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

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ABSTRACT

Virtual Reality (VR) can be used to create immersive infotainment experiences for car passengers. However, not much is known about how to best incorporate the essentials of their surroundings for balancing real-world awareness and immersion. To address this gap, we explored *2D* and *3D* 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 game in VR. 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 propose real-world task types, synchronous visual cues, and various input and transition approaches as promising future research directions.

CCS CONCEPTS

• **Computing methodologies** → **Virtual reality**; *Mixed / augmented reality*; • **Human-centered computing** → *Human computer interaction (HCI).*

KEYWORDS

everyday mobile VR, transitional interfaces, passenger, HMD

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1 INTRODUCTION & BACKGROUND

Virtual Reality (VR) is increasingly used in everyday contexts, such as healthcare [32], productivity [10], entertainment [29] and transportation [22]. With recent advances in tracking technology, truly mobile VR head-mounted displays (HMDs) enable immersive use of entertainment media [9] and work environments [15] anywhere, anytime. In recent years, the use of VR systems for passengers in cars has emerged as an interesting field of application of such systems [19]. In industry, Audi launched the Holoride [1], in which the rear-seat passenger can play first-person games in VR with their movements in the virtual environment synchronized to real-time car motion. As self-driving cars become more widespread and the human responsibility for driving diminishes, the car is increasingly becoming a place where users can pursue other activities [5]. Early studies exploring in-car VR indicate that it can provide a range of passenger experiences, such as relaxation [17, 28], mobile work [14, 15], entertainment [9], and interaction with other road users [12]. To pursuit immersive infotainment experiences for passengers, most of the previous studies explored this mobile context by fully transporting users away from the real traffic environment, whilst omitting the fact that the car user sometimes need or want to interact with the physical world, like holding the handle in a sharp turn or lowering the armrest for a rest.

In other everyday contexts, such as offices, prior studies examined blending different amounts of reality into VR for maintaining awareness of the real world, but avoiding distraction from the VR experience [20]. Our work builds on these prior studies and specifically targets an everyday mobile context, including the rear-seat passenger's operation task and entertainment activity, and balancing in-car space awareness and immersion in VR. We implemented two visual cues with different amounts of reality and levels of details (*3D*, *2D*) displaying the mapped car interior and regions in a VR game. The *3D* version showed a three-dimensional model of the entire in-car space, while the *2D* version displayed just a two-dimensional image of the specific operation part. In addition, we implemented four tasks representing passengers' daily activities inside the car (*lower armrest*, *take cup*, *close window*, and *hold handle*). The guiding research question was: *How can we support the user's awareness of their essential surroundings while keeping them immersed in mobile VR?* In a pilot study with 19 participants, we asked them to sit in a parked car and wear a HMD to play a first person shooter game in VR for entertaining. The participants' task was to operate the specific car regions when being prompted to do so by the mapped visualizations in HMDs. Our results revealed that the task *hold handle* introduced less workload than all other tasks

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and retained a higher immersion when back in the virtual environment than after *take cup* and *close window*. The main contribution of this work can be summarized as: 1) Examining in-car-space-aware interaction in everyday mobile VR and 2) Providing potential future research directions: real-world task types, synchronous visual cues, and various input and transition approaches.

2 RELATED WORK

2.1 Real-world Awareness in VR

Real-world awareness for interaction in everyday VR has been investigated in the literature with mixed results, showing improved usability of HMDs in daily life through enhanced task performance, but broken illusion through the higher discrepancy between the two realities. In various studies, one approach to maintain real-world awareness is to substitute the entire real environment with different virtual environments, mapping physical environments and objects into VR with varying degrees of matching. Simeone et al. [31] found that the greater the degree of mismatch between the physical objects and their virtual counterparts was, the lower was the believability of the experience. Another approach aims to render the selectively extracted parts of reality into VR based on the intended purpose. McGill et al. [20] incorporated different amounts of an office into VR and showed evidence that keeping the user aware of the physical keyboard corrected the impaired performance of typing in VR. Some studies explored specific moments demanding the user's real-world awareness, such as encountering the real-world boundaries through auditory and haptic signals [6] and the initiation of the transition between two realities via a virtual portal showing a view of the real environment [7]. Besides, some studies investigated the communication of bystander existence to VR users through visualizations and auditory cues of bystander's positions and behaviors such as a door knock and footsteps [23, 27, 33], as well as multi-modal notification design for room-scale domestic VR [8]. However, these approaches are less well-researched in the everyday in-car VR context, which features ever-changing real street environments with more frequent distractions in the less controlled real world. This further challenges the design of real-world awareness while maintaining VR immersion.

