Building Verisimilitude in VR With High-Fidelity Local Action Models: A Demonstration Supporting Road-Crossing Experiments

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Figure 1: A moment in time where one of our participants, inserted into a Virtual Geographic Environment (VGE), recognizes an approaching car too late. VR offers many affordances atypical in standard, real-world observational studies such as the ability to conduct dangerous and risky scenarios in the safety of a lab room.

ABSTRACT

We examine how issues of investigative and experimental parity between real-world domain science and virtual reality (VR) involving human-environment behavior might be advanced, particularly in the use case of safety science for road-crossing. Our contribution centers on a VR-based traffic flow simulation to recreate, with high fidelity relative to the real world, dynamics of hyper-local interaction between traffic, people, and the roadside environment. An initial demonstration of the system shows that 22 participants responded with high levels of presence, and with high propensity toward natural behavior across road-crossing dimensions. We report these findings even with low-resolution graphic elements. Our results highlight that high levels of user-identified *situational verisimilitude* (i.e., appearing authentic, particularly to the senses) can be achieved, even with low-resolution graphical depictions. The key, we argue, is the design of appropriate low-level action models to drive user embodiment relative to VR assets. We contend that this finding has wider relevance to consideration of potential channels for VR experience more generally.

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CCS CONCEPTS

• **Human-centered computing** → *User studies*; **Virtual reality**; • **Computing methodologies** → **Interactive simulation**; **Simulation evaluation**.

KEYWORDS

Virtual reality, Pedestrian, Simulation, Microscopic traffic flow, AI, Behavioral tree, Pathfinding, 3D interaction, Presence, Realism, Task load, Embodiment

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1 INTRODUCTION

Virtual Reality (VR) is a popular investigative tool for studying human responses to real-world phenomena via simulation. VR has been used to support road-crossing research across a various experimental axes, including investigating accident avoidance opportunities [63], the impact of ADHD on crossers [67], design factors of crosswalks [39], specifics of children's road-crossing [62], and the geography of crossers' attention [69] and social gaze [68]. VR benefits over traditional in-the-wild observational studies through its controllability, reproducibility, standardization, ease in data collection, safety, and novel feedback and instruction paradigms [10, 11]. With special regard to eliminating risk to human subjects during experimentation, VR affords new means of evaluating people's perception, action, and cognition relative to key factors of crossing phenomena.

Inspired by these prior successes, this paper investigates the effect of simulating real-world phenomena through microscopic traffic models and behavior models in agent-pedestrians on the classic road-crossing task, delivered through head-mounted display (HMD) VR. The primary goal of this study is to identify whether this approach inspires a sense of verisimilitude with the real world from the participants' perspective, i.e. the simulation appears and behaves with enough convincing authenticity to elicit feelings of risk and hesitation in participants. A within-subjects user study was performed to evaluate participants' reactions to the vehicle and agent-pedestrian models employed in the simulation, through objective metrics and qualitatively empirical anecdotes polled from participants' user experience in the simulation. Our findings show that participants who interacted with our VR system were persuaded to induce risk avoidance strategies employed in real-world road crossing scenarios. Semi-structured interviews and surveys highlight they did so out of high levels of immersion and presence in the VR environment as well as a high degree of appreciation in the authenticity of virtual vehicles' and agents' behaviors. We expect this approach to reveal opportunities to assess simulation results in ways that can "map back" to open problems in the theoretical literature.

2 RELATED WORKS

VR-based setups to simulate road-crossing tasks have long been a subject of inquiry, forming a sizeable corpus of existing literature on the topic [59]. Early immersive VGEs delivered through kiosk-based and HMD VR systems were found to induce participants from all age groups into adopting decision-making, risk-taking, and temporal strategies that correlate with real-world findings [62, 63]. Further support for VR-based VGEs towards pedestrian simulators emphasized the technology's ability to afford naturalistic walking - a quality shown to be important in measuring pedestrian skill [44] and in reducing underestimation in distance perception among VR users [60]. [45] also showed that temporal pressure encouraged VR pedestrians of all age groups to adopt shorter traffic appraisal times, select shorter and more hazardous temporal gaps to cross, and accept smaller thresholds of distance from vehicles, echoing previous findings from real-world observation. Given these benefits, CAVE-based VR and HMD VR are currently considered the foremost means of immersive pedestrian simulation. In direct comparison between the two VR systems, [49] highlighted that though HMD users did not perform as well as CAVE users at synchronizing their crossing initialization with oncoming traffic, HMD VR not only produced similar age-group patterns in road-crossing behavior as CAVE but also produced higher levels of presence and was preferred over CAVE.

Many VR-based models of road-crossing have typically utilized vehicle movement models that are hard-coded to control for specific pedestrian-vehicle interactions. For example, a usual approach sees the applications of predetermined constant vehicle speeds [5, 12, 15, 44, 63, 68, 75, 76] and gap distances [12, 15, 44, 62, 63, 67, 75, 76] to produce experimental conditions. This invites the question of whether the fidelity of vehicle simulation can be further extended to better align with VR users' expectations for verisimilitude. To this end, we look towards microscopic traffic models, which have been shown to predict and simulate traffic dynamics in the real world [9]. Publicly-available traffic simulators such as SUMO [41], PVT VISSIM [16], PARAMICS [8], AIMSUN, MITSIM [80], MATSIM [74], and CORSIM [24] typically employ such models, including Krauss's Model [38] (SUMO), which in of itself is an extension of Gipps' Model [19], Wiedemann's Model [78] (PVT VISSIM), and Fritzsche's Model [17] (PARAMICS). Other well-known microscopic models include Treiber, Hennecke and Helbing's Intelligent Driver Model (IDM) [70], Newell's Model [47], the Biham-Middleton-Levine Traffic Model [6], the Nagel-Schreckenberg Model [33], the Gazis-Herman-Rothery (GHR) Model [18], and Bando's Optimal Velocity Model [3, 4]. However, no single model has been adequately demonstrated to fully predict movement metrics derived from real-world vehicles [35, 51]. Comparisons between IDM, GHR, Gipps, Wiedemann, MITSIM, Newell, Nagel-Schreckenberg, and Fritzsche show that all models performed remarkably similarly when calibrated with various traffic datasets, such as GPS platoon data from Naples, Italy [51] and from double-loop detectors at the Berkeley Highway Laboratory (BHL) [7]. Such comparisons converge on the sentiment that simpler models, quantified by the number of parameters to calibrate, are perhaps the better option in model selection. With this in mind, the IDM was chosen as the representative traffic flow model of this paper's simulation.

Various approaches to model virtual pedestrian movement have been developed within different application domains including urban design and planning [72], transportation studies [46], physics for understanding complex adaptive systems [30], investigations into pedestrian flocking and herding behavior of structured groups [23], dynamics of escape and panic behavior in emergency scenarios [29], and studies of kinesiology and biology of walking [1, 2, 20, 81]. For all of their sophistication, a unified model of pedestrian movement **also** remains elusive, largely because of the high level of uniqueness in walking behavior that comes as a by-product of the variation in human physiology and differences in human behavior as sourced from perception and cognition [50, 77]. Known advances towards a unified model, including early graphics and animation work by Reynolds [53–57], Continuum models such as vector fields [71] and navigation graphs [65, 66], and recent attempts to build animated virtual humans from motion capture and video data [1, 13, 14, 20–22, 32, 36, 37, 40, 42], center around the goal of generating realistic-*looking* pedestrian movement rather than authentic *behavior*. These approaches are useful for building procedural crowds that appear realistic from afar but reduce in authenticity upon closer inspection. We need an alternative approach as we require agents that can interact with users in ways that (1) evoke a true behavioral response or signal, and (2) that have fidelity in reasonably exactly matching the behavioral dynamics of their real-world counterparts.

3 METHODOLOGY

Our motivation was to reduce the prevalence of repetitive behaviors among virtual agents and vehicles, thereby introducing unpredictability into the simulation where human users may expect preconceived or predictable patterns to emerge. Doing so, we postulate, would reduce immersion breaks and produce dynamics that appear to VR users as being "organic", i.e., with plausible parity to experiences within their everyday walking. An exploratory study was conducted to evaluate whether the IDM traffic flow model and NavMesh/RVO combination for agent-pedestrian movement, the latter of which is typically used in video games built with *Unity3D*, would evoke sufficient believability and immersion to the extent that VR human participants would be convinced to enact real-world strategies in the virtual simulation.

3.1 Virtual Environment

3.1.1 Virtual Street Environment. The static virtual environment features a 5.5m wide bi-directional 2-lane road with a 5m-wide zebra crossing in the middle of the road. Each lane is 2.75m wide (common design specifications for the United States) and 150m long. Trees were added at 20m intervals along both sidewalks as potential visual obstructions. The distance scale of the VR simulation space was a 1:1 match with that of the real world. A pair of traffic and pedestrian light signals were placed at the ends of the crosswalk and would transition between “STOP”, “WARNING”, and “GO” states in a manner similar to that found in the real world.

