# In Search of Social Presence: Evoking an Impression of Real Pedestrian Behavior Using Motion Capture*

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Abstract— Virtual Reality (VR) is commonly utilized to examine driver interactions with vulnerable road users (VRUs) in an effective and secure manner. Recent studies, however, have highlighted issues in VR simulations, particularly concerning the authenticity of state-of-the-art pedestrian agent behaviors. These inaccuracies can compromise the perceived realism of the situation, potentially leading to unrepresentative driver reactions. This paper aims to showcase enhancements in pedestrian agent models and evaluate their subsequent advantages. To this end, real pedestrian movements, captured via motion-capture technology, were compared with outputs from a contemporary pedestrian agent model within a VR driving simulator experiment. The findings underpin the advantages of using motion-captured pedestrians to enhance social presence. Additionally, participant feedback emphasized that certain elements, such as head movements, explicit gestures, and subtle cues like hesitation before entering the road, were crucial in distinguishing realistic from unrealistic agents. These insights contribute significantly to refining the focus for systematic advancements in (pedestrian) agent models in VR environments. Such improvements are pivotal in augmenting the users' sense of presence and the behavioral accuracy of the simulations.

## I. Introduction

Motion capture (MoCap) has been utilized for recreating the movement of humans in games and cinema for decades [1]. Its popularity is attributable to the fact that realistic motion and behavior of characters are essential for creating a connection between the characters and the user or viewer. MoCap can be understood as 'the process of digitally tracking and recording the movements of objects of living beings in space' [2, p. 1]. Meanwhile, in the automotive industry, virtual reality (VR) solutions, such as driving simulators, have become essential to vehicle development and testing. Experiments involving human participants can be conducted safely here. This is especially relevant when investigating driving situations involving interactions with vulnerable road users (VRUs), such as pedestrians, due to the high risk of physical injury. In 2021, there were 7,388 pedestrians killed in traffic accidents. This accounts for 17 % of the total fatalities, while the trend is still increasing. Most pedestrian fatalities occur in urban areas, and 80 % of pedestrian fatalities occur in single-vehicle traffic accidents, where pedestrians are most often hit by the vehicle fronts [3]. To avoid these types of accidents, it is necessary to understand the causes of accidents. Driving simulators are helpful tools to this end. Adequate agent models are required to realistically depict traffic scenarios in driving simulation. However, several issues connected to state-of-the-art pedestrian agent models have been reported [4], [5]. Some of these were observed in [6], and summarized by [7]:

- pedestrians appear like rigidly following rules,
- pedestrian movements are choppy and angular,
- virtual pedestrians do not seem to make eye contact, and
- virtual pedestrians do not react to hazards in their environment.

Overall, pedestrian models in driving simulation are still lacking behind the implementations in other application domains. Implausibilities in pedestrian movements and behavior may induce unrealistic driver responses, limiting the transferability of results to the real world. Therefore, in this research, we investigate the impact of pedestrian realism on drivers inside the driving simulation.

We will present the results of a two-folded user study. In the first step, pedestrian movements were recorded using a MoCap suit on real persons acting as pedestrians in a virtual environment (pedestrian experiment). In the next step, the recorded movement patterns were subjected to virtual characters in a driving simulator experiment (driver experiment). In the driver experiment, these MoCap recordings were contrasted to a state-of-the-art pedestrian model. Participants in the driving simulator experienced the same simulated road crossing situations, in which they were forced to interact either with a MoCap pedestrian or with a state-of-the-art pedestrian. Participants provided ratings on social presence as well as open feedback throughout the experiment. Overall, this resembles the procedure proposed by [7].

## II. Related Work

A major concern when using simulation is whether the driver reacts to the virtual world the same way as they would react to the real world, which may be summarized as the behavioral validity of the simulation

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[8]. The lack of physical harm in the simulator may lead to more careless driving behavior towards VRUs. This could be particularly problematic when the VRU behaves unrealistically. The subjective sense of presence, defined as “the extent to which something (environment, person, object, or any other stimulus) appears to exist in the same physical world as the observer” [9, p. 1] could act as a mediator towards a more realistic driving behavior: If the VRU is perceived as part of the real world, it is anticipated that the driver in the simulation will respond to it in a natural manner.