2.2 In-Car VR

In the transportation context, prior work explored other ways for maintaining real-world awareness in the passenger use of HMDs. One way is to map real-time vehicular movements with the visual information in VR. Coordinated sensory cues from vision (received from VR) and the vestibular system (received from the real world) increase enjoyment and immersion while motion sickness is reduced [1, 9, 21]. Another solution aims to convey ambient vehicle information, such as the journey progress and the vehicle speed, using symbolic simulated artifacts embedded in the virtual environment [17]. Despite these solutions, prior studies tend to fully transport the passenger away from the distracting traffic environment to various virtual environments, such as calming underwater scenes for relaxation [28] or a virtual office for mobile work [15]. This occludes the user from their physical surroundings while using VR in cars, which makes passengers worry about their physical integrity in VR [14] and they might even drop out of VR in emergencies during transit [16]. To our knowledge there are no studies that investigated the user's awareness of their essential operable surroundings across the in-car space while using VR HMDs during transit. Our work differs from the mentioned prior work mainly in the following two aspects: 1) Adaption to everyday mobile context: we adopt the substitutional reality approach [31] using the *3D* model of the entire in-car space as a one-to-one mapping, and the selective rendering approach [20] using the *2D* real-captured photo of the specific operation part. 2) Real-world operation tasks across rear-seat space: we incorporate these two visual cues into a VR game and showed experimental evidence about users' perceived workload in real-world operation tasks and immersion in the VR game after completing the tasks.

3 USER STUDY

We conducted a between-subjects experiment to investigate the effects of the visualizations on the perceived workload and the immersion. In total, 19 participants (6 female, 13 male) aged between 20 and 61 ($M = 31.57, SD = 10.81$) took part in the study. Participants were employees of BMW Group and they all had prior VR experience. The user study was approved by the local ethics review boards of LMU Munich and BMW Group. Nine participants tried the experiment version using the *3D* interior model and the other ten participants tried the version using the *2D* image of the car region. Each participant completed four trials (real-world operation tasks) with the assigned visualization. We randomized the order of the tasks using a Latin square, with the exception that the task *take cup* always appeared after *lower armrest*, as the cup is taken from an unfolded armrest, resembling the daily use case.

3.1 Set-Up and Apparatus

To create an interactive experience and provide immersion in VR, we designed and implemented a first person shooter VR game using the Unity Game Engine. The user's goal is to navigate in an open forest environment, aiming to collect a total of 40 mushrooms which are randomly distributed in the terrain. The trees, bushes, and mushrooms inserted onto the map were assets taken from the Unity asset store[1]. Using the hand-held controller, the user can either walk around the map using the analog stick or press the A button to use the teleport function, which allows faster movement. Both options were presented to the users beforehand, so they could freely choose. Ambient piano music was played at a low volume in the background and a simple sound effect was played each time a mushroom was collected for increased engagement. We used a credit-based rewarding system to motivate users, displaying the collected number of targets attached to the virtual controller.

