SafeARCross: Augmented Reality Collision Warnings and Virtual Traffic Lights for Pedestrian Safety

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ABSTRACT

Augmented Reality (AR) holds great potential for enhancing pedestrian's urban experiences; however, its use in road traffic poses safety concerns due to potential distractions from interacting with AR interfaces. This paper investigates the effectiveness of AR applications for assisting pedestrians in crossing scenarios, against traditional crossing methods, by incorporating a collision warning system that uses an arrow to indicate the direction of a potential danger, and a virtual traffic light showing whether it is safe to cross. By leveraging Vehicle-to-Everything (V2X) communications within the living lab of Aveiro, Portugal, we conducted a user study to evaluate involved workloads, perceived safety and system usability in a realistic scenario. The findings from our study involving 20 participants reveal significant improvements in pedestrians' perceived safety and a decrease in the perceived workload when using AR for pedestrian crossings, with both collision warning systems and virtual traffic lights demonstrating excellent usability.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; **User studies**; • **Networks** → *Mobile ad hoc networks*; Wireless access networks.

KEYWORDS

Vulnerable Road User, Augmented Reality, Mixed Reality, Smart City, Pedestrian Safety

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1 INTRODUCTION

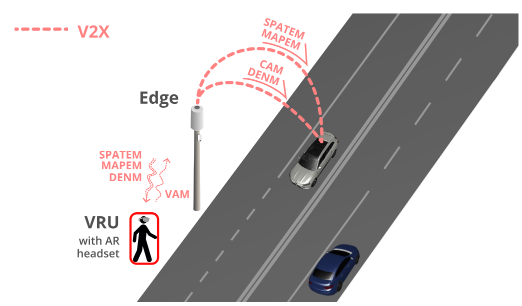

Figure 1: Use case scenario diagram showcasing a VRU wearing an AR headset communicating with the vehicles through vehicular messages.

As mixed reality (MR) permeates various sectors, its ubiquity underscores a transformative shift in how we perceive and engage with reality [47]. Urban environments in particular can enrich the user experiences due to their diverse and dynamic nature, presenting a multitude of stimuli and interactions that can be harnessed to create compelling and immersive engagements [65]. Recently, the National Highway Traffic Safety Administration (NHTSA) has warned users of the latest Apple Vision Pro AR headset not to wear the devices in road traffic [48]. In contrast, Augmented Reality (AR) opens up new forms of immersive experience and is promised as a solution for enhancing road safety through Vehicle-to-Everything (V2X) communication and collision warning messages displayed in the field of vision [2].

Smart cities are leading the way by implementing Intelligent Transportation Systems (ITSs), a sophisticated network of technologies, including sensors, communication systems, and advanced applications designed to enhance the efficiency, safety, and sustainability of urban mobility. Furthermore, it is anticipated that V2X technology will be integrated into devices in the near future. According to the 5G Automotive Association (5GAA), mass deployment of traffic efficiency and safety V2X use cases including complex interactions with vulnerable road users (VRUs) [12, 25] is expected by 2027 [1]. Living labs across the globe are now investigating potential solutions for safe and seamless integration of new technologies [32, 52].

In this paper, we develop an innovative solution that enhances VRU safety, specifically, pedestrian safety at crossings leveraging AR systems, and ITS devices in a real-world scenario. For that, we present SafeARCross: an AR application designed to improve awareness in pedestrian crossing scenarios using two systems, (1) a collision warning system, and (2) virtual traffic lights. We examine different AR warning messages deployed in real-world crossing scenarios, supported by V2X infrastructure integrated into the living lab of Aveiro, Portugal (see Fig. 1). In a study with 20 participants, we assess the impact of AR warnings on workload and perceived safety in relation to traditional crossing scenarios. We show that AR can significantly enhance the perceived safety and reduce the workload compared to crossings without AR assistance, while providing an excellent system usability.

2 RELATED WORK

The topic of VRU safety has been the subject of much research. Given the scope of this problem, the following section outlines several technological approaches developed to improve VRU safety, specifically through AR/MR, V2X communication systems in living labs, and direct VRU-vehicle interaction methods. In the following subsections, we discuss prior work through the prism of these three areas, and highlight challenges such as user acceptance, real-world feasibility and effectiveness in enhancing VRU safety.

2.1 Augmented and Mixed Reality for VRU Safety

Considerable research has focused on the safety of VRUs, especially in cycling through multimodal systems that present warnings [37, 43], and safety recommendations [38, 39] located on bicycles and helmets. MR is gaining recognition as a promising technology, largely due to its high degree of interaction with the user, and studies are beginning to explore its potential uses on VRU safety [46]. Our paper examines the impacts of warning notifications and directional information on collision avoidance, which have already demonstrated great potential for influencing driving performance [5, 8, 56, 57], and acceptance from VRUs [31]. Schwarz et. al, validated the impacts of modality and specificity of in-vehicle AR warnings, finding that visual-specific warnings consistently improve various measures of effectiveness [56]. Aiming at overtaking scenarios, Rameau et al. [50] have presented an AR system designed to 'see-through' vehicles ahead by projecting an image of the road covered by a leading vehicle. Building on these findings, there has also been an investigation into implementing AR systems that interact directly with the VRU. In [40] by Matviienko et al., the focus was to explore the use of AR to assist cyclists at uncontrolled intersections, proposing the visualization of vehicles through sight-blocking elements and displaying a timer countdown that signals when it is safe to cross. A user study (N=24) concluded that AR assistance improved the performance and safety of users at uncontrolled intersections. Also focusing on cyclists, the studies conducted by von Sawitzky et al. have explored how multimodal awareness messages (AMs) can alert cyclists to potential "dooring" scenarios — passing parked vehicles that still have occupants inside. Results revealed that users preferred visual and auditory cues, and that using AMs reduced the risk of accidents [67, 68].