3.1.2 Vehicular Agents. Five vehicle sub-classes were incorporated into the simulation: Cars, Jeeps, Microbuses, Sedans, and Trucks. Vehicle movements are governed by a modified version of the Intelligent Driver Model (IDM) originally proposed by Treiber, Hennecke and Helbing in 2000 [70], and extended in [34]. We refer to Son et al.'s overview of the IDM equations as the basis for all mathematical formulas related to IDM mentioned in this paper [64]. The IDM is a second-order model that calculates each individual vehicle's acceleration to match their preferred velocity and headway spacing between themselves and a leading vehicle, if present [34, p. 4585]. Stochasticism in vehicles' acceleration was induced via pseudo-randomization of three IDM parameters upon spawning in the virtual world: targeted speed v_{targ}, minimum headway distance from the leading vehicle S_{min}, and the desired time to move forward T_{pref}. Among these, only v_{targ} is the outcome of a weighed randomization between a range of potential speeds, controlled by probability distributions informed by observations of vehicle movement patterns common in New York City, New York. While the implementation used here relies on anecdotal experiences to inform the distributions, this can easily be extended and informed by empirical measurements of real-world vehicle speeds in future experiments. To emulate continuous traffic, a new vehicle is only spawned if the current number of cars does not exceed a threshold value. This enforces the existence of gaps that create opportunities for red-light violations among pedestrians. Vehicles were not programmed to slow down or stop if a pedestrian were to be present in front of the vehicle.

3.1.3 Agent-Pedestrians. Agent-pedestrians are defined as virtual pedestrians that are programmed to cross the street at opportune gaps in traffic flow. When spawned, an agent-pedestrian is given a set of target positions and tasked with moving through all target positions, after which they are de-spawned from the current trial. The shortest path determination to each target position adheres to an A* best-first heuristic [26] implemented using *Unity3D*'s NavMesh system. Obstacle avoidance is integrated through NavMesh as well as Reciprocal Velocity Obstacles (RVO), which prevents agents from bumping into one another [73]. While starting and target positions are randomized for each agent-pedestrian, all paths require agent-pedestrians to cross the road once, thereby forcing them to engage in the road-crossing task alongside VR participants. During this task, agent-pedestrians are programmed to estimate when the safest moment is for them to cross based on time-to-collision (TTC) and will transition between four explicit states: "Idle", "Walking", "Body-Turning", and "Head-Turning" (see Fig 3). All states and transitions are visualized to VR participants as character animations managed by *Unity3D*'s Mecanim animation engine.

To induce variability among agent-pedestrians, agent-pedestrians are assigned either a “safe” or a “risky” personality. Safe agents will always wait until the pedestrian light signifies “GO” to cross the road, while risky pedestrians will estimate TTC at every frame with respect to approaching cars and will only cross if there is sufficient time to cross the road without any collisions. During each simulation trial, parameters such as pedestrians' walking speed, visual

Table 1: Parameters of the IDM model

Parameter	Description	Example Value
v_{targ}	The greatest speed the vehicle can move	Weighted random value, ranged (5m/s - 15m/s)
S_{min}	Minimal desired distance to $h(i)$	Unweighted random value, ranged (0.25m - 0.75m)
S_{max}	Maximum distance to identify obstacles ahead of the vehicle	6m, constant
T_{pref}	Desired time to move forward with current speed	Unweighted random value, range (0.25s, 0.75s)
a_{max}	Maximum level of possible acceleration	$10m/s^2$, constant

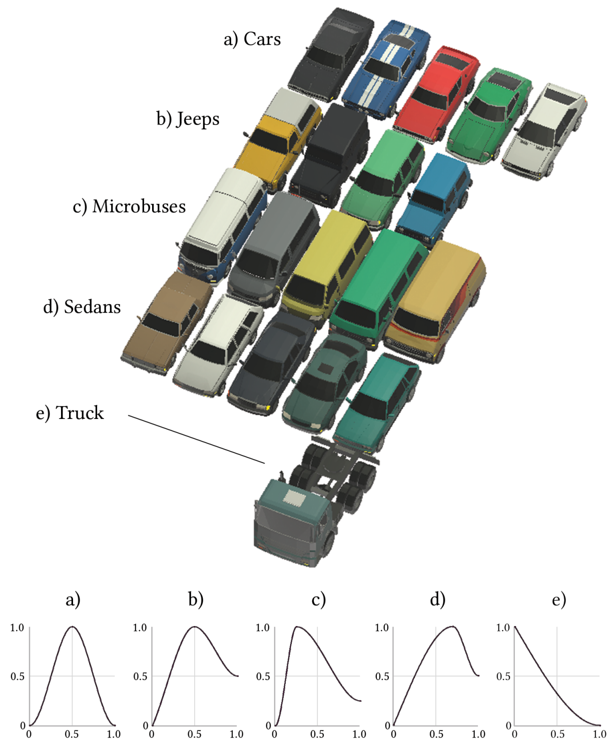

Figure 2: Vehicle models used in the simulation, divided by subtype. Each subtype's velocity is weighted randomly by distributions between 0 and 1. Distribution curves are hard-coded but open to modification using real-world metrics in future implementations.

appearance, and their TTC threshold will be randomly generated to reduce the likelihood of pattern-forming among agent-pedestrians.

3.2 Experiments with the System

3.2.1 Simulation Space. The simulation took place in a research studio that had a traversable area of 8.2m x 3.67m. The virtual simulation was developed and run in *Unity3D* with an RTX 3070 GPU, 6-core AMD Ryzen 5 5000 Processor, and 6 gigabytes of RAM. An *HTC Vive Pro* fitted with a *Vive Wireless Adaptor* was used during the evaluation and streamed video feed data at a near-constant frame rate of 90Hz between the HMD and *Unity3D* engine. To enhance user safety, a virtual grid barrier appeared when participants approached within 0.5m of the edges of the traversable space.

3.2.2 Participants. Out of 24 individuals (9F, 15M) who participated in this evaluation, 22 participants' data were anonymized and used in the post-experiment analysis due to hardware complications preventing reliable data collection. No participants reported problems relating to Simulator Sickness (SS). Participants were recruited through a public recruitment campaign with posters and by physically approaching potential participants using snowball sampling. Participation was limited to individuals who had lived in the city where the user study took place for at least six months

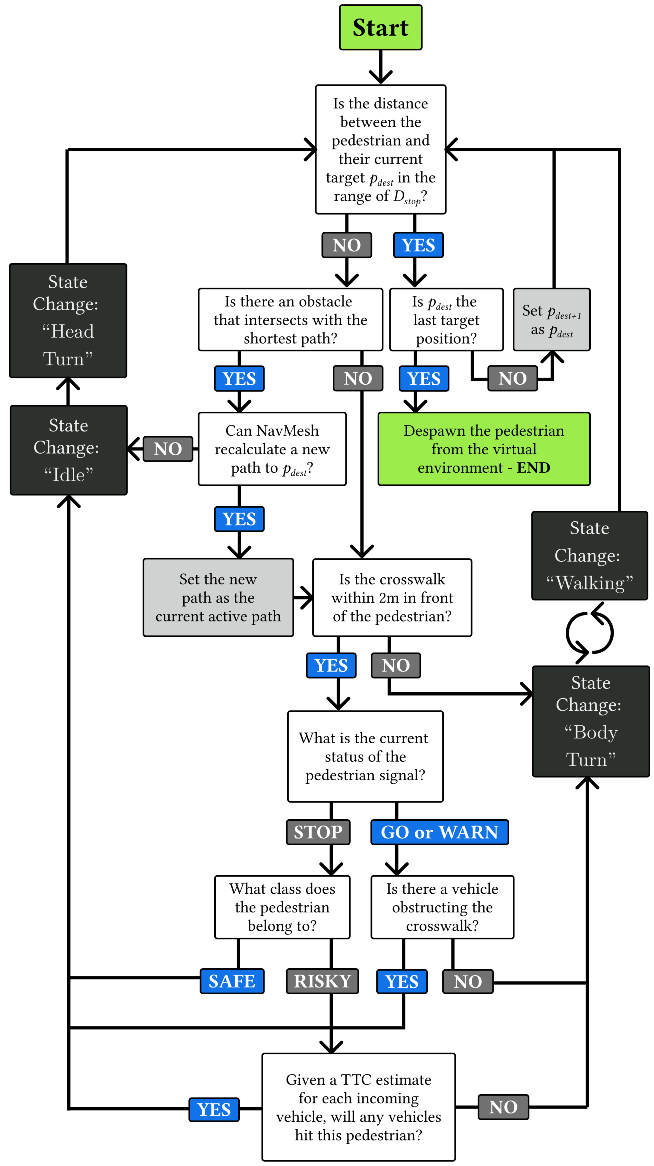

Figure 3: Diagram depicting the behavioral model that dictates the states and logical decisions of each agent-pedestrian. The logical flow starts from the topmost box and flows downward along the arrows, leading into different states represented by the black nodes. Boxes represent conditions or operations that the agent must consider or perform.

and regularly navigated streets while they resided there. Each participant was compensated a $5 gift card for participating in the study.

