Report #20-UR-088

NSTSCE

National Surface Transportation Safety Center for Excellence

Virtual Reality as a Tool to Evaluate Pedestrian Safety

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Submitted: June 25, 2020

Technology
Impairment
Mobility
Infrastructure

Housed at the Virginia Tech Transportation Institute
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ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Tom Dingus from the Virginia Tech Transportation Institute; John Capp from General Motors Corporation; Chris Hayes from Travelers Insurance; Terri Hallquist and Nicole Michel from the Federal Motor Carrier Safety Administration; Cathy McGhee from the Virginia Department of Transportation and the Virginia Transportation Research Council; and Jane Terry from the National Safety Council.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

EXECUTIVE SUMMARY

Virtual reality (VR) promises to be an effective tool to evaluate changes to the built environment that could improve safety for pedestrians. However, in order to draw actionable conclusions from VR, it is important to understand the degree to which pedestrians' perceptions and behaviors match across real and virtual environments. In this study, participants experienced equivalent real and virtual environments and performed similar tasks in each. Tasks included the intention to cross an intersection, the estimation of the speed and distance of an approaching vehicle, and the perceived safety and risk of crossing a road. Results showed no statistical difference between the real and virtual environments for participants' intention to cross, estimation of distances, and perceptions of safety and risk. Statistically significant differences between real and virtual environments were observed in the estimation of speed and measures of presence. These results indicate that at lower vehicle speeds (25 mph and lower) VR can be used as tool to evaluate pedestrian safety in built environments.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

M	mean
mph	miles per hour
SD	standard deviation
VR	virtual reality

CHAPTER 1. INTRODUCTION

Virtual reality (VR) can provide nearly complete sensory immersion for a user in a controlled environment. It allows users to safely engage in situations that in real life could be risky or even fatal and enables the creation of scenarios that would be prohibitively expensive or impossible in the real world. For these reasons, VR has been used in the military and healthcare domains for training and evaluation (Bohil, Alicea, & Biocca, 2011; Mantovani, Castelnuovo, Gaggioli, & Riva, 2003; Pedowitz, Esch, & Snyder, 2002; Reger, Gahm, Rizzo, Swanson, & Duma, 2009), as well as for wide-ranging research purposes, including the analysis of human movement (Fajen & Warren, 2004; Owens, 2008). VR has been used in the domain of traffic safety to prevent child pedestrian injuries (Schwebel, Gaines, & Severson, 2008) and to improve pedestrian safety (Deb, Carruth, Sween, Strawderman, & Garrison, 2017). VR can allow researchers to evaluate the effectiveness of a wide variety of interventions to and features of the built environment from the point of view of pedestrians. For example, VR offers an opportunity to quickly develop models of new and alternative intersection and interchange designs like diverging diamond interchanges and displaced left-turn intersections. These newer intersection and interchange designs often involve traffic lanes that are not laid out traditionally, which could lead to confusion and conflicts among pedestrians and vehicles.

Enabling pedestrians to experience these complex intersection and interchange designs by being immersed in a virtual environment would afford researchers opportunities to better understand the safety issues that pedestrians could encounter when crossing an intersection, as well as allow quantitative and qualitative evaluations of pedestrian comfort level and crossing intention. VR-based research could serve an important role in the intersection design process by narrowing down multiple intervention options to a final few that could be evaluated in a realistic setting. VR could further enable the evaluation of features other than intersection layouts, such as median placement, lighting design, and signage. In general, research projects such as these that utilize VR could lead to better-developed roadway interventions and improved safety.

At present, VR systems powered by high-performance computers are available commercially at a price point significantly lower than in years past, which allows the development of a high-fidelity simulation experience for a relatively low investment. Since VR promises a very realistic immersive experience, it can give researchers insights into traffic safety related to pedestrians and other motorized and non-motorized road users. However, prior to developing recommendations based on research in virtual environments, it is important to ensure that pedestrians' responses in virtual environments are similar to those in real-world environments. Thus, there is an existing need to validate the responses of people in virtual environments against their responses in real environments. Such a validation will help to identify areas where pedestrians' perceptions are aligned in virtual and real environments, as well as where pedestrians' responses in VR do not match those in real environments, which can help in designing better VR systems. Thus, the goal of this study is to validate pedestrian responses in the same tasks across matched virtual and real environments. Such a validation will increase the external validity of using VR for the evaluation of proposed changes to the built environment and its effects on pedestrian and vulnerable road user safety.