### A. Presence

Two aspects must be given according to this definition of presence, which is a) that the driver feels spatially present, i.e., the driver feels like being physically located within the virtual environment, and b) that the VRU is perceived to coexist in the same entity, or as a real person, indicating social presence [9]. For our specific context, we suppose that social presence is the most relevant component of presence. This counts especially since this paper only deals with the behavior of humanoid virtual characters.

### B. Effects of (un)realistic agent behavior

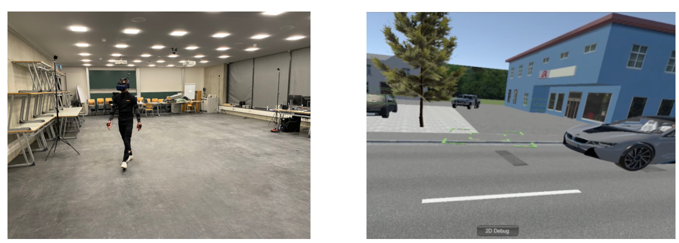
In areas other than traffic simulation, the effect of agents in virtual environments on behavior and presence was also evaluated. [10] observed that the mere presence of virtual bystanders did not change the recipient’s behavior in a VE. Skarbez et al. [11] found moving agents to be preferred over static ones, though there was no clear preference for agents capable of realistic conversation. [12] reported that participants treat humanoid objects differently than non-humanoid ones, though they could not prove a positive effect of more realistic behavior. Given these observations, it seems questionable whether more realistic agent behavior can actually induce more presence or evoke more realistic behavioral responses. However, note that in both [12] and [11], there was no need to interact with the presented virtual characters. Hence, the desire for interaction may have been low.

Numerous papers also indicate positive effects of realistic agent behavior on driving behavior or subjective ratings. [13] noted that participants corrected their vehicle’s position more in scenarios where pedestrians and oncoming traffic were present. [14] reported that enhancing agents with virtual personalities improved presence and perceived realism. [6] confirmed that surrounding traffic had a positive effect on perceived realism in driving simulation. Interaction and behavior-response correlation are recognized to contribute to a high sense of presence [15]. Meanwhile, state-of-the-art pedestrian agent implementations do not support a sufficient level of intelligence to evoke the impression of interactiveness. To overcome this, [7] suggested an extension connecting state-of-the-art pedestrian models to visualization models. Ultimately, to allow true interactivity, pedestrian models require improvement to a large degree. The ASAM Open Simulation Interface[1] (OSI) pedestrian model is a standardized pedestrian model, which was used as state-of-the-art comparison model for the present study. It underlines the incapabilities and capabilities of pedestrian models used in driving simulation: The OSI pedestrian can output trajectories, adapt to changes in the road surface, and plan its path around known obstacles. The current OSI pedestrian, however, cannot output any head or limb movements or other information beyond a trajectory, which is sent to a visualization module and provided with a body animation there.[2] Summarizing, we suggest that a higher fidelity pedestrian model is needed to overcome the above-listed issues.

To understand what exactly contributes to perceiving a virtual pedestrian as realistic, it is necessary to look at real pedestrian behavior. This will allow for a more purposeful improvement of pedestrian models.

## III. Method

For both studies, participation was voluntary and not financially compensated. At any point, participants had the opportunity to abort the study. Participants signed an informed consent form before the experiment started. The study was conducted in accordance with the ethical guidelines stated in the Declaration of Helsinki. Ethics board approval was waived for this study since no risk of physical or mental harm was to be expected. The same OpenDRIVE[3] map was used for both experiments. For practical reasons (pedestrian experiment performed at university, driver experiment at BMW), Unity was used in the pedestrian experiment, while Unreal was used in the driver experiment, and the head-mounted displays (HMDs) differed due to the different hardware used in the two involved institutions.



(a) Pedestrian simulation in a large lecture hall.

(b) First person view of the pedestrian inside the virtual environment.

Fig. 1: Motion capture process which was used in the pedestrian experiment.

