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IMPROVING SAFE PEDESTRIAN BEHAVIOR THROUGH VIRTUAL REALITY: AN EMPIRICAL STUDY

Mejorar el comportamiento de los peatones mediante la realidad virtual: un estudio empírico

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INTRODUCTION. Over the last few years, the number of pedestrian fatalities on urban roads has increased, largely due to infractions associated with their behaviors (e.g., crossing when traffic lights are red). It is argued that these behaviors reflect a lack of risk perception. Road safety programs have tried to raise awareness through various methods, using quite often emotionally powerful experiences (e.g. testimonies of people who have experienced an accident themselves). Recently, Virtual Reality (VR) has been deployed with the aim of increasing the efficacy of these safety programs. Previous studies have demonstrated the potential of VR to improve pedestrian safety, especially when it is accompanied bydebriefing and critical reflection. **METHOD.** A total of 43 participants (M = 24.5 years old; SD = 5.14; 65.12% female) were involved in an experimental study with a 2x2 factorial design and pre-post measures. They were randomly assigned to one of four groups (Experience a VR accident /Experience VR without an accident; having a debriefing after the VR experience/not having a debriefing after the VR experience). Pre-post measures were of two kinds, (a) self-report measures and (b)VR behavioral measures. Multivariate Analysis of Variance (MANOVA) and general linear mixed models (GLMM) were used to analyze the data. **RESULTS AND DISCUSSION.** The main results revealed that (a) participants reported a general reduction in the number of rules violations, regardless of condition, and (b) there was a significant reduction in the number of violations committed in VR (i.e., crossing when the traffic light is red) in the condition where participants had previously experienced an accident. These results support the potential of using VR environments to improve pedestrian safety-related behavior. Implications for future research are delineated.

Keywords: *Virtual reality (VR), Debriefing techniques, Safety programs, Pedestrian behavior, Accident risk, Safety.*

Introducción

According to World Health Organization (2018), pedestrians, cyclists and motorcyclists represented more than half of global road traffic deaths (28% motorized 2-3 wheelers, 23% pedestrians and 3% cyclists). Consequently, the United Nations General Assembly (2020) proclaimed the Decade of Action for Road Safety 2021-2030 with the goal of improving global road safety and preventing at least 50% of road traffic deaths and injuries by 2030. In the case of Spain, pedestrians are also among the most vulnerable groups of users on roads, accounting for 11% of the total number (126 pedestrians) of deaths in 2022 (National Road Safety Observatory, 2023). Specifically, the percentage of pedestrians killed in urban areas in Spain was 44%, compared to the European Union's average of 37%. In addition, the number of pedestrian fatalities over the year of 2022 increased 7%.

Urban roads accounted for the highest proportion of accidents involving pedestrians (93% of these accidents, 61% of pedestrian fatalities, and 89% of pedestrian injuries in hospitals), according to National Road Safety Observatory (2021). The most prominent unsafe actions by pedestrians in urban roads were walking on the roadway or roadside (21%), crossing the road outside an intersection (17%), and crossing an intersection (14%). Furthermore, 53% of pedestrians involved in an accident committed a violation, such as being or walking on the road in an unregulated way (19%), not using zebra crossings to cross (8%), and other offenses (6%). This high number of transgressions and the relatively low frequency of pedestrian accidents may reduce the risk perception associated with these behaviors (Granié *et al.*, 2013). Consequently, pedestrians with scarce traffic safety consciousness usually developed hazardous traffic behaviors such as running a red light and diverted crossing (Hou *et al.*, 2022).

Road safety programs have traditionally increased the risk perception of pedestrians to decrease fatalities (Assailly, 2017; Twisk *et al.*, 2014). For example, raising awareness through generating emotional impact on the individual can be accomplished by sharing the testimony of people who have suffered serious accidents or using explicit media advertising campaigns (Delgado, 2021).

Advances in technology, including Virtual Reality (VR) or Augmented Reality (AR), have helped develop more effective educational intervention programs (Ferguson *et al.*, 2020; Seo *et al.*, 2021; Purcell & Romjin, 2020; Vankov & Jankovsky, 2021; Marrero Galván, & Hernández Padrón, 2022; Palacios Ortega *et al.*, 2022; Baeza González *et al.*, 2023) and provide new opportunities for human factors research in areas that are dangerous or difficult to study in the real world (Deb *et al.*, 2017a). Importantly, an overall increase in pedestrian awareness after exposure to simulated environments has been demonstrated to be transferable to real road traffic contexts (Cook *et al.*, 2013; Çakiroğlu & Gökoğlu, 2019; Saadati *et al.*, 2022), which can be due to (1) the development of many skills without fear of negative consequences (e.g., learning to pilot an airplane, see Aguilar-Reyes *et al.*, 2022); and/or (2) self-reflection on one‘s own experience in a way that allows one to become aware of what has been learned (Gardner, 2013). In line with the latter, some authors (Levett-Jones & Lapkin, 2014; Feng *et al.*, 2021) recommend following the simulated intervention with the debriefing technique, a method that develops critical conversations and engages learners to discover the thinking behind the actions performed during the simulation (Lee *et al.*, 2020). Facilitating debriefing immediately after the intervention has been encouraged to make the experience as fresh as possible (Gardner, 2013).

It is worth noting that human factors are the primary cause of road accidents, constituting up to 90% of incidents (Gicquel *et al.*, 2017). Indeed, these factors significantly influence pedestrian behavior, shaping risk-taking tendencies and exposure levels (Deb *et al.*, 2017a; Wang *et al.*, 2010). Valuable insights by eliciting self-reports on walking and crossing practices, thus, enable the exploration of crucial accident-related behaviors (e.g., traffic violations) and their underlying psychological mechanisms (Zhou & Horrey, 2010; Granié *et al.*, 2013; O'Hern *et al.*, 2019).

Traditionally, the behavior of street users can be classified according to deviations from common practices (Deb *et al.*, 2017b; Reason *et al.*, 1990). If the deviation is unintentional, the action shall be classified as an error. Instead, if the deviation is intentional, the action is classified as a violation. Because intentional deviations from social norms are usually not intended to cause injury or harm, it is therefore reasonable to conclude that attitudes towards traffic rule violations are related to the distracted behavior of pedestrians (Hou *et al.*, 2022). Unintentional deficiencies in the decision-making involved in choosing a goal and/or the resources for reaching it can be of two types (Reason *et al.*, 1990). On the one hand, knowledge errors occur when finding the right solution to a new problem requires a trial-and-error procedure, and on the other hand, rule-related errors occur when a pre-established performance rule is inappropriately implemented to the situation, whether the individual applies the correct rule incorrectly or not at all or applies the wrong rule.

Finally, positive behaviors in pedestrians are those that are defined as behaviors that seek to foster social integrations with other road users (Granié *et al.*, 2013). In this line, Deb *et al.* (2017b) claimed that positive behaviors try to reduce violations or errors, as well as to achieve the fulfillment of safety rules.