CHAPTER 2. METHODS

PARTICIPANTS

Sixteen participants between the ages of 18 and 35 years (*M* = 22.4 years, *SD* = 2.9 years) completed the study, including 11 males and 5 females. All participants had a minimum visual acuity of at least 20/40 (corrected) measured with a basic visual acuity test.

EXPERIMENTAL DESIGN

A repeated measures experimental design was employed to understand if the environment (real vs. virtual) had an effect on pedestrians' intention to cross the road at an intersection when a vehicle was approaching. Participants performed the task in both a real environment and a virtual environment that was developed to be as similar to the real one as possible. In addition, participants were asked to rate their perception of the risk and safety of crossing, as well as estimate the vehicle's speed and distance. Participants encountered all the environments in an experimental session, and the presentation of environments was counterbalanced across participants to eliminate order-related confounding effects. All activities were approved by the Institutional Review Board at Virginia Tech. Participants were paid $30 per hour for participating in the study. The entire experimental session lasted up to an hour.

EXPERIMENTAL SETUP

The participant's environment (real world or VR) was the main categorical independent variable.

Environment

Real Environment

The real-world portion of the study was conducted at the intersection on the Virginia Smart Road at the Virginia Tech Transportation Institute. The Smart Road is a 2.2-mile long, controlled access roadway research facility built to United States highway standards. The intersection has signal lights and pavement markings associated with a signalized intersection.

Figure 1. Photo. Intersection on the Virginia Smart Road.

Virtual Environment

The virtual environment was rendered using a commercially available HTC Vive VR headset. Lighthouse sensors mounted on the walls of the room tracked the headset, which enabled the user's orientation in the virtual environment to be determined. Two different virtual environment renderings of the Smart Road intersection were used in the study. The first environment was rendered using the Unity Engine, and the second environment was rendered using a 360-degree VR video that was captured using a VUZE video camera.

The intersection in Unity was modelled to replicate the intersection on the Virginia Smart Road as closely as possible. To make the rendered intersection look realistic, road textures were extracted from drone photography of the real intersection. The dimensions of the Smart Road intersection were measured and were replicated in the rendered environment. As a result of this approach, the Smart Road intersection in the virtual environment looked nearly identical to the real one (Figure 2).

Figure 2. Screen capture. Smart Road intersection rendered in Unity.

For the second virtual environment, a VUZE video camera was placed at the location alongside the intersection where the participants would stand while they recorded their responses (Figure 3). The camera was used to create two 360-degree videos, one for each direction of vehicle travel.

Figure 3. Photo. The location of the VUZE video camera at the intersection of the Virginia Smart Road.

Direction of Vehicle Approach

During the experiment, a 2016 Ford Explorer approached the intersection from two directions, uphill and downhill (see Figure 4), to measure the participants' crossing behavior.

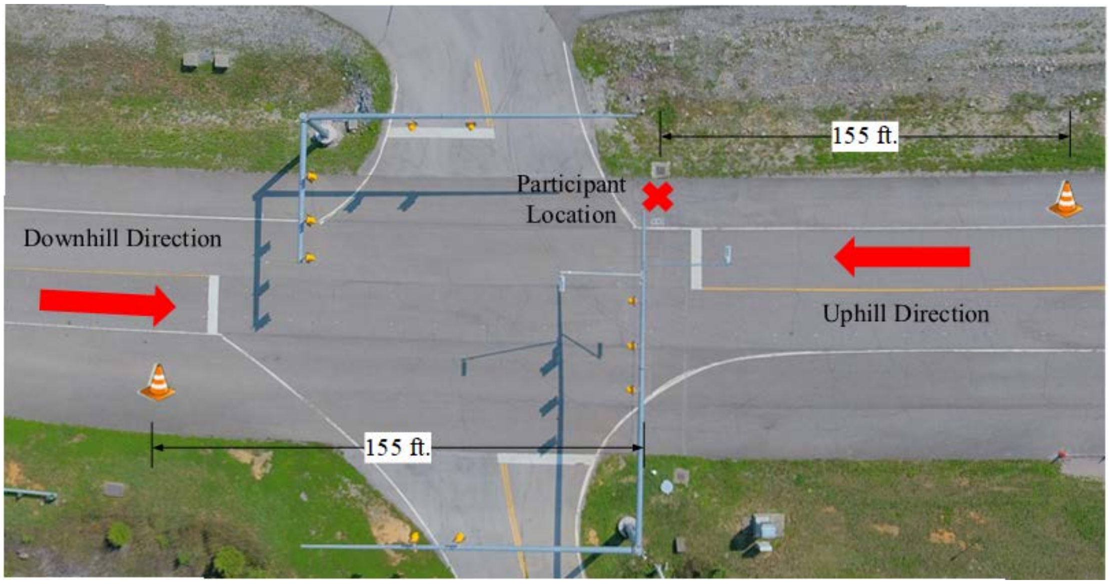

Figure 4. Illustration. Location of the participant at the Smart Road intersection along with the approach directions of the experimental vehicle.