3.2.3 Procedure. Prior to the study, participants answered a pre-study survey inquiring about demographic characteristics, prior experience with VR, and real-world experience crossing streets in the city where the user study took place. Participants were then placed into the VGE through the *HTC Vive Pro*. A brief training

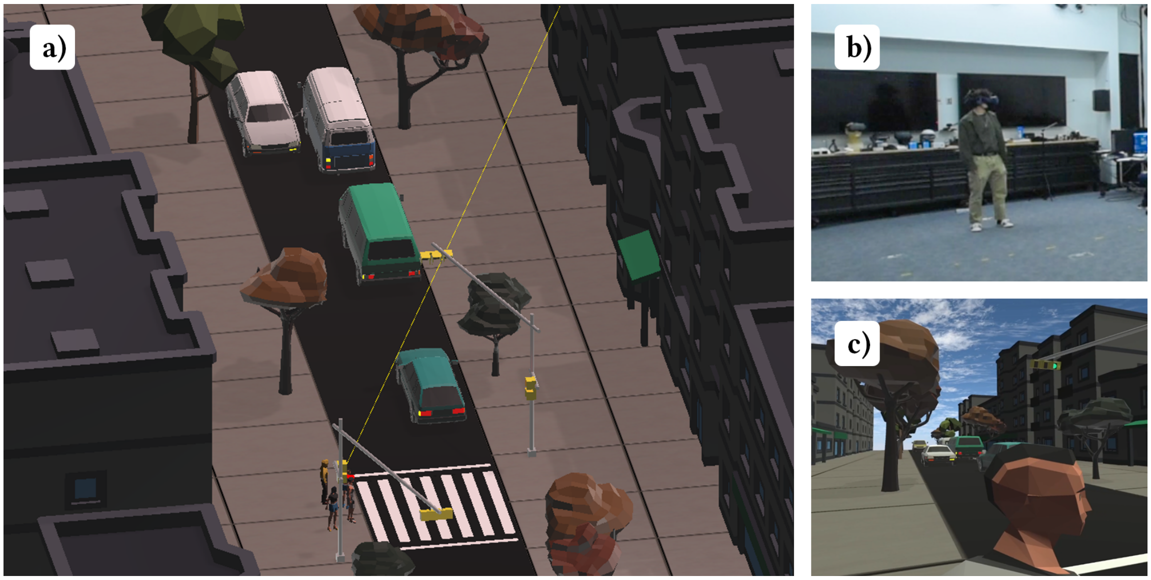

Figure 4: A moment in time during one session when the participant is deciding whether to cross the road. a) A 3rd-person snapshot of the scene. b) The participant in the real world. c) The scene from the participant's viewpoint.

session was conducted to assess any potential lag, graphic anomalies, or misalignment between real-world and virtual movement speeds. During this time, participants had a chance to explore and acclimate to the VRE.

After the training session, participants were transported into the VGE and instructed on their primary task: to cross to the other side of the road as they would in the real world. Participants were engaged in 36 road-crossing scenarios in the VGE, with each scenario depicting a randomized assortment of virtual agent-pedestrians. No variations were made to the number of cars or timing of traffic lights due to the randomized nature of car-spawning logic. 36 scenarios were believed to be sufficient enough to observe participants' behavior toward vehicles. Experimental conditions were split into two sessions of 18 experimental trials with an additional 3 dummy trial conditions added to the beginning of each session to reduce the effect of novelty bias, totaling 42 trials across two experimental sessions. A two-minute resting period was enforced between sessions to give participants time to rest from the first session, and this resting period was extended if needed on a case-by-case basis. Participants could move around anywhere within a traversable safety boundary and were encouraged to move at their own pace.

Upon completion of all 42 trials, a post-experiment questionnaire concerning their feelings of presence (**P**), the realism of the VRE (**R**), and their experience with task load (**T**) was provided to participants. An additional 20-30 minute semi-structured interview was conducted afterward to assess participants' subjective experiences in the VR simulation.

4 RESULTS AND DISCUSSION

4.1 Presence, Realism, and Task Load Questionnaire

Post-study questionnaire prompts were formatted as Likert-scale inquiries ranging between 1 (negative sentiment) and 7 (positive sentiment). Presence questions were adapted from the iGroup Presence Questionnaire (IPQ) by Schubert et al. [61], while Task load questions were adapted from Nasa's Task Load Index [27]. Questions were modified to contain both positive and negative-toned questions (e.g., **P7**: "I was focused towards trying to pay attention to the real-world environment"). The full list of questions is provided in Appendix A.

High presence scores indicate that participants felt successfully immersed in the VRE. We reported high scores for questions **P1**, **P2**, and **P5**, alongside low scores for questions like **P3** and **P4**. A substantial negative response to **P11** has been identified from interviews as a take on the VRE's visual fidelity, as most participants immediately knew the VRE wasn't a realistic world from the low-poly models alone. Regardless, results indicate that participants felt that they were part of and present in the virtual environment. The fact that no participants experienced SS suggests that little to no visual-vestibular mismatches occurred among participants, implying that the simulator sufficiently conveyed movement interactions similar to those in the real world.

Realism-related responses were positive-leaning for **R1** and **R2** but were distributed on **R3** and **R4**. Responses to **R4** were clarified via interviews to also correlate with people's behaviors in the real world (meaning their responses here are actually how they would behave towards real-world traffic lights as well). Some participants mentioned that the pedestrians "seemed realistic" in that they don't just run into the middle of the street, while other mentioned that the fact they would not react the participant's movement around them

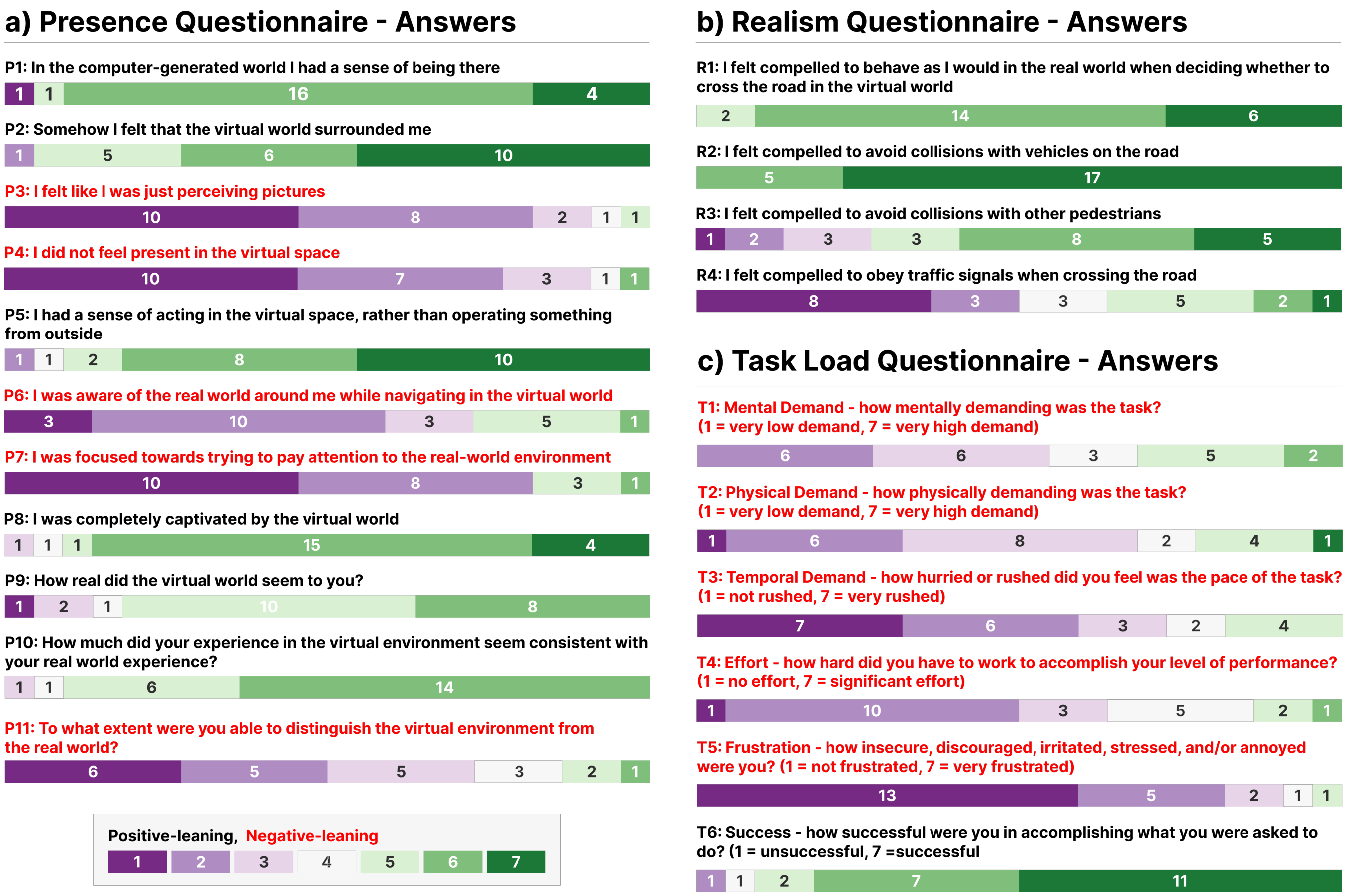

Figure 5: Aggregated responses to questions in the a) "Presence", b) "Realism", and c) "Task Load" post-experiment survey.

made them seem less real. Low scores for **R3** were generated from participants who viewed the pedestrians as incredibly risky, noting that their decisions to cross when they did seemed too dangerous and too precise to the timing of vehicles. Participants who noticed this decided to no longer pay attention to the virtual agents, treating them more as visual obstacles that hindered their view of the road.

