Immersive In-Situ Prototyping: Influence of Real-World Context on Evaluating Future Pedestrian Interfaces in Virtual Reality

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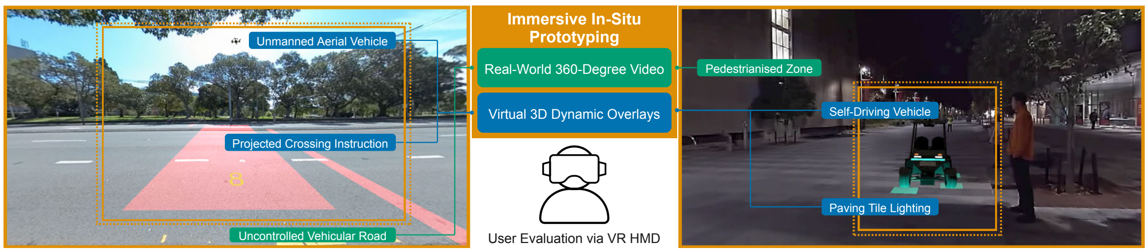

Fig. 1. Immersive in-situ prototypes for evaluating futuristic pedestrian interfaces.

Pedestrian interfaces support people's interaction with autonomous agents in traffic scenarios. Early studies relied on computer-generated (CG) environments to evaluate pedestrian interfaces in virtual reality (VR). More recently, real-world 360-degree videos have been used as an alternative to CG environments as they support immersive and realistic experiences. This paper reports on the combined use of 360-degree videos and dynamic CG interfaces as a new approach for evaluating pedestrian interfaces, referred to as *immersive in-situ prototyping*. We analyse participant feedback from two case studies that used this approach for evaluating pedestrian interfaces from a drone and from an autonomous vehicle. Results show that participants considered the immersive in-situ prototypes realistic, natural, and familiar and found them to facilitate connections to real-life experiences. We describe the process for developing immersive in-situ prototypes and offer technical considerations for future studies.

CCS Concepts: • **Human-centered computing → Systems and tools for interaction design**.

Additional Key Words and Phrases: Prototyping, 360-Degree Videos, Virtual Reality, Pedestrians, Human-Machine Interfaces

1 INTRODUCTION

With the rapid advancement of technologies such as artificial intelligence and the internet of things, the human-computer interaction (HCI) community is continuously researching novel human-machine interfaces (HMIs); for example, to support pedestrian interactions with autonomous vehicles (AVs) [4, 12] or to provide drone-aided navigation services [6, 20]. These kinds of HMIs support the activity of pedestrians in urban environments, which this paper collectively refers to as "pedestrian interfaces", represent a new area of research within the field of HCI. Prototypes that convey novel HMI concepts to prospective stakeholders play an important role in evaluating the effectiveness and acceptance of early design proposals or informing future development and deployment [7, 24]. However, there are design concepts that are pushing the boundaries of existing technologies, introducing technical, legal, or risk challenges in early-stage testings in the real world; for instance, externally projected pedestrian crosswalks [32] or augmented driving head-up displays [45]. The evaluation of these HMIs usually opt for virtual reality (VR) prototypes to ensure the safety of participants. Nevertheless, it is important for HMI prototypes to consider real-world dynamics and stimuli, as the physical deployment of the final product needs to consider contextual factors related to the location, environment, and local culture [14, 17, 27, 40].