The present study aims at responding two research questions (RQ) regarding the role of VR on safe pedestrian behavior:

- **RQ1:** Having an accident as a pedestrian in a VR might help to improve the behavior in urban environments? Does it help to reduce violations and errors and increase safety behavior? Hypothesis 1 states that having an accident as a pedestrian in VR will reduce the number of violations and errors and increase positive behavior.
- **RQ2:** Having a reflection and debriefing on the experience in an urban VR environment might help to improve pedestrian behavior? Does it help to reduce violations and errors and increase safety behavior? Hypothesis 2 states that having a reflection and debriefing on the experience will reduce the number of violations and errors and increase positive behavior.

Method

A 2x2 factorial experimental design with pre- and post-measures was used in this study (León & Montero, 2015). The two independent variables and levels were, IV1: experiencing an accident with VR (ACC)/ no experiencing an accident with VR (NOACC); and IV2: debriefing after the VR experience (DEB)/no debriefing after the VR experience (NODEB).

Sample

A total of 49 students participated in the present study. However, six participants were excluded from the analysis due to task incompletion. Thus, the sample finally comprised 43 students (67.4%

women; aged between 18 and 45; *M* = 24.49; *SD* = 5.14). They attained various educational levels (master's degree (62.8%), undergraduate degree (32.5%), and other degree (4.7%), with a predominance of the Social and Legal Sciences field of study (69.8%). They were mainly Spaniards (86%) and other nationalities such as Peruvian, Chinese, Moroccan, Venezuelan, or Colombian (14%).

Sampling was collected by convenience and snowball techniques, principally through social media networks such as WhatsApp. As Parker *et al.* (2019) noted, social networks are useful to settle initial links to develop sampling, thus, gaining a growing chain of samples. In this study, students were chosen because they fell within the targeted population, thus all of them were Spanish-speaking pedestrians involved in a student context in Madrid (Spain).

Finally, the Ethics Committee of Research of the Complutense University of Madrid (UCM) approved the project. Furthermore, an Informed Consent Statement was required, where all the main information and the ethical principles were explained and acknowledged by the participants.

Procedure

Participants were randomly assigned to one of the following four conditions: (1) ACC+DEB: participants who experienced VR as pedestrians and were involved in an accident if they transgressed the rule (e.g., cross when the light is red). The accident comprised a visual stimulus where the avatar of the participant (in first person) was hit by a car. No physical impact was deployed (see Figure 1, 2 and Supplementary material for more details). Next, they received a debriefing where they reflected upon the VR experience about actual data regarding pedestrians' fatalities (see Supplementary material for the structure and questions of the debriefing); (2) ACC+NODEB: participants who also experienced an accident in VR as pedestrians, but without following debriefing. Instead, they had an informal conversation with researchers as emotional discharge; (3) NOACC+DEB: participants who experienced VR as pedestrians, but they were not involved in an accident. Afterwards, they received a debriefing where they reflected upon the experience in VR about actual data regarding pedestrians' fatalities; and (4) NOACC+NODEB: Group four neither experienced an accident in VR nor received a debriefing. Data was collected over three weeks (February 7-24, 2023), with individual sessions that lasted approximately 45 minutes per person.

Figure 1. VR experience

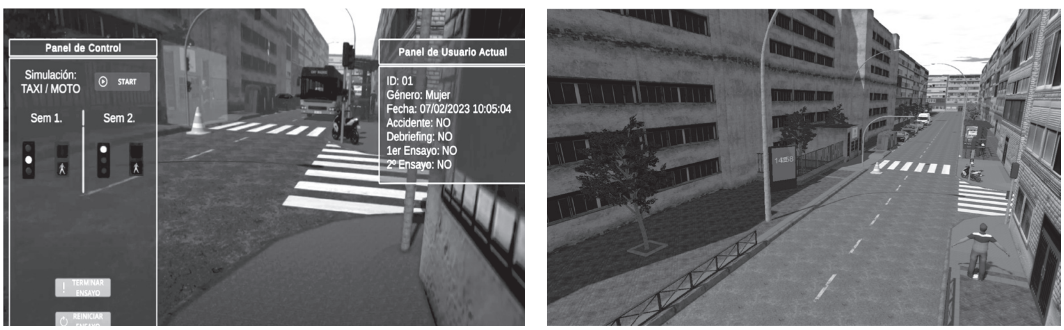
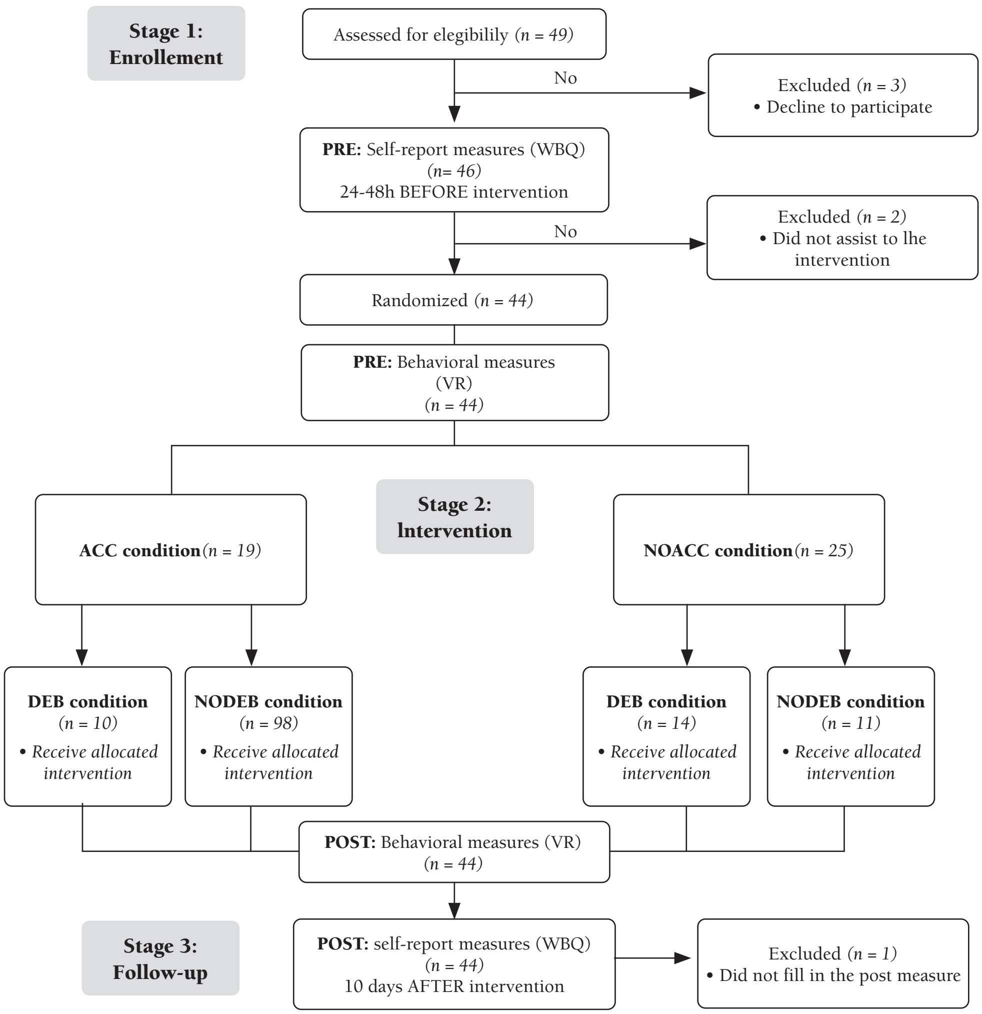


Figure 2. Accident condition

Next, the sequential stages of the process are described (see Figure 3 for a flowchart).

