# You'll Never Walk Alone: Inter-Pedestrian Distance, eHMIs, and Crossing Decisions in Virtual Reality

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Traffic interactions rarely happen in sanitised, one-on-one, dyadic settings, and automated vehicles (AVs) are no exception: they will encounter pedestrians not only walking alone, but also in groups or scattered co-located individuals. However, AV-pedestrian research rarely considers this social context. We conducted a virtual reality (VR) study (N = 50) to examine how a co-located pedestrian and an external Human–Machine Interface (eHMI) shape perceived crossing safety. The participants stood at the kerb alongside a second pedestrian while an AV approached. In a within-subjects design we varied vehicle yielding (yielding vs. non-yielding), eHMI (off vs. on), inter-pedestrian distance (2–10 m, 2 m increments) and whether the other pedestrian stood in front of the participant, facing the oncoming AV, or behind them. Participants held a controller trigger whenever crossing felt unsafe and later rated how much the other pedestrian and the inter-pedestrian distance influenced their crossing decision. The perceived crossing risk was substantially lower for yielding than non-yielding AVs, with an active eHMI further reducing risk in yielding trials. Distance-influence ratings were modest but strongly depended on visibility. The correlations between perceived risk and distance influence were small and negative, indicating that vehicle behaviour dominated safety judgments, while social spacing primarily shaped subjective impressions. These findings suggest that, while clear AV yielding cues (including eHMIs) should remain the primary focus for supporting pedestrian safety, AV evaluation and interface design should also account for co-located pedestrians and their visibility, as these factors can shape pedestrians' perceptions and decision-making in realistic street-crossing contexts.

Additional Key Words and Phrases: Automated Vehicle, Behaviour, Pedestrian safety, Virtual Reality

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## 1 Introduction

Pedestrians in busy public spaces are often encountered in the presence of other people rather than as truly isolated individuals. Field observations in urban walkways and crowd settings report that a substantial share of pedestrians-even up to 70% in some commercial streets-belong to small social groups such as couples, friends, colleagues, or family members rather than walking alone [3, 11, 52]. At the same time, many everyday walking trips, such as commuting or walking to public transport, are undertaken alone. However, by the time pedestrians arrive at a crossing or other

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Fig. 1. Virtual reality street-crossing scenario with two pedestrians and an approaching AV. The top panel shows an overhead view of the straight residential street and the initial positions of the AV, the participant, and the virtual co-pedestrian at an inter-pedestrian distance of 6 m; the yellow line indicates the planned trajectory of the AV. The bottom panel shows a third-person view of a yielding AV without an eHMI stopping in front of the first pedestrian in its path.

bottleneck, they frequently find themselves locally co-located with one or more other pedestrians that they are not familiar with in close proximity. Importantly, such co-location does not always reflect a genuine social group with pre-existing bonds: nearby pedestrians may be strangers whose paths merely happen to intersect in space and time. Nevertheless, both small social groups and more incidental co-located clusters can exhibit interaction patterns that differ markedly from those of solitary pedestrians, as movement is guided not only by physical and environmental constraints, but also by social norms, mutual adaptation, and implicit coordination strategies. When pedestrians do share a social bond, they typically pursue a common goal or destination and intentionally maintain proximity, adapting their trajectories and walking speeds to avoid separation [63, 72]. This coordinated movement is facilitated by continuous social interaction, including verbal communication [52], gestures [67], gaze exchange [9], and body language [53], which fosters mutual awareness and enables them to negotiate dynamic environments as cohesive units. However, even in the absence of explicit group membership, the mere presence of another pedestrian nearby can shape how individuals perceive and respond to their surroundings.

The structure and size of pedestrian groups further shape these dynamics. Most social groups observed in pedestrian flows comprise two to six individuals, with dyads and triads being the most common configurations [5, 52, 54]. As the group size increases beyond four members, maintaining close interaction becomes more difficult, often resulting in spontaneous fragmentation into smaller subgroups while still preserving a broader group identity [13, 21, 57]. This behaviour is often attributed to cognitive and communicative constraints: individuals tend to focus their attention and interactions on those in their immediate vicinity, optimising coordination and communication [52]. These findings highlight a strong interplay between social behaviour and locomotion and have motivated pedestrian models that explicitly incorporate social grouping phenomena. At the same time, they suggest that even minimal constellations-such as a focal pedestrian and a single nearby other, regardless of whether they form a social group-may be sufficient to alter movement patterns and safety-relevant decisions.

Understanding these local social dynamics is particularly important in the context of road safety, where pedestrians are commonly classified as vulnerable road users (VRUs)—those most at risk in traffic because they are unprotected by an outside shield (e.g. pedestrians, pedal cyclists, and motorcyclists) [12, 34]. Globally, road traffic accidents continue to pose a major public health challenge. In 2023, approximately 1.19 million people lost their lives in traffic-related incidents, with pedestrians accounting for a significant share of these fatalities (https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries). Road traffic crashes impose substantial societal costs: across the European Union, the total cost of road crashes has been estimated at around €280 billion per year [23]. Pedestrian safety is also an increasingly urgent concern in the United States, where 7,314 pedestrians were killed in 2023 and fatalities in the first half of 2024 were 48% higher than a decade earlier [29, 39]. Pedestrian fatalities occur predominantly in motor-vehicle crashes, and severe injuries frequently involve the head, thorax, and lower extremities [35, 58]. The risk and severity of such injuries increase substantially with age, especially among pedestrians 65 years and older [51, 69]. In many of these situations, pedestrians are not entirely alone at the roadside but stand or walk in close proximity to others, and these local social configurations may subtly influence how and when they choose to cross.

A growing body of research indicates that pedestrian decision making, particularly at road crossings, is strongly influenced by the social context. Social influence and conformity can increase the likelihood of risky behaviour, even when individuals are aware of potential dangers. Hashemiparast et al. [32] reported that young adults aged 18–25 years frequently cited "conformity to the masses" as a primary reason for unsafe crossing, particularly when others ignored traffic signals. Similarly, a cross-cultural study comparing France and Japan demonstrated that pedestrians often rely on the actions of others when deciding whether to cross, illustrating an "information cascade" effect in which early crossers trigger successive risky crossings by others [55]. In such scenarios, the influential "others" are not necessarily friends or family; they may simply be strangers waiting at the same crossing whose behaviour nevertheless provides social information. Although cultural factors modulate the extent of this effect, evidence consistently shows that social signals, especially the behaviour and positioning of nearby pedestrians, irrespective of formal group membership, play a central role in shaping individual decisions at crossings.