Responses to Task Load-related questions are largely negative, showing that participants did not feel much mental, physical, or temporal demand put onto them by the experience. We regard this as an encouraging finding. Occasional high scores for questions **T1** correlate with participants who noted that they treat road-crossing really seriously but the limited field of view (FOV) of the HMD made it harder to view from their peripheral vision. The lack of peripheral vision contributed to other responses in this category as well, with participants noting that the fact their range of senses was limited both visually and sometimes auditorily (some participants could not hear approaching cars) meant they had to struggle to memorize the relative positions of approaching vehicles. However, participants were able to adapt to this scenario as trials continued on in their respective scenarios. High responses to question **T6** indicate that despite some mental demand put onto participants, participants did feel like they were able to complete the task of road-crossing without much trouble.

4.2 Empirical Metrics Across Demographic Factors

In Figures 6 and 7, we illustrate details of the general performance of participants based on demographic factors. These findings are layered with substantive relevance to the theoretical domain science of crossing safety and show the usefulness of VR as an experimental platform. For example, Male participants tend to commit more red-light violations than their Female counterparts and often experience a greater number of failed attempts. This correlates with higher numbers of collisions with vehicles among Males. In addition, Females generally take longer to complete trials than Males. While the overall number of rejected gaps is similar across demographics, Males reject more opportunities to cross when they feasibly could, given each participant's fastest time-to-cross. These results fall in line with existing knowledge regarding different strategies employed by real-world pedestrians [25, 28, 31, 43, 48, 58, 79], which observed the same trends in red-light violations and caution between Males and Females. In addition, prior research [25] highlights that those who have experienced road crossing accidents tend to demonstrate more caution in their behavior at the roadside, especially as measured by longer waiting times prior to crossing. Our

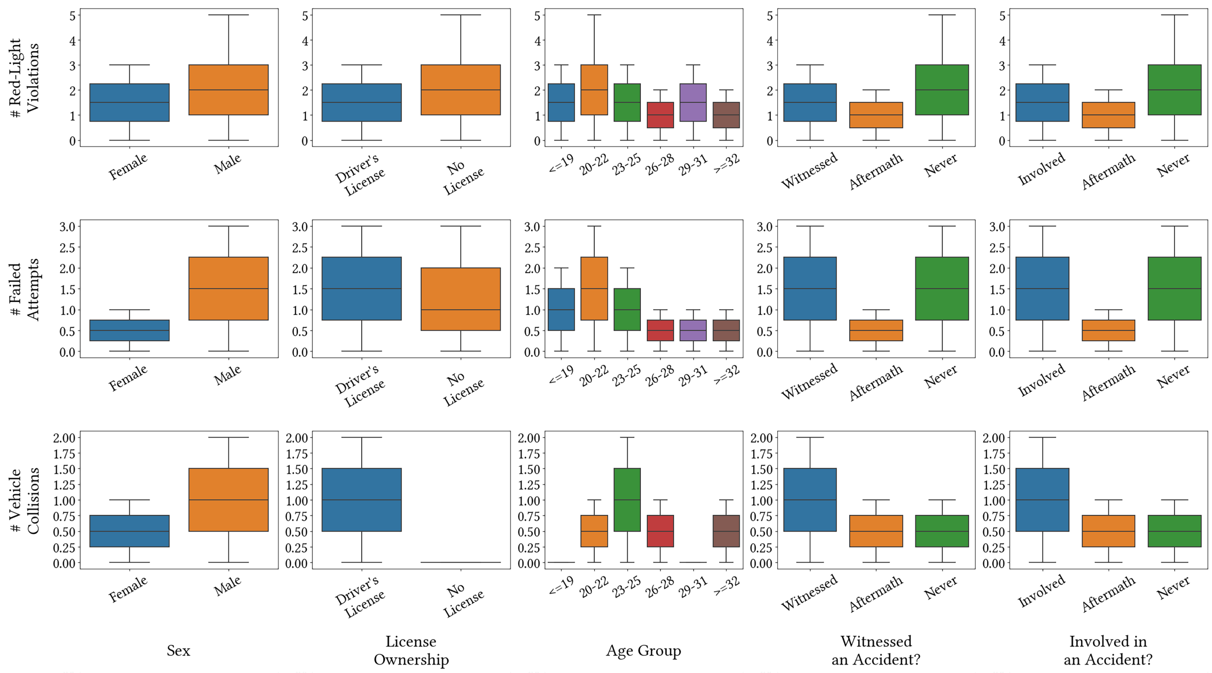

Figure 6: Box plots that visualize empirical metrics across demographic categories among all 22 participants. Key metrics to observe are the number of red-light violations, the number of failed attempts, and the number of vehicle collisions.

results corroborate these findings, as participants who had witnessed or been involved in pedestrian-related accidents tended to have fewer red-light violation attempts. Finally, a general trend can be observed where younger participants in our study tended to experience more vehicular collisions and perform more red-light violations than their older counterparts. This falls in line with studies in the real world, which typically validate that younger pedestrians such as children and adolescents tend to demonstrate risky behaviors than adults in the real world [25, 52, 58]. Somewhat counter-intuitively, however, some results showed trends and patterns that go against known knowledge. These moments highlight potential areas where further study and applications of VR can be extended towards. For example, our study's findings indicate that participants with prior experience being involved in accidents collided with vehicles more than other groups. This can be potentially explained by the fact that vehicle collisions in the VRE were rare and sparse enough that occurrences of vehicle collisions are mostly chance occurrences, but it is worth noting.

4.3 Post-Experiment Interview Responses

Participants highlighted that the varying velocities of vehicles in the VGE closely followed expectations of real-world vehicle behavior, quoting how vehicles in urban areas are often "unpredictable". One participant remarked that despite recognizing that the world was visually fake, their immersion was not affected because of dynamic events in the VGE that aligned with their expectations for how vehicles, ambient pedestrians, and traffic lights ought to work in the real world. For example, a vehicle's wheels animated to turn in response to the vehicle's velocity was a visual cue that implied the virtual vehicles matched the abstract notion of how cars ought to appear and move in the real world. Participants reported that the lack of deceleration in response to potential collisions with pedestrians differed from how real-world cars tend to slow down to let waiting pedestrians cross (in adherence to local red light turning rules). Fortunately, this did not detract people from treating moving vehicles as any less dangerous or realistic.

Agent-pedestrians received mixed responses from participants. Some cited that the agent-pedestrians moved realistically according to their expectations for how people normally behave at roadsides. For example, some participants highlighted that the way agent-pedestrians rotated their heads to look at approaching vehicles was suitably realistic. One participant attributed this head-turning to a "judgmental" reaction from the agent-pedestrians in response to the participant's red-light violation attempts. Another participant simply regarded the head-turning as pedestrians "swishing their hair". These examples indicate the strength of rather simple gesturing behavior of our agents towards producing a quite distinctly-recalled reaction from a user due to what could conceivably be regarded as social peer pressure and norm expectations. However, other participants were discouraged from treating the agent-pedestrians as realistic due to their "awkward" movement animations and their occasional "risky" crossing decisions that surpassed participants' thresholds for safety. These participants believed the agents were too skilled at crossing to be regarded as authentic. Interestingly, the same participants also noted that it was also how they treated pedestrians in the real world and generally do not trust other pedestrians. These participants frequently adjust their position on the

