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Who goes first? A distributed simulator study of vehicle–pedestrian interaction

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ABSTRACT

One of the current challenges of automation is to have highly automated vehicles (HAVs) that communicate effectively with pedestrians and react to changes in pedestrian behaviour, to promote more trustable HAVs. However, the details of how human drivers and pedestrians interact at unsignalised crossings remain poorly understood. We addressed some aspects of this challenge by replicating vehicle–pedestrian interactions in a safe and controlled virtual environment by connecting a high fidelity motion-based driving simulator to a CAVE-based pedestrian lab in which 64 participants (32 pairs of one driver and one pedestrian) interacted with each other under different scenarios. The controlled setting helped us study the causal role of kinematics and priority rules on interaction outcome and behaviour, something that is not possible in naturalistic studies. We also found that kinematic cues played a stronger role than psychological traits like sensation seeking and social value orientation in determining whether the pedestrian or driver passed first at unmarked crossings. One main contribution of this study is our experimental paradigm, which permitted repeated observation of crossing interactions by each driver-pedestrian participant pair, yielding behaviours which were qualitatively in line with observations from naturalistic studies.

1. Introduction

Pedestrians constitute a great proportion of the traffic ecosystem and their interaction with other road users, especially vehicles, has a great impact on traffic safety and efficiency. With the deployment of highly automated vehicles (HAVs) on roads in the future, they will share the road space with other road users, such as pedestrians and conventional vehicles. Hence, HAVs need to communicate their intent and be able to negotiate different driving strategies such as right of way (Koopman & Wagner, 2018). Those HAVs that communicate effectively with pedestrians and react to changes in pedestrian behaviour may promote greater acceptance of their driving performance and make them seem more trustable (J. E. Domeyer et al., 2020). To this end, understanding competing as well as communication strategies that exist between pedestrians and drivers/vehicles is necessary to achieve a safe, efficient and transparent traffic flow.

Research suggests that the safety and efficiency of interactions can be defined by movement, distance and time-based factors (J. E. Domeyer et al., 2020; Ismail et al., 2009). The literature suggests that road user communication is predominately achieved by factors such as implicit cues, and explicit communication (such as hand gestures) is rarely used in vehicle–pedestrian interaction (Amini et al., 2019; Dey & Terken, 2017; Fridman et al., 2017; Jayaraman et al., 2019; Lee et al., 2021; Palmeiro et al., 2018; Rasouli and Tsotsos, 2020). For instance, a study on six observation sites (including both marked and unmarked crossings) across three European countries revealed that both pedestrians and drivers used explicit cues quite rarely in crossing situations and this was in correspondence with the results of the post-crossing questionnaire on the cues that were used by the pedestrians to cross the road (Lee et al., 2021). Some of the most commonly reported implicit cues in the literature are time-to-arrival (TTA) or time gap (J. Domeyer et al., 2019; Gorrini et al., 2018; Velasco et al., 2021) and vehicle's speed and deceleration profile (Ackermann et al., 2018, 2019; Palmeiro et al., 2018; H. Schmidt et al., 2019; Sucha et al., 2017). Besides, other factors

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such as delay or waiting time for both agents (J. Domeyer et al., 2019; Sucha et al., 2017; Y. Wang et al., 2021; W. Wu et al., 2019), demographics (Amini et al., 2019; Rasouli and Tsotsos, 2020) and type of conflict zone/crossing (Cloutier et al., 2017; Habibovic et al., 2018; R. Tian et al., 2019) have been found to affect crossing behaviour. However, research suggests that the causal impact of these various factors on interaction outcome is not well understood.

There are cultural, geographic and legal differences regarding road user behaviour at locations with right of way such as marked crossings. In the UK, drivers should give way to pedestrians waiting to cross as well as those on a zebra crossing (see Rule H2 in The Official Highway Code, 2023). This is similar to many western European countries. A study in the UK found that people have a higher tendency to use a zebra crossing to pass the road, spend significantly less time waiting to cross, and cross more slowly compared with unmarked crossings (Havard & Willis, 2012). It has also been found that pedestrians in the UK feel much safer and have a higher perceived behavioural control when interacting at marked crossings (Havard & Willis, 2012; O'Dell et al., 2022). That said, drivers might not always yield to pedestrians even though they know they should (Dąbrowska-Loranc et al., 2021; Varhelyi, 1998), for instance, to reach their destination sooner as a matter of urgency or when they fail to see the pedestrian in time making the pedestrians abort the crossing and step back (Dąbrowska-Loranc et al., 2021).