At the same time, advances in automated vehicle (AV) technology have introduced new dynamics into pedestrian-vehicle interactions. The use of external Human Machine Interfaces (eHMIs) has been shown to significantly influence pedestrian decision making by explicitly communicating the intentions of a vehicle, such as yielding, thus increasing confidence and perceived safety [14, 27]. For example, pedestrians are more likely to cross in a timely manner when an eHMI communicates the vehicle's intention to yield, which could reduce hesitation and conflicts [49]. Importantly, such messages should be understood as communicating the current state and the intended manoeuvre—not as an instruction or assurance that the crossing is safe—since the vehicle cannot guarantee the safety of the entire traffic situation [16]. This distinction is consistent with ongoing standardisation and regulatory discussions on external AV signalling in UNECE forums [25] and ISO guidance on external visual communication [40], while the precise content and form of such communication remains an open question. However, reliance on eHMIs also introduces new challenges. Overdependence on these signals can cause pedestrians to ignore other important environmental signals, leading to risky behaviour if the interface is malfunctioning or misunderstood [33, 44]. Additionally, inconsistent designs and environmental factors such as lighting and weather can reduce the effectiveness of eHMIs and create confusion [65]. Crucially, pedestrians often interpret these signals not in isolation, but against the backdrop of what nearby others are doing, for example, whether another person at the kerb appears to trust or distrust the approaching AV.

Despite these advances, existing research has focused mainly on individual pedestrian behaviour, overlooking complex social interactions that occur when multiple pedestrians are present [9, 60]. Work on AVs and eHMIs has frequently adopted experimental paradigms with a single pedestrian facing a vehicle, or has treated social groups primarily as cohesive units with shared intentions. In particular, it remains unclear how the presence and proximity of another pedestrian - who may or may not belong to the same social group - influence crossing decisions in the context of AV and eHMIs [36, 62, 71]. Understanding these interactions and how they evolve as the distance between co-located pedestrians changes is critical to developing AV communication strategies that support safe, natural and socially aware pedestrian behaviour [42].

### 1.1 Aim of the study

The aim of the study is to examine the perceived safety of pedestrian crossing in encounters with an approaching AV when another pedestrian is located in the kerb. Specifically, we investigated whether (i) inter-pedestrian distance and (ii) the visibility of the co-pedestrian line-of-sight (in front vs. behind the participant), in combination with (iii) the yielding behaviour of the AV and (iv) the activation of an external human–machine interface (eHMI; on vs. off), influence the perceived safety of pedestrian crossing and their willingness to cross. This research question was examined in a fully within-participant VR street-crossing experiment in which participants stood alongside a life-sized virtual co-pedestrian while an AV approached.

## 2 Method

### 2.1 Participants

The study received ethical approval from the Ethics Review Board of the Eindhoven University of Technology, and all participants provided informed consent prior to participation. Fifty participants took part in the experiment (28 male, 21 female, and one who did not disclose their gender), with a mean age of 28.3 years (SD = 7.3). The nationalities of the

Fig. 2. Participant immersed in the virtual reality setup, wearing a Meta Quest 3 head-mounted display and handheld controller while standing in the designated starting position in the laboratory.

participants were Dutch (16), Chinese (10), Greek (4), Indian (4), Spanish (2), German (2), Pakistani (2) and Yemeni (2), as well as one participant each from Colombia, Indonesia, Iran, Nepal, Poland, Portugal, Romania, and Taiwan.

All participants had normal or corrected-to-normal vision (15 wore glasses and 3 used contact lenses during the VR session). Previous experience with VR was limited: 32 participants had not used VR in the past month, 10 used it less than once per week, and only 7 reported regular VR use. All 50 participants completed the full experiment and no data were excluded from analysis.

### 2.2 Apparatus and virtual reality setup

The experiment was conducted in an immersive VR laboratory setting using a Meta Quest 3 head-mounted display (HMD) with a handheld controller. The HMD was connected through Meta Quest Link to a Windows PC equipped with an Intel Core i7-10750H CPU, 32 GB RAM, and an NVIDIA GeForce RTX 2080 Super GPU.

The virtual street-crossing environment was developed in Unity 2022.3.5f1 and adapted from an open-source coupled AV-pedestrian simulator by Dey et al. [20], which was also used by Bazilinskyy et al. [6, 7]. The behaviour of the participants, including head position/orientation (HMD pose) and trigger values of the controller, was sampled and recorded at 50 Hz for subsequent analysis.

### 2.3 Stimuli and virtual environment

The virtual environment represented a straight residential street with terraced houses, trees, and pavements on both sides (Figure 1). No zebra crossing, traffic light, or other formal crossing facility was present at the pedestrian location, to avoid participants relying on an assumed right of way. No other traffic was present in the scene (i.e. no additional vehicles, cyclists, or pedestrians beyond the approaching AV and the scripted co-pedestrian). See supplementary material for the implementation (section 6).

The participant always stood on the pavement on the kerb. A second pedestrian (a life-sized virtual human avatar) was always present on the same pavement at a predefined distance from the participant. The co-pedestrian was placed on the kerb and orientated towards the direction from which the AV approached, serving as a stationary bystander (i.e. the avatar did not move or step onto the road). Across conditions, the co-pedestrian was positioned either in front of or behind the participant (from the vehicle's perspective), such that line-of-sight visibility differed when participants orientated towards the approaching vehicle. We did not record eye movements and therefore interpret this factor as visibility rather than gaze or eye contact.

The AV approached from the participant's left-hand side along a fixed kerb-side lane position, aligned with the carriageway directly adjacent to the pavement. Its lateral position was fixed such that it remained close to this side of the road and never crossed the centre line or deviated towards the opposite kerb. Consequently, when the vehicle passed the pedestrians, it did so at a realistic lateral distance of 1.77 m, comparable to a real car driving in the lane next to the pavement.

Each trial started at t=0 s, defined as the moment the AV appeared at the far end of the street and started moving towards the pedestrians. The vehicle motion profiles and kinematic parameters were adopted from Dey et al. [20] and are described relative to the fixed world-coordinate position of the *first person in the vehicle's path*. Following Dey et al., the AV's baseline approach speed was set to 50 km/h (13.9 m/s), corresponding to a standard city driving speed; this baseline speed represents the vehicle's steady cruising speed before any yielding manoeuvre. In non-yielding trials, the AV maintained this baseline speed and passed the first person without slowing. In yielding trials, the AV initiated braking when it was 43 m upstream of the first person and decelerated at 2.4 $m/s^2$ until it came to a complete stop with its front bumper positioned 3 m before the first person; it then remained stationary before accelerating again and continuing past the pedestrians.