Among prototyping methods that capture contexts, such as in-situ mockups and concept videos, extended reality (XR)[1] offers promising platforms to simulate environments and scenarios where HMIs are intended for use. In recent years, computer-generated (CG) VR has gained considerable popularity for evaluating AV–pedestrian HMIs, as it is found to be immersive and flexible for rapid refinement [9, 31, 40]. Leveraging the naturalness of the physical world, HCI researchers have also started to develop traffic simulators based on realistic environments, including augmented reality (AR) vehicle-pedestrian simulators [28] and real-world video-based mixed reality (MR) driving simulators [48]. Considered a lightweight tool to construct XR applications [3, 50], 360-degree panoramic videos provide omnidirectional recordings of the real world. Previous studies found that 360-degree videos are both immersive and realistic when viewed through head-mounted displays (HMDs) [19, 35, 46]. In addition, they offer a relatively simple and inexpensive way (e.g., not requiring programming or 3D modelling skills) [2, 18, 50] to create contextualised environments in high fidelity [38, 46, 49]. While there is a growing interest in using 360-degree videos for immersive HMI evaluation [8, 15, 17], no research has yet explored the approach of combining 360-degree videos with visually dynamic CG pedestrian interfaces and its implications in supporting user evaluations.

Building on prior work, we present a rapid and cost-effective approach to introduce realistic contexts into early prototypes of futuristic and often speculative HMI proposals. The approach uses 360-degree recordings of the real world that are overlaid by 3D-rendered virtual objects (e.g., an AV with pedestrian interfaces). We refer to this prototyping approach as *immersive in-situ prototyping*. The term *immersive* denotes the prototypes being presented in a non-physical world (e.g., accessed via VR headsets). In-situ evaluation refers to evaluating a product in its real usage context [44]. In our method, the term *in-situ* captures the aspect of situating the HMI into its context of use with a fidelity that closely resembles reality. To provide early insights, we present two case studies that employed this approach for evaluating novel HMI proposals. Both studies investigated pedestrian interfaces related to intelligent traffic systems, notably drones and autonomous vehicles, in different urban settings. Based on our findings and prototyping processes, we discuss considerations for using and developing immersive in-situ prototypes.

2 RELATED WORK

2.1 Immersive Real-World Video Applications

360-degree videos, offering the ability to capture reality in panoramic views, have become an increasingly popular technique for creating immersive experiences [19, 35, 46, 49]. Since 360-degree videos contain ample on-site information, they have been utilised in areas like tourism (e.g., cultural heritage visiting [3], destination promotion [47]), education (e.g., remote lecture [19], surgical training [49]) and journalism [22, 43]. Empirical studies in these fields have discovered that immersive 360-degree videos, i.e., viewing via HMDs, provide users with a high visual-audio realism [38, 46, 49, 50], sense of presence [19, 35, 43, 47], and situational awareness [46, 50]. Their applications in experiential media have been found to be engaging [3, 19, 38] and effective for storytelling [22, 43].

[1] In this paper, we use XR as an umbrella term to encompass VR, AR, and MR [3, 50], referring to blending physical and virtual environments through computer and display technologies [29, 30].

As 3D development platforms (e.g., Unity 3D[2], Unreal Engine[3]) currently provide vast libraries and ease of deployment to various devices, researchers have started to explore methods to augment solely 360-degree video-based environments with virtual content. Hoggenmueller and Tomitsch [16] proposed the concept of "hyperreal prototyping" for urban pervasive displays, referring to the potential of such techniques in creating VR simulations where the distinction between the virtual and the physical becomes blurred. Similarly, Lee et al. [21] proposed "augmented virtual reality" for comparing interior design plans, emphasising real-world videos could help enhance the realism of completely CG VR. Using 360-degree videos to simulate a presence in the real world, some studies have prototyped AR experiences [5, 33] or added UI elements for interaction purposes [2, 3, 18, 50]. Our research builds on the conceptual and empirical foundations in literature and contributes to prototyping pedestrian experiences with HMIs in urban traffic situations.

2.2 Simulate Human-Machine Interfaces in Traffic

VR simulators are increasingly recognised for their flexibility and safety for pedestrian research [9, 40], allowing for the creation of diverse traffic scenarios with reduced time, cost, and safety risks compared to physical setups [10, 27, 31]. They are also useful for developing mockups of speculative HMI concepts that are difficult to physically implement with existing technologies, and therefore, facilitating early user feedback and concept refinement [11, 25, 32, 41]. Studies also highlight the importance of contextual setups in VR; for example, the visual realism and social atmosphere of VR environments can influence experiential qualities like sense of presence, level of comfort, and feeling of naturalness [36, 37, 40]. Real-world videos provide authentic representations of reality and hence are often employed in traffic research to increase the ecological validity of simulations, such as monitor-based videos [1, 26], projector-based immersive "CAVE" [14], and 360-degree video-based VR [8]. The latter has gained increasing attention in recent years, demonstrating that immersive real-world videos are effective in conveying contextual information with high visual fidelity, spatial presence, and engagement [13, 17, 48].