In addition to the use of objective metrics such as implicit cues, subjective reports like perceived safety and trust are shown to be useful in assessing the intentions behind road user encounters (Habibovic et al., 2018; Liu et al., 2021). However, there is less known about the role of personality traits such as sensation seeking (SS) and social value orientation (SVO) in interactions as they can explain some of the mechanisms of human decision-making. SS is defined as the inclination to look for intense, varied, complex, and novel experiences (Arnett, 1994). SS is reported to be associated with risky traffic behaviours (Rosenbloom, 2006; A. Wang & Wang, 2021) and pedestrians with low SS have been found to miss more road-crossing opportunities compared to high sensation seekers (H. Wang et al., 2022). Additionally, adolescents have been found to be the age group influenced more by SS (Wang et al., 2019; Wang et al. 2022). SVO formalises one's concern for the welfare of others and is an individual's preference about how to distribute resources (e.g. money) between the self and another person. SVO has been found to be capable of imitating human driver behaviour when integrated into automated vehicle (AV) motion controller design. This integration was found helpful when AV interacted with other cars (Geary & Gouk, 2020; Le & Malikopoulos, 2022; Schwarting et al., 2019) and pedestrians (Crosato et al., 2021; Crosato et al., 2022). This past work all rests on the idea that the SVO of road users involved in interaction has an impact on the interaction outcome, but as far as we are aware this hypothesis has never been tested empirically.

To investigate road user interactions, many studies have used naturalistic data (Brosseau et al., 2013; J. Domeyer et al., 2019; Gorrini et al., 2018; Ismail et al., 2009; Madigan et al., 2021; Sucha et al., 2017; Zhao et al., 2020) in which the initial conditions of the scenarios in questions are not controlled. This means even by selecting certain subsets of naturalistic data, e.g. certain ranges of initial conditions, one could never know for sure if there are no correlations with various latent factors (e.g., road user personalities) which simultaneously affect both initial conditions and outcomes. This is especially important for testing and validating the models of road user interaction as using naturalistic data could be less helpful for the development of these models which seem necessary for understanding road user interactions in automation (Markkula & Dogar, 2022; Markkula et al., 2022).

Controlled studies provide an opportunity for traffic scenarios to be tested in a way not possible in reality, not least with respect to safety (Dey & Terken, 2017; Dommès et al., 2021; Sadraei et al., 2020), by allowing traffic conditions to be controlled to a high degree of accuracy and traffic scenarios to be repeated between and within participants. Controlled studies can be represented as test track studies (Habibovic et al., 2016; Palmeiro et al., 2018) and studies in virtual reality (VR) (Tran et al., 2021) either using head-mounted displays (Dey & Terken, 2017; Morrongiello et al., 2015), CAVE-based pedestrian simulators (Dommès et al., 2021; Lee et al., 2022; Velasco et al., 2021) and/or driving simulators (Ali et al., 2020; Bella & Silvestri, 2015; J. Wu et al., 2018). Because pedestrians cannot cross the road in front of AVs in test track studies, for ethical reasons, VR-based studies are considered a safer alternative. However, most previous VR studies involved human interaction with a pre-programmed computer agent. For instance, a human agent (driver/pedestrian) encountered a computer-programmed agent (driver/pedestrian) and this made it less possible to consider the computer-programmed agent as an interactive participant. Thus, it is less clear if the decision made by the human agent would be the same if they were interacting with another human in the real life. Distributed simulation in traffic context in which two or more human agents can interact in a controlled manner is a potential solution to address the mentioned shortcomings (Andersson, 2019). In distributed simulation, one can collect data from both pedestrians and vehicles simultaneously which can be used to explore the interactions precisely, repeatably, and controllably. This will help identify the communication pattern between road users (Sadraei et al., 2020).