[1] https://www.asam.net/standards/detail/osi/

[2] With OSI release v3.6.0 (https://github.com/OpenSimulationInterface/open-simulation-interface/releases/tag/v3.6.0, (published during the writing of the paper), skeleton data can now be transmitted. However, most driving simulation software does currently not support this.

[3] https://www.asam.net/standards/detail/opendrive/

### A. Pedestrian experiment

1) Sample: In total, the movements of seven participants were recorded in the pedestrian simulation, of which three were women and four men. All participants were aged between 25 and 36 years, M = 31 years, SD = 4 years. The test persons were between 1.63 m and 1.85 m tall, with an average of 1.75 m.

2) Materials: A crossing task was chosen for the experiment. The virtual scene included buildings, streets, sidewalks (Figure 1), and some bystanders, though no traffic participants except for the participant and one manipulated vehicle, which was triggered to start driving in a hidden position as soon as the pedestrian started walking. This timing forced the pedestrians to interact with the vehicle when crossing the street. Participants wore an HTC Vive Pro Eye HMD with the HTC Vive wireless kit. An audio file resembling a suburban ambient was played using the HMD's headphones. A total of five lighthouse trackers were set up in a large, full ground-level lecture hall, which measured approximately 12 m × 6 m, Fig 1a). A sticker was placed on the floor to mark the starting position.
MoCap was performed using an XSens MVN Link suit (Figure 1). For ease of use, we opted to use velcro bands to fasten the sensors to the participants' bodies instead of using the entire suit. This allowed for quicker turnover times. During the experiment, the experimenter checked the recorded movements on the MVN screen to detect irregularities. Sensors were re-positioned during the experiment and re-calibrated if necessary. This had to be done in several trials. To filter out any recordings containing unwanted artifacts for the driver experiment, two researchers scanned the recording files and hand-picked MoCap files for the subsequent driver experiment. In summary, although many MoCap files suffered from quality issues, those MoCaps that were implemented had a high quality. Of the feasible MoCaps, we took care to select some with vehicles approaching from left and right, as well as one zebra crossing. The motion captured in the pedestrian experiment was then applied to virtual avatars for the driving simulation experiment.

3) Procedure: One trial consisted of two road crossings: The participants started on the sidewalk and crossed the road towards the opposite sidewalk. They then returned to their starting position. A rectangle was projected onto the floor of the virtual scene to indicate the pedestrian where to go (Figure 1). Arrows indicated the direction of movement. Participants experienced 25 trials, which contained vehicles approaching from either side of the road or no vehicles. There were trials including zebra crossings, phones, and trials in which participants were urged to hurry (to "catch a bus"). Only a subset of the trials presented here was used in the follow-up experiment. Further trials were recorded for use in other projects. The order was not completely randomized for reasons of feasibility in experiment conduction, but the direction from which vehicles approached and whether a vehicle approached or not was mixed to avoid predictability.

### B. Driver experiment

1) Sample: There were N = 49 participants in the driving simulator study, of which one participant was excluded due to responding exactly the same to all situations. Another participant aborted the drive due to simulator sickness. While drivers experienced five pedestrian crossings per condition, some crossings were excluded in single drives due to the participants reporting not to have noticed the pedestrian. This was the case for nine single crossings, where we still consider all other drives and crossings of the concerned participants. Participants were aged between 25 and 56 years, M = 38 years, SD = 7 years.

2) Materials: The driver experiment was performed in a static VR driving simulator. Visualization was performed using the Varjo XR-3. The same virtual scene as in the pedestrian experiment was used. The driving simulation was performed based on proprietary software, including a realistic vehicle dynamics and sound model. Sound was displayed from four speakers placed around the seat. Head-tracking was performed using two lighthouse trackers. Except for the pedestrians crossing the road, there were no other road users in the simulation. No other pedestrians were implemented to avoid confusion about items related to "pedestrian" realism or behavior. The mirrors were displayed in the virtual scene by streaming the mirrors into their respective positions. Both MoCap and OSI pedestrians were implemented to appear in the same places. The timing of the MoCap pedestrians was manually adapted to match the timing of the OSI agent pedestrians by adjusting the animation trigger.