VR Experience

Participants were asked if they had prior experience with VR (yes or no), as prior experience could potentially affect the participants' responses. Their response to prior experience with VR was included as an independent variable.

PROCEDURE

Participants were scheduled to arrive 30 minutes prior to the start of an experimental session. Sessions were conducted during the day (between 10 a.m. and 4 p.m.) and only in clear weather. On arrival, participants signed an informed consent form and reviewed the experimental activities listed for the session. An experimenter provided detailed information on the experimental tasks for the participants and measured their visual acuity. Participants who met the visual acuity criteria participated in the study. After the visual acuity screening, participants were either assigned to the Smart Road task or the VR task first and then switched to the other task after completing the first one. The presentation of Smart Road and VR conditions was counterbalanced in order to minimize order-related confounding effects.

Smart Road Task

For the Smart Road task, participants were escorted to a shuttle vehicle, which an experimenter subsequently drove onto the Smart Road. The experimenter parked on a side road near the Smart Road intersection and asked the participants to step out of the vehicle. Participants stood on the shoulder of the road at the intersection, as if preparing to cross the street at a crosswalk, but did not cross the street. Instead, they were asked to watch an approaching vehicle driven by another experimenter as it passed through the intersection at 25 mph. When that vehicle reached a specific location 155 ft. from the participant, the driver flashed the headlights. This distance was also marked by a traffic cone as reference for the in-vehicle experimenter to flash the headlights.

This distance is the stopping sight distance for a vehicle travelling at 25 mph, which is the total distance required for a vehicle to come to a complete stop. After the vehicle passed through the intersection, participants answered a short questionnaire (see Appendix A) that asked if they would cross at the moment the vehicle flashed its lights, and if so, how risky and safe it would be to do so (on a seven-point rating scale). The questionnaire also asked the participants to estimate the vehicle's speed and distance at the moment it flashed its lights. The vehicle then passed through the intersection again from the opposite direction, and participants answered the same questions for that condition. The participants answered the questionnaires approximately 5 seconds after the vehicle flashed it headlights, thus there was not much time delay to affect their recall.

Once all conditions were complete, participants answered the last questionnaire, which measured the participant's *presence*. Presence is defined as the subjective experience of being at a certain place and is used as a measure of the effectiveness of a virtual environment (Witmer & Singer, 1994). This questionnaire was developed by Slater and colleagues and used in Slater, McCarthy, and Maringelli (1998), Usoh, Arthur, Whitton, Bastos, Steed, Slater, and Brooks Jr (1999), and Usoh, Catena, Arman, and Slater (2000). The presence questionnaire in the cited studies was used, with the only change being that all references to the *virtual environment* were changed to *intersection* (see Appendix B).

After completing the presence questionnaire, the participant was escorted back to the shuttle vehicle and driven back to the main building.

VR Task

For the VR task, participants were escorted to the laboratory housing the VR system. Participants were introduced to the VR system, and the experimenter assisted them in obtaining a comfortable headset fit. Participants were then shown a 360-degree video depicting the same scenarios as the Smart Road task and were asked to verbally answer the same questions as in the Smart Road task. Participants were then shown a simulated version of the same task using Unity, and they verbally answered the same questionnaire again.

When participants completed both tasks, they were paid for their time and released.

ANALYSIS

To assess the effect of environment on crossing intention, a mixed-model logistic regression was used as the dependent variable, which was categorical in nature (yes vs. no).

Five different linear mixed-model analyses were used to assess the effect of the environment on the perceived safety of crossing, perceived risk of crossing, perceived speed of the vehicle, and perceived distance of the vehicle. The vehicle's direction of approach was used as an independent variable in all analyses, and experience with VR was used as a blocking variable.