Vehicle communication was manipulated using an eHMI consisting of a RGB(0, 255, 255) cyan light bar mounted horizontally on the front bumper. Cyan was selected because it has been proposed as a "neutral" eHMI colour and can help avoid the potential ambiguity associated with red/green traffic-signal conventions [8]. In the eHMI-active condition, the bar was illuminated throughout the trial to indicate automated operation and changed its pattern when the vehicle transitioned to an active yielding state, following the implementation by Dey et al. [20]. Specifically, as the vehicle approached without yielding, the bar emitted a steady turquoise glow; once yielding began (i.e. at braking onset), it changed to an inward "wiping" animation that remained active during deceleration and the stationary yielding phase. When the vehicle departed again, the animation stopped and the bar returned to a steady glow. In the no-eHMI condition, the light bar was not illuminated at any time, so that cues about vehicle intent were provided only by vehicle kinematics.

### 2.4 Experimental design

The experiment followed a fully within-subject design with two practice trials followed by 40 main trials (42 trials in total; one repetition per condition). Four independent variables were manipulated:

(1) **Vehicle yielding** (2 levels): yielding vs. non-yielding.
(2) **Vehicle communication** (2 levels): no eHMI vs. active eHMI (front bumper light bar; see subsection 2.3).
(3) **Pedestrian position** (2 levels): participant as the first person in the vehicle's path vs. participant as the second person.
(4) **Inter-pedestrian distance** (5 levels): centre-to-centre distance between participant and virtual pedestrian of 2 m, 4 m, 6 m, 8 m, or 10 m.

Across all conditions, the world-coordinate position of the first person in the vehicle's path was fixed in the virtual environment; only which agent occupied this position (the participant or the virtual pedestrian) varied. The second pedestrian was placed on the same pavement at the specified inter-pedestrian distance behind the first person from the vehicle's perspective. In yielding trials, the vehicle's stopping point was defined relative to this fixed position such that the vehicle came to a complete stop with its front bumper located 3 m upstream of the first person's position along the kerb-side trajectory. As a result, the vehicle did not reach or pass the longitudinal position of the first person; therefore, the agent occupied the first position was the one to whom the vehicle yielded.

For each participant, the 40 scenarios were presented in pseudo-random order using C#'s `System.Random` together with a LINQ `OrderBy(rand.Next)` shuffle.[1] Optional short breaks were offered after trials 14 and 26 to mitigate fatigue [4].

### 2.5 Procedure

At the beginning of each session, participants were provided with an information sheet in PDF format describing the study set-up, the structure of the trials, and how to use the controller trigger, and were asked to read it carefully. After reading the information sheet, the participants completed a Google Forms pre-experiment questionnaire that included the informed consent form (signed electronically) and demographic items (age, gender, nationality and recent use of VR). PDF copies of the information sheet and both questionnaires (pre-experiment and post-experiment; administered via Google Forms) are provided in the supplementary material (see section 6).

The experimenter then discussed the key points aloud and demonstrated the trigger mechanism. The participants were instructed to imagine that they intended to cross the road in front of an approaching vehicle and that their task was to indicate moments when they felt that initiating a crossing would be unsafe. The approaching vehicle was described as an automated Level 5 car (SAE classification [59]). Participants were also informed that they would not be required to physically step onto the road in the virtual environment and should remain on the pavement throughout the trials; accordingly, both the participant and the virtual co-pedestrian remained standing on the pavement and the co-pedestrian did not step off the kerb. Participants were explicitly invited to ask questions before continuing.

Only after completing these steps did the experimenter help the participant put on the VR headset and controllers. In Meta Quest 3, a fresh standing limit was defined from a designated starting position in the lab to calibrate the virtual position and eye height of the participant. The Unity application was then launched, and the participant was aligned with the predefined starting position in the virtual scene. Participants were asked to adopt a comfortable neutral stance while facing straight along the road (i.e. the forward direction of the street scene). This aligned starting pose

[1] https://learn.microsoft.com/en-us/dotnet/api/system.random

served as the reference for head-orientation analyses: head yaw was expressed in the scene coordinate frame, with 0° corresponding to this forward-facing road-aligned direction (positive yaw = leftward rotation; negative yaw = rightward rotation).

Upon entering the virtual environment, participants encountered an instructional reminder screen stating: "Hello! You need to hold the trigger button only when you feel it is NOT SAFE to cross the road. Please click to start." The same reminder screen was shown again after each optional break. After acknowledging the prompt and pressing a virtual start button, the street scene was presented and the approaching vehicle appeared from the participant's left.

In each trial, participants indicated perceived unsafety continuously by pressing and holding the controller trigger whenever they felt it was not safe to initiate a crossing; releasing the trigger indicated that they would feel safe to cross. The trigger press was pressure-sensitive, returning a continuous value between 0 (not pressed) and 100 (fully pressed). The experimenter emphasised that participants could press and release the trigger multiple times within a trial if their perception of safety changed.

At the end of each trial, participants provided three trial-wise subjective ratings using on-screen sliders (0–100 scale):

- **Q1:** On a scale of 0 to 100, how much did the behaviour of the other pedestrian influence your decision to cross the road?
- **Q2:** On a scale of 0 to 100, how much did the distance between you and the other pedestrian affect your decision to cross the road?
- **Q3:** On a scale of 0 to 100, rate how well you understood the intention of the vehicle.

The two practice trials served to familiarise participants with the VR setting, trigger input, and vehicle behaviour. During these practice trials, no second pedestrian avatar was present so that participants could focus on the traffic scenario and the response method. The two practice scenarios illustrated the vehicle behaviour and communication manipulations: in one practice trial, the oncoming car did not yield while the eHMI was active; in the other, the car yielded without an active eHMI. After completing the practice trials, and once the participant confirmed that they had no remaining questions, the experiment continued with the main trials.

After the final trial, a VR debrief screen thanked the participants. Participants then removed the headset and completed a post-experiment questionnaire administered via Google Forms about their overall experience and impressions of the interaction; this questionnaire also included an open-ended text field for comments or suggestions to improve the set-up.

### 2.6 Measures and data processing

The trigger-press data and the head orientation (yaw) of the HMD were recorded at 50 Hz throughout each trial. The controller trigger returned a continuous value from 0 (not pressed) to 100 (fully pressed). Head orientation was logged as unit quaternions. These signals were used to derive behaviour measures and head-movement measures, which were analysed as a function of the experimental factors.

*2.6.1 Trigger-based measure of perceived 'unsafety'.* The primary behavioural measure was the continuous trigger signal from the VR controller. For analysis and visualisation, the raw trigger values (0–1) were normalised to a 0–100 range by multiplied by 100. A value of 0 indicates that the participant did not mark the situation as unsafe at that moment, whereas any value above 0 indicates that the participant was signalling unsafety; intermediate values reflect partial trigger presses (e.g. 0.10 corresponds to a 10% press) and were retained as recorded. Each trial yielded a time series which was aligned to key events in the vehicle trajectory (e.g. onset of braking and the time of stopping or passing the participant) based on logged timestamps. From these signals, we derived summary measures such as the proportion of trial time with non-zero trigger values (i.e. time marked as unsafe), as well as the timing of changes between "unsafe" (trigger pressed) and "safe" (trigger released). These measures were analysed across conditions (yielding, eHMI presence, pedestrian position, and inter-pedestrian distance).