To investigate real-world awareness in the car, we designed four operation tasks that rear-seat passengers may possibly encounter in everyday life: *lower armrest*, *take cup*, *close window*, and *hold handle*. The choice of these four tasks varied regarding the operation position distributed across the rear-seat space, i.e., either in the middle of the seat (*lower armrest* and *take cup*) or on the side door (*close window* and *hold handle*). These car regions were rendered

[1]https://assetstore.unity.com/packages/3d/environments/nature-starter-kit-2-52977, last accessed March 2, 2022

Figure 1: Notifications (Middle) and visual cues of the operation tasks (seat side on the left, door side on the right). The top row shows the *3D* version, the bottom row the *2D* version.

in the virtual environment to provide an aid to the user for real-world position estimation. In line with the prior substitutional and selective reality approaches [20, 31], we implemented two visual cues. A *3D* model of the entire BMW iX interior and *2D* photos of the specific operation regions, shot inside the real car. The interior model recaptures the spatial structure and the features of the in-car space. The position of the *3D* model was mapped to the real car, by aligning the user's seated position in the car back row. In the *2D* version, only two-dimensional pictures of the areas of interest were shown (the right door and the left seating area). They were spatially positioned at the same time to match the real areas of the car. A view of the *3D* and *2D* visual cues from the perspective of the user can be seen in Figure 1. In preliminary tests, we ensured that the position alignment was optimal with acceptable mismatches for completing the tasks. As an example, the button to open and close the windows was only a few centimeters wide, so even a small misalignment of the references could lead to participants missing it entirely. Meanwhile, an in-VR text notification was included in the game. It was placed at the back of the front seat to make it easier for the user to view them (Figure 1).

We used an Oculus Quest VR system [25] in the study, a standalone VR headset with 6-DoF inside-out tracking, a 2880×1600 twin OLED display, 72 Hz refresh rate, a FoV of 94° horizontal and 90° vertical, and two 6-DoF hand-held controllers. The HMD also provides a fully integrated open ear headphone with spatial audio. In this study, participants used the HMD alone and in a parked car to omit motion sickness from the vehicle motion and the question of social acceptance when other co-located passengers are present.

3.2 Procedure and Measures

The participants arrived at the laboratory and were given the consent from, asked to discuss any questions they might have with the experimenter, then sign it when they felt comfortable. They then answered the demographics questionnaire and were randomly assigned to the *3D* or *2D* version. The experimenter lead the participant to sit in the back row (behind the co-driver) and helped them in wearing the HMD. The experimenter demonstrated the operation tasks and the VR shooting game (without visual cues) to familiarize the participant with the usage of the car interior and the controller. During this tutorial, the participants were then asked to experience the car and the game by themselves and to raise any potential questions. After the tutorial, each participant started the assigned *3D* or *2D* version, in which the participant completed four trials of the operation tasks in randomized order. Immediately after each trial, two in-VR questions about workload and immersion were rated by the participant using the same shooting button on the controller (as instructed in the tutorial). In the end, the experimenter helped the participant in taking off the headset and getting off the car. The participant was asked to fill the post-experiment questionnaire on a laptop. The experiment was completed with a semi-structured interview about the participant's overall experience and opinions. Each session took around 45 minutes.

We were interested in whether the *3D* version of the visual cues that indicated the user's surroundings would enhance their real-world task performance through increased real-world awareness whilst maintaining their immersion in VR. Thus, we implemented two customized in-VR questions to capture the user's prompt **perception of workload** in the real-world operation tasks and **immersion**. During each session, immediately after completing each real-world task, a pop-up window appeared in VR asking the question about perceived workload: "*Completing this task felt easy and did not require a lot of effort.*" and immersion: "*How immersed in the VR game do you feel after completing the task?*". The participant self-rated on a scale from 1–7 with 1 indicating "strongly disagree/ not at all" and 7 for "strongly agree/ completely immersed". With these short in-VR questions, we ensured the least disruption of the VR experience. The post-experiment questionnaire included an **IPQ presence questionnaire** [30], **system usability scale (SUS)** [4], and **user experience questionnaire (UEQ-S)** [13]. In the background, the user's **game scores** were recorded in Unity. In the semi-structured interview, we asked for the participant's comments and suggestions about the experienced version.

4 RESULTS

For the game score and post-experiment questions, we used independent t-tests for normally distributed data and a Mann–Whitney U test for abnormally distributed data. For in-VR ratings, we used the mixed factor align-and-rank ANOVA [35]. Statistical significance is reported for $p \leq 0.05$.

