Road crossing behaviors of Pedestrians in two different Virtual Reality Environments

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ABSTRACT

About 20% of all people killed on roads are pedestrians. Virtual Reality (VR) simulators can be used to train street crossing and improve pedestrian safety, but the use of this technology has some limitations that need to be addressed. Common issues are related to the ecological validity of the experience because of poor immersion, movement limitations, and lack of visual and audio effects. In addition, these simulators are often very expensive. To address this, we developed a pedestrian street-crossing simulation that can be delivered through two mediums, a low-cost CAVE (Cave Automatic Virtual Environment) or a Head-Mounted Display (HMD). These two environments provide a high immersive experience, simple architecture, and a lower cost of deployment. Following an independent samples design, 20 participants were randomly allocated to the CAVE or HMD group and performed a street-crossing task. We measured the percentage of collisions with vehicles and presence through the Witmer and Singer Presence Questionnaire. Our results show that the percentage of collisions was significantly higher in the HMD group. Presence scores were high for both groups, but not significantly different. These results can be used to inform the design of VR simulators for safe street-crossing.

Keywords: Pedestrian Safety Simulator; VR Environments; User Experience; Pedestrian Behaviors

1. INTRODUCTION

The increasing number of vehicles and traffic in the last decades is leading to a higher number of casualties on the road, particularly of pedestrians that account for about 20% of all deaths in USA. In Europe, 5320 pedestrians were killed in road accidents in 2016, which corresponds to 21% of all road fatalities (European Commission, 2018). For the case of Portugal, in 2016-2017 there were approximately 10,000 accidents involving pedestrians (European Commission, 2017). A survey on pedestrian and bike rider activities in 2012 showed that some of the reasons for traffic accidents are related to low standard traffic services such as unavailability of footpaths and dark streets (Schroeder, 2013), and lack of traffic lights (Maillot et al., 2017). Interestingly, in 80% of the cases, the behavior of pedestrians is the cause of collision between vehicles and pedestrians (Lochhead, 2013). Therefore, more research is required to examine pedestrian behavior and to develop training procedures that could be used to train pedestrians (Dommes et al., 2017).

There are however limitations to conducting real-world studies on pedestrians such as creating a special risk-free traffic environment for an experiment and ensuring pedestrian safety. Moreover, every user has a different experience and behavior in real traffic environments, making it difficult to replicate such special traffic conditions. Virtual Reality (VR) based simulations have been used to train street-crossing, with the advantages of allowing safe environments that allow creating multiple traffic scenarios while preserving pedestrian safety (Deb et al, 2017). These traffic conditions are closely mapped to real-world traffic conditions in which pedestrians perform their actions. Several studies with VR simulation applications have been found to prevent pedestrian accidents (Schwebel, Gaines, & Severson, 2008) and to improve pedestrian safety (Bhagavathula, 2018). Nevertheless, these systems still have some limitations. One of the limitations is to create high quality virtual experiences that are realistic and immersive and that elicit presence (J. Hvass et al, 2017). And to create realistic experiences of street crossing in a limited space represents an additional challenge (Mallaro et al, 2017). To provide some examples, a study on child-pedestrian hazard perception skills used 180 spherical screens with three projectors to create a simulated dome projection environment where participants observed traffic scenarios while performing a hazard detection task (Meir, 2015). The results showed that when making street-crossing decisions, participants were more aware of hazards event with limited viewing angles, when compared to a control condition. Another study used a simulator which consisted of three projectors, an eye-tracking system, a photoelectric sensor, and an infrared light beamer, that used head and eye movements to record the decisions of pedestrians (Zito et al., 2015). Results from a street-crossing task with young and older adults showed that young participants were more conscientious during street crossing than older participants. Data of head and eye movements showed that this happened because older participants looked less at the sides of the street before crossing (Zito et al., 2015). Holland and Hill developed a similar virtual environment for recording collisions with vehicles, missed opportunities to cross the road, and attempts of road-crossings (Holland, 2010). In a study with 218 adults, the authors analysed if gender and/or age were factors modulating crossing decisions. The results showed women made more unsafe street crossing decisions as age increased, mainly because of limited mobility, but not men. Another VR simulator used real-traffic videos in a study with 359 participants that had to judge the speed of the oncoming vehicles to cross the road (Rosenbloom et al., 2015). Participants who were trained with the simulator achieved higher scores, and the results were modulated by age and gender. Men and young adults had higher scores compared to women and older participants (Rosenbloom et al., 2015). While showing interesting results, all the systems in these studies allowed only limited movement during crossings. To address this, Dommes and co-authors developed a virtual environment in such a way that participants could walk up to seven meters on an actual street of 5.7 meters in width (Dommes et al., 2017). This was achieved by using ten projector screens. Other studies used a CAVE (Cave Automatic Virtual Environment) and a treadmill to simulate road-crossings, but with the limitation that participants cannot step back (Banducci et al., 2016) (Nagamatsu et al., 2011). In one of these studies, the effect of dual-task performance was analysed in a VR environment in which participants crossed a virtual street by walking on treadmill while listening to music and talking on phone (Nagamatsu et al., 2011). The results showed that those who were at risk of falling had more collisions with oncoming vehicles during the dual-task.