3) Procedure and Design: The driver experiment was set up as a 2 × 2 × 5 design, including the factors pedestrian type (MoCap vs. OSI, within-subjects), driving style ("aggressive" vs. "defensive", within-subjects), and crossing (1 to 5, within-subjects). The manipulation of driving style served another research goal [?]. The order was counterbalanced using the Latin Square method. One ride lasted about eight minutes, with a total driving time of $< 40$ minutes. Each ride included five crossings (Table I. Pedestrians were instructed to pay attention to the pedestrians. The Unreal Metahumans, which were used for the present study, use a detailed Skeleton model. MoCaps were exported as animations from MVN Analyze and retargeted to the visualization model matching its skeleton properties and bones. The timing of the crossings was fine-tuned in an iterative procedure: The replay of the MoCap pedestrian motion (or the OSI pedestrian) was triggered based on the distance of the simulated vehicle to the pedestrian and adjusted if necessary. The ride was recorded by one of the examiners, with the pedestrian visible to allow

the driver to react to the pedestrian's behavior. The OSI pedestrian was tuned to match the trajectory and timing of the MoCap pedestrian. To the participants, the ride was explained as being fully automated. Even if we ultimately aim at achieving a more realistic driving behavior by improving pedestrian models, this option was decided as the captured pedestrians were incapable of true interaction.

4) Dependent variables: After each crossing, participants rated the single item 'I felt I could interact with the pedestrian.' (adapted from [16]) on a seven-point Likert-type scale from 'does not apply at all' to 'fully applies' ('perceived interactiveness'). After each drive, participants answered the Slater-Usoh-Steed (SUS) presence questionnaire as adapted to the use in driving simulators [17], which is aimed at measuring spatial presence, and single items adapted from other presence questionnaires [16], [18], [19] to measure social presence. Participants were further openly asked in which aspects the pedestrian they saw in each drive differed from a real pedestrian. After completing the last ride, participants were asked whether they noticed any differences across the pedestrians, which served as a manipulation check. They were then asked to specify the noticed differences (openly). We further asked what could be done to make pedestrians appear more realistic.

## IV. Results

Questionnaires were analyzed using the ART procedure [20]. In case only two conditions were compared, Wilcoxon tests were applied. The interview data was coded using Microsoft Excel.

### A. Quantitative findings

Perceived interactiveness was rated after each crossing, thus five times per drive. The ART analysis indicated a significant main effect of crossing, $F(4,894.28) = 53.26$, $p < .001$. A Bonferroni-corrected pairwise post-hoc test indicated higher perceived interactiveness in Crossing 5 compared to all other crossings (see Fig 2). Crossing 1 was perceived as less interactive than Crossing 2 and Crossing 3 (see Fig 2). The MoCap pedestrians were generally perceived as more interactive compared to the OSI pedestrians, $F(1,894.28) = 437$, $p < .001$ (see Fig 2). Further, there was an ordinal interaction effect of crossing and pedestrian, $F(4,894.28) = 32.48$, $p < .001$, with the largest differences across the pedestrian types appearing in Crossing 3 and Crossing 4, and the smallest in Crossing 5. The presence ratings showed no significant differences between the MoCap and the OSI pedestrians, $V = 1943$, $p = .809$, $r = -0.03$ (Figure 3a). The quantity of eye contact was perceived as higher with the MoCap pedestrians, $V = 242$, $p < .001$, $r = -1.00$ (Figure 3b). There was no evidence of a difference in the perceived responsibility to look out for the pedestrian, $V = 1456.5$, $p = .709$, $r = -0.05$.

### B. Qualitative findings

In total, 47 out of 49 participants stated that they noted differences in pedestrian behavior across the experiment. Regarding the perceived differences,

- n = 20 participants remarked that there had been differences in head movements or eye contact across the pedestrians,
- n = 15 participants noted that some pedestrians made gestures while others did not,
- n = 10 participants noted that some pedestrians slowed down when approaching the streets while others did not,

Regarding potential improvements in pedestrian behavior,

- n = 17 participants mentioned that pedestrians would benefit from more natural movement patterns,
- n = 13 participants noted that pedestrians should have more eye contact with the drivers,
- n = 6 participants stated that the pedestrians needed to react more to the simulated vehicle,
- n = 6 participants noted that mimic should be implemented (but would require a high visual resolution),
- n = 5 participants remarked that more variance in pedestrian behavior would be helpful,

Aspects mentioned $\geq 5$ times are reported.