To assess the effect of environment on presence, a negative binomial regression was used with *presence score* as the dependent measure. Presence score was calculated as the number of responses (r) out of the number of questions (n) that had a score of 6 or 7. For example if a participant's responses for the six questions in the presence questionnaire were 5, 6, 7, 6, 7, and

7, then the *presence score* would be 5. In addition to the *presence score*, a *composite presence rating* was calculated by summing the ratings across the six questions. Higher *composite presence rating* indicated higher immersion and realism. For analyzing the effect of the environment on *composite presence rating*, a linear mixed-model analysis was used. The standardized Cronbach's alpha for the presence ratings was 0.9 in the Smart Road environment, 0.92 in the Unity environment, and 0.85 in the VUZE environment.

The level of significance was established at $p < 0.05$ for all statistical tests. Where relevant, post hoc pairwise comparisons were performed using Tukey's Honest Significant Difference.

CHAPTER 3. RESULTS

CROSSING INTENTION

The mixed-model logistic regression showed that the main effects of the environment ($p = 0.32$) and vehicle direction ($p = 0.60$) were not significant on the crossing intention of the participants. No statistically significant differences were observed between the crossing intention rates across the real (26.5%) and the virtual environments (Unity – 13.9%, VUZE – 21.9%).

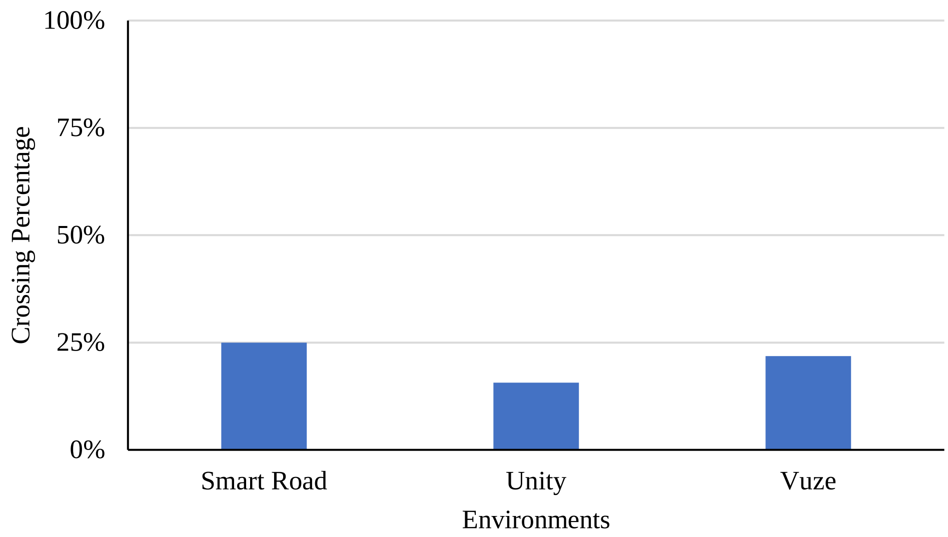

Figure 5. Graph. Effect of environment type on crossing intention.

PERCEPTION OF SAFETY

The two-way interaction between environment and vehicle approach direction for perception of safety was significant, $F(2, 70) = 4.11$, $p = 0.0205$. However, post hoc pairwise comparisons yielded no significant differences between the environments in any direction of approach (Figure 6).

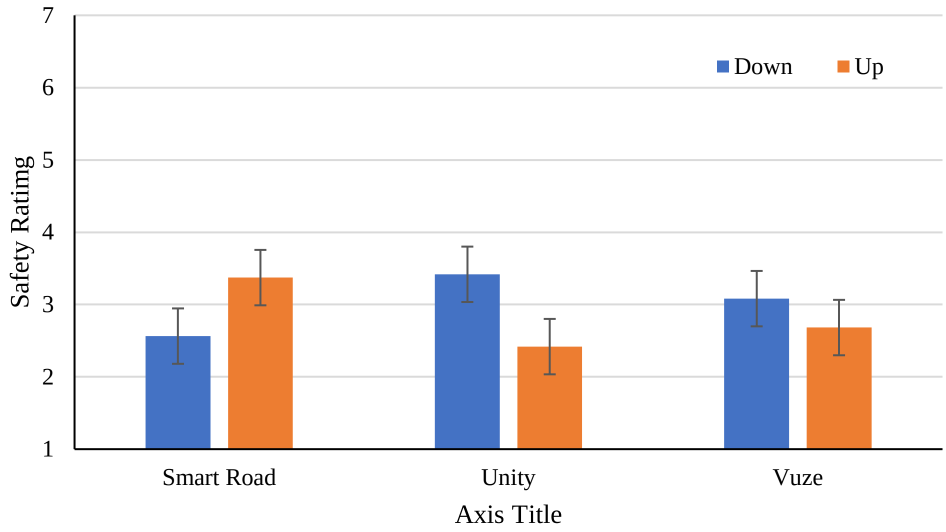

Figure 6. Graph. Effect of environment type and vehicle approach direction on safety ratings. Values are mean safety ratings. Error bars represent standard errors.