The results of the game score and the post-experiment questionnaire are presented in Table 1. Overall, we found no significant differences between the *3D* and *2D* versions. Out of 40 targets in the VR game, our participants completed more than half of them on average in each version. With regards to the entire session, i.e., completing real-world operation tasks while playing the VR game, the results were similar across versions. The IPQ overall presence scores were above average, and only the sub-scale of experienced realism was below average in both versions. The participants rated the system usability above 68 in both versions, which signals a good usability [4]. Similarly, the user experience of the *3D* version was evaluated by our participants as positive while the *2D* was neutral.

In-VR Ratings: We conducted a mixed factor ART-ANOVA [35] with the visualization as a between-subjects factor and the task as

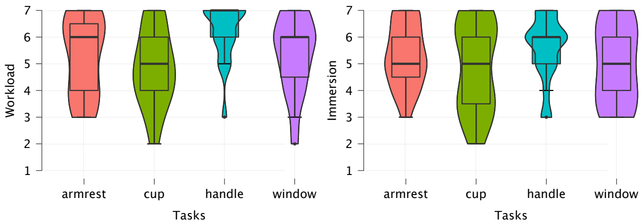

Figure 2: In-VR ratings of perceived workload in the real-world operation tasks and immersion in VR game after completing the tasks. The higher the numbers, the less workload, and the higher immersion our participants rated their experiences.

a within-subjects factor. The results are presented in Table 2. We found no significant interaction effect between the task and the visualization for workload and immersion, but two main effects for the task. Post hoc tests using ART-C [35] revealed that the participants rated the *hold handle* task with a significantly lower workload than all other tasks: armrest–handle: $t = -3.172, p_{tukey} = .013$; cup–handle: $t = -4.261, p_{tukey} = .0005$; handle–window: $t = 3.045, p_{tukey} = .019$ (see Figure 2). Moreover, we saw significantly higher ratings of the immersion for *hold handle* compared to *take cup* ($t = -2.958, p_{tukey} = .024$) and *close window* ($t = 3.351, p_{tukey} = .008$).

Subjective Comments: In the end of the experiment, we asked participants to describe their opinions and suggestions about the experienced version. Two experimenters developed a set of recurring themes, using thematic analysis on the original notes as demonstrated in [3]. We summarized the results below, citing some exemplary quotes with the participant ID.

Dimension and layout influence how well visualizations blend into VR. The participants found both *3D* and *2D* visual cues were weaved into the virtual environment without noticeable interruptions during the VR game. However, the *2D* version was criticized regarding its (lack of) dimension and layout. The nature of the elements being flat images positioned in a three-dimensional virtual environment was perceived by some participants as off-putting and disorienting, since not the whole in-car space was represented but only the areas of interest. *"I found* 2D *pictures a little irritating, because the pictures were flat" (P12).* Additionally, the image of the door (*hold handle* and *close window*) was always within the field of view of the user, while the picture of the back seat (*lower armrest* and *take cup*) was not visible unless they turned their heads left towards it. Because of this layout, when an action had to be performed in the middle of the back row, the first thing the users saw was still the picture of the door on the right, which sometimes led to confusion as to which task had to be performed. *"When I had to do the task with the armrest I was confused because I had to do something on the left but the image I saw was on the right, which irritated me a bit" (P19).*

Table 1: Descriptive statistics of the mean (M) values with standard deviation (SD) in brackets. Two-sample T-test (equal variances assumed) results for game score (a maximum of 40 mushrooms/credits), usability (0–100 score scale), IPQ presence (1–7 Likert Scale), and user experience (−3–3 Likert Scale). A Mann-Whitney U test is used for abnormally distributed data.