Additionally, auditory cues are also an important aspect of alerts. Schrapel et. al investigated augmented footstep sounds and directional warning sounds in urban environments, and found that pedestrians incorporate virtual and real sounds into an overall reality [55]. More recently, they proposed a similar system for cyclists [41]. Another research by San Martin et al. [53] incorporated augmented sounds in an alerting system, finding auditory feedback, alone or with visuals, most effective for safety. The authors noted that further research is needed due to the tendency for auditory alarms to become irritating or disregarded by users over time.

2.2 V2X applications in living labs

Recent advancements in vehicle-to-pedestrian (V2P) communications systems provide promising solutions for VRU safety. Starting with MR and AR technologies, the system explored by Maruta et al. [36] enhances the driver perception by using AR to visualise blind spots, leveraging cooperative perception with millimetre-wave V2X communications. However, due to the convoluted communication architecture and complexity of the data, the delays obtained (400 ms indoors or more outdoors) do not meet the requirements for road safety use cases defined by the European Telecommunications Standards Institute (ETSI) [11].

Leveraging smart city infrastructure and ITS devices [64] integrates sensors dispersed in vehicles, VRUs, and on the city's infrastructure using communications via ITS-G5, LTE and 5G. It proposes using Cloud and Edge processing to predict collisions and alert VRUs. It concludes that a hybrid solution is preferable, as it proves the most effective, with high accuracy and low latency.

Focusing on direct communications and having autonomous vehicles in mind, Hussein et al. [26] developed a mobile application that uses V2P communications. They designed a system with high detection rates for collisions and high user satisfaction, proving its effectiveness in the real world. Building upon direct communications, the work in [71] implements a similar warning system using C-V2X technology allowing direct communication between connected vehicles and VRUs via a specialised smartphone case. Similarly, [20] focuses on a scenario where pedestrians are occluded by a parked vehicle when crossing the street. Their study uses Decentralized Environmental Messages (DENMs) to alert drivers through IEEE802.11p and pedestrians using LTE.

To understand the evolution of these systems, Kabil et al. [28] offers a comprehensive survey of V2P communication technologies. Their study tracks the shift from vision-based mechanisms like radars to vehicular ad hoc networks (VANETs). Understanding the evolution of V2P communications and their challenges is crucial for comprehending the potential of the aforementioned studies.

2.3 Vehicle-pedestrian interactions

The future of urban mobility is trending towards autonomous traffic [3][1]. Recent studies are increasingly focused on overcoming the challenge of the integration of autonomous vehicles (AVs) in the urban setting due to the lack of effective interaction between these vehicles and VRUs. One approach for this interaction is through information augmentation of the surrounding environment using external stimuli. Previous research explored the use of external Human-Machine Interfaces (eHMIs) [27, 33, 59], exaggerated sound [60], and dynamic vehicle motion [49, 54]. For instance, prior research has shown the significant role of eHMIs alongside AV behaviors in assisting pedestrians recognising their intentions, improving decision-making at road crossings [9, 34, 59].

Expanding on the interaction methods, Löcken et al. [33] go a step further using virtual reality (VR) to investigate eHMIs like smiling, making eye contact, and familiar settings such as zebra projections. It concluded that participants favoured the well-known crossing concept. Similarly, [49] explored more complex user interfaces (UIs) in VR, that represent safe zones for the VRU to cross the road. Despite a higher mental load for these complex representations, users considered it one of the best interfaces. Schmitt et al. [54] further showed that expressive behaviors like exaggerated brake noises, gradually stopping, and stopping farther away from pedestrians improve safety, confidence and situational awareness in decision-making.

Leveraging a greater degree of direct interaction with AR, the work done by Tabone et al. [61] proposes nine different prototypes of AR pedestrian-AV interaction using theory, expert opinion, literature, brainstorming and Unity [2] platform. The authors provide their developed code as supplementary material and encourage further development of these interfaces for future research. Despite being designed for interactions with AVs, these interfaces are potentially useful for interactions with any type of road user. They have served as inspiration for our designs. Complex approaches like the ones proposed by Hesenius et al. [24] create UIs that blend in with the environment creating navigational paths, and identifying safe zones for crossing and vehicle intentions. Other solutions argue that, due to the wide adoption of smartphones, they offer a convenient way for user interaction. For example, a study in [35] found that users were highly likely to heed smartphone-based permissive alerts.