PERCEPTION OF RISK

For perception of risk, the main effect of direction of approach, $F(1, 70) = 5.25$, $p = 0.025$, and the two-way interaction between environment and direction of approach, $F(2, 70) = 5.33$, $p = 0.007$, were significant. Post hoc pairwise comparisons showed that there were no significant differences between environments in either direction of approach (Figure 7).

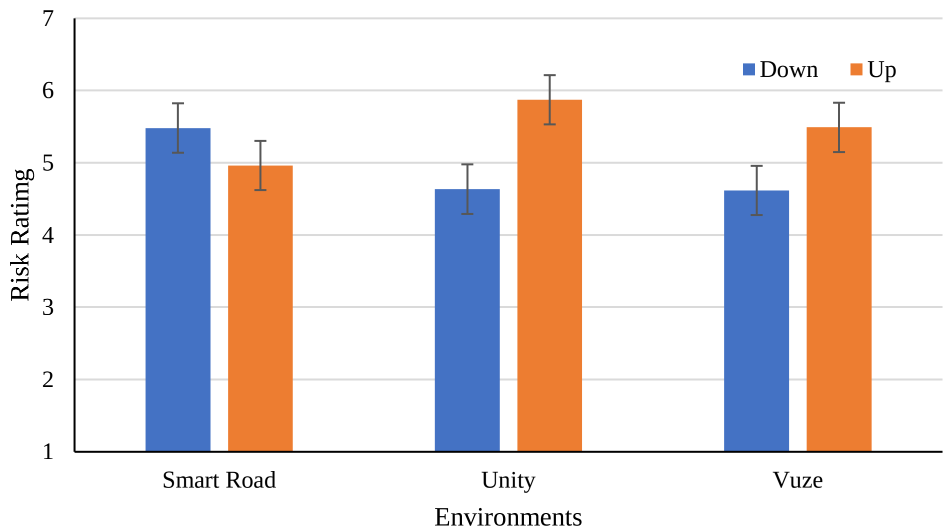

Figure 7. Graph. Effect of environment type and vehicle approach direction on risk ratings. Values are mean risk ratings. Error bars represent standard errors.

PERCEPTION OF SPEED

The main effect of speed was significant, $F(2, 70) = 8.86$, $p = 0.0004$. Post hoc pairwise comparisons showed that the perceived speed of the vehicles was significantly higher in both Unity and VUZE compared to the Smart Road (Figure 8).

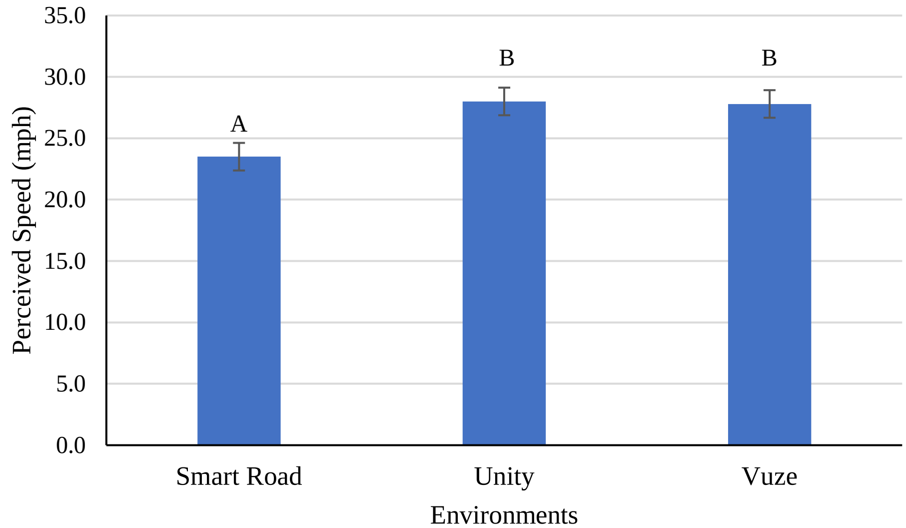

Figure 8. Graph. Effect of environment type on perceived speed. Values are means of perceived speed. Error bars represent standard errors. Uppercase letters denote significant pairwise comparisons (*p* < .05).