A few studies related to traffic HMIs have started to apply rendered overlays onto real-world video-based VR, including driving simulators (interior UIs [15, 48] and other on-road cars [48]) and AV–pedestrian HMIs (preprocessed static interfaces [42] and synthesised sounds [13]). However, so far, there has been no empirical evaluation of dynamic visual overlays of pedestrian interfaces that are integrated into immersive real-world videos. Furthermore, it is unclear how realistic environments can impact pedestrian evaluations of futuristic HMI proposals.

3 METHODOLOGY

We report on two case studies, in which we created immersive in-situ prototypes for testing speculative HMIs designed for pedestrians: (1) Drone–Pedestrian: the HMIs provided drone-assisted crossing instructions at an uncontrolled road; (2) AV–Pedestrian: the HMIs conveyed the AV's intention to stop in a pedestrianised zone. Both case studies involved an evaluation with users to gather feedback on the HMI proposals. Analyses of user data were conducted and combined to understand our research question: *How can real-world contexts in virtual reality influence pedestrian evaluations of futuristic human-machine interfaces?*

3.1 Case Study Context

Investigating HMIs that can support pedestrian safety has gained considerable research attention in the last decade due to the rising of autonomous systems in the urban mobility infrastructure [10, 31]. This is motivated by the

[2] https://unity.com/
[3] https://www.unrealengine.com/

critical role of HMIs in conveying vehicle intention and facilitating pedestrian interactions [4, 12]. Considering future traffic as an intelligent, interconnected network, the Drone–Pedestrian study investigated how drone-based interfaces could guide pedestrians through dangerous road situations, utilising the birds-eye view advantage of drones for traffic monitoring [16, 20]. Building upon this body of work, the AV–Pedestrian study explored design options of AV–pedestrian communication interfaces in highly urbanised areas [27, 40]. The speculative nature of the HMIs involved in both case studies introduced difficulties in evaluating them in the real world. Therefore, the immersive in-situ prototypes provided opportunities to collect early user feedback with the inclusion of real-world contexts.

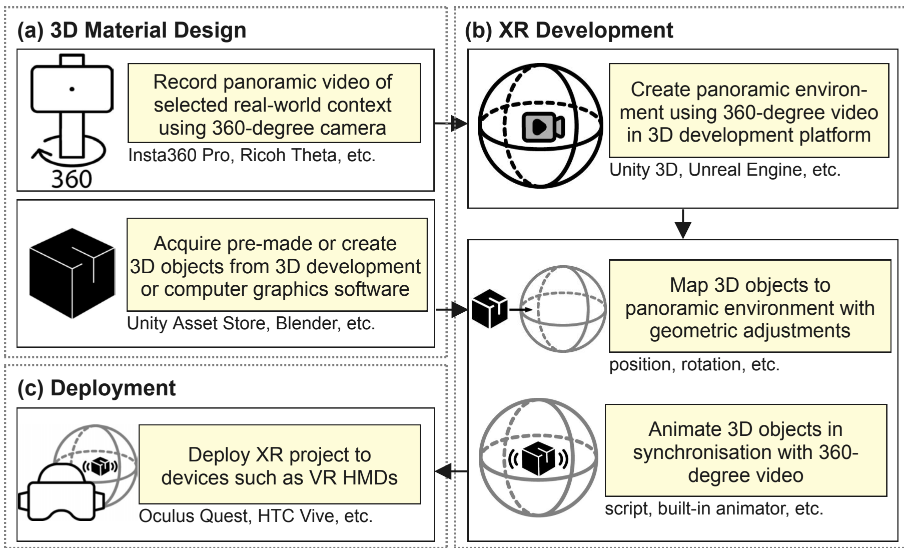

Fig. 2. An overview of the immersive in-situ prototyping process.

