerse in VR, e.g., *"The arrows were a bit distracting. I felt like I had to stop the game and like some kind of obligation to look in that direction to focus on the person"* (P5).

In comparison, participants found the *Avatar* cues with the same arrow design less distracting, given its initial placement at the edge of the field of view in HMD, e.g., *"it was slightly on the left side. I felt the interruption was not intrusive"* (P17). As a result, some participants were too immersed in the game to notice the seatmate in time, e.g., *"When I looked there, the person looked already urgent"* (P12), or nearly missed as *"I feel that I have almost over-looked something from the person"* (P11). Additionally, we found mixed opinions for the visualization design. P1 found that the avatar body emulated the seatmate: *"when I saw the whole body of the 3D avatar, I remembered you (the experimenter) and felt like talking to a real person."* However, some found the 3D-model size *"so big"* (P9), especially with the situated placement, *"It is so close to me. That's why I was shocked the first time I saw it"* (P24).

In the *Animoji* condition, participants found the in-view icon *"was really easy to stay aware whether the bystander was looking at me or not"* (P12). Meanwhile, it lacked the arrow guidance, and thus participants expressed that it was challenging to find the seatmate's actual location, such as *"the notification had almost nothing to do with locating the bystander next to me, that was a completely separated thing"* (P6). As a result, an *Animoji* annoyed some participants who tried to find the other person and gradually ignored the actual location, e.g., *"I couldn't move my head to the bystander because the animoji followed me and was always in the top left"* (P7) and *"The animoji always stayed in the top left of my view. I just gave up trying to locate the bystander and just talk into the room"* (P15). Moreover, participants disliked the flat animoji icons in the 3D virtual environment as *"it doesn't feel like a real person"*(P18), rather more like *"a programmed element in the game"* (P10), or *"FaceTime and a phone call, so I feel like no one is next to me"* (P3).

Finally, in the *Baseline*, participants mainly identified the seatmate's intention dependent on the verbal questions. Some participants found it *"less distracting"* (P24) and helpful to *"focus on the game"* (P11). Yet, when intending to interact with the seatmate, some missed the questions as they only heard *"the game was playing music"* (P2).

## 6 DISCUSSION

Our results show that viewing the visualizations of other people in close proximity supported VR users' bystander awareness in close-space interaction. We found that the visualization *Avatar* preserved social presence but did not ensure fast identification of the seatmate. The *Animoji* was effective in grabbing the participant's attention but challenged their locating of the person. In contrast, the *Mixed* visualization allowed for more pleasant social interactions in which users could efficiently notice the seatmate's presence and were directed to the actual location.

### 6.1 From Far- to Close-Space Bystander-Visualizations

Our results show that adding visualizations of the seatmate allowed for more accurate identification with fewer misses on average, significantly increased social presence, and ease of engaging in conversations, which aligns with the previous research on far-space bystander awareness [18, 28, 38]. On average, participants rated the game flow worse for all visualizations than for the *Baseline* condition, which mirrors prior work conducted in far space [18]. Thus, we suggest that adding a visualization of non-VR users is important to make VR usable in shared spaces across different spatial scales, but this might be at the expense of an impaired gaming experience.

Comparing our visualizations, we found a trade-off between facilitating the social interaction and distraction from the primary task. When the system provided information on a change in seatmate orientation overtly in the player's view (*Animoji* and *Mixed*), participants reacted faster. While the *Avatar* condition produced the longest reaction time to pause, along with the shortest task completion time and the smallest dwell time, it introduced efficient angular guidance to find the seatmate's actual location. This indicates that it was hard to notice and stay aware of the *Avatar*, but once a need for interaction was registered, it was easy to find and talk to the seatmate. On the other hand, granular visualizations could benefit extended social interactions. We found the longest pause and focus on seatmate when viewing continuous visualizations (*Mixed*) that first grabbed the attention with the head-up icons and then directed users to the actual location through arrows as a guide. This longer interaction with the visualization also prompted participants to turn more and faster toward the seatmate as compared to the *Animoji* condition. Therefore, guiding the user more granularly could be beneficial to achieve an improved social interaction between the VR user and seatmate. Taken together, participants had a clear preference for the *Mixed* visualization as it provided the user with efficient orientation cues to initiate a conversation with the seatmate and effective proxemic cues to find the location of the seatmate. Therefore, we recommend that VR systems leverage dynamic proxemic cues for optimal system usability when used in social spaces with diverse spatial scales.