Figure 3. Flowchart of the procedure



Stage 1 (pre self-report measures): In this phase, all participants completed the Walking Behavior Questionnaire (see Instruments below) and a set of demographic questions. This was conducted via online using GoogleForms within 24-48 hours before the intervention started (Stage 2).

Stage 2 (pre post behavioral measures): This phase was carried out in the gym of the School of Education at Complutense University of Madrid (see Materials for further description). Participants experienced different situations, depending on the condition they were randomly assigned (ACC+DEB, ACC+NODEB, NOACC+DEB, NOACC+NODEB). Seven participants initially assigned to ACC+DEB avoided the accident during the intervention due to different reasons (e.g. they run too fast to be hit by the car). Thus, they were finally assigned to NOACC+DEB condition. Stage 2 comprised four sequential parts:

(1) ***Familiarization scenario.*** Once in the gym, participants became pedestrians. All four groups were asked to walk around and explore the space recognizing the boundaries of the play area. The familiarization scenario was presented with no traffic, and it aimed to make the pedestrian feel as comfortable as possible (see Figure 4).

FIGURE 4. Familiarization scenario

(2) ***Scenario 1 (pre behavioral measures).*** When participants were ready, they were asked to stand at the start position and began to listen to the instructions in which they were prompted to cross the street, behaving as if it were a real situation to get to the endpoint of the scenario. There were two possible scenarios, depending on the subject's condition (ACC/NOACC). If participants were in an accident condition, when the traffic light at the second junction turns red, cars were moving alongside. Otherwise, there were no cars circulating at the time of the crossing. The scenario was designed so that the student would be in a hurry to get to the endpoint. For this purpose, some instructions and conditions were given. Participants had to pretend to be students in the day when they must defend their final dissertation project. The time for it was set at 3:00 pm, and a sign in the VR environment informed them it was 2:59 pm. So, they were late. Additionally, another conditioning factor was that while the participants were listening to the initial instructions, the pedestrians on the stage started to run as the weather changed and it started to rain. All these factors were intended to encourage the participant to commit an infraction.

(3) ***Debriefing/Nodebriefing.*** Once pedestrians completed the scenario, there were two options depending on their condition. Those assigned to the debriefing condition were

asked a series of questions in a semi-structured interview, in which they had to reflect on their experience. The main objective was to make participants aware of their own behavior and the risks they often take as pedestrians. On the other hand, those allocated to the opposite condition only had a chat as a way of emotional discharge.

(4) ***Scenario 2 (post behavioral measures).*** This time, all participants experienced the same scenario all over again. Regardless of the condition, no cars were circulating at the time of the crossing, and thus, there was no accident under any of the conditions. This scenario was conducted on the same day and at the same location as the previous intervention, just after the debriefing/non-debriefing phase.

(5) ***Stage 3 (post self-report measures):*** Ten days after their participation in Stage 2, participants filled the WBQ out again. In addition, they were asked to answer an open-ended question about the effect their VR experience had had on their daily life as a pedestrian since they took part in the study.

Instruments

Participants completed a pre-post questionnaire which included (a) individual and demographic information, including age, gender, nationality, or educational level. It also included a set of questions related to accidents suffered in the last two years by participants or people close to them, as well as the type of accidents and their severity; and (b) the Walking Behavior Questionnaire (WBQ) (Useche *et al.*, 2020), a 30-item self-report instrument that evaluates risky (errors and violations) and positive walking behaviors, following a Likert scale from 0 to 4 (0 = Never (at all); 1 = Almost never ; 2 = Sometimes; 3 = Frequently; 4 = Very frequently). WBQ comprises three factors: Violations (V), 16 items (α = .871; ω= .873); Errors (E), 10 items (α = .909; ω= .913); and Positive Behaviors (PB), 4 items (α = .800; ω=.814) (Useche *et al.*, 2020). The Cronbach‘s Alpha and McDonald´s Omega coefficients for the three factors ranged between good and excellent internal consistency. In the last part of the posttest, an open-ended question was raised to reflect on what effects their participation in VR had on their real life.

Materials

Location. The intervention was carried out in the gym of the School of Education-CFP, Complutense University of Madrid, an open space of 414 m2 (Figure 5) which allowed complete mobility and no risk of hitting objects or obstacles while participants were immersed in the VR environment.

Figure 5. Participant demonstration in the gym

VR environment and equipment

The 3D environment has been implemented with Unity3D, a state-of-the-art, cross-platform game engine for VR applications. The scenario (Figure 6) has been modeled to reproduce a typical street configuration (e.g., intersections, number of lanes, crosswalks) in Madrid. To enhance the feeling of immersion and realism, it contains 3D models of urban furniture elements (e.g., buildings, decorative elements, bus shelters, traffic, and streetlights) whose textures have been generated from close-up photos of the real materials. Similarly, the virtual scene includes some dynamic elements, such as pedestrians' avatars and circulating vehicles, to add more plausibility to the reconstructed scenario. Additionally, noise related to traffic elements (e.g., car engines and brakes) and weather conditions (e.g., rain) has been included as background, stereo sound. The virtual environment and its elements have been modeled using 3D Studio Max and texturized with Adobe Substance. Sounds have been adapted from available, online repositories.

Moreover, the functional behavior of the application has been implemented through a set of C# scripts to reproduce features such as traffic regulation, run-over simulations, the setting-up of environmental and simulation variables, the collation and storage of the experimental data in CSV (Comma Separated Values) files.

The Virtual Reality application has been built for Oculus Quest 2 headsets. The application runs on a Windows 10 Pro laptop, carrying 16 GB of RAM, an Intel i7-10750H CPU @2.60 GHz, a monitor with 144 Hz of refresh rate, and an NVIDIA GeForce RTX 2060. The headset and the laptop communicated through a dedicated, high-speed wireless connection. This configuration is particularly suitable for a smooth and comfortable VR experience.

The VR scenario is composed of two intersections regulated by two traffic lights and two pedestrian crossings. Participants started at the same point and had to reach the red cubicle to finish the simulation. They had to behave in the same way as they would if the situation were real. Those participants who were in the ACC condition could have the accident in two situations: (1) If they crossed the road diagonally at the first junction; (2) If they crossed at the second junction when the traffic light turned red (see Figure 6).

