Location-Aware Virtual Reality for Situational Awareness On the Road

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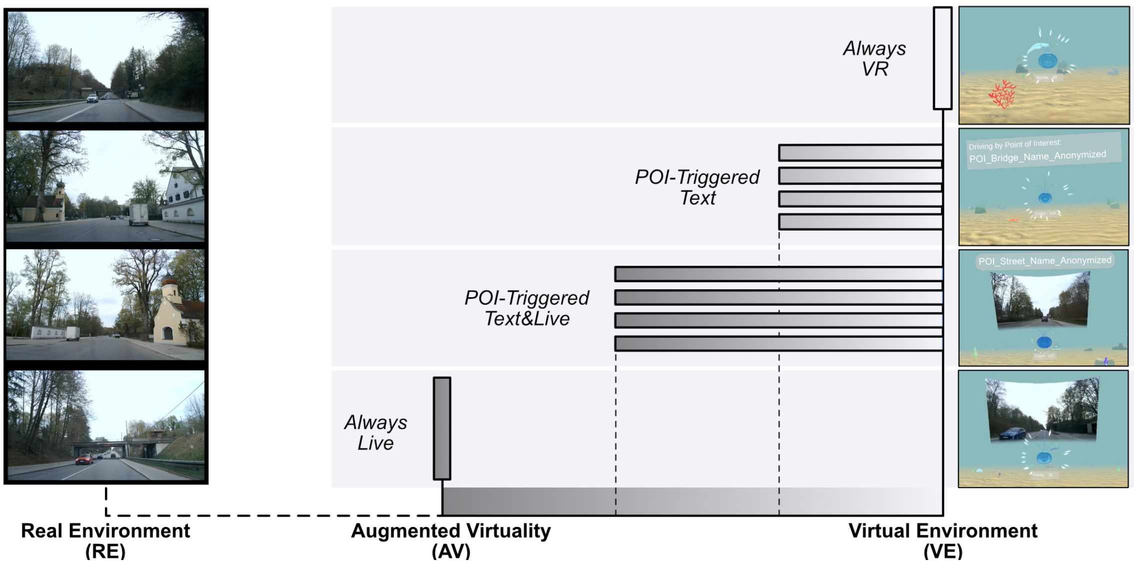


Figure 1: We investigated situational awareness during mobile virtual reality (VR) interaction on the road, along the Reality-Virtuality (RV) continuum [42] focusing on the subset between augmented virtuality (AV) and virtual environment (VE). These endpoints represent two baselines that persistently 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*).

ABSTRACT

When future passengers are immersed in Virtual Reality (VR), the resulting disconnection from the physical world may degrade their situational awareness on the road. We propose incorporating real-world cues into virtual experiences when passing specific locations to address this. 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 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 situational awareness challenges for using mobile VR on the road and potential incorporation strategies across transport contexts.

SUI '23, October 13–15, 2023, Sydney, NSW, Australia

ACM ISBN 979-8-4007-0281-5/23/10…$15.00
https://doi.org/10.1145/3607822.3614530

CCS CONCEPTS

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

KEYWORDS

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 *The 2023 ACM Symposium on Spatial User Interaction (SUI '23), October 13–15, 2023, Sydney, NSW, Australia.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3607822.3614530

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 or 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]. At the same time, this full immersion empowers passengers to block real-world distractions from traffic environments just like they do by wearing noise-canceling headphones already in today's commutes. 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 for more suitable ergonomics [33, 35, 59]. While feeling present and secluded in the virtual world, mobile VR users, i.e., users who wear VR headsets while moving in real world, 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 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, and, 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

[1]https://developer.oculus.com/blog/mixed-reality-with-passthrough/, last accessed August 28, 2023
[2]https://vrscout.com/news/oculus-quests-space-sense-feature-detects-people-and-pets/, last accessed August 28, 2023

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 Theater 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, 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 [24, 26, 34, 50], 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 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

[3]https://www.bmw.com/en/events/ces2022/theaterscreen.html, last accessed August 28, 2023
[4]https://www.holoride.com/en, last accessed August 28, 2023
[5]https://www.flixbus.com/virtual-reality, last accessed August 28, 2023

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 on-demand 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 visualization cues were found unrealistic when viewing these computer-animated artifacts in captured 360-degree videos, which limits their generalizability 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

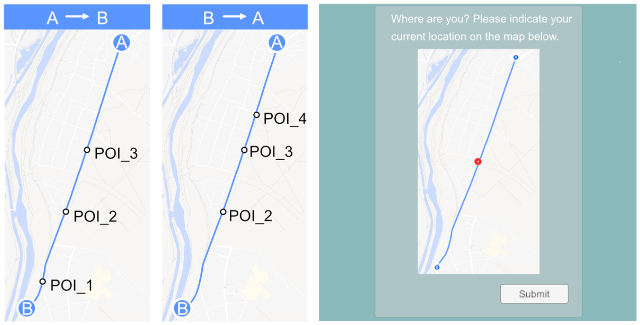
We evaluated our concepts to answer the research question: *"How can we preserve in-car VR users' sense of presence in virtual entertainment environments while maintaining their on-road situational awareness during the ride?"*

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 was between point A Klinikum Harlaching (48.086910, 11.554790) and point B Gartenweg (48.061717, 11.542246), which was about 3 kilometers long and took around 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



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

Figure 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.

step. After completing this task, they resumed interaction with the virtual entertainment scene.