	3D	2D	
Game Score	24.33 (9.25)	30.30 (5.12)	$t(17) = 1.765, p = .095$
Overall Presence	4.60 (0.70)	4.33 (0.99)	$U = 44.0, p = .967$
General Presence	5.33 (1.0)	4.90 (1.66)	$t(17) = -0.678, p = .507$
Spatial Presence	5.24 (0.94)	5.24 (1.34)	$t(17) = -0.008, p = .994$
Involvement	4.33 (0.84)	4.48 (1.34)	$t(17) = -0.272, p = .789$
Experienced Realism	3.89 (0.97)	2.90 (1.17)	$t(17) = -1.989, p = .063$
Usability	75.0 (15.7)	68.3 (24.3)	$t(17) = -0.710, p = .488$
Overall User Experience	1.21 (0.81)	0.45 (1.28)	$t(17) = -1.53, p = .146$
Pragmatic Quality	1.28 (1.01)	0.48 (1.82)	$t(17) = -1.17, p = .259$
Hedonic Quality	1.14 (1.02)	0.43 (1.0)	$t(17) = -1.54, p = .143$

Table 2: Statistical testing for main effects on Visual Cues and Tasks, with interaction effects. $p < .05$ highlighted in gray.

	Visual Cues	Tasks	Visual Cues×Tasks
Workload	$F(1, 17) = 0.204, p = .657$	$F(3, 51) = 6.742, p = .0006$	$F(3, 51) = 1.065, p = .372$
Immersion	$F(1, 17) = 2.858, p = .109$	$F(3, 51) = 4.475, p = .007$	$F(3, 51) = 1.833, p = .153$

Demand for synchronous visualization regardless of its dimension. For example, when the armrest is lowered by the user in the real car, this action should also be represented in the virtual world. This would increase the level of acceptance of these elements and as a consequence also improve immersion. Instead, when the real action does not have any representation in the virtual world, it reminds the users that they are in a fake environment and only brings more attention to the real world around them. *"[...]for example with the armrest and the cup, there was no virtual cup so that was not helpful at all" (P4).* Others suggested to smoothen the way in which the 3D model of the car suddenly appeared, seemingly out of nowhere. *"I believe the transition between the game and the representation of the car should have been more fluid" (P6).* To fix this issue, one suggestion given by a participant was to integrate the car model in the environment at all times but keeping it at a very high transparency, only fully blending it in when the time came to complete a task. This way the transition would not be as stark and the user could be mentally prepared for the change. *"Perhaps you could have the car always shimmering in the background, so that it's always there in the background and then you bring it to the front when it's relevant" (P3).*

Wish for hand visualizations in addition to virtual controllers. During the experiment, different behaviors were observed, from putting down the controller to moving it to the other hand and even keeping a hold of it and using unusual hand movements to perform the operation tasks. For example, in the real-world video (see the supplementary video figure 0:13), the participant handed the controller from the right to the left hand and pressed the window button with the right hand. In contrast, the VR video recorded another participant who did not switch the controller and performed the window task with the controller holding in the right hand. Therefore, the VR video shows the virtual controller pressing the window button. Eight out of 19 participants stated that the missing virtual representation of hand movements hindered their task performance, despite of the virtual controller visible all the time. In particular, P6 said *"I couldn't see the hands, therefore it (the 3D model) didn't help all that much"*. Since the users could not see where precisely their hands were positioned in VR, they had to approximate the position relative to the car elements. Finally, 13 out of 19 participants claimed that they would personally use VR only if motion sickness was not a factor. Of the other six participants that would not, two explained that the reason for that choice was the lack of confidence in the driver, as they would want to always pay attention to the surroundings.

5 DISCUSSION & FUTURE WORK

Our preliminary data analysis showed significant differences across tasks, especially the *hold handle*. Specifically, users perceive a lower workload in the task *hold handle* than all other tasks. In addition, they feel more immersed in the virtual environment after completing this task than *take cup* and *close window*. Based on this preliminary data analysis, we found that the difficulty of the real-world task influences users' immersion in the virtual world after they transition from reality to VR. However, it is unclear which factor played a dominant role in the implemented task. This result requires further validation with structured control variables, for example, if this discrepancy lies in the spatial position of the task (seat side on the left vs. door side on the right) or the task action itself (take up vs. hold on to an object). In a follow-up study, we will include these insights into the variable design of the real-world task according to multiple dimensions, such as the spatial position, the required hand movement, and the task sequence (the order of multi-tasks like first *lower armrest* and then *take cup*).