*2.6.2 Head yaw estimation.* To characterise how participants orientated themselves in the scene over time, we analysed head orientation using the yaw rotation of the HMD as a coarse proxy for horizontal viewing direction. Unit quaternions were averaged using the eigenvalue-based method introduced by Markley et al. [50] and converted to Euler angles to extract yaw. Because we did not record eye movements, this measure reflects head orientation rather than gaze and is interpreted as an indirect indicator of horizontal visual attention.

*2.6.3 Trial-wise subjective ratings.* At the end of each trial, participants completed three 0–100 slider ratings (Q1–Q3; see subsection 2.5). For analysis, we computed participant-level condition means for each question across repetitions of the same condition and then summarised these at the group level.

*2.6.4 Near-far contrast for inter-pedestrian spacing.* To summarise the effect of inter-pedestrian spacing within each experimental context, we computed, for each outcome $X$, a near–far contrast

$$\Delta_X \;=\; M_{X,\text{near}} - M_{X,\text{far}}, \tag{1}$$

where $M_{X,\text{near}}$ is the mean of $X$ in the near-spacing conditions (2–4 m) and $M_{X,\text{far}}$ is the mean of $X$ in the far-spacing conditions (8–10 m). Under this definition, $\Delta_X > 0$ indicates that the outcome takes larger values at near spacing, whereas $\Delta_X < 0$ indicates smaller values at near spacing. For outcomes where larger values correspond to greater perceived unsafety (perceived crossing risk, Q1, and Q2), positive contrasts reflect greater perceived unsafety in the near condition; for Q3 (trust), the interpretation is reversed, as larger values indicate greater trust.

## 3 Results

The means and standard deviations of the condition for the perceived risk of crossing and the three measures of the questionnaire (Q1–Q3), stratified by AV behaviour (yielding vs. non-yielding), eHMI status (on vs. off), visibility of the other pedestrian and distance between pedestrians, are reported in Table 1.

We report near–far contrasts $\Delta_X$ for each outcome (defined in subsubsection 2.6.4). Across all combinations of yielding, eHMI, and visibility, the near-far contrast for perceived crossing risk was small in magnitude, with $\Delta_{\text{risk}}$ ranging from −2.95 to +3.06 points on the 0–100 scale. For Q2, the overall mean across conditions was $M_{\text{Q2}} = 27.70$ ($SD = 15.13$), and $\Delta_{\text{Q2}}$ ranged from −3.53 to +11.13 points, taking positive values in 7 of 8 contexts, indicating that near spacing was typically associated with higher Q2 ratings. For Q1, the overall condition-level mean was $M_{\text{Q1}} = 21.30$ ($SD = 13.41$), and $\Delta_{\text{Q1}}$ ranged from −4.66 to +8.79 points. For Q3, the overall mean was $M_{\text{Q3}} = 68.10$ ($SD = 11.87$), and $\Delta_{\text{Q3}}$ ranged from −4.67 to +4.60 points, implying at most modest near-far differences in trust.

At the condition level, the Pearson correlations between mean perceived crossing risk and the three questionnaire measures were $r = -0.21$ for Q1, $r = -0.25$ for Q2, and $r = -0.40$ for Q3.

Head-orientation data showed that participants mostly kept their heads orientated down the street in the direction from which the AV approached (i.e. along the road/traffic direction rather than across the intended crossing direction). Consequently, 0° denotes a road-aligned forward direction in the scene reference frame (see Procedure), and looking across the road would correspond to a large yaw rotation away from 0°. Because the approaching AV entered from the

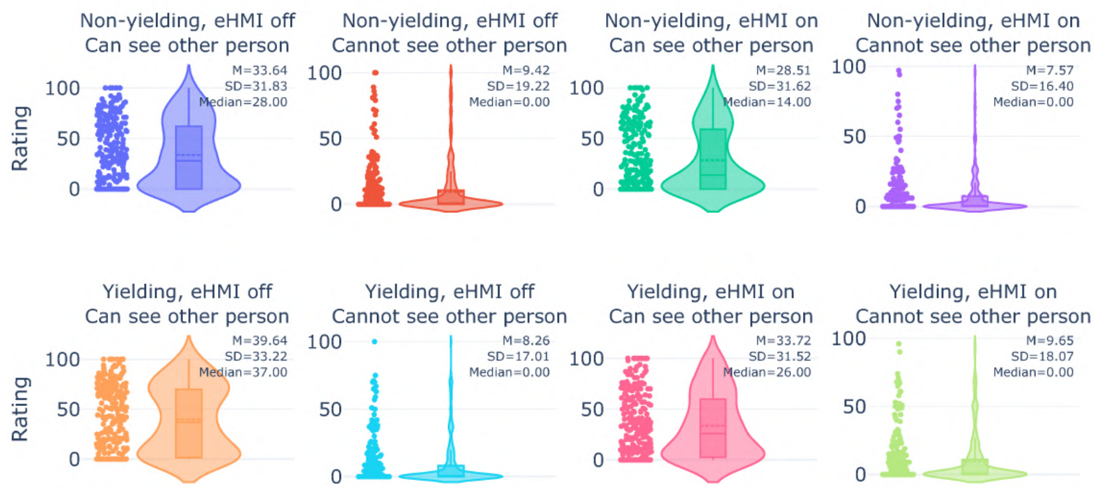


Fig. 3. Distributions of trial-wise ratings to Q1: "On a scale of 0 to 100, how much did the behaviour of the other pedestrian influence your decision to cross the road?". Each violin corresponds to one combination of vehicle yielding (non-yielding vs. yielding), eHMI status (off vs. on), and visibility of the other pedestrian (can vs. cannot see the other person). Individual dots show single-trial responses, and the violin shapes with embedded boxplots summarise the central tendency and variability of Q1 ratings.