Figure 6. Different views of the VR scenario

Data analysis

The analysis was twofold. The pedestrian behavior was tested using both self-report (i.e., using WBQ) and behavioral measures (i.e., pedestrian behavior in VR). Post data were collected in both cases. Statistical analyses were performed using both JAMOVI version 2.3.22 and SPSS version 27.

Self-report measures. Prior to the application of MANOVA, assumptions for normality and homogeneity were tested. Multivariate normality assumption was tested using Shapiro-Wilk ($W = 0.737$; $p < .001$), where the means of the variable "errors" were not normally distributed (W = 0.908; $p = .002$). The homogeneity was tested using Box's M (= 33.1; $p = <.0016$). Excluding the errors variable, all data distributions were normal and met the requirements of MANOVA's assumptions ($W = 0.971$; $p = .052$; = 4.29; $p = .232$). Then, a follow-up MANOVA explored relations between the rest of variables.

Furthermore, for descriptive analysis, mean of the pretest and the posttest were calculated and represented in graphs. MANOVA was used to determine the effect of independent variables at two levels (ACC/NOACC; DEB/NODEB) on the dependent variables (Violations, Errors, and Positive Behavior).

Behavioral measures. Pedestrian behavior in VR was recorded and analyzed. A total of 86 clips were collected (i.e., two per participant, regarding the pre-post measures). Prior to the final analysis, two different members of the research team separately evaluated 10% of the videos. Table 1 summarizes the dependent variables considered in VR.

Table 1. Dependent Variables (DVs) considered in VR

DV1	Looking right at the first crossing
DV2	Looking left at the second crossing
DV3	Looking right before the bus at the second crossing
DV4	Looking right after the bus at the second crossing
DV5	Crossing on red at the second crossing

The inter-rater reliability was almost perfect for all variables, $\kappa = 1$ (p = .005), 95% CI, except for DV2, $\kappa = 0.6$ (p = .064), 95% CI, which had a moderate agreement. Descriptive measures were used to have a first visual inspection of the data.

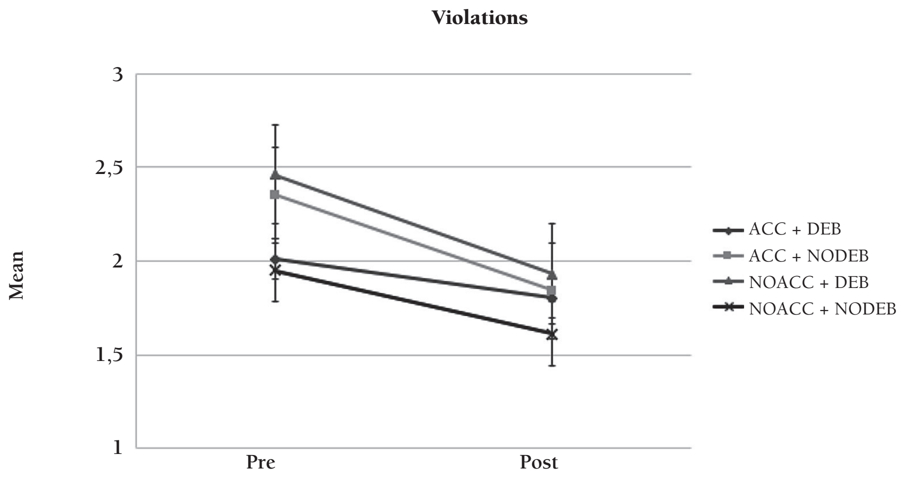
A generalized linear mixed model analysis (GLMM) was performed for repeated measures design with the module GAMLj in JAMOVI (Gallucci, 2019). We examined the between-subject effect (i.e., ACC/NOACC; DEB/NODEB), the intra-subject effect (i.e., pre-post), and the interaction effect (group × time) as fixed effects. Participants ID was used as a cluster variable, and the participants' intercepts were established as a random effect for addressing individual variations in the repeated measures model. Moreover, in one of the analyses, the GLMM did not converge, so McNemar's test was used to compare the change in the distribution and determine whether the difference was not due to chance and if there was significance.

Results

Self-report measures (WBQ)

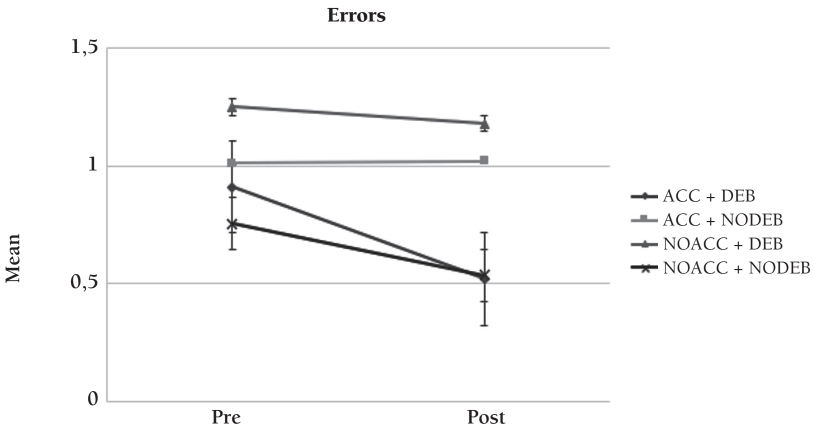
Descriptive analysis showed a general decrease in the number of Violations (V) reported by the participants. Thus, regarding the ACC+DEB condition, M_{pre}=2.01; SD_{pre} =0.554; M_{post}=1.8; SD_{post}=0.817; the ACC+NODEB condition, M_{pre}=2.35; SD_{pre} =0.409; M_{post}=1.84; SD_{post}=0.53; the NOACC+DEB condition, M_{pre}=2.46; SD_{pre} =0.526; M_{post}=1.93; SD_{post}=0.5; and finally the NOACC+NODEB condition, M_{pre}=1.95; SD_{pre} =0.769; M_{post}=1.61; SD_{post}=0.793.