An active approach might use gestures from pedestrians to convey their intentions. For instance, Gruenefeld et al. [21] used gesture-based interaction in VR between pedestrians and AVs in addition to eHMIs. However, their results showed that participants struggled to perform the gesture correctly, leading to increased hesitation to cross the road. Alternatively, our research investigates the use of familiar real-world metaphors for interactions between pedestrians and vehicles. Specifically, we introduce an implementation using virtual traffic lights, getting their status from V2X messages.

[1]https://waymo.com/
[2]https://unity.com/

3 COMMUNICATION SETUP

To facilitate the development of AR applications that assist pedestrians in crossing scenarios, it is crucial to establish an architecture that enables seamless interactions among all road users. This architecture, illustrated in Figure 2, depicts the integration of two road users: the VRU equipped with an AR headset and a vehicle.

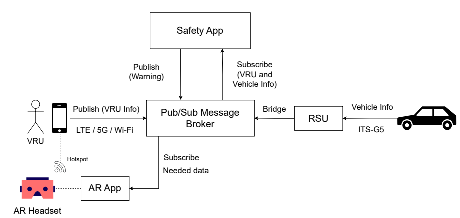

Figure 2: Communication architecture diagram.

The message broker, deployed in a remote server, is central to this architecture, serving the critical role of receiving and transmitting messages to all intervening road users. The VRU interacts with the system via a smartphone, publishing crucial information regarding its location and characteristics through Wi-Fi, LTE or 5G technologies. Vehicles transmit their data through an On-Board Unit (OBU), which is a mobile communication unit that communicates with a fixed Road-Side Unit (RSU) using ITS-G5 technology. A RSU facilitates data exchange between vehicles and infrastructure, enhancing traffic management and safety. This setup allows for medium-range wireless communications associated with vehicular networks, facilitating data transmission between road users and the smart city infrastructure [52, 62]. It is assumed that the RSU relays the received messages to the message broker. Leveraging ITS-G5 technology, vehicles can use V2X messages already defined by ETSI to transmit relevant information through the RSU, including position, heading, yaw rate, velocity, and acceleration, among others.

A safety application is also hosted in the server, and aggregates data from the various road users through the message broker. This application is able to predict a collision between two road users, and consequently publish warning messages to signal a hazardous event. This algorithm of predicting and alerting about collisions is described further in the work [64]. Importantly, the architecture proposed adheres to the standards set by ETSI [11], mainly the critical 300ms end-to-end latency requirement for real-time safety applications [45].

In parallel, the AR headset — connected to the smartphone's hotspot, and consequently connected to the message broker — acts as the interface for displaying warning messages directed to the VRU. This setup allows for a mobile setup wirelessly connecting the AR headset to the smartphone that bridges all communications to the message broker.

These AR applications are designed to capture the user's attention and provide them with real-time, actionable information, enhancing their situational awareness and safety.

4 AUGMENTED REALITY ASSISTANCE FOR PEDESTRIANS AT CROSSINGS

When developing AR applications for assisting pedestrians at crossings, we draw inspiration from Tabone et al. [61], as previously mentioned in the related work section. Concepts 8 and 9 are recognized as the easiest ones to implement, since other prototypes presented are anchored to the environment and moving objects, adding complexity to the associated need for spatial mapping and depth perception in real-time.

Our Collision Warning System is inspired by concept 8, with a Heads-up Display (HUD) that follows the pedestrian's head orientation, adhering to text placement recommendations for users tasked to continuously monitor the central or near-peripheral visual field, such as observing a crossing vehicle [30]. The HUD is designed in a billboard notification style using a white Montserrat sans serif typeface of size 34 in the foreground. This text contrasts with the red background plate, offering readability [19, 51]. The text displays "VEHICLE APPROACHING!" with a stop sign on the left (see Fig 3). The stop sign was chosen due to its ubiquitous usage around the world, with the majority of countries having a red octagon with the word stop in either English, the national language of the country, or both. Forty European countries are part of this convention making it the ideal sign [7]. Furthermore, the HUD is positioned in the top center of the user's Field of View (FOV), following guidelines for text positions in complex environments requiring continuous monitoring. As an additional benefit, positioning the notification at the top leaves the bottom part of the FOV unobstructed for the pedestrian to see where they are walking.

Based on concept 9, the Virtual Traffic Lights uses the familiar concept of traffic lights. These lights pop up to alert the user whether it is safe to cross. The model interface implemented was the same as in concept 8, using a 3D traffic light model instead. The traffic light model used does not present a human figure mainly for two reasons. Firstly, the model used in this implementation was a combination of a free asset from the Unity store and some modifications made by the research team, which did not allow for the cutout of a custom figure. Secondly, this application is aimed at pedestrians, but future work might introduce its use for bicyclists. Therefore, it was determined to maintain a visual representation that was ambiguous for both use cases.

4.1 Collision Warning System

As mentioned earlier, the motivation for this system stems from the need to assist pedestrians in crossing scenarios, particularly a collision warning system. Using the architecture mentioned in the previous section, we have chosen the Microsoft HoloLens 2 as the AR headset, primarily due to its availability. The AR application was built using the Unity platform, which has been selected due to its familiarity and wide support for AR development.