3.2 Prototype Development

We summarised the development procedures based on the two case studies and present an overview of the process in Figure 2. Figure 3 reports details of the prototype setups. To record the 360-degree videos, we selected filming locations in a neighbourhood close to the city centre and used Insta360 Pro 2 as our video and sound recording device. The Drone–Pedestrian study contained two scenarios requiring participants to cross back and forth respectively on a busy public road next to a popular park. The AV–Pedestrian study involved participants walking down a pedestrianised corridor connecting a main road to a university campus. We obtained the 3D quadcopter model from Unity Asset Store and created the passenger transport pod using Autodesk 3ds Max (as a replica of one of our university's real-world AVs). For the HMIs, a variety of interface modalities were encompassed by the two studies, ranging from displays to projections to tile changes (see Figure 3). Besides the drone displays and drone projections, which were modelled in Blender, the rest of the interfaces were developed using Unity 3D libraries.

We developed the 3D scenes integrating the 360-degree videos and the virtual 3D objects using Unity 3D (see Figure 4 for final scenes). To simulate a 360-degree video as background environment, we applied the video as a render texture to a panoramic skybox material. The viewers would be able to see the environment from the perspective of the 360-degree

	Study I: Drone-Pedestrian	Study II: AV-Pedestrian
360-Degree Video		
Road Structure	Uncontrolled multi-lane road	Pedestrianised zone
Time of Day	Day time	Night time
Number of Scenarios	Two	One
Sound	Ambient audio recording	Ambient audio recording
Virtual 3D Overlay		
Vehicle Model	Quadcopter	Passenger transport pod
Vehicle Behaviour	Flying around overhead	Approaching slowly
HMI	(1) Drone movement, (2) On-drone display, (3) Ground projection	(1) On-vehicle light strip (2) Pulsating vehicle exterior (3) Ground projection (4) Paving tile lighting
Communication Message	Advise crossing	Indicate stopping intent
Sound	Flying noise, alert beeps	Fading engine sound

Fig. 3. The prototype setups across the two case studies.

camera that filmed the video. Based on the design scenarios, we mapped the 3D objects into the 3D skybox environment with geometric adjustments, including scaling, position and rotation, to overlay the objects in relation to the spatial layout in the video. Further, we animated the 3D objects, e.g., changing their movements or appearances, using coding scripts and Unity built-in animators. In this process, we repeatedly adjusted parameters of the animations and of the geometric or visual properties of the objects to achieve good synchronisations with the videos. Finally, the prototypes in both studies were deployed to Oculus Quest 2 for user evaluations.

3.3 User Evaluation

3.3.1 Participants and Tasks. Eighteen participants (13 male, 5 female) between the ages of 20–34 years (M=24.8, SD=3.0) were recruited for the Drone–Pedestrian study. Twenty-five participants (10 male, 15 female) between the ages of 20-50 years (M=28.7, SD=6.6) were recruited for the AV–Pedestrian study. Both user studies were approved by the human research ethics committee at the University of Sydney. In the Drone–Pedestrian study, upon encountering each drone interface, participants were asked to indicate their street-crossing decision by pressing a trigger button on the right controller when they felt like starting to cross. In the AV–Pedestrian study, as participants encountered the AV, they were asked to verbalise any thoughts, including any immediate feelings or intended actions, via the think-aloud protocol. In each study, participants experienced the proposed designs in randomised order.