FIGURE 7. The mean score in the Violations factor



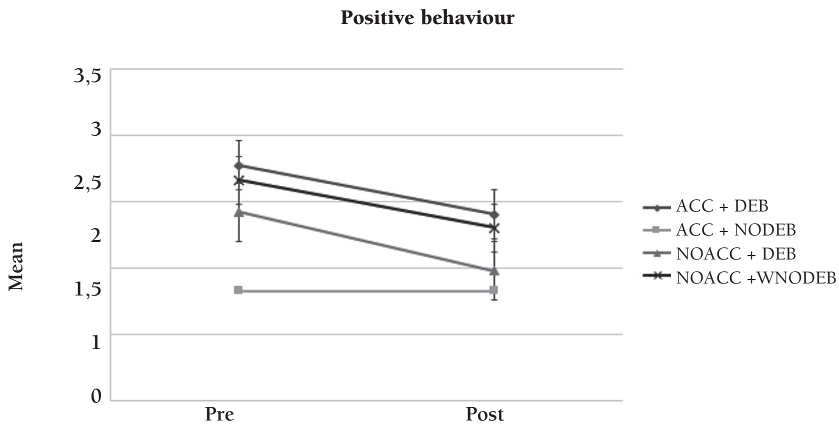
Descriptive analysis revealed a general decrease too in the number of Errors (E) reported by the participants, except for the condition ACC+NODEB, where no change was found. Thus, regarding the ACC+DEB condition, M_{pre} = 0.91; Sd_{pre} = 0.869; M_{post} = 0.52; Sd_{post} = 0.377; the ACC+NODEB condition, M_{pre} = 1.01; SD_{pre} = 0.314; M_{post} = 1.02; Sd_{post} = 0.703; the NOACC+DEB condition, M_{pre} = 1.25; SD_{pre} = 0.774; M_{post} = 1.18; Sd_{post} = 0.554; and finally, the NOACC+NODEB condition, M_{pre} = 0.755; SD_{pre} = 0.572; M_{post} = 0.536; Sd_{post} = 0.499.

Figure 8. The mean score in the Errors factor



Surprisingly, descriptive analysis revealed a general decrease too in the number of Positive Behaviors (PB) reported by the participants, also with the exception of the condition ACC+NODEB, where no change was found. Thus, regarding the ACC+DEB condition, $M_{pre} = 2.77$; $Sd_{pre} = 0.671$; $M_{post} = 2.4$; $Sd_{post} = 0.719$; the ACC+NODEB condition, $M_{pre} = 1.83$; $SD_{pre} = 0.81$; $M_{post} = 1.83$; $Sd_{post} = 0.82$; the NOACC+DEB condition, $M_{pre} = 2.42$; $SD_{pre} = 0.949$; $M_{post} = 1.83$; $Sd_{post} = 0.82$; and finally, the NOACC+NODEB condition, $M_{pre} = 2.66$; $SD_{pre} = 0.896$; $M_{post} = 2.3$; $Sd_{post} = 0.539$.

Figure 9. The mean score in the Positive Behaviour factor



Regarding the MANOVA, the results revealed nonsignificant differences between the four groups (Pillai's Trace = .207, *F*= .962; *df*= 9.117; *p*= .475). However, there was a main effect on pedestrian behavior regarding pre-post measures (Pillai's Trace = .234, *F* = 7.721; *df* = 3.76; *p* < .001). In particular, univariate analysis pointed out towards a significant difference in Violations (*F* (1,84) = 8.60; *p* < .005) and marginal in Positive Behavior (*F* (1,84) = 3.36; *p* = .007). In other words, there was a significant reduction in the number of Violations (V), and marginally in the number of Positive Behaviors (PB), independently of the condition assigned. The effect size (Cohen's f) was calculated (*f* = .035) by G*Power (version 3.1), which represents a small effect.

Behavioral measures in Virtual Reality (VR)

Findings regarding the measures in VR depicted mixed results. First, there was no significant difference in the number of participants who looked to the right at the first crossing (DV1) between pre-post measures. Thus, in ACC+DEB condition, $f_{pre\text{-}post}$ = 80%-70%; ACC+NODEB condition, $f_{pre\text{-}post}$ = 56%-45%; NOACC+DEB condition, $f_{pre\text{-}post}$ = 92%-92%; NOACC+NODEB condition, $f_{pre\text{-}post}$ = 73%-82%. The GLMM revealed no main effect of the variables ACC/NOACC (χ^2 (1) = 0.472; *p* = .492), DEB/NODEB (χ^2 (1) = 0.002; *p* = .964), and TIME (χ^2 (1) = 0.325; *p* = .569), but there was a significant interaction between DEB/NODEB*TIME (χ^2 (1) = 4.685; *p* = .03; $p\eta 2$=.038). In other words, there were differences between pre-post, depending on whether the participants received debriefing or not, though it was small/medium effect.

Second, there was no significant difference in the number of participants who looked to the left at the second crossing (DV2) between pre-post measures. Thus, in ACC+DEB condition, $f_{pre\text{-}post}$ = 30%-30%; ACC+NODEB condition, $f_{pre\text{-}post}$ = 34%-34%; NOACC+DEB condition, $f_{pre\text{-}post}$ = 23%-38%; NOACC+NODEB condition, $f_{pre\text{-}post}$ = 26%-27%. The GLMM showed neither main effect of the variables ACC/NOACC (χ^2 (1) = 1.58; *p* = .990), DEB/NODEB (χ^2(1) = 0.083; *p* = .773), and TIME (χ^2 (1) = 0.09; *p* = .921), nor significant interaction between them.

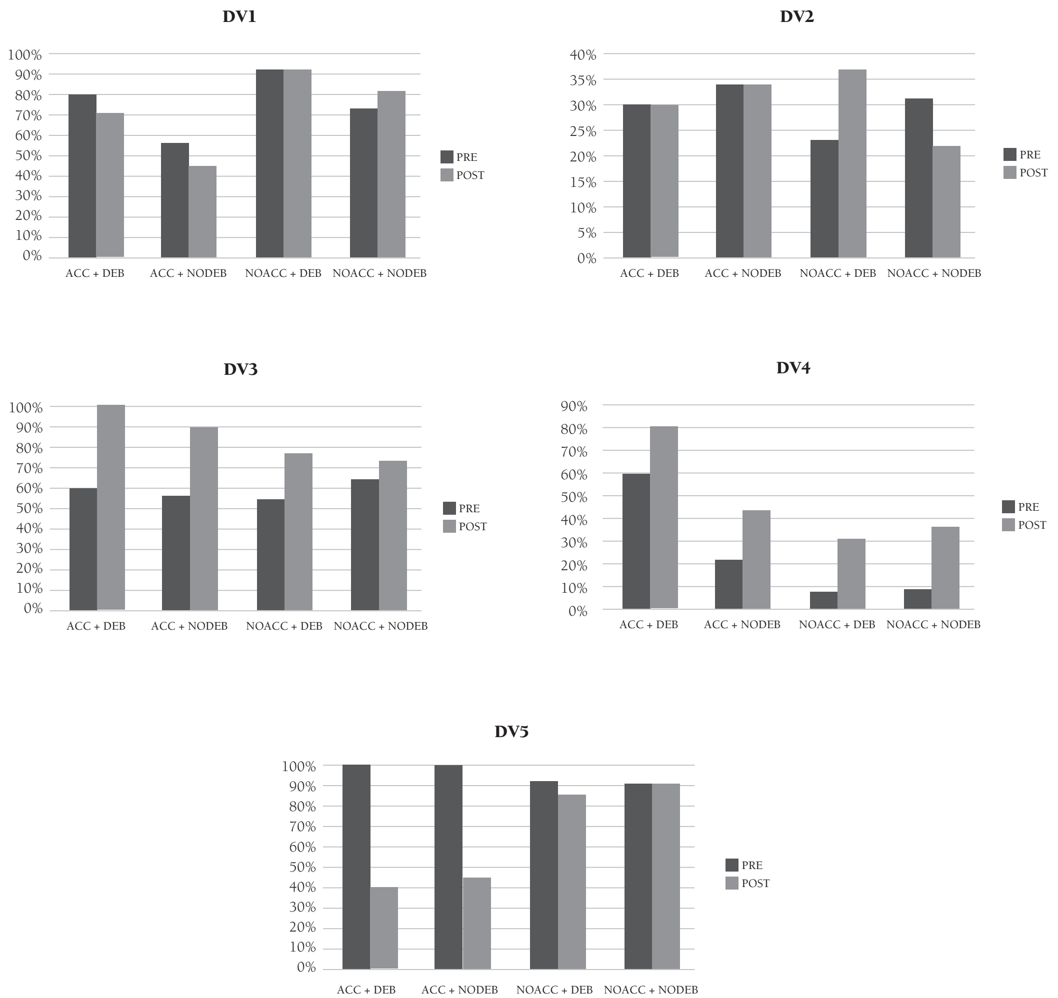
Third, the model did not converge when applying GLMM with DV3. This means results may be misleading or uninterpretable. Analysis of frequencies suggest there was a general increment in the number of participants who looked to the right before the bus at the second crossing (DV3) between pre-post measures. Thus, in ACC+DEB condition, $f_{pre\text{-}post}$ = 60%-100%; ACC+NODEB condition, $f_{pre\text{-}post}$ = 56%-89%; NOACC+DEB condition, $f_{pre\text{-}post}$ = 54%-77%; NOACC+NODEB condition, $f_{pre\text{-}post}$ = 64%-73%. Furthermore, the McNemar test for repeated measures suggests this difference was significant (χ^2 (1) = 6.00; *p* = .014).