To date, very few studies have employed this method to understand vehicle–pedestrian interactions (Kearney et al., 2020; Lyu et al., 2021; Sadraei et al., 2020). In a study by (Kearney et al., 2020), pedestrians wearing a head-mounted display interacted with both simulated and human-driven cars at two locations: an intersection and a midblock with a crosswalk. In both cases, the drivers are required to yield to the pedestrian in many US states such as Iowa (the location of the experiment) (The Iowa Legislature, 2022) and Illinois (Illinois Legal Aid, 2023). The pedestrians were told that they would see three oncoming cars, and they need to see how many times they can cross the road (back and forth) without being hit. The authors studied the crossing and yielding behaviours of the agents and also pedestrians' looks and gestures towards the vehicles. The results showed that pedestrians crossed more in front of both human-driven and simulated cars when at intersections, compared to midblock crossings. Drivers also had a lower yielding rate at midblock crossings, compared to intersections. Lyu et al. (2021) studied pedestrians' head-turning frequency and the change in head-turning angle before and during the actual road crossing. This was done by connecting a desktop driving simulator to a CAVE-based pedestrian simulator. The drivers experienced two types of scenarios: (1) braking trials when the driver was asked to stop the car from a specific distance to the pedestrian or the AV decelerated from a specific distance and stopped before reaching the pedestrian and (2) non-braking trials: when the driver was asked to yield to the pedestrian if they stepped into the road or the AV did not brake and passed the pedestrian. They found that pedestrians crossed less in front of the AV in the non-braking trials and the peak value for the head-turning behaviour was achieved at the crossing initiation. Moreover, the vehicle's stopping/braking distance to the pedestrian was the prominent factor in the pedestrians' crossing decisions and head-turning behaviour.

That said, the following research gap still exists: there has been no controlled study where two road users can interact with each other, to investigate how time gap, different crossing types, and personality traits affect interaction outcome. Additionally, none of the previous controlled studies explicitly considered whether their results were comparable to the knowledge about pedestrian-vehicle interactions from naturalistic data.

This distributed simulator study was conducted with the aim of understanding vehicle–pedestrian interactions by showing the specific impact of crossing type, time gap, SVO and SS on a number of interaction-related metrics including pedestrians' decision to pass first. This work became possible by connecting a high-fidelity motion-based driving simulator to a CAVE-based pedestrian lab. The following research questions were of interest:

1. What does the interaction behaviour look like as a function of time gaps and crossing types, SVO and SS?
2. What factors play a role in determining the interaction's outcome (who goes first)?

The rest of the paper consists of the following sections: Section 2 explains the methodology, Section 3 describes the results, Section 4 is the general discussion of the findings and Section 5 is conclusion.

2. Methods

2.1. Participants

Sixty-four participants (32 drivers: M = 31.53, R = 21–50, SD = 1.72; paired with 32 pedestrians: M = 25.09, R = 19–34, SD = 0.87) with 8 pairs for each possible combination of genders (i.e. male-male, male–female, female-male and female-female in the driver and pedestrian roles, respectively) took part in the study. Participants were recruited via adverts using different social media platforms, and also via an existing University of Leeds Driving Simulator e-mail distribution list. They received £20 compensation for their participation in the study. The pedestrians had lived in the UK for at least one year, and drivers had at least 3 years' UK/EU driving experience with an average annual mileage of 7384.59. The study was approved by the University of Leeds Ethics Committee (Reference No AREA 21–022).

2.2. Apparatus

The study was conducted by connecting a CAVE-based pedestrian simulator - the Highly Immersive Kinematic Experimental Research (HIKER) pedestrian lab, to a high-fidelity driving simulator known as the University of Leeds Driving Simulator (UoLDS). HIKER is a 9 × 4 m CAVE simulator that consists of a wooden floor and four glass walls (Fig. 1d). Eight Barco F90 4 k projectors are used to project virtual