3.3.2 Data Collection and Analysis. To collect feedback specifically on the simulations, we asked participants to complete the ITC-Sense of Presence Inventory (ITC-SOPI) [23]. The questionnaire consists of 38 items on 5-point Likert scales to measure four factors, namely *spatial presence* (the feeling of "being there"), *engagement* (the intensity of the experience and the feeling of being involved), *naturalness / ecological validity* (how natural is the displayed environment and the sensation that the scenes are plausible), and *negative effects* (e.g., motion sickness). In addition, participants were asked to provide any comments on their VR experiences. All study sessions were audio-recorded. For quantitative analysis, we combined the scores for each of the four factors in ITC-SOPI after confirming the internal

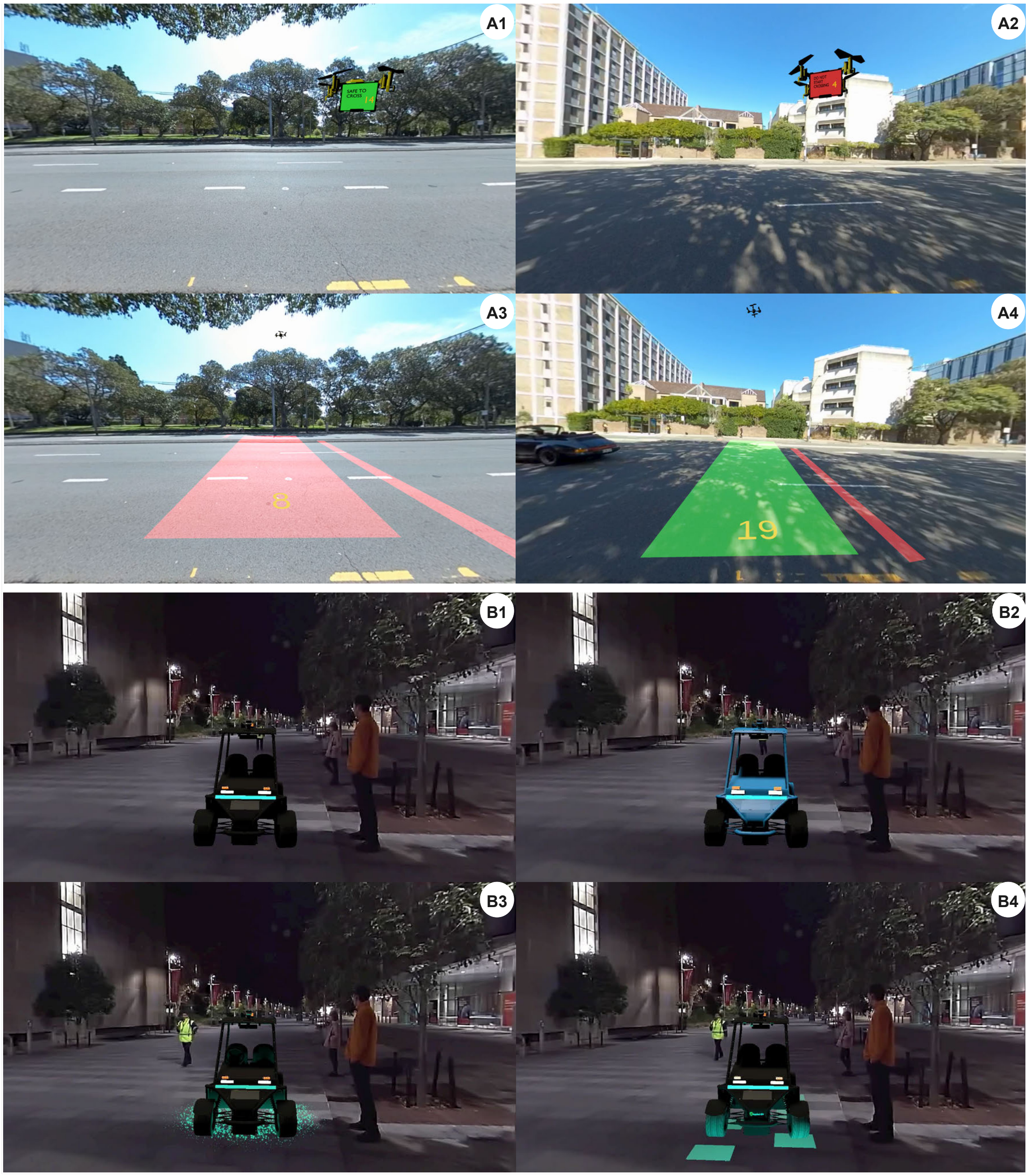

Fig. 4. VR scenes: Drone–Pedestrian (top), AV–Pedestrian (bottom). Colour and text cues via a display equipped on the drone (A1-A2) and colour cues and countdowns via projections from the drone (A3-A4) to advise crossing. On-vehicle light strip (B1), pulsating vehicle exterior (B2), ground projection (B3), and paving tile lighting (B4) to convey the AV's intention to stop.

consistency of the data, followed by a descriptive analysis of the data. For qualitative analysis, we transcribed the audio recordings from the two studies and analysed comments pertaining to the effects of the real-world contexts on user evaluations. Initially, one researcher from each case study independently performed open coding. Then, both researchers collaboratively discussed common patterns from their findings.

4 RESULTS

4.1 Sense of Presence

Results of the ITC-SOPI questionnaire (see Figure 5) show similar high ratings for the perceived naturalness or the ecological validity of the VR environments for both studies. Similarly, engagement ratings are generally high across the two studies. While spatial presence receives above middle ratings for both studies, the rating for the AV–Pedestrian study is lower than that for the Drone–Pedestrian study. Negative effects are low for both studies.

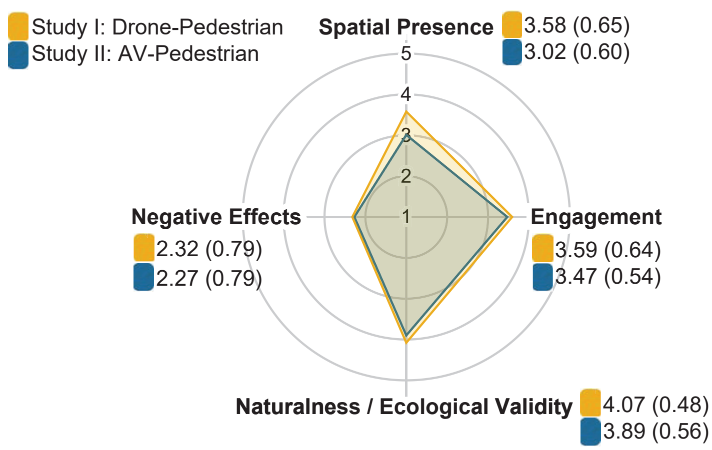

Fig. 5. Means (SD) of the ITC-SOPI questionnaire [23] across the two case studies.