The qualitative feedback unveiled the demand for synchronous visual cues. We found that it is important to have the live visual cues of these moving elements, like the window, the armrest, and the cup in the holder, match the changes that users applied to them in the real car. The participants envisioned animated visual cues showing real-time changes. Furthermore, the way these visual cues (dis)appear can benefit from a smooth animation, as voiced by some participants. In the follow-up study, we will explore the animation principles (Slow-in-and-out, Anticipation, Follow-through, Exaggeration) which were found to influence user experience in mobile user interfaces [24]. For example, 1) initiating or finishing the transition from the virtual world to the passenger's real surroundings inside the car, showing a view window to the car using Slow-in-and-out and Anticipation to diminish breaks in presence, and 2) the transition across two realities by adhering to Follow-through and Exaggeration, integrating the physical law of inertia.

The participants found that our concept provided good usability, but they missed the virtual representation of their hand movements on top of the virtual controller. Although the VR industry and research widely adopted the controllers as input devices, it is questionable how the controllers can facilitate the real-work tasks that may require the user's hands. A potential alternative is the mid-air gesture interaction, which avoids the conflict between the usage of the controller and the hands, especially when manipulating small objects requiring delicate finger operation. However, it could still cause physical discomfort such as arms fatigue after interacting for a long time. Furthermore, recent advances in VR technology such as passthrough API and see-through VR headsets [26] enabled users to see the real surroundings and real hands while performing real-world tasks and transition to virtual environments and virtual hands for VR tasks. One potential challenge is the design of the transition between virtual and real environments, such as the proper amount of reality and the trigger interaction, maintaining necessary real-world awareness and VR immersion simultaneously. For example, the transition can be hand-enabled (reality around user's hands [20]) or object-enabled (reality around targeted objects), which might introduce different levels of cognitive workload among users. As a future step, we plan to study the impact of varying input (controller vs. mid-air gesture) and transition approaches (hand-enabled vs. object-enabled) on the performance and perceived workload of two tasks in VR and the physical rear-seat space, respectively.

5.1 Limitations

We reflect on the limitations of the stationary testing environment in a parked car. Our results might differ if users need to perform these tasks in a moving vehicle, such as increased workload perception due to the lack of precise control under frequent vehicle movements. We call for future research to test dynamic traffic environments and their impact on passenger sickness and simulator sickness while transitioning between two worlds [18]. Additionally, in this study, we omitted the question of social acceptance when other co-located passengers are present [2]. Future work can explore the real-world awareness of bystanders in the transportation context, considering scalability and proximity design, such as the number of co-located passengers and their distance and orientation changes to the VR user[11, 23, 34]. Finally, we reflect on our small sample size, which can cause the lack of statistical significance in the two visual cues.

6 CONCLUSION

In this paper, we introduced the concept of incorporating essentials of the passenger's surroundings into VR for balancing real-world awareness and immersion to support tasks in both realities. The results from our pilot study revealed that the real-world task design influences the user's perceived workload and feeling of immersion in VR after completing the task. Specifically, the implemented task *hold handle* received lower ratings of workload than all other tasks and higher ratings of immersion than *take cup* and *close window*. Seeing the visual cues of the car interior and regions incorporated inside VR when performing rear-seat operation tasks were perceived by users with good usability and moderate levels of presence and user experience on average. Based on the results, we plan to investigate real-world task types, synchronous visual cues, and various input and transition approaches in a follow-up study in the wild to deepen our insights in this everyday mobile VR context.

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REFERENCES

[1] Audi. 2019. holoride: Virtual Reality meets the real world. https://www.audi.com/en/experience-audi/mobility-and-trends/digitalization/holoride-virtual-reality-meets-the-real-world.html Accessed: 2022-3-2.

[2] Laura Bajorunaite, Stephen Brewster, and Julie R Williamson. 2021. Virtual Reality in transit: how acceptable is VR use on public transport?. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, Lisbon, Portugal, 432–433.

[3] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qual. Res. Psychol.* 3, 2 (Jan. 2006), 77–101. https://doi.org/10.1191/1478088706qp063oa

[4] John Brooke et al. 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry* 189, 194 (1996), 4–7.