PERCEPTION OF DISTANCE

None of the effects were significant for perception of distance. The estimated mean distances in the real environment *(M* = 140.9 ft.) and the virtual Unity environment *(M* = 142.1 ft.) were lower than the real distance of 155 feet (Figure 9). In the VUZE virtual environment, the estimated distance (*M* = 155.2 ft.) was closer to the real distance.

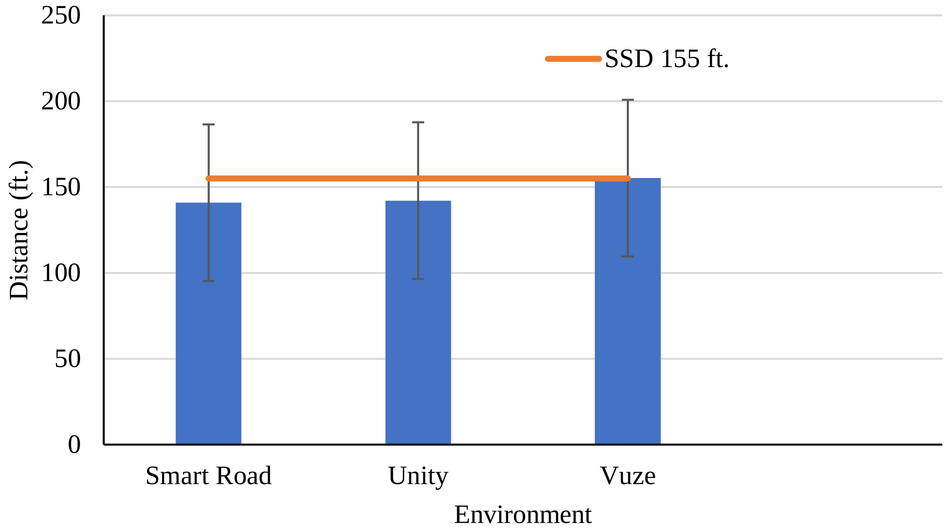

Figure 9. Graph. Effect of environment on perceived distance. Values are means of perceived distance. Error bars represent standard errors.

PRESENCE

The effect of environment on *presence score* was significant, $F(2, 28) = 3.88$, $p = 0.032$. Post hoc comparisons showed that the presence score in the Smart Road environment was significantly higher than in the Unity environment (Figure 10). There were no significant pairwise comparisons between Smart Road-VUZE and Unity-VUZE environments.

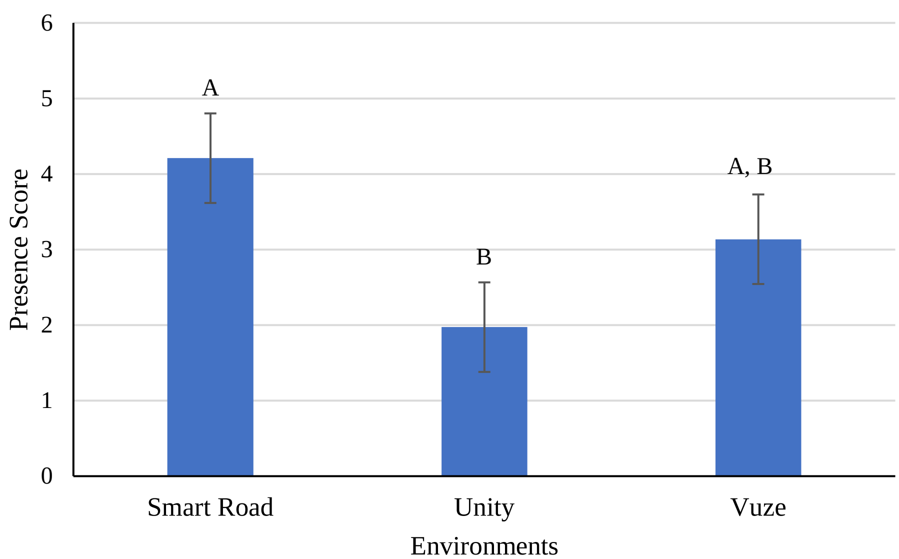

Figure 10. Graph. Effect of environment type on presence score. Values are means of presence score. Error bars represent standard errors. Uppercase letters denote significant pairwise comparisons (p < .05).

However, the main effect of environment on *composite presence rating* was significant, $F(2, 28) = 6.89$, $p = 0.003$. Post hoc pairwise comparisons showed that *composite presence rating* in the Smart Road environment was significantly higher than in the Unity and the VUZE environments (Figure 11). There were no differences in *composite presence rating* between the Unity and VUZE environments.