4.2 Influence of Real-World Contexts

The qualitative analysis from both studies revealed three common patterns in how participants reacted to the prototypes.

4.2.1 Perceiving the environments as realistic and familiar. After experiencing the prototypes in VR, the majority of participants reported a high degree of realism in the scenarios they encountered. They noted that the highly realistic scenes created a strong sense of presence, as if they were truly present in those real-world situations: *"I feel that I'm in the real physical environment. I can see the pedestrians and the cars and hear traffic sounds" (P8, Drone).* This sensation even extended to emotional aspects; for instance, one participant mentioned feeling genuinely nervous while preparing to cross a street in the simulation: *"I did feel nervous to cross, even though I know it's just VR. I really felt like I was there" (P17, Drone).* Such experiences can largely be attributed to the scenes being recorded from the real world, where everything was considered natural and vivid, exhibiting high fidelity: *"I can see that the real people on the street have their own goals and intentions" (P23, AV).* Notably, the human behaviours within these environments were perceived by participants as very lifelike and consistent with those in reality: *"people were acting very normal, like they were just pedestrians. They were standing there, chatting. So, the whole VR scene seems quite daily" (P22, AV)*, which further intensified the sense of authenticity: *"there was one time when a pedestrian crossed at the back. I just looked and thought 'oh, there's a pedestrian behind me'. Yeah, the lady. At that moment. I felt like 'oh, this seems to be very realistic'" (P12, Drone).* Additionally, since the filming locations were in areas familiar to most participants, many were able to immediately recall their real-life experiences in these settings, noting a strong sense of familiarity: *"it's the road around [name of the building], so it feels very realistic to me. I can relate myself and it reminds me of my daily life" (P11, Drone).* Some participants further expressed their appreciation for this familiarity: *"what I thought was really good was that it did look like [name of the street] and had that feeling" (P14, AV).*