The validation of this system has taken place within the Aveiro Tech City Living Lab (ATCLL) platform [52] in Aveiro, Portugal; therefore, pre-existing infrastructure for communications was used, namely a public central broker from Message Queuing Telemetry Transport (MQTT)[3] and vehicular messages standards such as ETSI Cooperation Awareness Messages (CAMs) [14], VRU Awareness Messages (VAMs) [16], and DEMNs [13]. The AR system subscribes to DENMs from the message broker, produced by the safety app, that signal the hazardous event presence and location.

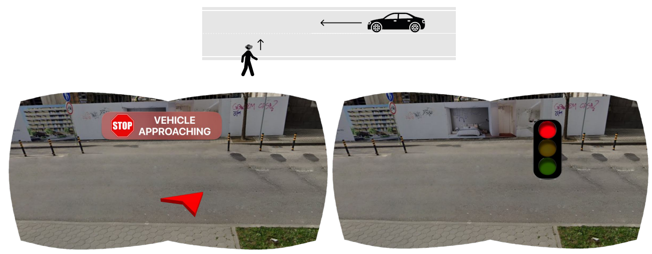

Figure 3: Use case scenario and visual representation of the AR applications. Collision Warning System on the left, and Virtual Traffic Lights on the right.

Figure 3 showcases the use case scenario of a pedestrian crossing a road, where there can be a potential collision with an oncoming vehicle. The AR interface is designed to alert the user through a multi-modal warning system, that is activated when it receives a new DENM, immediately alerting the user with: (1) a visual notification within the user's center of view prompting to halt; (2) a 3D arrow pointing to the direction of the hazard; (3) and an 800 Hz sine tone lasting one second, adhering to standard guidelines for warning sounds [44]. As DENMs are continuously being transmitted, the visual alert remains active, only disappearing when a new message has not been received for one second. This approach to a warning system, particularly, the arrow indicating the direction of the danger, draws from previous literature for AR hazardous notifications to VRUs. For instance, the study referenced in [69] uses a circle that has a section highlighted, to indicate the direction of the danger.

The system is designed to minimise user effort and error potential, offering an efficient and user-friendly experience. It operates on a "no input needed" basis, requiring no action from the user to work effectively. Moreover, the system leverages user-centric data to avoid issuing warnings if the user is not facing the direction of the hazard, specifically if the angle between the user's head orientation relative to the hazard's location is within a 180-degree range.

To extrapolate the user's bearing, we used Unity's camera rotation. This is chosen for its simplicity and built-in mechanisms to filter and adjust for drift and potential errors that might occur when using the headset's gyroscope. Unity initialises applications with a default position and rotation of 0; therefore, we need to set the user's bearing using a compass and insert the observed value into the message broker. When the application receives that message, it calculates an offset based on the user's current camera rotation and the published value. This way, it can always calculate the current bearing of the user (*cameraBearing*).

The Harvesine's formula is used to calculate the bearing between the geographical coordinates of the user (location sent on the VAMs), and the geographical coordinates of the dangerous

[3] https://mqtt.org/

event (location sent on the DENMs), resulting in the bearing of the dangerous event (*collisionBearing*):

$$\text{collisionBearing} = atan_2(y, x) \times \frac{180}{\pi}$$

where $y = \sin(\Delta\text{longitude}) \times \cos(\text{latitude}_2)$ and $x = \cos(\text{latitude}_1) \times \sin(\text{latitude}_2) - \sin(\text{latitude}_1) \times \cos(\text{latitude}_2) \times \cos(\Delta\text{longitude})$

The arrow's yaw is then adjusted to point in the direction of the dangerous event by taking into account the *collisionBearing* and the *cameraBearing*. As a way to improve usability, the arrow also tilts and shifts positions according to its direction, conveying an extra sense of direction.

4.2 Virtual Traffic Lights

As AVs are gradually introduced into our roadways, the need for traditional traffic management systems, such as traffic lights, is diminishing due to the vehicles' capacity to communicate with each other. However, a significant challenge in autonomous traffic is the lack of interaction between VRUs and AVs [33]. The absence of direct eye contact with a human driver raises concerns regarding the clarity of the vehicles' intentions, potentially leading to dangerous situations when pedestrians are crossing a road.

To address this issue, our system leverages ITS technology to introduce a virtual traffic light displayed through an AR interface. This solution informs the user about the vehicle's intentions intuitively and familiarly. The use case scenario, depicted in Figure 3, illustrates a connected vehicle approaching a VRU with no intention to stop, with the AR interface signalling the VRU that it is not safe to cross. Traditional crosswalks have sound signals, mainly for people with visual impairments [22]. Recognizing the contribution of those mechanisms for non-impaired people to have a better understanding of the crossing overview, the AR application produces a bell-like sound for one second every time the traffic light changes to capture the user's attention [58]. The goal is to signal the user to the light change rather than aiding those who cannot visually see the traffic light.

Although this approach uses the same architecture as the previous application, the main differences of this system lie in the type of data exchanged — namely, VAMs, Signal Phase and Timing Messages (SPATEMs), and MAP Extended Messages (MAPEMs) [15]. MAPEMs provide detailed descriptions of the intersection's layout, identifying each lane with geographical coordinates, while SPATEMs present the correct traffic light phase associated with each lane. These elements are crucial for the system to identify whether a user is on a traffic lane or not. Despite receiving MAPEMs and SPATEMs, the system cannot automatically assume presence at an intersection. Instead, it analyzes the geographical nodes described by MAPEMs, along with lane width, to build a bounding box for each lane segment. Using VAMs to identify the location of the VRU, it then checks whether that location falls within any of these bounding boxes. After identifying the lane where the user is located, the system will display the correct traffic light signal phase described in the SPATEMs.