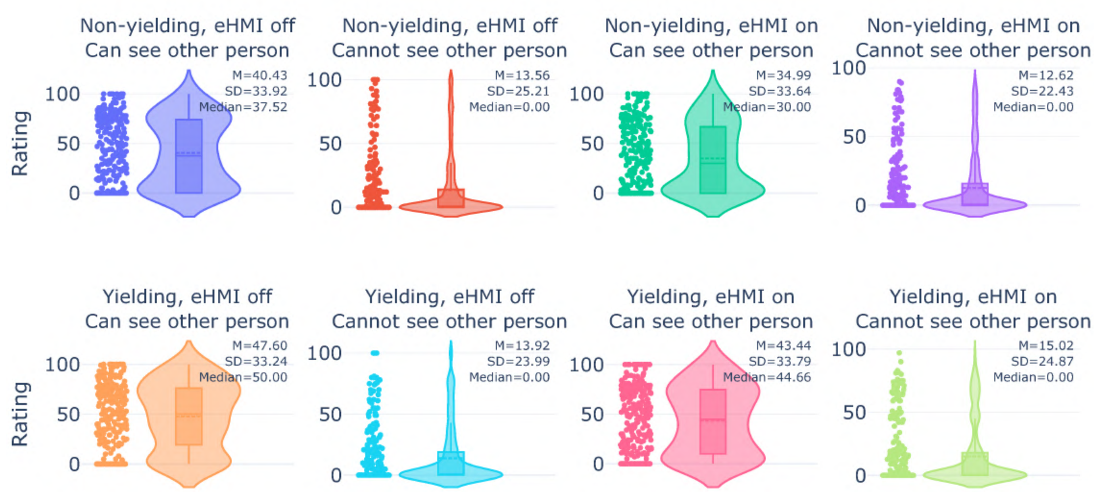


Fig. 4. Distributions of trial-wise ratings to Q2: "On a scale of 0 to 100, how much did the distance between you and the other pedestrian affect your decision to cross the road?". Each violin corresponds to one combination of vehicle yielding (non-yielding vs. yielding), eHMI status (off vs. on), and visibility of the other pedestrian (can vs. cannot see the other person). Individual dots show single-trial responses, and the violin shapes with embedded boxplots describe the central tendency and variability of Q2 ratings.

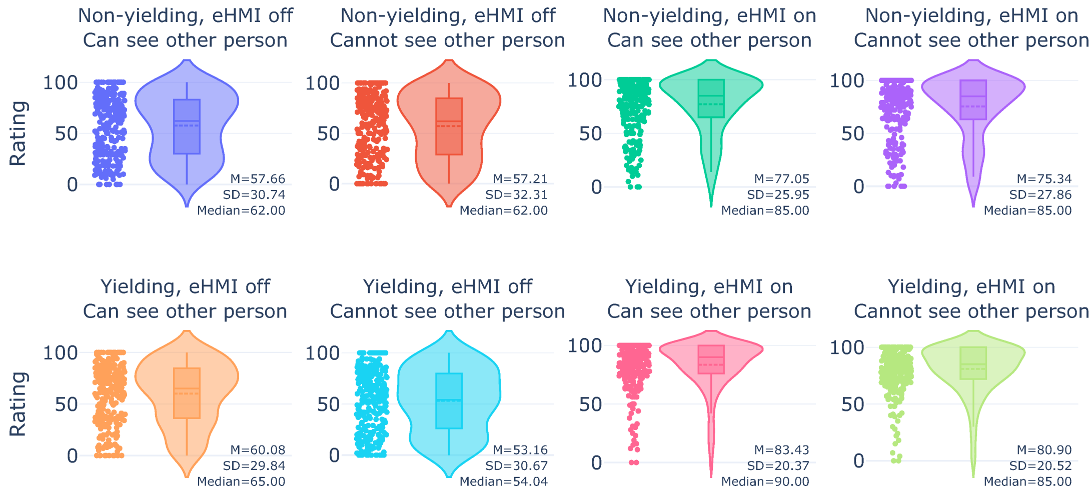


Fig. 5. Distributions of trial-wise ratings to Q3: "On a scale of 0 to 100, rate how well you understood the intention of the vehicle". Each violin corresponds to one combination of vehicle yielding (non-yielding vs. yielding), eHMI status (off vs. on), and visibility of the other pedestrian (can vs. cannot see the other person). Individual dots show single-trial responses, and the violin shapes with embedded boxplots summarise the central tendency and variability of perceived understanding of the vehicle's intention.

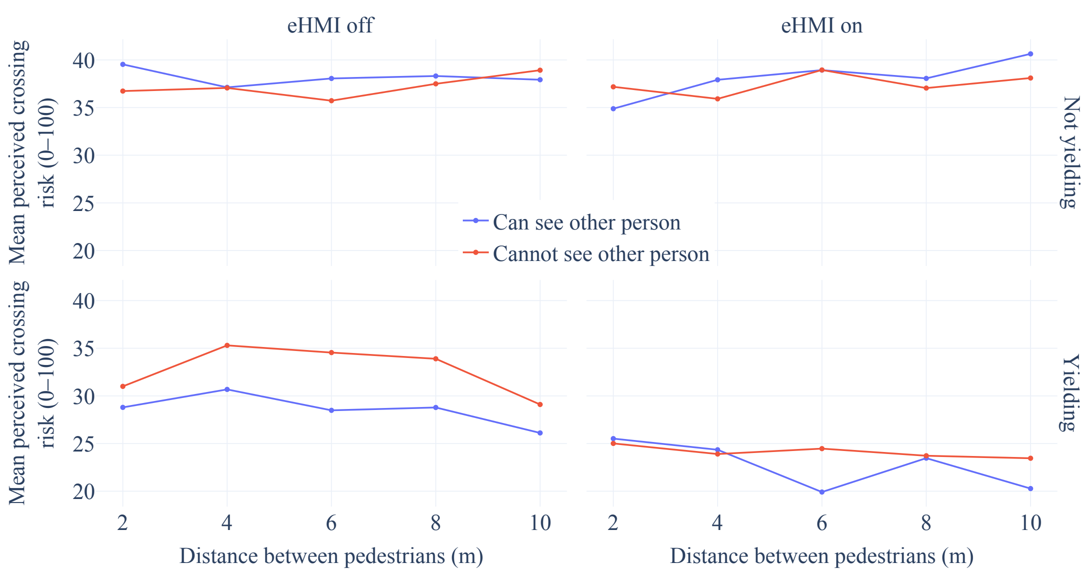


Fig. 6. Mean perceived crossing risk (0–100 scale, derived from the trigger-based measure of perceived unsafety) as a function of the distance between the participant and the virtual pedestrian (2–10 m). The left and right panels correspond to trials in which the other pedestrian was visible vs. not visible, respectively, and separate curves show the combinations of vehicle yielding (yielding vs. non-yielding) and eHMI status (off vs. on).