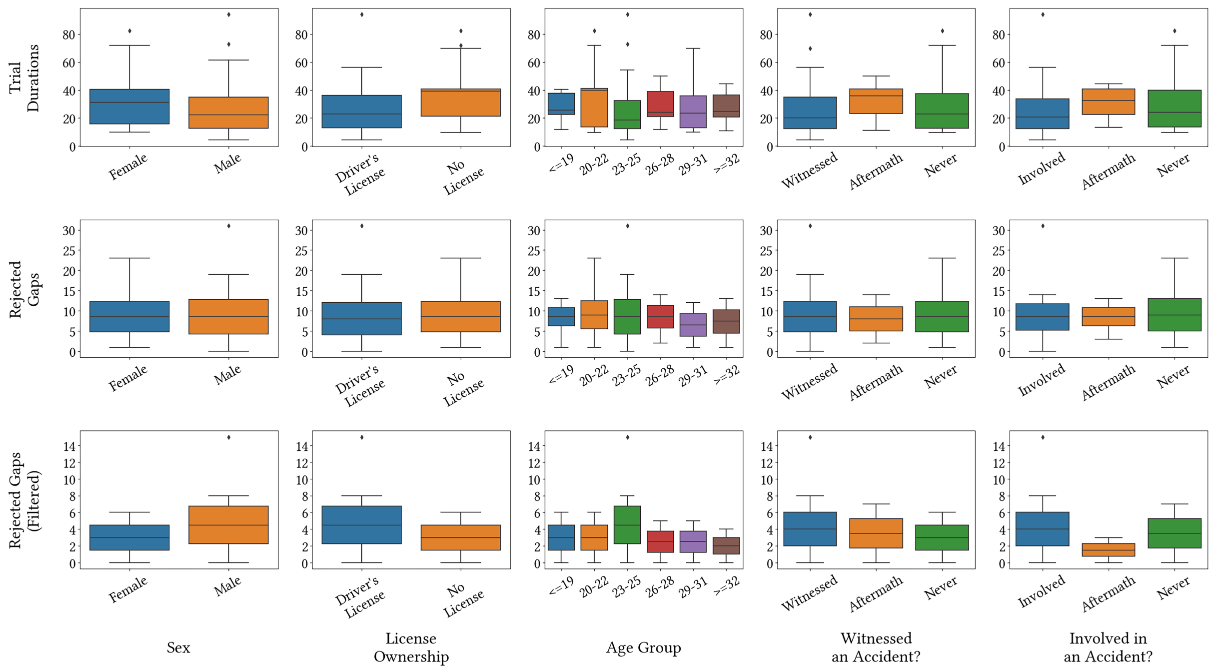

Figure 7: Box plots that visualize empirical metrics across demographic categories among all 22 participants. Key metrics to observe are trial durations, the number of rejected gaps, and the number of filtered rejected gaps. Filtered gaps consist of gaps that were equivalent or longer in duration than the participant's fastest successful time-to-cross. Filtered gaps were those that likely would have provided sufficient time for a participant to cross at the pace they were comfortable with, in other words.

sidewalk to find better angles to look at the road due to visual occlusion caused by crowding among pedestrians.

Our results suggested that additional qualities of the VR experience were at work alongside and perhaps beyond visual fidelity in driving people's perception of consistency and consequence within the VGE. This was evidenced in the contrasting answers between **P11** and **P10** / **R1** / **R2**. When asked about their thoughts on verisimilitude of the roadside that they were presented with, many participants cited that the vehicles and agent-pedestrians seemed realistic, despite their low-fidelity appearance. We attribute this to "situational verisimilitude", i.e., the appearance of contextual reality. We argue that this verisimilitude comes from combining the user's ability to marshal their own senses and skills naturally in the VGE with their belief that the local actions of simulated pedestrians and vehicle drivers were in some way doing the same. In other words, users behaved realistically in the VGE because they thought the phenomena that they encountered were running realistically.

5 CONCLUSION

This study has tested the ability of low-level action models to endow dynamic agents in VR with *realistic-seeming* and *realistic-behaving* actions. Our experiments demonstrated that low-level action models for simulated pedestrians and vehicles in VR can elicit natural behavior from user-participants as well as produce experimental scenarios that have application value relative to theory. The fact that discrepancies between known knowledge and our findings exists opens the broader question of where high-fidelity models should be developed to underpin VR assets, and what aspects of verisimilitude might be important considerations for designers of VR media. This is a topic for future research, which would benefit from analysis of other domain experiments, beyond road-crossing. Nevertheless, our results indicate that an approach that embraces this task with dedicated location action models can be useful in two critical ways: by emphasizing (1) verisimilitude, alongside (2) fidelity in VR. This can ultimately lead to the use of VR in diagnostically useful and theoretically valuable experimental scenarios for real domain science.

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REFERENCES

[1] N.I. Badler, R. Bindiganavale, J.P. Granieri, S. Wei, and Zinmin Zhao. 1994. Posture interpolation with collision avoidance. In *Proceedings of Computer Animation '94*. 13–20. https://doi.org/10.1109/CA.1994.324011

[2] Norman I. Badler, Kamran H. Manoochehri, and Graham Walters. 1987. Articulated Figure Positioning by Multiple Constraints. *IEEE Computer Graphics and Applications* 7, 6 (1987), 28–38. https://doi.org/10.1109/MCG.1987.276894

[3] Masako Bando, Katsuya Hasebe, Akihiro Nakayama, Akihiro Shibata, and Yuki Sugiyama. 1994. Structure stability of congestion in traffic dynamics. *Japan Journal of Industrial and Applied Mathematics* 11 (1994), 203–223. https://doi.org/10.1007/BF03167222

[4] M. Bando, K. Hasebe, A. Nakayama, A. Shibata, and Y. Sugiyama. 1995. Dynamical model of traffic congestion and numerical simulation. *Phys. Rev. E* 51 (Feb 1995), 1035–1042. Issue 2. https://doi.org/10.1103/PhysRevE.51.1035

[5] Rajaram Bhagavathula, Brian Williams, Justin Owens, and Ronald Gibbons. 2018. The Reality of Virtual Reality: A Comparison of Pedestrian Behavior in Real and Virtual Environments. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 62, 1 (2018), 2056–2060. https://doi.org/10.1177/1541931218621464 arXiv:https://doi.org/10.1177/1541931218621464

[6] Ofer Biham, A. Alan Middleton, and Dov Levine. 1992. Self-organization and a dynamical transition in traffic-flow models. *Phys. Rev. A* 46 (Nov 1992), R6124–R6127. Issue 10. https://doi.org/10.1103/PhysRevA.46.R6124

[7] Elmar Brockfeld, Reinhart D. Kühne, and Peter Wagner. 2005. Calibration and Validation of Microscopic Models of Traffic Flow. *Transportation Research Record* 1934, 1 (2005), 179–187. https://doi.org/10.1177/0361198105193400119 arXiv:https://doi.org/10.1177/0361198105193400119

[8] Gordon DB Cameron and Gordon ID Duncan. 1996. PARAMICS—Parallel microscopic simulation of road traffic. *The Journal of Supercomputing* 10 (1996), 25–53. https://doi.org/10.1007/BF00128098

[9] Kang-Ching Chu, Li Yang, Romesh Saigal, and Kazuhiro Saitou. 2011. Validation of stochastic traffic flow model with microscopic traffic simulation. In *2011 IEEE International Conference on Automation Science and Engineering*. 672–677. https://doi.org/10.1109/CASE.2011.6042479

[10] Mark Colley, Marcel Walch, and Enrico Rukzio. 2019. For a Better (Simulated) Woxrld: Considerations for VR in External Communication Research. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 442–449. https://doi.org/10.1145/3349263.3351523

[11] Joost de Winter and Riender Happee. 2012. Advantages and Disadvantages of Driving Simulators: A Discussion.

[12] Shuchisnigdha Deb, Daniel W. Carruth, Muztaba Fuad, Laura M. Stanley, and Darren Frey. 2020. Comparison of Child and Adult Pedestrian Perspectives of External Features on Autonomous Vehicles Using Virtual Reality Experiment. In *Advances in Human Factors of Transportation*, Neville Stanton (Ed.). Springer International Publishing, Cham, 145–156.

[13] Petros Faloutsos, Michiel van de Panne, and Demetri Terzopoulos. 2001. The virtual stuntman: dynamic characters with a repertoire of autonomous motor skills. *Computers & Graphics* 25, 6 (2001), 933–953. https://doi.org/10.1016/S0097-8493(01)00171-6 Artificial Life.

[14] Rodolfo Migon Favaretto, Leandro Lorenzett Dihl, and Soraia Raupp Musse. 2016. Detecting Crowd Features in Video Sequences. In *2016 29th SIBGRAPI Conference on Graphics, Patterns and Images (SIBGRAPI)*. 201–208. https://doi.org/10.1109/SIBGRAPI.2016.036

[15] Ilja Feldstein, André Dietrich, Sasha Milinkovic, and Klaus Bengler. 2016. A Pedestrian Simulator for Urban Crossing Scenarios. *IFAC-PapersOnLine* 49, 19 (2016), 239–244. https://doi.org/10.1016/j.ifacol.2016.10.531 13th IFAC Symposium on Analysis, Design, and Evaluation ofHuman-Machine Systems HMS 2016.