5 STUDY

The following section discusses the user study performed in this work. It outlines the participant demographics, the methodology and study design to evaluate the effect and usability of AR applications on pedestrian safety in real-life crossing scenarios.

5.1 Participants

We recruited twenty participants (four female and sixteen male) around the campus of the University of Aveiro using primarily social contacts. The age group of the participants was between 20 and 24 years (M=22.3;SD=0.9), which is indicative of a younger population who is more prone to novel systems. Among the participants, 30% reported wearing prescription glasses.

In order to classify the user's affinity with technology, we used the ATI (Affinity for Technology Interaction) Scale [18]. Our participants achieved an average ATI score of 4.08, a standard deviation of 0.47 and a value of Cronbach's alpha of 0.74, indicating that the demographics in hand have a medium-high degree of technological affinity.

To assess the participants' familiarity with VR and AR technologies, users were asked to rate their knowledge and frequency of use. The results showed that most participants had some familiarity with these technologies, with three participants having never used them, and one using it frequently describing it as "weekly or more often".

5.2 Design

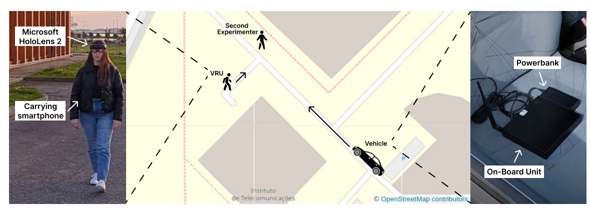

Figure 4: Visual representation of the user study's location and the intervening subjects. A VRU (left) is wearing a Microsoft HoloLens 2 and is carrying a smartphone, and a vehicle (right) is carrying an OBU battery-powered.

The study began with participants being invited to the test track, where they were briefed on the systems' characteristics and the respective tasks they would be undertaking. The study was conducted during the day, and the brightness of the Microsoft HoloLens 2 was maximized to ensure good visibility of the AR display. Consent for recording was sought from each participant, followed by distributing a questionnaire dedicated to characterizing the audience's demographic relating to age group, gender, technology affinity, profession, whether the participant wears prescription glasses, familiarity with VR/AR, and the frequency of use of these technologies.

5.2.1 Methodology. In the process of validating a collision warning system, one of our main concerns was balancing the participants' safety while maintaining a realistic scenario. Addressing these concerns, the research methodology employed a testing scenario on which participants would be positioned close to a road they must cross, with a vehicle travelling at approximately 30km/h on the nearest lane, as depicted in Figure 4. The testing site was on a restricted road, therefore no external road traffic was present, ensuring a safe environment and a high degree of task reproducibility between subjects. A secondary experimenter was positioned across the road to coordinate the task, and his responsibility was to control the timing for participants to start their crossing. This timing was strategically designed to bring participants into proximity with the vehicle's path, simulating a real-life encounter with a potential collision, while ensuring a safety margin to eliminate the possibility of actual risk. This approach was instrumental in preserving the experiment's integrity, allowing for the reproducibility of conditions, and a high level of ecological validity.

The study adopted a within-subject design, encompassing all participants to examine the impact of AR interactions during pedestrian road crossings. Three independent variables were considered: (1) utilization of the arrow-based Collision Warning System, (2) displaying Virtual Traffic Lights on the road, and (3) a control condition devoid of any AR system assistance. Participants performed a road crossing under each condition, allowing for a direct comparison of their responses to each one. The order of the tasks performed by each participant was randomized to reduce learning effects.

5.2.2 Data Collection. There were four dependent variables selected to encompass both objective and subjective aspects of the road-crossing experience: the System Usability Scale (SUS) [6] scores to evaluate the usability of the AR systems; raw NASA Task Load Index (NASA-TLX) [23] scores to measure the perceived workload imposed by each task; participants' self-reported feeling of safety during road crossing; and the number of head movements performed by the user throughout the task as a potential inference of situational awareness. The head movements were measured by one researcher who analyzed the recorded videos of each participant after the study has ended. A head movement was defined as the rotation of the user's head exceeding 45 degrees from the central axis, which was set to be the initial forward-facing position of the user. Additionally, head movements were counted, even if the user was not looking towards the vehicle (e.g. for the scenario in Fig 1, a vehicle had already crossed, but the user still looked to his right).

Following each task, participants were provided with a questionnaire including the SUS, NASA-TLX, perceived safety assessment during the task, and a final section with a suggestion box. All results can be represented on a scale from 0 to 100, despite using the original grading scales for SUS and NASA-TLX. Participants were encouraged to complete the questionnaire using their smartphones. The SUS questions were excluded from the questionnaire for the task that did not use an AR system.