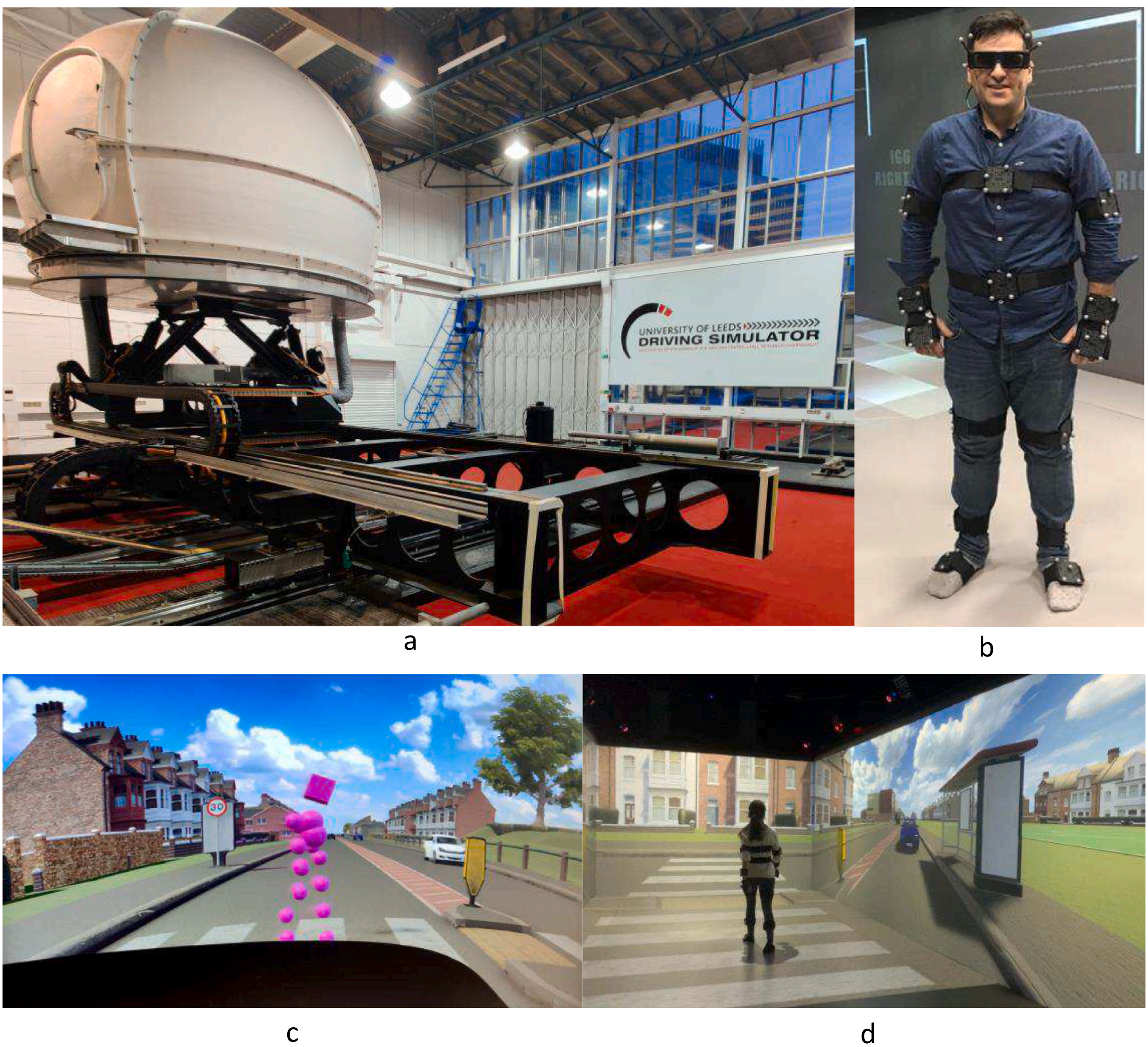

Fig. 1. (a) The high fidelity driving simulator (b) The motion trackers (c) The driver's view of the pedestrian: the driver is stationary on the road, and the pedestrian is the pink bubbles (d)The pedestrian's view of the vehicle in the CAVE-based pedestrian lab: the pedestrian is crossing the zebra and the vehicle is to their right.

scenes at 120 Hz to the floor and walls. Two designated points depicted by markers were considered on the HIKER floor which showed the standing point and the point for the 'move on' for the pedestrians, respectively which will be explained below (Fig. 2b).

UoLDS (Fig. 1a) is a controlled and safe environment for studying drivers' behaviour. The simulator consists of a Jaguar S-type cab, housed in a 4 m-diameter spherical projection dome, with a 300° field-of-view projection system. The simulator also incorporates an eight degree-of-freedom motion base consisting of a 5x5 m long x-y table and a hexapod.