## V. Discussion

This paper explores how pedestrian agent models in driving simulation can be improved, providing a proof-of-concept and identifying promising enhancements. We found clear benefits of the MoCap pedestrian regarding social presence. The MoCap pedestrians were clearly perceived as more interactive than the OSI pedestrians, and participants had a greater feeling of having eye contact. This effect varied depending on the situation. In situations where the differences were smaller, such as Crossing 5, the OSI pedestrian stopped and turned towards the approaching vehicle. Similarly, in Crossing 1, the pedestrian was also turned towards the vehicle, indicating awareness. Overall, it seems like pedestrians were perceived as interactive when facing the driver. In Crossing 2, moderate differences were observed. With a zebra-crossing present, less interaction was needed as pedestrians clearly had the right of way. Post-hoc interviews revealed that crossing without checking for vehicles seemed realistic at zebra crossings, but unnatural in unregulated situations. In Crossing 3 and Crossing 4, differences were especially large. In Crossing 3, the pedestrian approached the road at a more perpendicular angle, making a sudden and less predictable turn compared to Crossing 1. In Crossing 4, the pedestrian walked parallel to the vehicle. The MoCap pedestrian stopped and watched for the approaching vehicle, while the OSI pedestrian's stopping intention was unclear.

| | direction | walking direction | regulated | captured pedestrian behavior | vehicle behavior (aggressive) | vehicle behavior (defensive) |
|---|---|---|---|---|---|---|
| Crossing 1 | right to left | oncoming | unregulated | slowing down, turning head | let pedestrian pass | let pedestrian pass |
| Crossing 2 | right to left | oncoming | zebra crossing | slowing down, turning head, but longer to the right | let pedestrian pass | let pedestrian pass |
| Crossing 3 | right to left | oncoming | unregulated | slows down, signals intention to cross, thank you-gesture | let pedestrian pass | let pedestrian pass |
| Crossing 4 | right to left | parallel | unregulated | stops, turns head, waits before crossing | went first | let pedestrian pass |
| Crossing 5 | left to right | oncoming | unregulated | stops, waits by the road, signals vehicle to go | went first | went first |

TABLE I: Pedestrian crossings per drive.

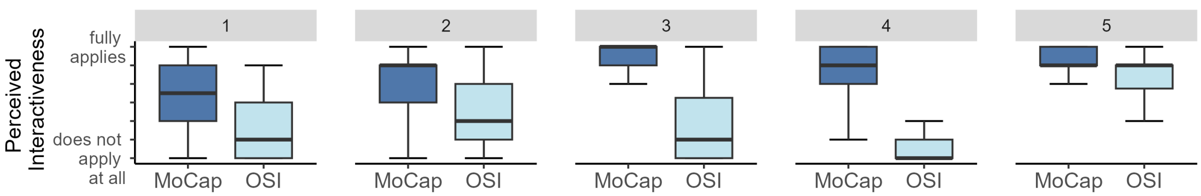
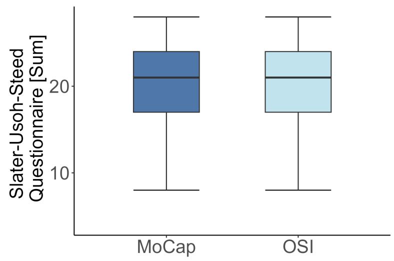
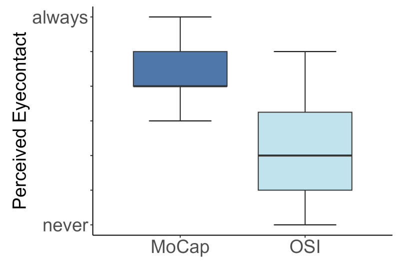


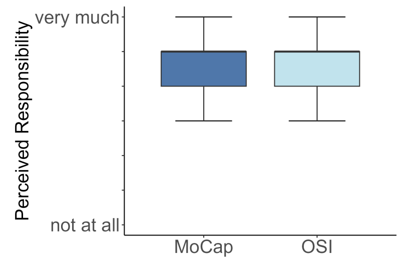

Fig. 2: Descriptive statistics for the single item 'I felt I could interact with the pedestrian' (adapted from [16]), depending on crossing and pedestrian.