5.2.3 Hardware Requirements. Each condition has specific hardware requirements. For conditions 1 and 2, the user carries a Microsoft HoloLens 2 headset and a Motorola Moto 5G smartphone loaded with an Android application that transmits messages pertaining to the user's information (Section 3). For condition 3, no equipment is required as the user crosses the road without any assistance. Common to all tasks, the study incorporated a vehicle equipped with an OBU that emits messages containing its characteristics using V2X CAMs; these messages were captured by an RSU located near the test location (Section 3), through ITS-G5.

5.2.4 Procedure. For the Collision Warning System task, the experimenter loads and starts the safety application on the AR headset. Once the application is ready, an in-situ familiarization process is conducted where the system's audio-visual warning notifications are artificially triggered. This ensures that participants are adequately prepared for what they will experience during the task. After familiarization, participants were assisted in wearing the AR headset properly and briefed on the task procedure, emphasizing the safety precautions to prevent accidents. The procedure required participants to maintain their gaze forward for a short period to calibrate the user's heading on the application. Subsequently, participants were handed the smartphone. The task unfolded with participants awaiting a signal from the second experimenter, upon which they would begin to cross the road. As the user approached the vehicle's path, the safety app (Section 3) detected a hazardous situation and issued warning messages, which the AR application received and then issued a warning notification prompting the user to halt. Once the vehicle moves away from the user, the warning is dismissed and the user completes their crossing task.

A similar procedure was applied to the Virtual Traffic Lights task, performing the same initial steps of loading the application onto the AR headset and initiating the familiarization process. Here, the experimenter manually went through all possible traffic light phases. After familiarization, participants were briefed on safety and the task procedure. They were then instructed to cross the road following the traffic light signal phase, controlled by the second experimenter. Since the user was already positioned at the crossing path, the UI always displayed the traffic light. Initially, the traffic light was set to red, and the second experimenter would change it to green to signal the participant to start walking. As the car approached the participant creating a potentially dangerous situation, the signal was changed to red. Similarly to the previous procedure, the second experimenter changed the light back to green after the vehicle had passed and no longer posed a threat. The user would then complete the crossing task.

For the task without AR assistance, the user only needed to wait for the signal from the second experimenter and cross the road as he would normally do.

At the end of the study, a brief discussion with the participant was done to spark some ideas that might not have been addressed in the questionnaire.

6 RESULTS

This section presents the results of our study for which we evaluated our two AR modes: Collision Warning System (CWS) and Virtual Traffic Lights (VTL), comparing them against a scenario with no AR support (NAR). All measurements are using a 0 to 100 scale, except for the number of head movements.

6.1 Workload

Exploring the impact of AR on workload during the street-crossing task, NASA-TLX scores serve as our primary metric. Since a Shapiro-Wilk normality test failed to reject the null hypothesis that the

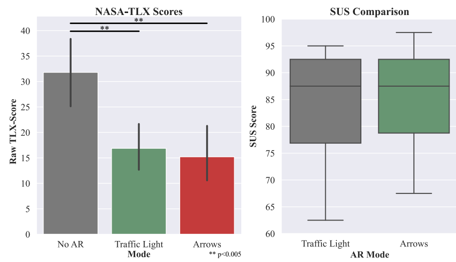

Figure 5: Raw NASA TLX scores (left) and SUS scores (right). The workload was significantly reduced when using AR indications of approaching cars when crossing the street. The system usability score of both AR modes was rated within acceptable limits.

recorded speed data is from a normally distributed population, we performed a Friedman's test that revealed a statistically significant difference in the calculated TLX scores among the three groups (df = 2, Q = 15.578, p « 0.01). A subsequent Nemenyi post-hoc test using Holm correction showed that there is a significant difference between no mixed reality [NAR] support (M=31.79; SD=14.38) and our AR applications. Although both apps have no significant difference (p=0.9), arrows in the field of vision [CWS] (M=15.21; SD=12.74) performed on average slightly better than virtual traffic lights [VTL] (M=16.88; SD=10.89).

6.2 System Usability

Both AR systems were perceived with an almost excellent SUS score (M[CWS]=84.5;SD[CWS]=11.63, M[VTL]=83.75; SD[VTL]= 10.37). The calculated SUS scores were not normally distributed according to a test for normality. A Mann–Whitney U test revealed no significant difference between both AR Apps (U=211.5, p=0.76»0.05).

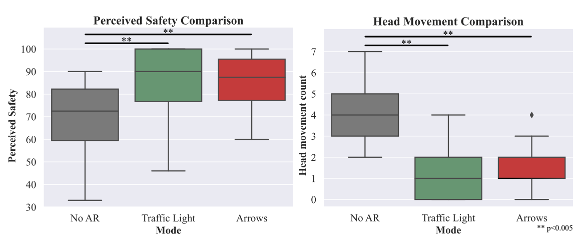

Figure 6: Perceived safety (left) and number of head movements (right). The participants felt significantly safer when crossing the street with AR support. This can also be observed by the number of observed head movements on the right. Between the AR modes no significant difference was found.

6.3 Perceived Safety

The self-perceived safety reported by the users was not normally distributed among our participants. The perceived safety was lower rated without AR support (M=69.55; SD=16.75) than for CWS (M=85.75; SD=12.24) and VTL (M=84.9; SD=16.02). According to Friedman's test, there was a significant difference among the three groups (df = 2, Q = 18.27, p « 0.001). A post-hoc test showed a significant difference between no AR support and both AR apps (p=0.001«0.05), while the perceived safety was not significantly different between CWS and VTL (p>=0.9»0.05).