Table 1. Condition-level means and standard deviations for perceived crossing risk (trigger-based measure) and questionnaire ratings Q1–Q3.

| Factor | Level | Crossing risk | Q1 | Q2 | Q3 |
|---|---|---|---|---|---|
| Overall | – | 32.38 (6.31) | 21.30 (13.41) | 27.70 (15.13) | 68.10 (11.87) |
| AV yielding | Non-yielding | 37.72 (1.35) | 19.79 (12.07) | 25.40 (13.74) | 66.81 (10.14) |
| | Yielding | 27.04 (4.45) | 22.82 (14.79) | 29.99 (16.42) | 69.39 (13.53) |
| eHMI | Off | 34.18 (4.23) | 22.74 (14.77) | 28.88 (16.52) | 57.03 (3.73) |
| | On | 30.59 (7.56) | 19.86 (12.11) | 26.52 (13.92) | 79.18 (4.13) |
| Visibility | Other visible | 31.89 (6.97) | 33.88 (4.76) | 41.61 (6.27) | 69.56 (11.57) |
| | Other not visible | 32.88 (5.72) | 8.72 (3.70) | 13.78 (4.77) | 66.65 (12.29) |
| Visibility × AV yielding | Non-yielding, other visible | 38.14 (1.51) | 31.08 (3.76) | 37.71 (6.19) | 67.35 (10.74) |
| | Non-yielding, other not visible | 37.31 (1.10) | 8.49 (3.84) | 13.09 (4.88) | 66.28 (9.59) |
| | Yielding, other visible | 25.64 (3.67) | 36.68 (3.55) | 45.52 (3.30) | 71.78 (11.99) |
| | Yielding, other not visible | 28.44 (4.90) | 9.10 (3.53) | 14.47 (4.80) | 67.52 (12.89) |
| Distance | 2 m | 32.33 (5.55) | 25.18 (11.96) | 34.09 (14.86) | 68.11 (11.86) |
| | 4 m | 32.78 (5.78) | 20.62 (11.91) | 26.98 (14.08) | 67.75 (13.14) |
| | 6 m | 32.38 (7.24) | 19.94 (14.55) | 25.85 (16.29) | 68.26 (12.12) |
| | 8 m | 32.60 (6.38) | 20.24 (14.38) | 25.62 (15.69) | 67.05 (13.51) |
| | 10 m | 31.82 (8.00) | 20.53 (16.65) | 25.96 (16.87) | 69.34 (11.80) |

participant's left in all trials, sustained monitoring of the oncoming vehicle would be expected to manifest itself as a modest positive (leftward) yaw offset rather than exactly 0°. Figure 7 shows the distributions of the head-yaw angles as a function of the visibility of the other pedestrian, yielding behaviour, and the status of the eHMI.

As a summary measure, we considered samples within ±15° of 0° as "looking roughly along the road", following driver-monitoring and gaze-classification studies that define a small forward cone around the road centre as representing looks to the road ahead [64, 66]. When the other pedestrian was visible in the participant's field of view and averaged over inter-pedestrian distances, the percentage of samples within ±15° ranged from 81.30% to 85.70% in the four combinations of yielding and eHMI status; the corresponding mean yaw angles were between 2.73° and 3.21°, with standard deviations between 11.65° and 13.29°. When the other pedestrian was not visible (i.e. positioned behind the participant), the percentage of samples within ±15° ranged from 83.90% to 89.40%, with mean yaw angles between 2.51° and 3.51° and standard deviations between 10.27° and 12.50°.

When analysed separately by inter-pedestrian distance, the proportion of samples within ±15° lay between 77.40% and 87.50% when the other pedestrian was visible and between 80.50% and 90.90% when the other pedestrian was not visible, with mean yaw angles between 0.49° and 5.00° in the visible case and between 1.97° and 4.71° in the non-visible case. Overall, the small but consistently positive mean yaw in the contexts suggests a slight left-hand orientation consistent with monitoring an approaching vehicle from the left, while the high proportion of samples within the forward cone indicates that participants largely maintained a forward-facing posture throughout the trials.

All 50 participants completed the post-experiment questionnaire. On 1–10 scales, they reported relatively low to moderate levels of stress and anxiety during the experiment: the mean self-reported stress was $M$ = 3.38 ($SD$ = 2.17) and the mean anxiety was $M$ = 3.08 ($SD$ = 2.11). The realism of the virtual environment was rated as $M$ = 6.36 ($SD$ = 1.82) on a 1–10 scale, and the general experience with the study was positively evaluated, with an overall rating of $M = 7.56$ ($SD = 1.28$) on a 1–10 scale. For the statement "The presence of another pedestrian influenced my willingness to cross the road" (1–5 scale), the mean response was $M = 3.12$ ($SD = 1.14$). For the statement "The type of car (with or without eHMI) affected my decision to cross the road", the mean was $M = 3.96$ ($SD = 1.28$). For the statement "I trust an automated car more than a manually driven car", the mean response was $M = 2.82$ ($SD = 1.10$).

The open responses provided additional context for these ratings. Specifically, 49 of 50 participants provided a free-text response to *"How did you feel during the simulation when the car approached?"* 40 of 50 answered *"What suggestions do you have to improve this experiment?"* and 11 of 50 provided additional remarks in the *"Comments"* field. We summarised the recurring themes descriptively; themes were not mutually exclusive (a participant could mention multiple themes).

For *"How did you feel during the simulation when the car approached?"* ($n = 49$ responses), participants frequently described monitoring vehicle kinematics to infer intent (14 of 49), for example, "actively scanning any signs of slowing down" (P7) and "uncertain if it will stop until i saw the car slowing down and coming to a stop" (P3). Several participants also described the eHMI as supporting interpretation when present (11 of 49), e.g. "When the lights indicate that the car is going to stop helped me to interpret my action way in advance" (P16) and "with eHMI it was more clear" (P18).

Responses to *"What suggestions do you have for improving this experiment?"* ($n = 40$ responses) primarily focused on further enhancing immersion and enabling richer pedestrian interaction. Common suggestions included making the co-pedestrian more behaviourally dynamic (26 of 40), adding contextual cues such as ambient sound and surrounding traffic (4 of 40 and 11 of 40, respectively), and extending the action space so that the participant and/or co-pedestrian could move and initiate a crossing in VR (18 of 40). Illustrative examples include "adding ambient sound to add to realism" (P8), "dynamic environment, pedestrian movement. introduce traffic noise" (P45), and "make the participants being able to move or walk" (P10). A smaller number of responses proposed increasing scenario variety (4 of 40), for instance "more different scenarios, since i knew what to expect" (P44).

## 4 Discussion

Based on the research question stated in subsection 1.1, this study examined how pedestrians evaluate crossing safety when interacting with an approaching automated vehicle (AV) while standing next to another pedestrian. Using an immersive VR street-crossing scenario, we combined a continuous trigger-based measure of perceived crossing risk with questionnaire ratings in the trial (Q1–Q3; see subsection 2.6) and head-orientation data. We manipulate AV yielding behaviour, the presence of an external human–machine interface (eHMI), and the co-pedestrian's visibility/position and spacing to assess how these factors shape perceived safety and willingness to cross.