Fourth, there was a significant difference in the number of participants who looked to the right after the bus at the second crossing (DV4) between pre-post measures. Thus, in ACC+DEB condition, $f_{pre\text{-}post}$ = 60%-80%; ACC+NODEB condition, $f_{pre\text{-}post}$ = 22%-44%; NOACC+DEB condition, $f_{pre\text{-}post}$ = 8%-31%; NOACC+NODEB condition, $f_{pre\text{-}post}$ = 9%-36%. The GLMM revealed a small main effect of TIME (χ^2 (1) = 4.546; *p* = .033; $p\eta 2$ = .011); a marginal main effect of ACC/NOACC (χ^2 (1) = 3.506; *p* = .061), and no main effect of DEB/NODEB (χ^2 (1) = 0.598; *p* = .439). There were no significant interactions between variables.

Finally, there was a significant difference in the number of participants who crossed on red at the second crossing (DV4) between pre-post measures. Thus, in ACC+DEB condition, $f_{pre\text{-}post}$ =

100%-40%; ACC+NODEB condition, $f_{pre\text{-}post}$ = 100%-44%; NOACC+DEB condition, $f_{pre\text{-}post}$ = 92%-85%; NOACC+NODEB condition, $f_{pre\text{-}post}$ = 91%-91%. The GLMM showed a main effect of ACC/NOACC (X^2 (1) = 12.82; p < .001), and TIME (X^2 (1) = 15.57; p < .001), and no main effect of the variable DEB/NODEB (X^2 (1) = 1.69; p = .194). Besides, there was a significant interaction between ACC/NOACC*TIME (X^2 (1) = 15.04; p < .001; $p\eta 2$ = .14), which represents a large effect. In other words, participants who experienced the accident in the first VR scenario were less likely to cross on red in the second one.

Figure 10. Percentage distribution of Behavioral Measures across groups



Note. DV1= Looking right at the first crossing; DV2= Looking left at the second crossing; DV3= Looking right before the bus at the second crossing; DV4= Looking right after the bus at the second crossing; DV5= Crossing on red at the second crossing.

Discussion

The present study aimed to provide evidence regarding to what extent the use of VR on road safety might improve safe pedestrian behavior. The purpose of using VR as an educational tool was to determine, on the one hand, if having an accident as a pedestrian in VR might help to improve the behavior in urban environments (RQ1); and, on the other hand, if having a reflection and debriefing on the experience in an urban VR environment might help to improve pedestrian behavior (RQ2).

Discussion regarding RQ1

Firstly, self-report measures findings (WBQ) indicate that the students significantly reduced their violations and marginally their positive behaviors after experimenting with VR. Surprisingly, in both cases, it happened regardless of the condition in which the participants were allocated. This result does not support Hypothesis 1 since having an accident in VR did not make a difference. However, it stresses the potential of VR to modify human behavior (Çakıroğlu & Gökoğlu, 2019; Deb *et al.*, 2017a; Schneider *et al.*, 2022). One possible explanation for the counterintuitive fact that participants reduced their positive behaviors is that taking part in this study made them more aware of their pedestrian behaviors. In this sense, after going through the different stages of the process, individuals realized they were not as good pedestrians as they thought when they filled out the WBQ for the first time. As one participant stated:

> *(Taking part in this study) has made me realize that I am not as good a pedestrian as I thought I was, and I should be more patient with certain things…* Participant nº 27, woman, 26 years old.

On the other hand, behavioral findings (VR) reveal that participants who have an accident in the VR1 environment significantly reduced the number of times they crossed on red in the VR2 and increased marginally the number of times they looked right after the bus at the second crossing. These results support Hypothesis 1 and reveal evidence of using VR to modify risky pedestrian behaviors (Luo *et al.*, 2021). In particular, all participants in ACC conditions violated the norm through crossing on red in the VR1 scenario, and these data were reduced by more than half in the VR2 scenario. In contrast, all participants of the NOACC conditions continued to cross red in the VR2 scenario, except for one participant. This may explain the effect of VR in participants, modifying their behavior in the VR2 scenario (Purcell & Romjin, 2020).

On the contrary, findings show that students barely reduced their errors after experimenting with VR. It may be due to a potential *floor effect* since participants were already informed of a few errors during the pre-test. Thus, there was little room for improvement during the post-test. Something similar happened regarding the number of times participants looked right at the first crossing. There was little increment during the post-test since the numbers were already high in the pre-test (above 70% in most conditions). In the case of the number of times participants turned left at the second crossing, findings reveal that there was hardly any change with very low values under all conditions. This may be strongly influenced by the direction of traffic (Osorio-García *et al.*, 2023), as cars were coming only from the right. Moreover, the further analysis seems to indicate pre-post differences in the number of times participants looked right before the bus at the second crossing. Future research should test these hypotheses.