Fourteen body markers (Fig. 1b) were attached to the head, arms, chest, pelvis, elbows, hands, thighs, ankles, and feet of the pedestrian, to track their position as they moved freely during the experiment. The head and body movements were captured in the HIKER with ten VICON Vero v2.2 (2.2MP) cameras placed on top of the glass walls, with their signal processed by a VICON Tracker (v 3.7). The entire scene responds to the participant's head movements using the HIKER glasses to show a perspective-correct virtual reality. The tracking system was used to constantly feed real-time positions and orientations to SimulatorD, our in-house developed simulation software. SimulatorD is designed with a service-oriented architecture, and runs different nodes, distributed over different machines. The virtual environment was rendered in Unity 3D-based nodes, integrated into the SimulatorD message-bus, using the UniCAVE plugin in the HIKER, ProNET for the warping, and projector blending in the UoLDS dome. The resulting set up allowed pedestrians in the HIKER lab and drivers behind the wheel of the UoLDS to experience the environment simultaneously, from their respective perspectives. To the driver, the pedestrian was represented by pink spheres (Fig. 1c), corresponding to the body tracking markers, yielding an effective representation of pedestrian position, pose, and movement (Sadraei et al., 2020).

Two personality trait questionnaires were used in this study namely the 20-item Arnett Inventory of Sensation Seeking (AISS) (Arnett, 1994) and the SVO slider measure (Murphy et al., 2011). The AISS is designed to measure the personality trait of SS in two subscales of novelty and intensity, which is believed to contribute to risk-taking (Arnett, 1994). The SVO slider measure is an online/paper-based choice task with six primary items and nine secondary items. The items are all resource allocation choices dividing money between oneself and another (fictional) person over a continuum of joint rewards. Hence, the SVO measure quantifies the degree to which individuals have concern for others' reward/outcome. At lower SVO values, individuals care less about others' outcomes. High SVO values indicate an altruistic personality and successively lower values indicate prosocial, individualist and competitor types, respectively (Murphy et al., 2011).

2.3. Experiment and road scene design

In this study, a two-way, straight section of urban road (890 m long) with traffic in both directions (each lane had 4.5 m width) and with four crossing locations (two zebra and two non-zebra crossings) as shown in Fig. 2 a-b was created in Unity. The start and end of the road were identical, making it possible to create an endless loop for the driver. A number of vision obstructions (i.e. bus stops) were presented at the roadside. Drivers could see that sometimes the pedestrians stepped out from one of the obstructions and they needed to decide whether to yield to the pedestrians or to pass the crossing first. Pedestrians, on the other hand, were standing behind a vision obstruction until an auditory cue prompted them to step up to the kerb and look for oncoming traffic and cross the road if they felt safe to do so. This auditory cue was triggered based on the temporal distance of the subject vehicle to the centre of the