6.4 Head movements

The observed head movements serve as an indirect measurement of the participant's perceived safety while crossing the street. Our observed head movements were normally distributed for the task without AR support (M=4.15; SD=1.42), while the observations for VTL (M=1.2; SD=1.32) and CWS (M=1.5; SD=1.0) followed no normal distribution. A Friedman's test showed significant differences among the three groups (df = 2, Q = 29.91, p «< 0.01), and the subsequent post-hoc test showed that the difference between conventional crossings and both AR support apps is significant (p«0.05) while both AR applications showed no significant differences between each other (p>=0.9»0.05).

7 DISCUSSION

The study demonstrates that the developed AR systems, significantly enhance pedestrian safety and reduce the workload compared to no AR support. These findings are evidenced by lower NASA-TLX scores indicating reduced perceived workload, higher perceived safety scores, and lower amount of head movements performed when AR is used.

7.1 AR Assistance for Pedestrians

Both AR applications performed similarly in terms of system usability obtaining high SUS scores. However, the absence of a significant difference in usability between the collision warning system and the virtual traffic lights suggests that user preference might be more influenced by individual characteristics or specific situational needs rather than the technology itself.

As a fourth independent variable, wearing a headset without any AR application active could be considered. This additional baseline condition could provide insights into how wearing an AR headset impacts user behavior, considering factors such as the novelty of the technology, constraints on head movements, and social perception. It could also help distinguish the effects of simply wearing the device from those of the AR applications themselves. Nevertheless, this research focused specifically on the impact of AR applications in assisting pedestrians at crossings, which inherently required the use of an AR headset to evaluate the effectiveness of the applications in real-world scenarios. Focusing directly on AR applications allowed for a more streamlined and targeted investigation, aligning with the core goals of the research in comparison to conventional crossings.

Different design approaches may have varying impacts on different types of vulnerable road users (VRUs), particularly when comparing the requirements of pedestrians and bicyclists. Bicyclists, for instance, could benefit from AR interfaces that provide precise information about the position of other road users. Given their higher level of integration in road traffic, bicyclists encounter unique spatial challenges that might necessitate warnings with specific location details. In contrast, pedestrians at crosswalks might find basic notifications, such as warnings about whether it is safe to cross, sufficient for their needs. Consequently, systems like collision warning systems could be more advantageous for bicyclists, while pedestrians might only require virtual traffic lights in analogy to physical traffic lights.

The novelty factor of wearing an AR headset, that prompts notifications to the user, might have caused them to stop independent of the notification's purpose. Future iterations should consider this aspect of the system. Nevertheless, the results show a significant improvement in pedestrians' perceived safety, and a decrease in the perceived workload when using AR for pedestrian crossings compared to traditional methods. Similar usability ratings and workload across different interfaces, compared to no HMDs, suggest that AR displays are effective for conveying the intentions of approaching vehicles, regardless of their specific design.

User feedback further contextualizes these findings. For instance, two participants noted visibility issues on the traffic lights under brightly lit conditions, pointing to the need for a design adjustment. However, they mentioned that the audio cues helped alert the change in the light phase. Regarding the collision warning system, one user expressed that the directionality of the arrow was insightful for quickly recognizing the dangerous situation, and another expressed concerns about using the system with multiple vehicles, worrying that they would not recognize the plurality of the scenario. Furthermore, one user reported head movement difficulties while wearing the headset, underscoring the need for integrated collision warning systems in public use. Investigating how wearing AR headsets in urban settings affects a user's head mobility and impacts the awareness on surrounding traffic is relevant to further contextualize the observed reduction of head movements.

When comparing interfaces for each participant, seven participants preferred the VTL over the CWS in terms of usability, while ten preferred the CWS over the VTL. Six participants rated both systems as equal in terms of perceived workload while the rest were equally divided as preferring one over the other. Finally, nine users rated the perceived workload of VTL higher than CWS, while six reported the opposite. These findings underscore the complexity of designing a universal AR system that is useful and addresses the needs of different VRUs. A potential solution could be to adapt the system to user preferences in different scenarios.

7.2 Comparative analysis

This research extends the findings of prior related studies about AR warnings for VRUs. By using V2X-enabled equipment and a real-life setup, we are able to test these systems with a higher ecological validity compared to studies that use simulated environments [40], or Wizard of Oz experiments [69].

When performing the task without AR, we recorded a mean raw NASA-TLX score of (M=31.79;SD=14.38) which is comparable to Dommes et al.'s [10] (M=37.98;SD=28.24) in a street-crossing task with vehicles approaching from two directions, confirming the enhancement of perceived workload when using AR assistance, despite variations in research methodology. Additionally, results on system usability show that the mean SUS scores not only highlight the AR systems' usability but also fall very closely within the range deemed as 'excellence' by prior literature [4]. Similar SUS scores ranging from 76 to 90 were reported in a study that explored AR interfaces for pedestrian-AV interactions [49]. Another study reported a SUS score of (M=86;SD=6.20) for their AR interface having an ATI score of (M=4.03;SD=1.001) [66], which mirrors our SUS results (M[CWS]=84.5;SD[CWS]=11.63, M[VTL]=83.75; SD[VTL]= 10.37). These comparisons validate our results, suggesting that our high SUS scores are consistent with findings from other studies under similar conditions. However, it is crucial to note that these high scores might have been influenced by the participants' medium to high affinity for technology.