[16] Martin Fellendorf. 1994. VISSIM: A microscopic simulation tool to evaluate actuated signal control including bus priority. In *64th Institute of transportation engineers annual meeting*, Vol. 32. Springer, 1–9.

[17] Hans-Thomas Fritzsche and Daimler-benz Ag. 1994. A model for traffic simulation. *Traffic Engineering+ Control* 35, 5 (1994), 317–21.

[18] Denos C. Gazis, Robert Herman, and Richard W. Rothery. 1961. Nonlinear Follow-The-Leader Models of Traffic Flow. *Operations Research* 9, 4 (1961), 545–567. http://www.jstor.org/stable/167126

[19] P.G. Gipps. 1981. A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological* 15, 2 (1981), 105–111. https://doi.org/10.1016/0191-2615(81)90037-0

[20] M Girard. 1991. Making Them Move: Mechanics, Control and Animation of Articulated Figures, edited by N. Badler, B. Barsky and D. Zeltzer, Chapter 10.

[21] Michael Gleicher. 1998. Retargetting motion to new characters. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*. 33–42.

[22] Michael Gleicher, Hyun Joon Shin, Lucas Kovar, and Andrew Jepsen. 2008. Snap-Together Motion: Assembling Run-Time Animations. In *ACM SIGGRAPH 2008 Classes* (Los Angeles, California) *(SIGGRAPH '08)*. Association for Computing Machinery, New York, NY, USA, Article 52, 9 pages. https://doi.org/10.1145/1401132.1401203

[23] Qin Gu and Zhigang Deng. 2011. Context-Aware Motion Diversification for Crowd Simulation. *IEEE Computer Graphics and Applications* 31, 5 (2011), 54–65. https://doi.org/10.1109/MCG.2010.38

[24] Abolhassan Halati, Henry Lieu, and Susan Walker. 1997. CORSIM-corridor traffic simulation model. In *Traffic Congestion and Traffic Safety in the 21st Century: Challenges, Innovations, and OpportunitiesUrban Transportation Division, ASCE; Highway Division, ASCE; Federal Highway Administration, USDOT; and National Highway Traffic Safety Administration, USDOT.*

[25] Mohammed M Hamed. 2001. Analysis of pedestrians' behavior at pedestrian crossings. *Safety Science* 38, 1 (2001), 63–82. https://doi.org/10.1016/S0925-7535(00)00058-8

[26] Peter E. Hart, Nils J. Nilsson, and Bertram Raphael. 1968. A Formal Basis for the Heuristic Determination of Minimum Cost Paths. *IEEE Transactions on Systems Science and Cybernetics* 4, 2 (1968), 100–107. https://doi.org/10.1109/TSSC.1968.300136

[27] Sandra G. Hart and Lowell E. Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Human Mental Workload*, Peter A. Hancock and Najmedin Meshkati (Eds.). Advances in Psychology, Vol. 52. North-Holland, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

[28] Norman W. Heimstra, James Nichols, and Gary Martin. 1969. AN EXPERIMENTAL METHODOLOGY FOR ANALYSIS OF CHILD PEDESTRIAN BEHAVIOR. *Pediatrics* 44, 5 (11 1969), 832–838. https://doi.org/10.1542/peds.44.5.832 arXiv:https://publications.aap.org/pediatrics/article-pdf/44/5/832/932190/832.pdf

[29] Dirk Helbing, Illés Farkas, and Tamas Vicsek. 2000. Simulating dynamical features of escape panic. *Nature* 407, 6803 (2000), 487–490.

[30] Dirk Helbing and Péter Molnár. 1995. Social force model for pedestrian dynamics. *Phys. Rev. E* 51 (May 1995), 4282–4286. Issue 5. https://doi.org/10.1103/PhysRevE.51.4282

[31] Carol Holland and Roslyn Hill. 2007. The effect of age, gender and driver status on pedestrians' intentions to cross the road in risky situations. *Accident Analysis & Prevention* 39, 2 (2007), 224–237. https://doi.org/10.1016/j.aap.2006.07.003

[32] Serge P Hoogendoorn, Winnie Daamen, and Piet HL Bovy. 2003. Extracting microscopic pedestrian characteristics from video data. In *Transportation Research Board Annual Meeting*. National Academy Press, 1–15.

[33] Kai Nagel and Michael Schreckenberg. 1992. A cellular automaton model for freeway traffic. *J. Phys. I France* 2, 12 (1992), 2221–2229. https://doi.org/10.1051/jp1:1992277

[34] Arne Kesting, Martin Treiber, and Dirk Helbing. 2010. Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 368, 1928 (2010), 4585–4605.

[35] Florian Knorr and Michael Schreckenberg. 2012. On the reproducibility of spatiotemporal traffic dynamics with microscopic traffic models. *Journal of Statistical Mechanics: Theory and Experiment* 2012, 10 (oct 2012), P10018. https://doi.org/10.1088/1742-5468/2012/10/P10018

[36] Lucas Kovar and Michael Gleicher. 2003. Flexible automatic motion blending with registration curves.. In *Symposium on Computer Animation*, Vol. 2. San Diego, CA, USA.

[37] Lucas Kovar, Michael Gleicher, and Frédéric Pighin. 2008. Motion Graphs. In *ACM SIGGRAPH 2008 Classes* (Los Angeles, California) *(SIGGRAPH '08)*. Association for Computing Machinery, New York, NY, USA, Article 51, 10 pages. https://doi.org/10.1145/1401132.1401202

[38] S Krauss. 1998. Microscopic modeling of traffic flow: investigation of collision free vehicle dynamics. https://www.osti.gov/etdeweb/biblio/627062

[39] Jae-Hong Kwon, Jeongseob Kim, Seungnam Kim, and Gi-Hyoug Cho. 2022. Pedestrians safety perception and crossing behaviors in narrow urban streets: An experimental study using immersive virtual reality technology. *Accident Analysis & Prevention* 174 (2022), 106757. https://doi.org/10.1016/j.aap.2022.106757

[40] Kang Hoon Lee, Myung Geol Choi, Qyoun Hong, and Jehee Lee. 2007. Group Behavior from Video: A Data-Driven Approach to Crowd Simulation. In *Proceedings of the 2007 ACM SIGGRAPH/Eurographics Symposium on Computer Animation* (San Diego, California) *(SCA '07)*. Eurographics Association, Goslar, DEU, 109–118.

[41] Pablo Alvarez Lopez, Michael Behrisch, Laura Bieker-Walz, Jakob Erdmann, Yun-Pang Flötteröd, Robert Hilbrich, Leonhard Lücken, Johannes Rummel, Peter Wagner, and Evamarie Wiessner. 2018. Microscopic Traffic Simulation using SUMO. In *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. 2575–2582. https://doi.org/10.1109/ITSC.2018.8569938

[42] Dimitrios Makris and Tim Ellis. 2002. Path detection in video surveillance. *Image and Vision Computing* 20, 12 (2002), 895–903. https://doi.org/10.1016/S0262-8856(02)00098-7

[43] R. L. Moore. 1953. Pedestrian Choice and Judgment. *Journal of the Operational Research Society* 4, 1 (1953), 3–10. https://doi.org/10.1057/jors.1953.2 arXiv:https://doi.org/10.1057/jors.1953.2

[44] Barbara A Morrongiello, Michael Corbett, Melissa Milanovic, Sarah Pyne, and Robin Vierich. 2015. Innovations in using virtual reality to study how children cross streets in traffic: evidence for evasive action skills. *Injury Prevention* 21, 4 (2015), 266–270. https://doi.org/10.1136/injuryprev-2014-041357 arXiv:https://injuryprevention.bmj.com/content/21/4/266.full.pdf

[45] Barbara A. Morrongiello, Michael Corbett, Jessica Switzer, and Tom Hall. 2015. Using a Virtual Environment to Study Pedestrian Behaviors: How Does Time Pressure Affect Children's and Adults' Street Crossing Behaviors? *Journal of Pediatric Psychology* 40, 7 (03 2015), 697–703. https://doi.org/10.1093/jpepsy/jsv019 arXiv:https://academic.oup.com/jpepsy/article-pdf/40/7/697/5107332/jsv019.pdf

[46] Bernard Moulin, Walid Chaker, and Jeremi Gancet. 2004. PADI-Simul: an agent-based geosimulation software supporting the design of geographic spaces. *Computers, Environment and Urban Systems* 28, 4 (2004), 387–420. https://doi.org/10.1016/S0198-9715(03)00063-2

[47] G.F. Newell. 2002. A simplified car-following theory: a lower order model. *Transportation Research Part B: Methodological* 36, 3 (2002), 195–205. https://doi.org/10.1016/S0191-2615(00)00044-8

[48] Pelin Onelcin and Yalcin Alver. 2015. Illegal crossing behavior of pedestrians at signalized intersections: Factors affecting the gap acceptance. *Transportation Research Part F: Traffic Psychology and Behaviour* 31 (2015), 124–132. https://doi.org/10.1016/j.trf.2015.04.007

[49] Prashant Pala, Viola Cavallo, Nguyen Thong Dang, Marie-Axelle Granié, Sonja Schneider, Philipp Maruhn, and Klaus Bengler. 2021. Analysis of Street-Crossing Behavior: Comparing a CAVE Simulator and a Head-Mounted Display among Younger and Older Adults. *Accident Analysis & Prevention* 152 (2021), 106004. https://doi.org/10.1016/j.aap.2021.106004

[50] Nuria Pelechano, Jan M Allbeck, and Norman I Badler. 2008. Virtual crowds: Methods, simulation, and control. *Synthesis lectures on computer graphics and animation* 3, 1 (2008), 1–176.