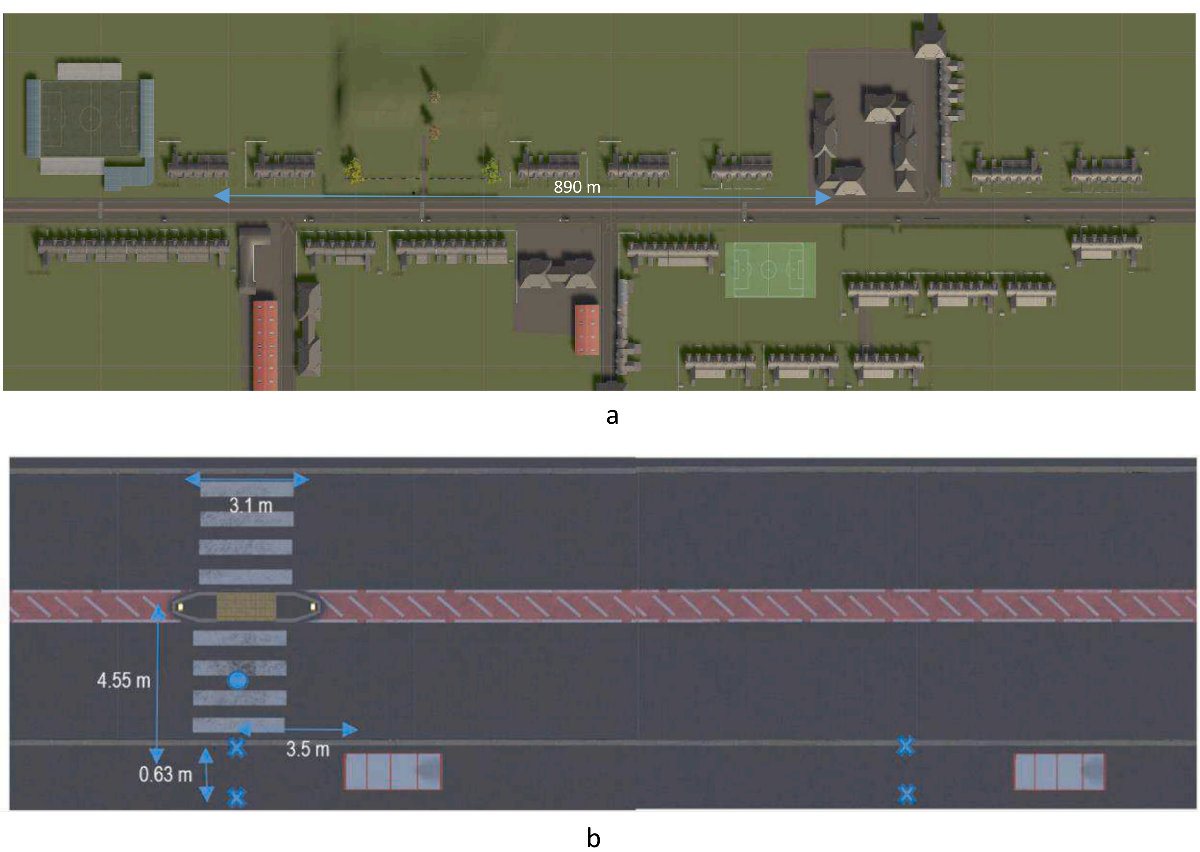

Fig. 2. (a) Road environment created in Unity: the arrow shows the distance from the start to the end point of the loop for the driver (b) Top view of the zebra (left) and non-zebra crossing (right) in Unity including the designated stand points (blue markers): the first one shows the pedestrian's standing point the second shows the point where the pedestrian needed to move on, which was the kerb of the virtual road, the grey rectangles: visual obstruction (bus stop) and the blue circle: the centre of the zebra crossing.

crossing (3, 4, 5, 6, or 7 s), providing experimental control over the initial time gap in each interaction. The auditory cue was only audible by the pedestrian in the HIKER lab and the driver could not hear it thus preventing them from changing their driving behaviour such as speed before observing the pedestrian. The choice of the specific time gaps was made based on the related literature (Lobjois & Cavallo, 2007), our previous experience regarding several experiments with similar scenarios in the HIKER (Lee et al., 2022; Velasco et al., 2021) and pilot sessions. We wanted to have time gaps starting from simulating a situation where road users can only see each other quite late before taking an action, due to visual obstructions, distractions, etc. (3 s) to a situation where pedestrians feel comfortable crossing the road even at unmarked crossings (7 s). The end of each trial for the pedestrian was indicated by briefly greying out the virtual scene before moving the pedestrian to the location for the next trial.

Each of the ten different crossing conditions (five time gaps, with and without a zebra crossing) was repeated twice resulting in 20 randomised trials in each block, per participant pair. The complete road scene for the driver with the placements of the crossings is depicted in Fig. 2a-b.

2.4. Procedure

Both participants: The specific information sheets describing the simulator and the experiment procedure regarding each role (one for the driver and one for the pedestrian) were sent to the participants before they arrived for the study. Upon arrival, they were asked to sit in their respective briefing areas in two separate rooms and read and sign the consent form. Thus, although both participants were told that they would interact with a human participant, they did not meet or see each other. While road user interactions in real traffic may be affected by factors such as the age, gender, ethnicity of others (Sullman & Mann, 2009), in this experiment this source of variability was excluded. Both participants were asked to have the following mindset in the experiment: '*Please assume that you are late for an important meeting, such that you want to avoid any unnecessary delays, but of course, you also want to stay safe.*' They were also reminded that at zebra crossings, pedestrians have the right of way. The study had one practice block for the driver to get used to the vehicle controls, one interactive practice block involving both agents (with ten randomised trials), and two identical blocks (with 20 randomised trials each) for the main experiment.