4.2.2 Making sense of the HMIs in relation to real-life observations. As participants encountered the speculative designs, many comprehended the designs by drawing on their real-life observations. Some participants were intrigued or even perplexed by concepts that extended beyond their everyday experiences; for instance, one participant asked *"how are the floors lighting up" (P8, AV).* Another participant expressed that the screen display felt more realistic than the projected crossing because *"there are indeed some drones [carrying a screen] like that...but you wouldn't see a light on the road" (P5, Drone).* P19 in the AV study noted that how one perceives such advanced concepts in VR *"depends on how these are adopted as general public understanding".* Notably, many participants used their experiences in similar real-world situations to explain what they saw in the virtual overlays. For example, some conjectured the function or purpose of the AV as *"security vans going around campus" (P20, AV)* and *"carrying something that needs to get from [name of the road] to us" (P18, AV).* Participants in the Drone study were found to understand flight patterns using norms they believed, as P1 stated *"if a drone is very close to you, I think it's like the drone has something to tell you"*, and P12 noted *"it's very interesting when the drone came back and emphasised [that I can cross], so at that moment I understand it better".*

4.2.3 Forming preferences based on habitual behaviours in similar settings. When assessing the design concepts, participants reflected on their own daily behaviours in similar settings and used that as a basis for forming their preferences. For example, some participants related to their walking habits in pedestrianised zones and therefore considered certain interface modalities being more suitable for them, e.g., *"if I had my noise cancelling headphones on, I will definitely be able to see the flashing lights more clearly compared to the light strip" (P13, AV)*, *"if I'm on my phone, I would probably see the ones on the ground a bit quicker than the ones in the air" (P7, AV).* Interestingly, we found that sometimes participants formed contrasted preferences based on their own analyses of the situations. In the Drone study, while some participants preferred the drone to be closer to *"catch the content on the screen" (P14, Drone)*, others perceived closer proximity as a safety risk, worrying *"what if there is an issue in its system" (P11, Drone).* Similarly, in the AV study, to avoid the car, some participants chose to move towards the side where other pedestrians (in the video) stood, seeing it as *"a safe place to stand" (P4, AV)*, whereas some preferred the side with more open areas since *"there are already people [on the other side] and there is more space over here" (P16, AV).*

5 DISCUSSION

5.1 Implications for Using Immersive In-Situ Prototyping

Our results suggest that immersive VR environments created from real-world recordings can enhance the realism of scenes through their high naturalness and familiarity. Based on prior studies using 360-degree video-based VR, immersive environments recorded from reality might have inherent advantages in ecological validity compared to those synthesised by computers, even in high visual fidelity [17]. Creating interaction scenarios in good naturalness can be important for evaluating traffic HMIs, as it can reduce potential uncanny valley effects of avatars or distractions from the novelty of virtual simulations [37, 40]. Furthermore, since the 360-degree video method supports conveying narratives with high plausibility [22, 43], it can be used to set up various environmental or social aspects often considered in testing pedestrian interfaces, such as the influence of other pedestrians [9, 27].

Our results further indicate that the familiarity of settings facilitated participants to immerse themselves as pedestrians and, furthermore, explicitly recognised the scenes as part of their daily lives and actively related to their everyday behaviours when assessing the futuristic interfaces. Such approaches open up opportunities for inquiring user requirements using representations of local contexts when conducting actual field studies is not feasible. This could serve as a useful phase in iterative design processes, for example, supporting the testing of early proposals with socio-cultural considerations, such as local traffic norms. With continued investigations, the immersive in-situ prototyping technique holds promise to assist the broader user-centred design research, as prior work using similar prototyping methods suggests its potential for user-engaged design [21], co-creation [50], and interface learning [35, 50].