Furthermore, our research methodology resonates with previous approaches on how to validate an awareness notification system for VRUs using AR. In [69], Sawitzky et al. evaluated the system by assessing workload (NASA-TLX), user experience, intuitiveness of hazard detection and perceived safety using AR. For measuring perceived safety, they used a questionnaire with 26 items regarding a multitude of dimensions related to perceived safety [67]. Distinguishing our approach, we drew inspiration from a study introducing a novel method for measuring perceived safety through a continuous slider device [70]. Recognizing its effectiveness, we added a final item to each task questionnaire, asking participants to rate "How safe did you feel during this task?", on a scale from 0 to 100 using a slider.

Additionally, our findings are consistent with previous studies conducted by von Sawitzky et al. [69], which showed that users' perception of safety varied when AR support was provided. Our results nearly matched those of von Sawitzky et al. (85% with AR, 75% without), with participants reporting higher levels of perceived safety during tasks involving AR (85%) compared to those without (70%). Moreover, while they reported a perceived workload of 37% without AR and 35% with AR assistance, our research demonstrated lower levels, measuring 32% and 16% respectively, with comparable standard deviation values for perceived safety and perceived workload. The discrepancy may be attributed to variations in the study setup, participants' demographics, and scenario specifics (cyclists and pedestrians).

7.3 Perception of safety and trust

Results show that AR assistance significantly enhances perceived safety, and reduces the number of head movements during road crossing compared to conventional crossings without AR. These measurements were not found to have any significant trend of a learning effect.

The increase in perceived safety can be linked to the concept of perceived risk in Mayer et al.'s [42] model of organizational trust. Meanwhile, the reduction in head movements is associated with the model's risk-taking behavior in relationships. Taken together, these factors illustrate strong evidence that participants trusted these AR systems for assistance at crossing scenarios.

Both AR applications demonstrated similar results in terms of perceived safety by the user. This similarity might indicate that solely knowing the intentions of approaching vehicles may have caused the user to feel safer. However, pinpointing the source of these results is challenging. Users themselves may not be aware of the reason for feeling more secure, as other factors could have been in play, such as knowing that this was a controlled experiment.

8 CONCLUSION AND FUTURE WORK

This study investigated the impact of AR on enhancing pedestrian safety in crossing scenarios integrating a real-world vehicle. The proposed systems, the Collision Warning System and Virtual Traffic Lights, were evaluated in a user study (N=20) conducted within a realistic setting at the Aveiro Tech City Living Lab. Our analysis showed that there was statistical evidence suggesting significant improvements in perceived workload, perceived safety, and a reduction in the number of head movements for these systems when compared to scenarios without AR assistance, concluding that the users trusted the AR systems. Furthermore, participants rated the systems as excellent in terms of usability. In the spirit of open science, the code developed along with the AR designs are provided as supplementary material in a GitHub repository[4]. Additionally, the repository also contains the questionnaires given to participants along with their results. The following demonstration video[5] showcases the SafeARCross system in action in the real world.

The lack of diversity of the participants limits the generalizability of the results. Future studies could involve a broader demographic that might respond differently to such technologies. This is particularly important for groups that differ from ours on the ATI scale, such as the elderly, children or those with impairments. Previous research has already revealed that these groups behave differently in conventional street-crossing tasks [72].

Aiming to improve the presented work, further research could evaluate the effectiveness of these applications by incorporating distracting AR scenarios, where users have to interact with the AR interfaces while approaching a dangerous situation. This setup would approach a more realistic scenario of users already wearing the AR headset in their daily activities aided by the SafeARCross system. Moreover, adding measurements such as eye-tracking and gap judgment probing for situational awareness, and variability of the heart rate related to stress [29] could be beneficial in comprehending the impact of these systems on user behavior, especially useful when comparing interfaces for different use cases (e.g. bicyclists on the road compared to pedestrians at sidewalks).

Looking forward, several areas present opportunities for further research and development. Applying our communication architecture to scenarios where occluded vehicles are visualized using AR [36], could produce a safety application that adheres to the end-to-end latency times defined by ETSI. The use of data from smart city's sensors through Cooperative Perception Messages (CPMs) [17], which are messages sent by vehicles or the infrastructure with information from sensing objects, would improve the interoperability of the scenario, as it would not require vehicles and VRUs to have ITS devices.

Furthermore, while the current focus has been predominantly on safety applications, there is potential to expand these systems to other use cases. The use of virtual traffic lights could be especially effective in managing pedestrian behaviors, such as jaywalking, by providing clear, real-time indicators of safe crossing times integrated seamlessly with the urban traffic flow. This could reduce the incidence of jaywalking, and improve safety and traffic efficiency [63].

[4] https://github.com/nap-it/SafeARCross

[5] https://youtu.be/PiCTL-jrqdQ

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