### 6.2 From Side-to-Side to Other Physical Spatial Arrangements

Everyday close-space interactions entail a variety of physical spatial arrangements, in which we tend to use different proximity signals to communicate. When using VR in these everyday scenarios, spatial configurations range from side-to-side as in public passenger seats [42] to face-to-face and corner-to-corner, e.g., in shared social spaces [34, 35]. These different arrangements between VR users and bystanders involve dynamic dimensions of their proxemic relationship, influencing how they communicate with each other. Specific arrangements even decrease the social acceptance of using VR on the go, like in face-to-face [35]. We envision a proxemic-aware system [24] to support interpersonal communication between VR and non-VR users in shared social spaces and enhance social acceptance of the technology [10, 23]. For example, in a face-to-face layout, the pitch *Orientation* gains importance when the seatmate looks upfront to signal interest. Likewise, in the corner-to-corner arrangement, the *Distance* or *Movement* can provide additional cues when the diagonal seatmate steps forward and waves to interrupt.

The placement of proxemic cues plays an important role in the system's new usability. We adjusted the initial position of *Avatar* from the actual location to the edge of the field of view in VR, expecting to support identification as previously confirmed when the bystanders showed up in front of users [18]. Still, the number of misses was higher than expected, as some participants could not react timely to the cues placed closer to the side yet far from the front game area. In contrast, extending the situated avatar forward to the head-up icons attached to the player's view (*Mixed*) satisfied both efficient identification and effective locating of the seatmate. From this, we learned that dynamic placements of bystander visualizations that compensate for the spatial shortcomings of the given physical arrangement are key to system effectiveness. Likewise, technical limitations influence the placement. A newer headset with a wider horizontal field of view might ease the identification of the side seatmate compared to our tested HMD. To conclude, we recommend adding out-of-view bystanders first in the primary task view to ensure fast and accurate bystander awareness.

### 6.3 Limitations and Future Work

*6.3.1 Extending our Visualizations.* We only tested a one-to-one proxemic relationship, in which the *Mixed* system can offer several proxemic dimensions valid in the given spatial arrangement while preserving game experiences to a certain extent (cf. GEQ Flow). However, in one-to-many proxemic relations, revealing full details of all bystanders' proxemic cues and presenting the gathered data the same way without filtering can be distracting and break the presence in VR. Future work can further explore the diverse availability of proxemic cues from system-triggered snoozing of all proxemic cues [39] to user-triggered areas of social engagement [22].

Besides, since we only used visual feedback to represent the proxemic changes of the person aside, we assume that additional auditory or haptic feedback [7] could increase bystander awareness more. Especially in verbal interactions between VR users and bystanders, adjusting in-VR audio improves users' auditory awareness so they can better converse with bystanders even at the cost of presence [26]. Future research is needed to test the use of multi-modal feedback considering user preferences.

*6.3.2 Other Virtual Environments.* In this paper, we focused on the single-direction notification, supporting VR users' awareness of non-VR users. Therefore, we did not implement the exact proxemic cues of the seatmate, e.g., based on the experimenter's real-time head tracking data, ensuring the experiment's controllability. Besides, we used a representative

VR game to ensure engagement in the virtual world, which requires players to look in front constantly. Other games that require frequent head movements of the player might shorten or extend this reaction time, depending on the relative distance gap between the notification and game focus. Moreover, we expect other tasks that require higher cognitive workloads to prolong users' reaction time and further break engagement in digital space. Future work needs to consider different VR tasks [33] when evaluating close bystander awareness, involving the *Orientation* changes in VR users and diverse cognitive workload.

## 7 CONCLUSION

In this paper, we investigated how to support bystander awareness of VR users for close-space interactions during games based on the proxemic cues. We compared three seatmate visualizations using a 2D animoji, a fully-rendered avatar, and a combination. We found that the head-up *Animoji* efficiently grabs users' attention to the seatmate but fails to support locating the partner during conversations. While the *Avatar* closely presents the seatmate's location, users spend less time looking at them. In contrast, the *Mixed* continuous visualization was preferred by users, supporting fast identification of the seatmate's presence, along with effective social interaction as it supports easy locating, focusing, and identifying the seatmate's intention.

Engaging in immersive virtual environments with someone else is not optimal yet common when anticipating VR interactions in everyday public and social spaces. Notably, using today's VR HMDs in public and shared spaces challenges the social acceptability and user adoption. On a broader view, our work underlines the vision of proxemic-aware VR to foster social acceptance, focusing on close bystander awareness, continuous visualizations, and dynamic physical spatial arrangements.

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