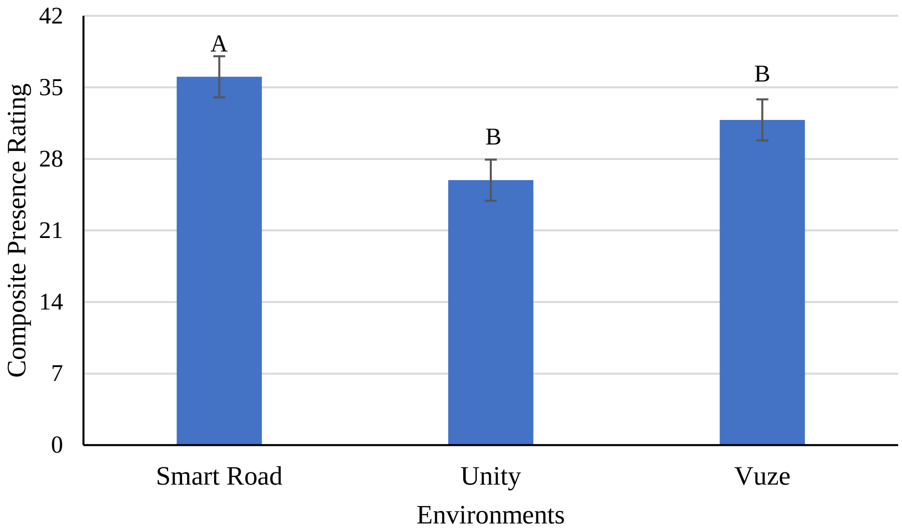

Figure 11. Graph. Effect of environment type on composite presence rating. Values are means of composite presence rating. Error bars represent standard errors. Uppercase letters denote significant pairwise comparisons (*p* < .05).

CHAPTER 4. DISCUSSION

The goal of this study was to validate pedestrians' responses in two virtual environments against their responses in a real environment. Comparisons were made to determine (1) how well participants judged the speed and distance of the oncoming vehicle; (2) their perceptions of risk, including willingness to cross in front of the oncoming vehicle; and (3) the immersiveness of the different environments. The results were similar in both virtual and real environments, indicating that VR may be used as a substitute for real environments for gauging pedestrians' responses. However, there are some differences that designers should consider when implementing VR for evaluating the effectiveness of pedestrian safety countermeasures.

There were no statistically significant differences in the pedestrians' intention to cross the road in both the virtual and real environments. However, it is important to note that the participants' intention to cross was lower in both virtual environments than in the real environment, indicating that pedestrians were more cautious in the virtual environments than in the real environment. These results indicate that under controlled conditions, this head-mounted VR system produced behaviors similar to or more cautious than real environments.

Similar to the pedestrian's intention to cross, there were no statistical differences between the pedestrians' perceptions of risk and safety to cross the road. However, the differences between the real and virtual environments depended on the direction of vehicle travel. When the vehicle was travelling in the downhill direction, pedestrians' perceived safety was higher and perceived risk was lower in the virtual environments than in the real environment. When the vehicle was travelling in the uphill direction, pedestrians' perceived safety was lower and perceived risk was higher in the virtual environments than in the real environment. It is important to note that in the downhill direction, the vehicle was travelling from the left to right from the pedestrian's point of view and was in the lane closest to the pedestrian. In the uphill direction, the vehicle was travelling from right to left and was in the lane farthest from the pedestrian. These results indicate that location of the vehicle and the travel direction influences pedestrians' perceptions of safety and risk of crossing in the virtual environments.

In the estimation of distance, no statistically significant differences were observed between the real and virtual environments. However, in the real (M_{SR} = 140.9 ft.) and the virtual environment that was rendered with the 360-degree camera (M_{VUZE} = 142.1 ft.), the estimated distance was lower than that actual distance (155 ft.). In the virtual environment rendered using Unity, the estimated distance (M_{Unity} = 155.2 ft.) was closer to the actual distance. These results indicate that pedestrians' estimations of distance are very similar in the real environment and in the virtual environments using 360-degree video of the real environment, but these estimations are lower than the actual distance. However, in the virtual environments rendered using Unity, pedestrians' estimates were higher than those in the real environments, but they ended up being very close to the actual distance. More research is required to examine if this holds true at multiple distances.