Generally, the results are promising because all participants improved. Specifically, results based on pedestrian behavior have affected crossing on red since this variable is considered to have an immediate consequence (having the accident or not). Specifically, the typical risky behaviors among participants were crossing without checking vehicular traffic or crossing at a red pedestrian light (Osorio-García *et al.*, 2023). The lack of negative consequences could lead to a low-risk perception. Future research should also test this hypothesis.

Discussion regarding RQ2

Firstly, self-report findings (WBQ) indicate that participants did not modify their behavior enough by having a debriefing experience after VR in violations, errors, and positive behaviors. In other words, data does not seem to support Hypothesis 2, as there is no indication of a significant improvement in pedestrian behavior after debriefing.

Secondly, findings regarding behavioral measures (VR) reveal that participants displayed a different pattern of behavior at the first crossing (DV1), depending on whether they received debriefing or not. As such, these results do not seem to support Hypothesis 2 either since participants who have debriefing did not improve their pedestrian behavior. Regarding the rest of behavioral measures, most participants improved in DV3 and DV4, independently of the condition. Therefore, in this case the data do not seem to support Hypothesis 2 either since having a debriefing after the experience in VR did not make a difference.

A possible explanation for these unexpected results refers to the nature of the debriefing technique used, since there are different approaches to do so (Feng *et al.*, 2021). According to Levett-Jones & Lapkin (2014), "it is not possible to form strong conclusions regarding a best practice model or debriefing framework" (p.e63). Elements such as length of the debriefing, level of participation (i.e., individually *vs.* in groups) or the debriefing format (e.g., using multimedia resources, self-guided debriefing, etc.) might have dramatic implications for the outcomes. Besides, it is important to note these conclusions were held for debriefings conducted in health professional education. As Feng *et al.* (2021) suggest, types of knowledge content and particular performance tasks associated might limit or boost the potential of debriefing for learning purposes. This is especially important in the study of pedestrian behavior given that little is known about what the optimum combination of features is to enhance debriefing in this field.

General discussion

Overall, participants stated that they had experienced changes in their pedestrian behavior after taking part in this study, regardless of the condition assigned. In some cases, they did not know whether it was because of filling out the questionnaire or experiencing the VR. As one participant clearly stated:

> *I would say that I have been a bit more careful these days, although I can't say for sure whether it was because of the VR or because I took the pre-test.* Participant nº 5, man, 28 years old.

It could be argued that filling out the WBQ questionnaire made participants more aware of their pedestrian behaviors. As Useche *et al.* (2020) pointed out, the WBQ can be especially useful for designing studies and educational road safety programs focused on road risk reduction and the development of safe walking behavior. Therefore, it seems reasonable that the fact that participants took part in the study has led to a change in their pedestrian behavior, regardless of the condition in which they experienced VR.

Conclusion

All in all, we can conclude that using VR environments might improve pedestrian behavior, especially under particular circumstances (e.g., having an accident). Some aspects of the behavior were more affected than others. For instance, there was a dramatic reduction in the number of times participants crossed with red lights, but there was not a significant change in looking at the right at the first cross. The most plausible explanation for this refers to how the participants made the connection between their behaviors and the accident. In other words, participants likely interpreted that crossing with red lights caused them to suffer an accident, whereas looking (or not looking) at the red light did not have any consequence.

Finally, the unexpected results might be due to limitations in the study, which are discussed next, as well as future avenues for research.

Limitations and Future Research

This study is not exempt from limitations. The results should be considered with caution, as the sample size is not large enough for generalization. Besides, cultural and gender differences might account for some variance in the outcomes, though the unbalanced distribution of the sample did not allow for those variables to be controlled. Gender differences in pedestrian behavior are well known so men usually display lower risk perception and higher risk behaviors than women (Useche *et al.*, 2021).

Regarding the research design, future research should include another condition where participants do not engage in VR environments but fulfill the WBQ. In doing so, we would be able to determine to what extent participants change their behaviors because of the VR experience or because of conducting the WBQ.

Although both self-report and behavioral measures were taken in this study, future research should include measures in natural environments too. The final goal of using VR for learning purposes is to improve pedestrian behavior in real contexts. In this vein, there are many unknowns yet about what exactly is transferred from learning VR to real contexts (Saadati *et al.*, 2022). Similarly, further research should consider later post-measures to determine how long the learning from VR experiences last. Finally, future studies should pay more attention to how the debriefing is designed and developed. In doing so, we could determine what would be the best combination of features in order to optimize the learning experience.

As technology continues to advance, it is crucial to explore innovative approaches like VR to address the persistent challenges of pedestrian safety. By harnessing the power of immersive experiences, we can pave the way for a future where pedestrian accidents and fatalities become minimized, fostering a society that prioritizes the well-being and protection of all road users. Further research may help to unlock the full potential of these technologies, while a safer and more inclusive environment for pedestrians worldwide is developed.

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Conflicts of interests

All authors declare that there are no competing interests.

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Appendix A. Walking Behavior Questionnaire (WBQ)

Violations	0	1	2	3	4
WBQ1: Crossing in the middle of the road, not on the crosswalk, in a city street.					
WBQ2: Crossing on the crosswalk when the traffic light is red.					
WBQ3: Walking on the driveway because the sidewalk is very narrow or there are many pedestrians already walking on it.					
WBQ4: Despite being relatively close to the crosswalk, crossing the road among cars.					
WBQ5: Crossing at a run when the pedestrian traffic light is flashing, even if you make cars wait.					
WBQ6: Making your place in order to overtake someone who is ahead of you, but is walking very slowly.					
WBQ7: Walking on the bike lane, even for a short time.					
WBQ8: Jumping a wall or a fence in order to shorten the way.					
WBQ9: Running at the last moment, so you won't lose the public transportation.					
WBQ10: Walking while under the effects of alcohol or drugs.					
WBQ11: Walking while listening to music with your headphones.					
WBQ12: Walking while watching a video or checking your social media on your phone.					
WBQ13: Walking while you send a text message or talk in a chat.					
WBQ14: Walking while talking on the phone, with or without a speaker.					
WBQ15: Walking so fast that people have to sidestep.					
WBQ16: Zig-zagging among people to reach your destination faster.					

Errors	0	1	2	3	4
WBQ17: Walking while being distracted, so that a car has to stop or honk at you.					
WBQ18: Bumping into someone because you were distracted.					
WBQ19: Bumping into an object because you were distracted.					
WBQ20: Forgetting, for a moment, the place you were going to.					
WBQ21: Stumbling upon an obstacle, a bump or a gap that you hadn't seen.					
WBQ22: Suddenly stopping or changing direction, almost making someone bump into you (for instance, looking at a store window)					
WBQ23: Realizing that you have just crossed the road without looking in both directions.					
WBQ24: Realizing that you have just crossed at a traffic light that was not green.					
WBQ25: Almost bumping into someone while turning a corner, because you were not looking.					
WBQ26: Looking at some billboard instead of focusing on traffic.					