[5] Peter Fröhlich, Clemens Schartmüller, Philipp Wintersberger, Andreas Riener, Andrew L Kun, Stephen Brewster, Orit Shaer, and Matthias Baldauf. 2021. AutoWork 2021: Workshop on the Future of Work and Well-Being with Automated Vehicles. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 164–166.

[6] Ceenu George, Patrick Tamunjoh, and Heinrich Hussmann. 2020. Invisible Boundaries for VR: Auditory and Haptic Signals as Indicators for Real World Boundaries. *IEEE Transactions on Visualization and Computer Graphics* 26, 12 (2020), 3414–3422.

[7] Ceenu George, An Ngo Tien, and Heinrich Hussmann. 2020. Seamless, Bidirectional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, Porto de Galinhas, Brazil, 412–424.

[8] Sarthak Ghosh, Lauren Winston, Nishant Panchal, Philippe Kimura-Thollander, Jeff Hotnog, Douglas Cheong, Gabriel Reyes, and Gregory D Abowd. 2018. NotifiVR: exploring interruptions and notifications in virtual reality. *IEEE transactions on visualization and computer graphics* 24, 4 (2018), 1447–1456.

[9] Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4034–4044. https://doi.org/10.1145/3025453.3025665

[10] Pascal Knierim and Albrecht Schmidt. 2020. The Virtual Office of the Future: Are Centralized Workplaces Obsolete? (August 2020). https://www.microsoft.com/en-us/research/publication/the-virtual-office-of-the-future-are-centralized-workplaces-obsolete/

[11] Yoshiki Kudo, Anthony Tang, Kazuyuki Fujita, Isamu Endo, Kazuki Takashima, and Yoshifumi Kitamura. 2021. Towards Balancing VR Immersion and Bystander Awareness. *Proceedings of the ACM on Human-Computer Interaction* 5, ISS (2021), 1–22.

[12] Matthew Lakier, Lennart E. Nacke, Takeo Igarashi, and Daniel Vogel. 2019. Cross-Car, Multiplayer Games for Semi-Autonomous Driving. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (Barcelona, Spain) *(CHI PLAY '19)*. Association for Computing Machinery, New York, NY, USA, 467–480. https://doi.org/10.1145/3311350.3347166

[13] Bettina Laugwitz, Theo Held, and Martin Schrepp. 2008. Construction and evaluation of a user experience questionnaire. In *Symposium of the Austrian HCI and usability engineering group*. Springer, Berlin, Heidelberg, 63–76. https://doi.org/10.1007/978-3-540-89350-9_6

[14] Jingyi Li, Ceenu George, Andrea Ngao, Kai Holländer, Stefan Mayer, and Andreas Butz. 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* (Virtual Event, DC, USA) *(AutomotiveUI '20)*. Association for Computing Machinery, New York, NY, USA, 92–95. https://doi.org/10.1145/3409251.3411732

[15] Jingyi Li, Ceenu George, Andrea Ngao, Kai Holländer, Stefan Mayer, and Andreas Butz. 2021. Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car. *Multimodal Technologies and Interaction* 5, 4 (2021), 15.

[16] Jingyi Li and Linda Hirsch. 2021. Multi-Modal Transition and Traces in Everyday Mobile Virtual Reality. In *ISS'21 Workshop Proceedings: "Transitional Interfaces in Mixed and Cross-Reality: A new frontier?"*, Hans-Christian Jetter, Jan-Henrik Schröder, Jan Gugenheimer, Mark Billinghurst, Christoph Anthes, Mohamed Khamis, and Tiare Feuchtner (Eds.). Association for Computing Machinery, New York, NY, USA. https://doi.org/10.18148/kops/352-2-1dhqpjucpo75v9

[17] Jingyi Li, Yong Ma, Puzhen Li, and Andreas Butz. 2021. A Journey Through Nature: Exploring Virtual Restorative Environments as a Means to Relax in Confined Spaces. In *Creativity and Cognition* (Virtual Event, Italy) *(C&C'21)*. Association for Computing Machinery, New York, NY, USA, Article 22, 9 pages. https://doi.org/10.1145/3450741.3465248