The procedure for each agent was as follows:

Drivers: The driver participants were asked to sit behind the wheel of the simulator and get prepared to drive. They were told that they will experience a practice session designed to allow them to become familiar with the equipment, virtual environment and speed management. The practice session stopped as soon as participants confirmed that they became accustomed to the equipment and the road environment. After completing this first practice block, the interactive practice block (ten trials), which included the pedestrian participant, began. Drivers were told that they would be driving on a two-way road with traffic on both lanes, and interacting with a pedestrian at a number of locations, with and without a zebra crossing. They were also asked to drive as they normally would and maintain the designated speed limit (30 mph). After completing the interactive practice block, the main experiment consisting of two blocks (40 trials) started.

Pedestrians: Once they signed the consent form, pedestrian participants were fitted with the motion trackers and HIKER glasses. The pedestrians were asked to initially stand at the first marker (Fig. 2b). From this position, they could see that vehicles were driving in both directions on the road, but they could not see the approaching vehicles in the nearest lane, due to a vision obstruction (bus stop), i.e. they were not able to anticipate when the human-driven vehicle was approaching. The participants were instructed to wait at the first floor marker until they heard an auditory tone, and then step up to the second marker (which was at the kerb of the virtual road), evaluate the situation and cross if they felt safe to do so (Fig. 2b). After the end of each trial which happened when the vehicle passed the centre of the crossing, they were asked to wait for the HIKER screens to fade out in grey, and then return to the starting point, waiting for the start of the next trial.

Upon completion of the experiment, participants were asked to fill out post-experiment questionnaires which included demographics (e.g. age, gender, nationality, driving experience, etc.), questions about the interactions with the other road user (e.g. what cue they used when deciding to cross/pass through or wait for each other) and their experience about being in a virtual reality environment. They were then asked to fill in the two personality trait questionnaires probing their psychosocial profiles as mentioned above. Doing the experiment before the questionnaires could affect responses in the questionnaires, and vice versa. However, it was more important for us to ensure that we would not affect the behaviour in the experiment itself by, for example, making the participants think that a key research interest of ours was their fairness in traffic interactions. Therefore, we administered the personality surveys after the experiment.

The duration for the whole experiment was about 1.5 h with the two practice sessions taking 20–25 min followed by two experimental blocks of 20 min with a 10-min break between them for the main experiment. Completing the questionnaires, on average, took about 20 min.

2.5. Data preparation

Data from 32 (participant pairs) × 40 trials, minus the last trial of the last session which was not recorded due to technical issues, 1279 trials were recorded. Out of 1279 trials, no collision was recorded but there were a few instances (<1 % of trials) where the pedestrians stepped out into the road at a time such that the drivers had to brake harshly, or increase their lateral deviation to avoid a collision. Table 1 shows all the variables and metrics used in this study, with a short description of each. To investigate the role of AISS and SVO metrics in the interactions, we calculated the relative values (differences in values between each role) for each participant pair, as shown in Table 1. The motivation for taking these differences was the assumption that the interactions are affected by the relative differences, between participants, in AISS and SVO, more than by the absolute levels of these traits.

2.6. Statistical analysis

A generalised linear mixed-effects model with a binary response variable of interaction outcome (1 = pedestrian crossed fist, 0 = vehicle crossed first) was used to investigate which factors affected which participant crossed first. Also, three linear mixed-effects models were built to account for CIT, crossing duration and vehicle delay. The full model of potential predictors based on theoretical reasoning (Maxwell et al. 2017) is proposed in Eq (1) which is written using Wilkson notation (Wilkinson and Rogers 1973).

$$\textit{Outcome variable}\ (\mathrm{Ppc/CIT/CD/VD}) \sim T + L + W + A(p) + G(p) + \Delta SVO + \Delta AISS + (1|\textit{Participant pair}) \tag{1}$$

The above Eq was used to fit generalised linear mixed-effects models to the data using R package lme4.

3. Results

3. 1. Personality traits, roles and gender

We conducted independent t-tests to see if there is any difference between the roles and genders regarding the personality traits. The results showed while the drivers had higher AISS scores than the pedestrians, 53.77 vs 50.18; $t(62) = -2.02$, $p = 0.04$, SVO values for both roles were not significantly different, 53.16 vs 53.67; $t(62) = 0.24$, $p = 0.88$. The results for gender showed that the mean score for AISS was significantly higher for men in both roles, 55.95 vs 51.38; $t(30) = 5.83$, p <

Table 1
Variables used in the study and for data analysis.