5.2 Technical Considerations

In examining the efficacy of integrating 360-degree videos and virtual overlays, we observed that most participants did not emphasise or distinctly mention the technical aspect of overlaying effects in our VR simulations. Their qualitative feedback around VR experiences primarily highlighted the feeling of realism in the scenes in general. We suspect two reasons behind this observation: (1) participants were mostly captivated by the novelty of those interfaces; and (2) they focused on the assigned tasks, which diverted their attention from analysing the technical aspects of the simulations. Despite this, we found indications of good integration of the two "materials": (1) most participants appeared to naturally engage with the scenes and express their views on the interfaces without any hindrance; (2) there were a few comments on the relationship between the rendered AV (including its interfaces) and the other real-world pedestrians in the videos, suggesting the perception that the virtual and the real elements were in the same world. Nevertheless, we report below technical challenges in blending the two materials, along with participant feedback about the potential unnaturalness associated with these challenges.

A notable challenge was the spatial mapping of the two materials. For example, we found that there could be slight discrepancies between the scale of objects at varying distances from the viewer (i.e., the camera's position). This phenomenon was primarily due to the 360-degree videos being projected onto a spherical surface, i.e., the panoramic skybox. Therefore, a practical solution that we employed was utilising the player's egocentric perspective, as seen in Unity's game mode, for closely tracking the overlaying effects during the video playback. This approach enabled us to identify and and adjust (e.g., through modifying scripts or animators) any misalignment at specific video moments. Nevertheless, three participants noted the feeling of the AV not being firmly attached to the ground, while this sensation was not observed in the Drone study, possibly because the drone was operating in the air. This could also explain why the spatial presence in the AV study was lower than that in the drone study (Figure 5). Other reasons might include the lower visibility during the night time, the different area sizes covered by the interfaces, among other factors.

Furthermore, to enhance the natural appearance of overlays, it is essential to accurately simulate natural phenomena that can support the intended interpretation of the modality. For example, a successful implementation in our work was the reflection of light on the AV's wheels from the paving tile lighting, which effectively observed by participants as lights emanating from the ground. Nonetheless, one participant mentioned the drone projections might be too bright to be considered fully realistic, despite the increased transparency of those projections being implemented.

5.3 Limitations and Future Work

Since immersive 360-degree videos are not inherently interactive beyond the viewer's ability to turn head and look in all directions [50], interactions initiated by pedestrians in our studies were represented through key-pressing on controllers (Drone) and through the think-aloud protocol (AV). While the two methods still allowed us to collect data essential to indicate participants' decision-making, some participants expressed the desire to physically move around the environments. We currently experiment with (1) filming multiple videos at various positions to support users to move through the space and (2) enriching controller- or gesture-based commands for interaction with the dynamic overlays [2]. Future research could explore methods with more sophisticated technical setups, such as live streaming 360-degree videos [34] with dynamic insertion of real-time objects [39].

6 CONCLUSION

This paper proposes immersive in-situ prototyping for evaluating pedestrian interfaces within autonomous traffic systems, presenting a cost-effective approach for early-stage testing of HMIs in contexts that closely mimic real-world situations. Based on case studies with a drone and with an autonomous vehicle, we found that immersive in-situ prototypes demonstrated high naturalness and was effective in eliciting participant resonance with real-life experiences, highlighting the potential of this approach to facilitate meaningful user feedback in assessing speculative proposals.

Moving forward, the application of immersive in-situ prototypes hold promise for supporting the rapidly evolving exploration of HMIs and enhancing the understanding of how users may interpret and relate to interface proposals in real-world scenarios. Future studies would benefit from exploring the scalability of this approach and its applicability across a broader range of speculative interfaces.

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