(a) Sums of the Slater-Usoh-Steed questionnaire items [17], [21].




(b) Single item 'How often did you feel there was eye contact with pedestrians?' (own formulation).




(c) Single item 'How much did you feel that it was your responsibility to look out for the pedestrian as a vulnerable road user?' [22].

Fig. 3: Descriptive statistics for the subjective evaluation of (social) presence, depending on pedestrian type.

No significant differences were observed in perceived responsibility. Ratings were generally high, indicating overall good compliance. Despite noticing implausibilities, participants reported feeling responsible for any virtual characters. This aligns with findings that participants gave more space to humanoid objects, regardless of their behavior. For spatial presence, there were neither clear effects. The level of presence was quite high in both pedestrian conditions, indicating that spatial presence may depend on aspects other than the behavioral realism of other road users. More nuanced questions on presence are needed to measure relevant differences. The suggested dimensions of spatial and social presence seemed appropriate for the present investigation.

Among the noted differences and improvements, the most prominent mentions were head movements and gestures, as well as implicit communication through movements. Positive effects of kinematic movement fidelity on presence were already shown by [23]. Implementing target-based head rotation, gestures, and a reactive trajectory can enhance pedestrian models. This can be achieved by updating the pedestrian agent model's speed when reaching a certain distance to the road. The new OSI release v3.6.0 allows for transmitting skeleton data, enabling head rotation and gestures. However, driving simulation software providers need to update their software to support these new options. It is important to re-evaluate the behavior of agents using automated head rotation and gestures to ensure their realism in different settings. While MoCap pedestrians were perceived as realistic, a refined agent model may not trigger body movements effectively, leading to uncanny valley effects. The study presented here is a proof-of-concept evaluation. Implementing MoCap single-actions in driving simulation experiments is not considered a realistic long-term solution. Instead, the findings from this research can be used to iteratively improve pedestrian agent models. Enabling true interaction between human drivers and agent pedestrians poses challenges, but intelligent algorithms can be used to detect and interpret driving behavior to enable appropriate pedestrian responses.

## A. Limitations

The OSI pedestrian solution enables a more interactive visual appearance by fine-tuning the pedestrian trajectory. The study results indicate that the perceived realism of the pedestrian model varies depending on the situation. However, there are opportunities to improve pedestrian models in driving simulation based on these findings. The evaluation in this work relies solely on subjective measures, as real interaction could not be implemented. The use of automated driving was necessary to create consistent interactive traffic situations. However, without behavioral measures, it is unclear if more realistic pedestrian agents actually result in more realistic behavior. Further research is needed to determine if the higher social presence experience observed leads to higher behavioral validity. The virtual environment did not include other road users. However, a promising approach for future research would be to integrate the pedestrian and driving simulators in real time. This would allow for genuine interaction between car drivers and pedestrians, leading to a deeper understanding of how pedestrian agent models can be enhanced.

## VI. Conclusion

This paper demonstrates the benefits of using more human-like pedestrian agents in virtual traffic environments. Motion-captured real pedestrian movements were transferred to virtual characters and compared to a state-of-the-art pedestrian agent model within a driving simulator experiment. The results showed that the motion-captured pedestrians were perceived as more interactive, with higher ratings for social presence and more perceived eye contact. However, there was no difference in spatial presence. Participants further reported feeling responsible for both types of pedestrians, indicating that they may react realistically despite perceived implausibilities in their behavior. The qualitative analysis suggests that improving pedestrian agent models should focus on implementing head movements, gestures, and more realistic trajectories. These findings can guide the targeted development of pedestrian models in the future.

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