[18] Jingyi Li, Agnes Reda, and Andreas Butz. 2021. 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* (Leeds, United Kingdom) *(AutomotiveUI '21)*. Association for Computing Machinery, New York, NY, USA, 28–38. https://doi.org/10.1145/3409118.3475137

[19] Mark McGill and Stephen Brewster. 2019. Virtual Reality Passenger Experiences. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 434–441. https://doi.org/10.1145/3349263.3351330

[20] Mark McGill, Roderick Murray-Smith, Daniel Boland, and Stephen A. Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 177. https://doi.org/10.1145/2702613.2732491

[21] Mark McGill, Alexander Ng, and Stephen Brewster. 2017. I Am The Passenger: How Visual Motion Cues Can Influence Sickness For In-Car VR. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 5655–5668. https://doi.org/10.1145/3025453.3026046

[22] Mark McGill, Julie Williamson, Alexander Ng, Frank Pollick, and Stephen Brewster. 2020. Challenges in passenger use of mixed reality headsets in cars and other transportation. *Virtual Reality* 24, 4 (2020), 583–603.

[23] Daniel Medeiros, Rafael dos Anjos, Nadia Pantidi, Kun Huang, Maurício Sousa, Craig Anslow, and Joaquim Jorge. 2021. Promoting reality awareness in virtual reality through proxemics. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, Lisboa, Portugal, 21–30.

[24] Benedikt Merz, Alexandre N. Tuch, and Klaus Opwis. 2016. Perceived User Experience of Animated Transitions in Mobile User Interfaces. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 3152–3158. https://doi.org/10.1145/2851581.2892489

[25] Metaverse. 2019. Oculus. https://www.oculus.com/ Accessed: 2022-3-2.

[26] VR Oculus. 2021. Mixed Reality with Passthrough. https://developer.oculus.com/blog/mixed-reality-with-passthrough/ Accessed: 2022-3-2.

[27] Joseph O'Hagan and Julie R Williamson. 2020. Reality aware VR headsets. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays* (Manchester, United Kingdom) *(PerDis '20)*. Association for Computing Machinery, New York, NY, USA, 9–17. https://doi.org/10.1145/3393712.3395334

[28] Pablo E Paredes, Stephanie Balters, Kyle Qian, Elizabeth L Murnane, Francisco Ordóñez, Wendy Ju, and James A Landay. 2018. Driving with the fishes: Towards calming and mindful virtual reality experiences for the car. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 4 (2018), 1–21.

[29] Sylvia Rothe, Alexander Schmidt, Mario Montagud, Daniel Buschek, and Heinrich Hußmann. 2021. Social viewing in cinematic virtual reality: a design space for social movie applications. *Virtual Reality* 25, 3 (2021), 613–630.

[30] Thomas W Schubert. 2003. The sense of presence in virtual environments: A three-component scale measuring spatial presence, involvement, and realness. *Z. für Medienpsychologie* 15, 2 (2003), 69–71.

[31] Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3307–3316. https://doi.org/10.1145/2702123.2702389

[32] Robert Stone, Charlotte Small, James Knight, Cheng Qian, and Vishant Shingari. 2014. Virtual natural environments for restoration and rehabilitation in healthcare. In *Virtual, Augmented Reality and Serious Games for Healthcare 1*. Springer, Berlin, Heidelberg, 497–521. https://doi.org/10.1007/978-3-642-54816-1_24

[33] Julius von Willich, Markus Funk, Florian Müller, Karola Marky, Jan Riemann, and Max Mühlhäuser. 2019. You Invaded My Tracking Space! Using Augmented Virtuality for Spotting Passersby in Room-Scale Virtual Reality. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 487–496. https://doi.org/10.1145/3322276.3322334

[34] Julie R. Williamson, Mark McGill, and Khari Outram. 2019. PlaneVR: Social Acceptability of Virtual Reality for Aeroplane Passengers. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3290605.3300310

[35] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963