There were, however, statistically significant differences between the estimation of the speed of the approaching vehicle in the virtual and real environments. Pedestrians perceived the vehicle's speed to be higher in both virtual environments than in the real environment. Compared to the actual vehicle speed of 25 mph, speed estimations were slightly higher in the virtual environments (M_{Unity} = 28.0 mph; M_{VUZE} = 27.8 mph) and slightly lower in the real environment (M_{SR} = 23.5 mph). It is important to note that while there are statistical differences in the perception of speed, the magnitude of this difference is within 3 mph of the actual speed, thus indicating that it is not a major practical difference. These results indicate that at speeds lower than 25 mph, VR can be used as tool to evaluate pedestrian safety in built environments. For speeds higher than 25 mph, further research is required as the video frame rate and resolution (especially on 360-degree cameras such as the VUZE system) could affect participants' perceptions and responses.

Presence measures the level of immersion in the environment. There were differences between the virtual and the real environments for the *presence score* and the *composite presence score*, where the Smart Road (real environment) had a higher score than both virtual environments. The differences in the results of the presence measurements could be a result of participants relativizing their response based on their experience of the environment, as suggested by Usoh et al. (2000).

This study has some limitations. It was an exploratory study wherein pedestrians' responses were only studied in one environment and at one speed. Future work should explore more complex scenarios so that pedestrians' responses in virtual environments can be better validated.

In conclusion, the results of the current study show that when the virtual environments are accurately modelled, several metrics of pedestrian response are similar to their responses in the real world. However, pedestrians were more cautious in the virtual environments and their perceived safety and risk of crossing were dependent on the direction of vehicle travel as well as the distance between the vehicle and pedestrian. Pedestrians' estimation of distance in the virtual environments depended on the type of rendering system used, with the Unity VR system providing a more accurate estimation than the 360-degree camera. Statistically significant differences in pedestrians' responses were observed for estimation of speed and measures of presence. These results also show that VR shows great promise as an effective tool in the evaluation of the built environment in terms of pedestrian safety, especially on roads where the speed limit is at 25 mph or lower.

APPENDIX A. POST SCENARIO QUESTIONNAIRE

Post Scenario Questionnaire

Participant Number:_____ Date:_______ Scene: Unity/Vuze/Smart Road

First Presentation

1. Would you cross the street in this situation?

   Yes No

2. If you were to cross the street, how **risky** would it be?

NOT AT ALL RISKY … VERY RISKY

3. If you were to cross the street, how **safe** would you feel?

NOT AT ALL SAFE … VERY SAFE

4. How fast was the vehicle travelling? _______mph

5. Approximately, how far away was the vehicle when it flashed its' lights (mark the line)?

0 ft 200 400 600 800

Second Presentation

1. Would you cross the street in this situation?

   Yes No

2. If you were to cross the street, how risky would it be?

NOT AT ALL RISKY … VERY RISKY

3. If you were to cross the street, how safe would you feel?

NOT AT ALL SAFE … VERY SAFE

4. How fast was the vehicle travelling? _______mph

5. Approximately, how far away was the vehicle flashed its' lights (mark the line)?

0 ft 200 400 600 800

APPENDIX B. PRESENCE QUESTIONNAIRE

Post Scenario Presence Questionnaire

1. Please rate your sense of being on the roadway by marking one of the boxes in the scale below.

   NOT AT ALL — VERY MUCH

2. To what extent were there times during the experience when the intersection was the reality for you?

   AT NO TIME — ALL THE TIME

3. When you think back about your experience, do you think of the intersection more as images that you saw or more as somewhere that you visited?

   "The intersection seems to me more like…"

   IMAGES THAT I SAW — SOMEWHERE THAT I VISITED

4. During the time of the experience, which was strongest on the whole, your sense of being on the roadway, or of being elsewhere?

   "I had a stronger sense of…"

   BEING ELSEWHERE — BEING AT THE INTERSECTION

5. Consider your memory of being on the roadway. How similar in terms of the structure of the memory is this to the structure of the memory of other places you have been today? By ''structure of the memory,'' consider things like the extent to which you have a visual memory of the intersection, whether that memory is in color, the extent to which the memory seems vivid or realistic, its size, location in your imagination, the extent to which it is panoramic in your imagination, and other such structural elements.

   "I think of the intersection as a place in a way similar to other places that I've been today. . ."

   NOT AT ALL — VERY MUCH SO

6. During the time of the experience, did you often think to yourself that you were actually on the roadway?

   "During the experience I often thought that I was really standing on the roadway. . ."

   NOT VERY OFTEN — ALMOST ALWAYS

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