[51] Vincenzo Punzo and Fulvio Simonelli. 2005. Analysis and Comparison of Microscopic Traffic Flow Models with Real Traffic Microscopic Data. *Transportation Research Record* 1934, 1 (2005), 53–63. https://doi.org/10.1177/0361198105193400106 arXiv:https://doi.org/10.1177/0361198105193400106

[52] Gang Ren, Zhuping Zhou, Wei Wang, Yong Zhang, and Weijie Wang. 2011. Crossing Behaviors of Pedestrians at Signalized Intersections: Observational Study and Survey in China. *Transportation Research Record* 2264, 1 (2011), 65–73. https://doi.org/10.3141/2264-08 arXiv:https://doi.org/10.3141/2264-08

[53] Craig Reynolds. 2006. Big Fast Crowds on PS3. In *Proceedings of the 2006 ACM SIGGRAPH Symposium on Videogames* (Boston, Massachusetts) *(Sandbox '06)*. Association for Computing Machinery, New York, NY, USA, 113–121. https://doi.org/10.1145/1183316.1183333

[54] Craig W. Reynolds. 1982. Computer Animation with Scripts and Actors. *SIGGRAPH Comput. Graph.* 16, 3 (jul 1982), 289–296. https://doi.org/10.1145/965145.801293

[55] Craig W. Reynolds. 1987. Flocks, Herds and Schools: A Distributed Behavioral Model. *SIGGRAPH Comput. Graph.* 21, 4 (aug 1987), 25–34. https://doi.org/10.1145/37402.37406

[56] Craig W Reynolds. 1993. An evolved, vision-based behavioral model of coordinated group motion. *From animals to animats* 2 (1993), 384–392.

[57] Craig W Reynolds et al. 1999. Steering behaviors for autonomous characters. In *Game developers conference*, Vol. 1999. Citeseer, 763–782.

[58] Tova Rosenbloom. 2009. Crossing at a red light: Behaviour of individuals and groups. *Transportation Research Part F: Traffic Psychology and Behaviour* 12, 5 (2009), 389–394. https://doi.org/10.1016/j.trf.2009.05.002

[59] Sonja Schneider and Klaus Bengler. 2020. Virtually the same? Analysing pedestrian behaviour by means of virtual reality. *Transportation Research Part F: Traffic Psychology and Behaviour* 68 (2020), 231–256. https://doi.org/10.1016/j.trf.2019.11.005

[60] S. Schneider, P. Maruhn, and K. Bengler. 2018. Locomotion, Non-Isometric Mapping and Distance Perception in Virtual Reality. In *Proceedings of the 2018 10th International Conference on Computer and Automation Engineering* (Brisbane, Australia) *(ICCAE 2018)*. Association for Computing Machinery, New York, NY, USA, 22–26. https://doi.org/10.1145/3192975.3193022

[61] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. 2001. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments* 10, 3 (06 2001), 266–281. https://doi.org/10.1162/105474601300343603 arXiv:https://direct.mit.edu/pvar/article-pdf/10/3/266/1623697/105474601300343603.pdf

[62] David C. Schwebel, Joanna Gaines, and Joan Severson. 2008. Validation of virtual reality as a tool to understand and prevent child pedestrian injury. *Accident Analysis & Prevention* 40, 4 (2008), 1394–1400. https://doi.org/10.1016/j.aap.2008.03.005

[63] Gordon Simpson, Lucy Johnston, and Michael Richardson. 2003. An investigation of road crossing in a virtual environment. *Accident Analysis & Prevention* 35, 5 (2003), 787–796. https://doi.org/10.1016/S0001-4575(02)00081-7

[64] Sanghyun Son, Yi-Ling Qiao, Jason Sewall, and Ming C. Lin. 2022. Differentiable Hybrid Traffic Simulation. *ACM Trans. Graph.* 41, 6, Article 258 (nov 2022), 10 pages. https://doi.org/10.1145/3550454.3555492

[65] Avneesh Sud, Erik Andersen, Sean Curtis, Ming C. Lin, and Dinesh Manocha. 2008. Real-Time Path Planning in Dynamic Virtual Environments Using Multiagent Navigation Graphs. *IEEE Transactions on Visualization and Computer Graphics* 14, 3 (2008), 526–538. https://doi.org/10.1109/TVCG.2008.27

[66] Avneesh Sud, Russell Gayle, Erik Andersen, Stephen Guy, Ming Lin, and Dinesh Manocha. 2008. Real-Time Navigation of Independent Agents Using Adaptive Roadmaps. In *ACM SIGGRAPH 2008 Classes* (Los Angeles, California) *(SIGGRAPH '08)*. Association for Computing Machinery, New York, NY, USA, Article 56, 10 pages. https://doi.org/10.1145/1401132.1401207

[67] Julia J. Rucklidge Tamera A. Clancy and Dean Owen. 2006. Road-Crossing Safety in Virtual Reality: A Comparison of Adolescents With and Without ADHD. *Journal of Clinical Child & Adolescent Psychology* 35, 2 (2006), 203–215. https://doi.org/10.1207/s15374424jccp3502_4 arXiv:https://doi.org/10.1207/s15374424jccp3502_4 PMID: 16597216.

[68] Paul M. Torrens and Simin Gu. 2021. Real-Time Experiential Geosimulation in Virtual Reality with Immersion-Emission. In *Proceedings of the 4th ACM SIGSPATIAL International Workshop on GeoSpatial Simulation* (Beijing, China) *(GeoSim '21)*. Association for Computing Machinery, New York, NY, USA, 19–28. https://doi.org/10.1145/3486184.3491079

[69] Paul M. Torrens and Simin Gu. 2023. Inverse augmentation: Transposing real people into pedestrian models. *Computers, Environment and Urban Systems* 100 (2023), 101923. https://doi.org/10.1016/j.compenvurbsys.2022.101923

[70] Martin Treiber, Ansgar Hennecke, and Dirk Helbing. 2000. Congested traffic states in empirical observations and microscopic simulations. *Phys. Rev. E* 62 (Aug 2000), 1805–1824. Issue 2. https://doi.org/10.1103/PhysRevE.62.1805

[71] Adrien Treuille, Seth Cooper, and Zoran Popović. 2006. Continuum Crowds. *ACM Trans. Graph.* 25, 3 (jul 2006), 1160–1168. https://doi.org/10.1145/1141911.1142008

[72] Alasdair Turner and Alan Penn. 2002. Encoding Natural Movement as an Agent-Based System: An Investigation into Human Pedestrian Behaviour in the Built Environment. *Environment and Planning B: Planning and Design* 29, 4 (2002), 473–490. https://doi.org/10.1068/b12850 arXiv:https://doi.org/10.1068/b12850

[73] Jur van den Berg, Ming Lin, and Dinesh Manocha. 2008. Reciprocal Velocity Obstacles for real-time multi-agent navigation. In *2008 IEEE International Conference on Robotics and Automation*. 1928–1935. https://doi.org/10.1109/ROBOT.2008.4543489

[74] Kay W Axhausen, Andreas Horni, and Kai Nagel. 2016. *The multi-agent transport simulation MATSim*. Ubiquity Press.