In all measures, perceived crossing safety was dominated by the AV's kinematics: yielding trials were consistently judged safer than non-yielding trials, consistent with previous work showing that willingness to cross is driven primarily by whether an approaching vehicle maintains speed or yields [17, 37, 47]. eHMIs modulated judgments asymmetrically, reducing perceived risk in yielding situations but having little impact when the vehicle did not yield, in line with evidence that eHMIs are most effective when they clarify an already cooperative manoeuvre rather than contradict vehicle motion [14, 38, 48, 68]. Q3 (understanding) supports this interpretation: participants reported a higher understanding when the eHMI was active under both yielding and non-yielding conditions, indicating increased perceived transparency, yet this did not make non-yielding situations feel safe. Together with previous findings that eHMI can improve perceived comprehensibility of vehicle intent without necessarily increasing willingness to cross

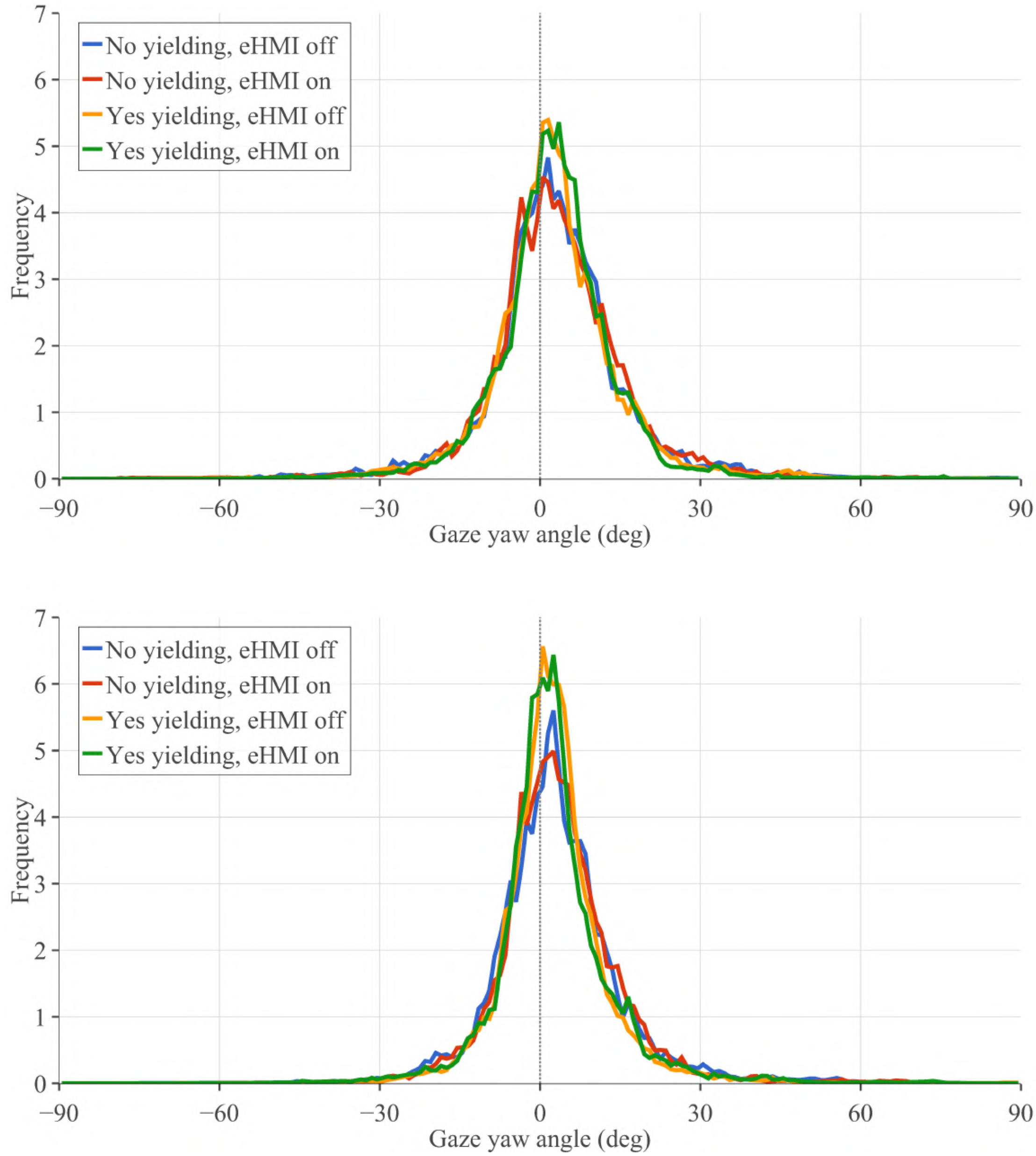


Fig. 7. Percentage-normalised distributions of head-yaw angle as a function of vehicle yielding behaviour (non-yielding vs. yielding) and eHMI status (off vs. on), shown separately by visibility of the other pedestrian. **Top:** other pedestrian visible. **Bottom:** other pedestrian not visible. Head yaw is defined such that 0° corresponds to looking straight along the road (positive values = turning the head to the left; negative values = turning the head to the right). Distributions were computed by binning head-yaw samples into 1° bins over $[-90°, 90°]$ and normalising the bin counts within each condition by the total number of samples in $[-90°, 90°]$ so that each curve sums to 100%.

when kinematic conditions remain unsafe [14, 18, 68], the results suggest that participants used the eHMI mainly as a confirmation cue rather than a "permission to cross" signal capable of overriding unsafe kinematics.

The co-pedestrian manipulations produced smaller and more context-dependent effects in the trigger-based risk measure. Visibility/position only slightly modulated perceived risk: when the AV yielded, the risk tended to be somewhat lower when the co-pedestrian was visible than when not, while in non-yielding trials the risk remained high and similar regardless of visibility [28]. The distance between pedestrians also had a modest effect: in the tested 2–10 m range, the spacing produced only small variations in the mean perceived risk when averaged over other factors, indicating that in this sparse two-pedestrian configuration the vehicle kinematics dominated perceived safety. Spacing may matter more when it changes occlusion/line-of-sight, group coordination, or local crowding; consistent with this, and as illustrated in Figure 6, the near–far difference (2–4 m vs. 8–10 m) remained confined to a narrow band even under the most extreme combinations of yielding, eHMI, and visibility/position. Overall, these patterns align with broader AV–pedestrian research showing that vehicle behaviour remains the dominant determinant of perceived safety even when contextual cues are present [17, 46, 71].