When developing VR simulators for street crossing training an important feature for their ecological validity is their level of immersiveness and the sense of presence they can induce (J. Hvass et al, 2017) (Estupinan et al., 2014). Capturing these subjective measures is important to understand to what their effect is on the training of participants that use VR simulators. Some studies have assessed the level of presence elicited by VR simulators for street crossing, with CAVEs and Head Mounted Displays (HMD) providing experiences with a higher sense of presence and immersion compared to other VR systems (Deb et al, 2017) (Feldstein et al, 2016).

The main objective of our work is to develop a safe, easy to use, and low-cost VR environment to be used for road-crossing training. For this purpose, we developed a VR simulator deployed in two different setups, using a VR CAVE or a HMD. CAVEs and HMDs are considered highly immersive systems, provide realistic virtual environments of traffic conditions, besides minimizing space and movement constraints. We used a between-groups design to compare the efficacy of these two setups in increasing safety through reduced collisions. We also compared the perceived level of presence. We hypothesized that a user would have a higher sense of presence in the HMD condition when compared to the CAVE because the HMD is more immersive and because the user is more isolated from his/her surroundings. We also expected that participants in the HMD environment would have more valid road-crossing decisions (fewer collisions) considering that the virtual environment is more realistic.

2. METHODS

2.1 Participants

A convenience sample of 20 participants (10 females, ages: M=29.37 SD = 6.49) participated in this study. The participants were undergraduate and graduate students, and research assistants, that had no physical disabilities and were able to understand and speak English. All participants provided written informed consent and received no compensation for their participation.

2.2 Apparatus

For the development of our system, we used the Unity 3D game development platform (unity3d.com), which is a powerful tool to create 3D virtual environments. It has special features such as a particle system, animations, and physics for more realistic applications. We developed two different versions of the VR simulator for street crossing. The first used a CAVE environment previously developed at our research lab, which consists of four Hitachi projectors positioned in such a way as to project on the floor and walls (Gonçalves, 2018) (Fig. 1). The height and width of the CAVE walls were 2.2 and 2.8 meters, respectively. A Kinect V2 sensor was installed at the front wall to detect full body gestures. External speakers were used to add sound effects .

The second setup consisted of an HMD, namely an HTC Vive headset (vive.com) (Fig. 2). Vive renders stereoscopic textures of 3D models, which are generated at specific angles to create an immersive effect. Vive also has supporting features such as lighthouse sensors for tracking the position and rotation of the headset, allowing interacting with the virtual environment more efficiently. Our setup used two lighthouse sensors that were facing each other, placed at the corners of the CAVE. To help on preventing sickness, Vive provides a high refresh rate to reduce lag in rendering graphics.