[75] Sebastian Wagner, Julia Belger, Fabian Joeres, Angelika Thöne-Otto, Christian Hansen, Bernhard Preim, and Patrick Saalfeld. 2021. iVRoad: Immersive virtual road crossing as an assessment tool for unilateral spatial neglect. *Computers & Graphics* 99 (2021), 70–82. https://doi.org/10.1016/j.cag.2021.06.013

[76] Huarong Wang, Anni Wang, Fen Su, and David C. Schwebel. 2022. The effect of age and sensation seeking on pedestrian crossing safety in a virtual reality street. *Transportation Research Part F: Traffic Psychology and Behaviour* 88 (2022), 99–110. https://doi.org/10.1016/j.trf.2022.05.010

[77] Ranxiao Frances Wang and James E. Cutting. 1999. Where we Go With a Little Good Information. *Psychological Science* 10, 1 (1999), 71–75. https://doi.org/10.1111/1467-9280.00109 arXiv:https://doi.org/10.1111/1467-9280.00109

[78] Rainer Wiedemann. 1974. Simulation des Strassenverkehrsflusses. (1974). https://trid.trb.org/view/596235

[79] D Yagil. 2000. Beliefs, motives and situational factors related to pedestrians' self-reported behavior at signal-controlled crossings. *Transportation Research Part F: Traffic Psychology and Behaviour* 3, 1 (2000), 1–13. https://doi.org/10.1016/S1369-8478(00)00004-8

[80] QI Yang and Haris N. Koutsopoulos. 1996. A Microscopic Traffic Simulator for evaluation of dynamic traffic management systems. *Transportation Research Part C: Emerging Technologies* 4, 3 (1996), 113–129. https://doi.org/10.1016/S0968-090X(96)00006-X

[81] Jianmin Zhao and Norman I. Badler. 1994. Inverse Kinematics Positioning Using Nonlinear Programming for Highly Articulated Figures. *ACM Trans. Graph.* 13, 4 (oct 1994), 313–336. https://doi.org/10.1145/195826.195827

A PRESENCE, EXACTNESS, TASK LOAD QUESTIONNAIRE

A.1 Presence Questionnaire

(1) **P1**: In the computer-generated world I had a sense of being there.
(2) **P2**: Somehow I felt that the virtual world surrounded me.
(3) **P3**: I felt like I was just perceiving pictures.
(4) **P4**: I did not feel present in the virtual space.
(5) **P5**: I had a sense of acting in the virtual space, rather than operating something from outside.
(6) **P6**: I was aware of the real world around me while navigating in the virtual world.
(7) **P7**: I was focused towards trying to pay attention to the real-world environment.
(8) **P8**: I was completely captivated by the virtual world.
(9) **P9**: How real did the virtual world seem to you?
(10) **P10**: How much did your experience in the virtual environment seem consistent with your real world experience?
(11) **P11**: To what extent were you able to distinguish the virtual environment from the real world?

A.2 Realism Questionnaire

(1) **R1**: I felt compelled to behave as I would in the real world when deciding whether to cross the road in the virtual world.
(2) **R2**: I felt compelled to avoid collisions with vehicles on the road.
(3) **R3**: I felt compelled to avoid collisions with other pedestrians.
(4) **R4**: I felt compelled to obey traffic signals when crossing the road.

A.3 Task Load Questionnaire

(1) **T1**: Mental Demand - On a scale between 1 (very low demand) and 7 (very high demand), how mentally demanding was the task?
(2) **T2**: Physical Demand - On a scale between 1 (very low demand) and 7 (very high demand), how physically demanding was the task?
(3) **T3**: Temporal Demand - On a scale between 1 (not rushed) and 7 (very rushed), how hurried or rushed did you feel was the pace of the task?
(4) **T4**:Effort - On a scale between 1 (no effort) and 7 (significant effort), how hard did you have to work to accomplish your level of performance?
(5) **T5**: Frustration - On a scale between 1 (not frustrated) and 7 (very frustrated), how insecure, discouraged, irritated, stressed, and/or annoyed were you?
(6) **T6**: Success - On a scale between 1 (unsuccessful) and 7 (successful), how successful were you in accomplishing what you were asked to do?

B DESIGN RECOMMENDATIONS TOWARDS HIGHER LEVELS OF VERISIMILITUDE

Compiled below is an aggregated list of observations and recommendations from participants towards the goal of inducing greater levels of verisimilitude, presence, and immersion within observers of VR-based pedestrian and traffic flow simulators.

B.1 Hardware Requirements

- **Choice of hardware dictates comfort, physical stress, and immersion**: Choose VR head-mounted displays (HMDs) that offer different levels of IPD (interpupillary distance) and are light to carry and/or distribute their weight evenly around the observer's head. HMDs that are too forward-heavy or do not offer customizability options restrict potential participant pools and may induce higher levels of physical stress. Heavy HMDs may also clue observers in that what they're seeing is not real and distract them from their tasks in the VRE.
- **Choose wireless options, if possible**: HMDs that offer wireless capabilities offer an extended level of freedom for observers. A tethered setup limits the traversable area and may distract participants by reminding them that they are not in the real world. A wireless setup also may reduce fears of breaking sensitive hardware.
- **Placement of base station sensors**: If the HMD of choice uses outside-in tracking through the placement of base stations (or lighthouses) around a traversable area, ensure that all base stations are oriented such that the HMD is always in line-of-sight with at least one base station. Improper calibration and/or placement of these sensors may create moments of lag in the simulation, which drastically reduces immersion, place illusion, and Plausibility Illusion.
- **GPU and CPU**: The choice of GPU and CPU is key to high performance and high frame rate in the simulation. However, these alone will not remove the simulation from lag or visual glitches. To reduce the chance of this happening while the simulation is running, ensure that the game engine the simulation is running on is allocated enough processing power first prior to any extraneous software such as video capture software.

B.2 Low Graphic Fidelity Options

Choices regarding the graphic fidelity of the system must be carefully selected to ensure that presence and immersion are maintained. The choice to go low-fidelity with a virtual environment may be preferred if hardware limitations exist, but certain factors must be accounted for to prevent presence and immersion from breaking.

- **Distractions in static elements**: The effect low-fidelity graphics have towards the verisimilitude of static environmental elements such as buildings, plants, and trees depends greatly on the amount of "abstraction" associated with that element in the real world. For example, trees can afford to be low-fidelity and simple due to how visually abstract they can be in appearance, whereas buildings are not afforded such abstraction. In this situation, the participant must be distracted from focusing on the appearance of these elements. This can be done through interactions and events that happen in relation to these elements (ex. doors opening/closing, smoke or noises coming from open windows, and people moving inside of buildings).
- **Little details in dynamic elements**: Similar to how abstractions of real-world objects may influence observers' perceptions of static objects, abstractions also affect perceptions of dynamic elements, though these abstractions will be more centered around how these dynamic elements move and behave. Small details that encourage those abstractions (ex. wheels moving on moving vehicles, lighting effects from cars' headlights or traffic signals in dark conditions, and pedestrians shuffling around while standing) will distract participants and give them an opportunity to embody real-world attributes in those dynamic objects.
- **Avoid too low-poly meshes**: While low-fidelity graphics may be preferred, do not attempt to reduce mesh complexity in elements close to the observer to the point that observers can clearly identify edges or vertices in a mesh. Doing so will reduce immersion.
- **Go for higher graphics if nothing else**: If the problems above cannot be avoided, then the only remaining option is to upgrade the graphic fidelity of the virtual simulation. Be warned that if one element is improved, all elements must

also be improved as well to avoid immersion from breaking due to disparate levels of graphic fidelity in the environment. Furthermore, the more realistic an environment is made, the greater the risk of the uncanny valley effect.
- **Use optimizations where necessary**: optimizations such as occlusion culling will help to reduce the amount of stress on the system's GPU. Optimizing scripts and meshes is usually performed near the end of development cycles, but doing so will increment the performance of the simulation in small ways.

B.3 Dynamic Elements

The goal of VR-based simulations is to induce observers into performing as they would in the real world. This can be done by implementing events that are not induced by the observer's actions or presence.

- **Pedestrian behaviors**: If the VRE requires pedestrians to be nearby the observer, then it is crucial that they display a high-enough level of verisimilitude with attitudes from real-world participants to induce some level of verisimilitude. This is highly context-dependent on location, time of day, and cultural norms. For example, pedestrians playing with phones, holding accessories such as coffee cups, listening to music, or talking with other pedestrians will instill high levels of verisimilitude in environments replicating heavily urbanized locations.
- **Ambience and sound**: Ambient noise will populate the background of the VRE and make observers feel more comfortable in the virtual environment, as long as ambient sounds are commonly heard in the real world the VRE is trying to mimic. Vehicle noises in the distance (ex. cars honking, tires skidding) and street noises (ex. pedestrians arguing, music playing, crosswalks beeping) will feel natural and improve immersion through higher levels of verisimilitude.
- **Animate interactions between vehicles, pedestrians, and the observer**: The observer needs to feel present within the environment to the extent that their actions have a tangible effect on the VRE's current state. Like with **pedestrian behaviors**, observers' actions must be able to incite a reaction out of other dynamic elements. Physics animations, other pedestrians reacting to observer movements, and vehicles reacting to pedestrians close to or on the road will increase feelings of verisimilitude, thereby improving immersion.
- **Add consequences**: A big part of verisimilitude, presence, and immersion is the threat of consequences. Observers in VR simulations must be able to feel that consequences carry over in some metaphorical way to the VR condition. A "Lose" state or condition, for example, when an observer is struck with a vehicle or performs a dangerous action may induce feelings of frustration and stress, but these will bring the simulation one step closer to a higher level of verisimilitude and consequently a higher level of presence and immersion.

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