Positive behaviour	0	1	2	3	4
WBQ27: Looking at both sides of the road before crossing, even if you take precedence.					
WBQ28: Waiting for the pedestrian traffic light to turn green before crossing, even when there are no vehicles approaching.					
WBQ29: *Trying to walk on the right side, to avoid bumping into another pedestrian who may come from the opposite direction*					
WBQ30: Walking till the crosswalk to cross the road, even if it requires a some more time.					

Note. 0=Never at all; 1= Almost never; 2=Sometimes; 3=Frequently; 4=Very Frequently. Adapted from "Validation of the walking behavior questionnaire (WBQ): a tool for measuring risky and safe walking under a behavioral perspective" by Useche et al., 2020, Journal of Transport & Health, 18, 100899. Copyright 2020 by Sergio Useche. Reprinted with permission.

Appendix B. Information collected and debriefing scripts

1.Instruments for Data Collection

SEC I: Demographics

1. **Id (ID)**
2. **Condition (CONDITION)**
3. **Gender (GENDER)**
4. **Country of origin (NATIONALITY)**
5. **Age (AGE)**
6. **Studies (STUDIES)**
7. **History of having suffered any traffic accidents (ACC)**
8. **Type of accident (TYPE)**
9. **Severity of accident (SEVERITY)**

SEC II: Interview script for joint reflection (Debriefing)

A) For the YES accident condition:

1. How was the experience in the VR environment? How do you feel? What has been the level of realism you have experienced?
2. What happened? Description of the accident (e.g., estimated vehicle speed).
3. What consequences do you think it would have had in real life if you had suffered the same accident? Provide real data.
4. To what extent do you think it could happen to you in real life? Why?
5. How could it be avoided? What measures could you have taken?
6. What learnings and conclusions do you take away?
7. Others. Final Thoughts.

B) For the NO accident condition:

1. How was the experience in the VR environment? How do you feel? What has been the level of realism you have experienced?
2. What happened? Description of the VR environment.
3. To what extent do you think you could have had an accident in real life in a similar situation? Why? Provide real data and consequences.
4. Do you think you could have acted better as a pedestrian? What measures could you have taken?
5. What learnings and conclusions do you take away?
6. Others. Final Thoughts.

Appendix C. Virtual Reality data and simulation recording

The data set and an example of a simulation are openly available in OSF:
https://osf.io/yxenq/?view_only=48d2cd0fbde0467e88046bb961662fd4

Resumen

Mejorar el comportamiento de los peatones mediante la realidad virtual: un estudio empírico

INTRODUCCIÓN. En los últimos años ha aumentado el número de peatones fallecidos en las vías urbanas, debido en gran medida a infracciones asociadas a sus comportamientos (por ejemplo, cruzar cuando el semáforo está en rojo). Se argumenta que estos comportamientos reflejan una falta de percepción del riesgo. Los programas de seguridad vial han tratado de concienciar a través de diversos métodos, utilizando muy a menudo experiencias emocionales impactantes (por ejemplo, testimonios de personas que han sufrido ellas mismas un accidente). Recientemente, la realidad virtual (RV) se ha desplegado con el objetivo de aumentar la eficacia de estos programas de seguridad. Estudios anteriores han demostrado el potencial de la RV para mejorar la seguridad de los peatones, especialmente cuando va acompañada de un *debriefing* y una reflexión crítica. **MÉTODO.** Un total de 43 participantes (M = 24.5 años; SD = 5.14; 65,12% mujeres) participaron en un estudio experimental con un diseño factorial 2x2 y medidas pre-post. Se los asignó aleatoriamente a uno de cuatro grupos (Experimentar un accidente en RV/Experimentar RV sin accidente; Tener un *debriefing* tras la experiencia de RV/No tener un *debriefing* tras la experiencia de RV). Las medidas pre-post fueron de dos tipos, (a) medidas de autoinforme y (b) medidas de comportamiento en RV. Para analizar los datos se utilizaron análisis multivariantes de la varianza (MANOVA) y modelos lineales generales mixtos (GLMM). **RESULTADOS Y DISCUSIÓN.** Los principales resultados revelaron que (a) los participantes informaron de una reducción general en el número de infracciones de las normas, independientemente de la condición, y (b) hubo una reducción significativa en el número de infracciones cometidas en RV (es decir, cruzar cuando el semáforo está en rojo) en la condición en la que los participantes habían experimentado previamente un accidente. Estos resultados respaldan el potencial del uso de entornos de RV para mejorar el comportamiento relacionado con la seguridad de los peatones. Se delinean las implicaciones para futuras investigaciones.

Palabras clave: *Realidad virtual (RV), Técnicas de debriefing, Programas de seguridad, Comportamiento de los peatones, Riesgo de accidentes, Seguridad.*

Résumé

Améliorer le comportement des piétons par la réalité virtuelle : une étude empirique

INTRODUCTION. Au cours des dernières années, le nombre de piétons décédés sur les voies urbaines a augmenté, principalement en raison d'infractions associées à leurs comportements (par exemple, traverser lorsque le feu est rouge). On soutient que ces comportements reflètent un manque de perception du risque. Les programmes de sécurité routière ont tenté de sensibiliser par divers moyens, utilisant souvent des expériences émotionnelles frappantes (par exemple, des témoignages de personnes ayant elles-mêmes été victimes d'un accident). Récemment, la Réalité Virtuelle (RV) a été déployée dans le but d'accroître l'efficacité de ces programmes de sécurité. Des études antérieures ont démontré le potentiel de la RV pour améliorer la sécurité des piétons, notamment lorsqu'elle est accompagnée d'un débriefing et d'une réflexion critique. **MÉTHODE.** Un total de 43 participants (M = 24,5 ans ; SD = 5,14 ;

65,12 % femmes) ont pris part à une étude expérimentale avec un plan factoriel 2x2 et des mesures pré-post. Ils ont été assignés de manière aléatoire à l'un des quatre groupes (Expérience d'un accident en RV / Expérience de RV sans accident ; avoir un débriefing après l'expérience en RV / ne pas avoir de débriefing après l'expérience en RV). Les mesures pré-post étaient de deux types, (a) des mesures d'auto-déclaration et (b) des mesures de comportement en RV. Pour analyser les données, des analyses de variance multivariées (MANOVA) et des modèles linéaires généraux mixtes (GLMM) ont été utilisés. RÉSULTATS ET DISCUSSION. Les principaux résultats ont révélé que (a) les participants ont signalé une réduction générale du nombre d'infractions aux règles, indépendamment de la condition, et (b) il y a eu une réduction significative du nombre d'infractions commises en RV (c'est-à-dire traverser lorsque le feu est rouge) dans la condition où les participants avaient précédemment vécu un accident. Ces résultats soutiennent le potentiel de l'utilisation des environnements de RV pour améliorer le comportement lié à la sécurité des piétons. Les implications pour de futures recherches sont énoncées.

Mots-clés : *Réalité virtuelle (RV), Techniques de débriefing, Programmes de sécurité, Comportement des piétons, Risque d'accidents, Sécurité.*

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