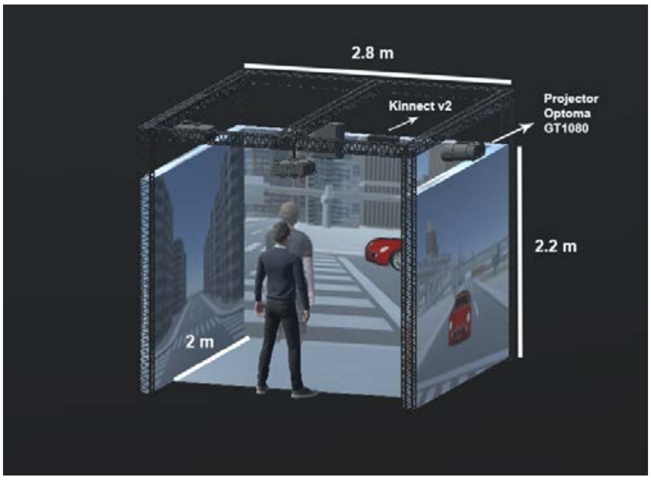

Figure 1. *CAVE setup*

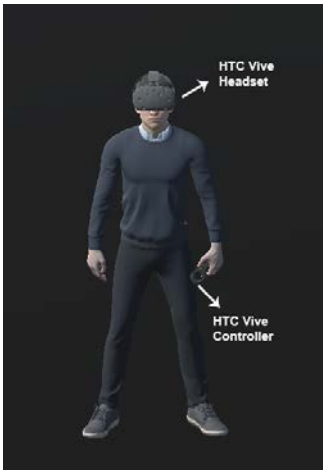

Figure 2. *HMD setup*

The VR environment simulates a 3D city with roads, downtown buildings, zebra-crossings, and traffic that simulated real-world conditions. The city environment was the same for both VR setups. Two different traffic speed limits were used, namely 40km/h and 60 km/h to assess how participants in behave in different speed limits, when they have a different gaps of time to cross (Fig. 3). Vehicles were spawned at different time intervals for the users to estimate valid gaps. A user could see his/her avatar in the VR environment, in front of him/her, standing at the curb of the footpath. Participants held a Vive controller that they should press when they decided to cross the road. The avatar walked at a speed of 1.20 m/s, which is the average speed of a pedestrian (FHWA, 2009). In case of a collision, or completion of the street-crossing session, the application re-spawned the avatar to the starting position.

2.3 Procedure

Participants were randomly allocated to one of the two conditions, HMD or VR CAVE. After being informed on the context of the study and signing the informed consent, the participants performed a training trial to familiarize themselves with the VR environment and to learn how to perform the task. After training, each participant executed two trials of 2 minutes each with different speed limits (40 km/h and 60 km/h). The number of times the avatar was hit by a vehicle (collisions) was recorded by the VR application. After the task, participants answered the Witmer and Singer Presence Questionnaire (WSPQ) (Witmer, 1998). The version used included 24 items addressing Involvement, Immersion, Visual Fidelity, Interface Quality and Sound (Witmer et al., 2005). Items 1-22 were rated on a 7-point scale. Sound items (20-22) were not included in the computation of the overall WSPQ score for comparison with other studies. Items 23 and 24 were removed because the application does not have haptics. A full session took about 10 minutes to be completed.