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. 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 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

[6]http://www.capsicumdreams.com/gps2ip/, last visited August 28, 2023
[7]https://www.nmea.org/content/STANDARDS/NMEA_0183_Standard, last visited August 28, 2023
[8]https://www.chiark.greenend.org.uk/~sgtatham/putty/, last visited August 28, 2023

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 η^2.

	POI-Triggered Text&Live		POI-Triggered Text		Always Live		Always VR		Friedman Test			
Measure	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	χ^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

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 of LMU Munich (ID: EK-MIS-2022-095).

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 η^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 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.

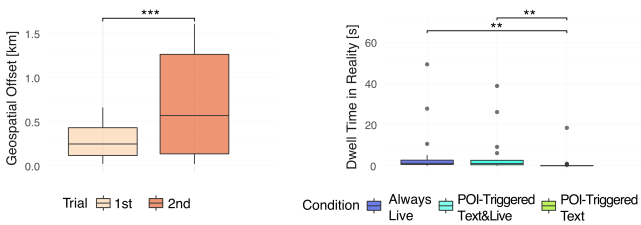


Figure 3: The significant differences in the geospatial offset between the temporal order of in-VR map tasks (left) and the dwell time on transit visual cues across conditions (right). $*$ **denotes** $p \leq .05$**,** $**$ **denotes** $p \leq .01$**,** $***$ **denotes** $p \leq .001$**.**

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.

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 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

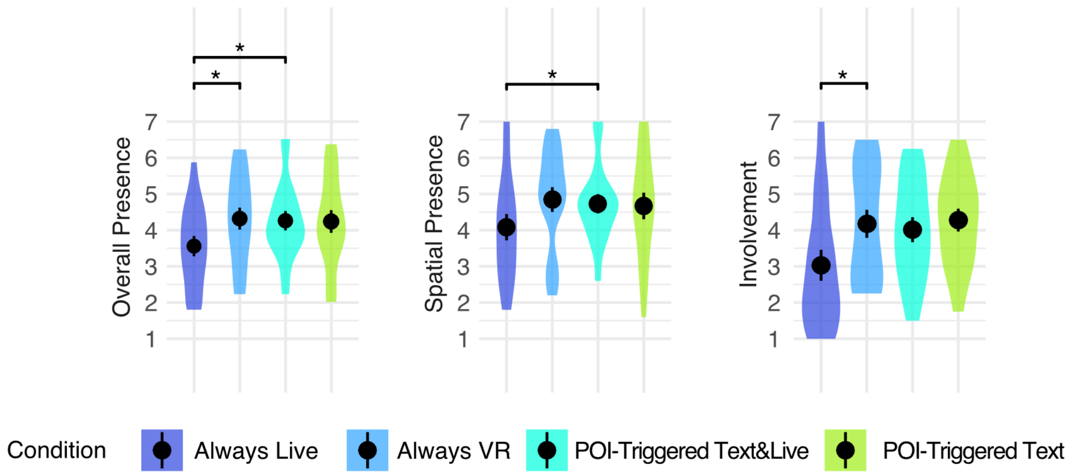


Figure 4: The distribution of the significant results in the IPQ presence questionnaire. $*$ denotes $p \leq .05$.

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

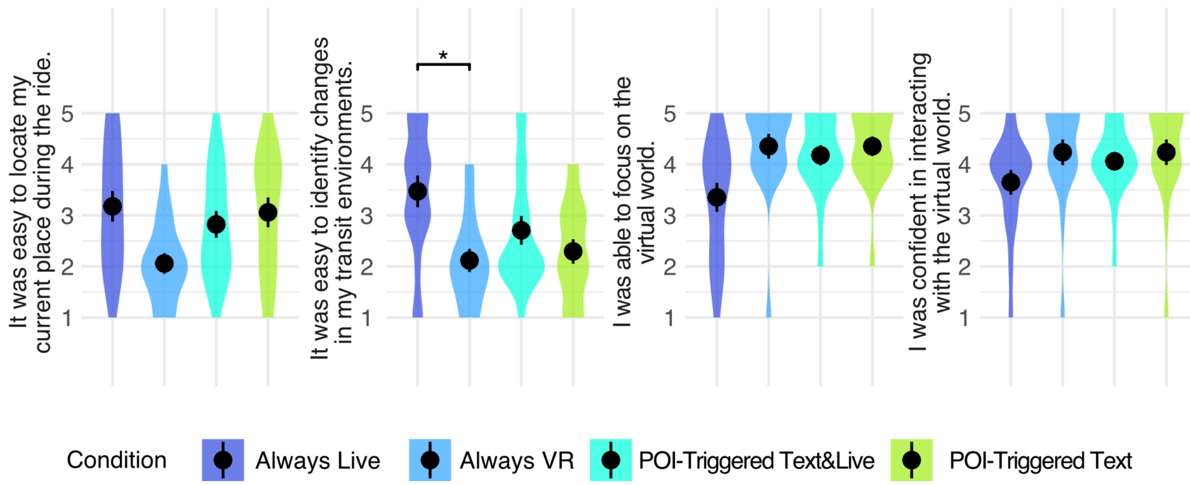


Figure 5: The participants' answers to our self-defined questions using a 5-point Likert Scale (1: strongly disagree, 5: strongly agree). $*$ **denotes** $p \leq .05$.

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 arrivals 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.

ACKNOWLEDGMENTS

We would like to thank all participants who took part in our experiment.

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