In contrast, the trial-wise questionnaire ratings indicate that participants were aware of the social configuration and attributed influence to it. Q1 (influence of the other pedestrian's behaviour) and Q2 (influence of distance) depended strongly on whether the co-pedestrian was visible, and Q2 tended to be higher at shorter separations when the co-pedestrian could be seen, consistent with field and VR studies showing that pedestrians use social information from nearby people and groups when deciding whether and when to cross [1, 24, 55, 71]. However, the stronger self-reported influence was not mirrored in the trigger-based measure, suggesting that post-trial attributions can overstate spacing effects in this paradigm; this is compatible with evidence that other pedestrians can affect timing and efficiency without necessarily producing large changes in objective safety margins [28, 36]. Condition-level correlations supported this dissociation: mean perceived risk was weakly negatively correlated with Q1 ($r = -0.21$) and Q2 ($r = -0.25$) and more strongly negatively correlated with Q3 ($r = -0.40$), echoing prior work where reported social influence coexists with strong responsiveness to traffic cues [1, 30, 55].

Head-orientation behaviour provides converging evidence that attention was primarily directed toward the traffic scene: head yaw clustered near $0^\circ$ across yielding, eHMI, visibility, and distance conditions, suggesting participants monitored the AV and roadway more than the co-pedestrian. This vehicle-centred allocation of visual attention is consistent with evidence that pedestrians' gaze is strongly guided by vehicles and motion cues across contexts, including social crossing situations [45, 71] and more general walking environments (e.g. attention to multiple vehicle features, including wheels and other car elements) [15]. Post-experiment responses further contextualised the limited behavioural social effects: several participants described the co-pedestrian as static and thus less informative than real pedestrians, and suggested increasing behavioural realism and pedestrian density, consistent with recommendations from multi-pedestrian VR studies emphasising group motion and spatial organisation in more interactive scenarios [1, 28, 36].

Collectively, the findings point to a layered decision process: moment-to-moment safety evaluation was anchored in AV behaviour and communication, consistent with prior AV–pedestrian work [14, 17, 68], whereas the social configuration was more prominent in retrospective reports [1, 24, 55, 71] but produced only modest changes in the continuous risk measure and head orientation in this low-interactivity implementation. For sparse encounters with a largely static co-pedestrian, the results therefore suggest that clear yielding behaviour and intelligible external communication are more important for perceived safety than precise pedestrian spacing, while motivating future work with more dynamic co-pedestrians and richer pedestrian traffic to identify when stronger social cues materially shape crossing decisions.

## 5 Limitations and future work

This VR paradigm enabled tight experimental control but necessarily reduces ecological validity: real streets are visually cluttered and uncertain, with occlusions, background traffic, and multiple road users whose behaviour varies over time. Moreover, participants did not physically step onto the road; they provided continuous risk judgements while remaining on the pavement, which may attenuate embodiment/commitment effects that influence crossing initiation in real interactions. The scenario was also deliberately regular: in yielding trials the AV always stopped for the pedestrian closest to its path, and the co-pedestrian remained stationary and never stepped off the kerb. Such repeated, low-ambiguity encounters may reduce the diagnostic value of social cues and help explain why inter-pedestrian distance had only a modest effect on the trigger-based risk measure in this constrained setting. Communication was further limited to a single eHMI design/logic on an AV explicitly described as fully automated (SAE Level 5), whereas real deployments vary in modality, placement, timing, semantics, and salience and may be occluded, fail, or be misinterpreted; pedestrians may also respond differently when a human driver is present or control is ambiguous. Finally, our measures are indirect proxies for safety (no accepted gaps, conflicts/near-misses, stepping trajectories, or full gaze analysis beyond head yaw), and the sample skewed young and internationally mixed, both of which constrain generalisation.

These constraints motivate several directions for future work. To progress towards the original goal of deriving a quantitative dependency between inter-pedestrian distance and willingness to cross, future studies should enable and record overt crossing behaviour (e.g. step-off time, crossing-initiation probability, trajectories) and manipulate distance more densely (ideally quasi-continuously and over a wider range), particularly in settings where distance changes information availability (occlusion/line-of-sight) and coordination demands (moving co-pedestrians, heterogeneous walking speeds, local crowding). With such data, an interpretable "spacing–willingness" relationship can be estimated using hierarchical models (e.g. psychometric or mixed-effects logistic functions of distance with moderators such as yielding, eHMI, and visibility/position), yielding fitted curves and uncertainty bounds rather than effects tied to a small set of discrete spacings.

Future studies should also embed pedestrians in richer traffic environments (multi-lane or two-way roads, varied approach speeds/accelerations, less predictable yielding) and include direct contrasts between automated and human-driven vehicles. Research on AV communication should broaden the eHMI design space and include non-ideal behaviour, by systematically manipulating modality [19], placement [41], timing [31], semantics [56], and salience [19], and introducing controlled lapses [33], delays [31], and inconsistencies between eHMI signals and vehicle motion [33]. The social side can be made more lifelike by giving pedestrians behavioural agency (walking, hesitating, initiating crossing), varying spacing and ordering, and scaling from dyads to small groups [24, 70], enabling targeted tests of coordination phenomena (leader–follower dynamics, opportunistic following, "herding") and whether vehicle-centric cues versus social cues dominate when others' behaviour is genuinely diagnostic [16, 43]. Where appropriate, controlled experiments can be complemented by analyses of naturalistic dashcam corpora [2] to prioritise which multi-pedestrian patterns are most important to reproduce.

Broader samples remain important: including older adults and stratifying by age can clarify lifespan changes in sensitivity to AV behaviour, eHMI cues, and spacing [51, 69], while cross-cultural studies can test robustness across norms for pedestrian priority and driver yielding [2]. Finally, methodological triangulation is essential: VR testbeds should be complemented with closed-track experiments and naturalistic observation to identify where VR findings generalise and where they diverge [10, 61]; group-aware trajectory models and simulation frameworks incorporating

AV signalling and pedestrian group behaviour can then be calibrated on such empirical data to bridge controlled experiments and complex multi-agent street interactions [24, 26].

## 6 Supplementary material

In line with current open science practices and recommendations for transparency in automotive user research [22], the authors openly provide these research artefacts to support reproducibility, collaboration and further advancements in the field. The materials used in the study, analysis code and anonymised responses of the participants are available at https://www.dropbox.com/scl/fo/4pphss4roc9stcue0904o/AN76AaVvkSZHDkR4rW9_xvs?rlkey=sfnc6k4neajka793zxlw845wx. The maintained versions of the analysis code and the VR environment are available at https://github.com/bazilinskyy/multiped.

## Declarations of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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