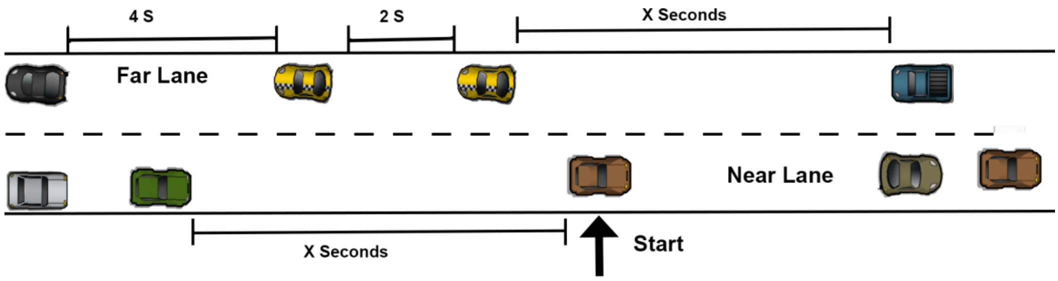

Figure 3. *Schematic Diagram of the Street Crossing Task*

2.4 Statistical Analysis

From the number of collisions, we computed the percentage of collisions for the two different speed limits, 40 and 60 km/h. The normality of the distributions was assessed using the Kolmogorov-Smirnov test. Data were considered normal for the 60 km/h speed limit, but not for 40 km/h. Hence, we decided to use nonparametric tests for both limits also because of the small sample size. Nonparametric tests were also used for the WSPQ because of its ordinal nature. For between-group comparisons, we used the 2-tailed Mann-Whitney test. Central tendency and dispersion measures are presented as median and interquartile range, respectively, Mdn (IQR). For the WSPQ, we present the mean (M) and standard deviation (STD) for comparison with the literature. The threshold for significance was set at 5% (α=0.5). Data were analysed using SPSS version 26.

3. RESULTS

The data of 1 participant was not included in the analysis because of technical difficulties with the setup during acquisition. For a sample of 19 participants, we compared the percentage of collisions between the two conditions (CAVE and HMD) for the speed limits (40 and 60 km/h) (Table1). When vehicles were moving at a speed of 40 km/h, participants in the HMD group displayed a significantly higher percentage of collisions when compared to participants in the CAVE group (CAVE: Mdn=0 (22.5), HMD: Mdn=50.0 (42.0); U=17.0, p=0.02, r=0.31). For a speed limit of 60 km/h, no significant difference was found between conditions (CAVE: Mdn=20.0 (33.0), HMD: Mdn=20.0 (31.5); U=41.5, p=0.77, r=.004) (Table 1) (Fig. 4).

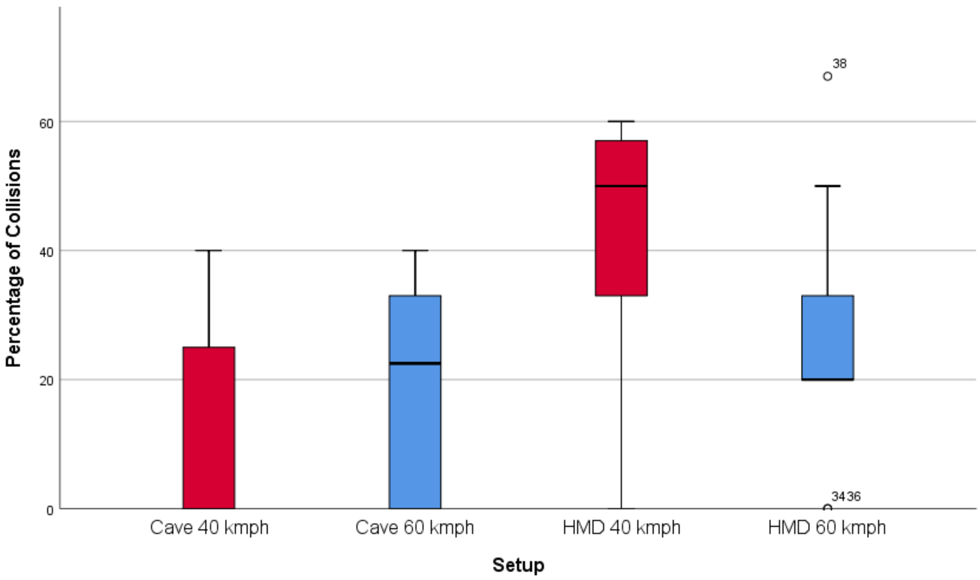

Figure 4. *Collisions in percentage for speed limit 40 and 60 kmph*

Table 1. *Median (IQR) percentage of collisions per condition*

Speed	CAVE (N=10)	HMD (N=9)	Mann-Whitney Test
40 km/h	0 (22.5)	50.0 (42.0)	U=17.0, p=0.02
60 km/h	20.0 (33.0)	20.0 (31.5)	U=41.5, p=0.77

The mean total score in the WSPQ for the CAVE group (M=122.7 (12.2)), although higher, was not significantly different from the HMD group (M=115.8 (17.5)), (U = 34, p=0.36, r=0.045) (Table 2). When analysing the separate items of the WSPQ, no significant differences were found between conditions (Table 2).

Table 2. *Mean (SD) scores in the Presence Questionnaire*

WSPQ	Items	CAVE (N=10)	HMD (N=9)
Total score	All execpt 20,21,22	122.7 (12.2)	115.8 (17.5)
Involvement	1,2,3,4,5,6,7,10,13	5.2 (0.6)	5.0 (1.2)
Immersion	8,9,14[a],15,16,19	6.1 (0.6)	5.6 (0.5)
Visual Fidelity	11,12	5.0 (1.1)	4.6 (1.3)
Interface Quality	17[a],18[a]	6.0 (0.9)	5.4 (1.9)
Sound	20,21,22	5.5 (1.2)	5.5 (0.8)

[a] Reversed items

4. DISCUSSION AND CONCLUSION

Here, we investigated and compared the efficacy for street crossing training and the user perception of presence of a VR environment deployed in two different setups: CAVE and HMD. Our results showed that the percentage of collisions is modulated by the speed at which vehicles were moving. With lower traffic speed, participants in the HMD group had a significantly higher percentage of collisions than those who were in the CAVE group. Fewer collisions indicate a more realistic environment that is more suitable to train pedestrians (Maillot et al, 2017). This could indicate that participants that used the HMD setup had more difficulties in deciding when to cross the street. The difference was, however, not significant at a higher speed (60 km/h). Although, HMDs have higher immersion than a CAVE, they might somewhat restrict looking at both sides of the street while wearing them. In contrast, the CAVE has larger screens and users can more easily look around. On the influence of the speed of the vehicles, it is important to note that pedestrians often judge the physical distance, not considering the speed, leading to poor estimation of the available time frame to cross the street. Other authors compared HMD with CAVE setups and found that participants took smaller gaps and performed faster in HMD when compared to the CAVE, suggesting that the HMD makes the scenario less threatening which leads to users taking more risks (Mallaro et al, 2017). This is plausible explanation to justify the higher number of collisions in the HMD setup. Another study where participants performed a train boarding task showed that the performance was better in a CAVE when compared to an NVIS nVisor ST HMD (Grechkinet al. 2014).

Concerning the WSPQ (Witmer et al, 1998), when comparing the total score over the 19-items in the two conditions, we observed that the mean score was slightly higher in the CAVE condition when compared to the HMD setup (122.7 (12.2) against 115.8 (17.5)), but not significantly different. Other studies that measured presence using the same version of this presence questionnaire on VR environments for pedestrians reported lower total scores. For example, a recent study reported a mean score of 109.35 (13.65) using a HMD (Deb et a, 2017). In another study, Feldstein et al reported total presence score of 93 (1.23) in an HMD setup (Feldstein et al, 2016). Our results indicate that both, the CAVE and the HMD, induced a stronger sense of presence when compared to the literature. On the subdomains of WSPQ, irrespective of the setup, we observed high scores for involvement and immersion indicating presence and realism of the virtual environment. We also observed high scores for visual fidelity and interface quality, suggesting the reliability of the simulator. The average score of sound also indicates realistic sound effects in the virtual environment for both setups.

Following the popularity of driving simulators, several studies developed pedestrian simulators through VR environments for street crossing training (Maillot et al., 2017). VR simulation has the advantage to train pedestrians in a safe environment that would not be achieved in a real traffic conditions. Our study compared the efficacy and presence of two VR environments by using the latest VR technology for pedestrian safety applications. Although the latest VR technology has removed barriers, there are still space constraints. To address this issue, our application represents the pedestrian as an avatar that the participant controls using a joystick/controller. This pedestrian simulator also includes sound effects to simulate real-world traffic experience. Both setups offer low-cost solutions with flexible and customizable traffic scenarios. But considering that the CAVE elicited a high sense of presence and taking into account that participants showed fewer collisions with vehicles, our results indicate that the CAVE is more effective as a simulator for street crossing.

The main limitation of this study is the small sample size and its lack of representativeness because all participants were young healthy adults. Children, elderly, and people with motor and/or cognitive deficits are at higher risk of being involved in traffic accidents. Hence, further studies should be done with these specific populations.

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