Variable	Type	Description	Symbol	Unit
Time gap	Independent	Temporal gap of the approaching vehicle to the centre of the crossing.	*T*	Seconds
Waiting time	Independent	Defined as the total time waiting time of the pedestrian and was calculated in two ways: In the first trial of each block (when there was no previous trial): from the time that the pedestrian stood at the first marker on the HIKER's floor to the time the auditory tone was triggered. In all other trials (when there was a previous trial): from the time the pedestrian started moving towards the first marker in the previous trial to the time the auditory tone was triggered in the current trial.	*W*	Seconds
Age	Independent	For both agents; only pedestrian age 'A (p)' was considered for the analysis as the response variable is for the pedestrian.	*A*	n/a
Gender	Independent	For both agents; only pedestrian gender 'G (p)' was considered for the analysis as the response variable is for the pedestrian.	*G*	n/a
Crossing type	Independent	Two categories: zebra & non-zebra.	*L*	n/a
ΔSVO	Independent	The difference in SVO values between the two participants (degree): ($SVO_{ped} - SVO_{driver}$).	ΔSVO	Degree
$\Delta AISS$	Independent	The difference in AISS scores between the two participants: ($AISS_{ped} - AISS_{driver}$).	$\Delta AISS$	n/a
Crossing Initiation time (CIT)	Dependent	Calculated from the time the auditory tone was triggered to the time pedestrians stepped off the kerb and started crossing the road.	*CIT*	Seconds
Crossing duration	Dependent	Calculated from the time pedestrians started crossing to the time they reached the central hatch.	*CD*	Seconds
Vehicle delay	Dependent	The time it took the driver to reach the centre of the pedestrian crossing in the trial, minus the time this would have taken if the driver had just continued at constant speed. This shows how much time was lost for the driver due to slowing down for the pedestrian.	*VD*	Seconds
Interaction outcome (1 = pedestrian crossed first, 0 = waited)	Dependent	The pedestrian was considered to have crossed first when they stepped out of the kerb after the auditory tone had played but before the car had reached the crossing, and then continued walking until reaching the other end of the crossing location (i.e. the pedestrian did not abort the crossing).	*Ppc*	n/a

0.001 for pedestrians and 55.09 vs 51.23; $t(30) = 10.92$, $p < 0.001$ for drivers, suggesting that they were high sensation seekers compared to the women participants which is in correspondence with previous research (Rahmani & Lavasani, 2012; W. Wang et al., 2000). Also, men, on average, had significantly higher SVO values in both roles, $t(30) = 8.35$, $p < 0.001$ for pedestrians and $t(30) = 5.83p < 0.001$ for drivers, suggesting that they were closer to an altruistic profile, whereas females were, on average, more prosocial (Murphy et al., 2011).

3.1. Participants trajectories

Fig. 3 provides an overview of the entire dataset in which both pedestrians and vehicles' distance to the centre of the crossing are illustrated, for all trials. The darker (green and orange) lines show trials where the pedestrian crossed first, and the lighter lines (light green and yellow) show trials where the vehicle passed first. A number of different qualitative patterns of interaction are discernible in this figure, for example: (1) in trials when the vehicle passed first, we can see how the pedestrian remains standing at the kerb (the light green lines), whereas the car continues on (yellow lines.) (2) When time gaps were lower, i.e. 3 or 4 s (the four panels on the left), there are more horizontal orange lines showing vehicle's position (with higher duration) compared with higher time gaps, i.e. 6 and 7 s (the four panels on the right). This suggests that for the lower time gaps, drivers who passed second (the orange lines) needed to slow down or stop completely more often before the pedestrian crossing in front of them (the dark green lines). The following sections provide quantitative analyses of this dataset.

3.2. Interaction outcome

Table 2 shows the results of the generalised linear mixed-effects model for the interaction outcome.

As can be seen in Table 2 both time gap of approaching vehicle and crossing type played a significant role in the pedestrian's decision to cross first. As expected (Dommès et al. 2021, Theofilatos et al. 2021), pedestrians crossed first more often at higher time gaps and in the presence of a zebra crossing (see Fig. 4). The left panel of Fig. 4 shows that while all pedestrians crossed before the vehicle in the zebra conditions, for time gaps of 5 s and higher, this was not the case for lower

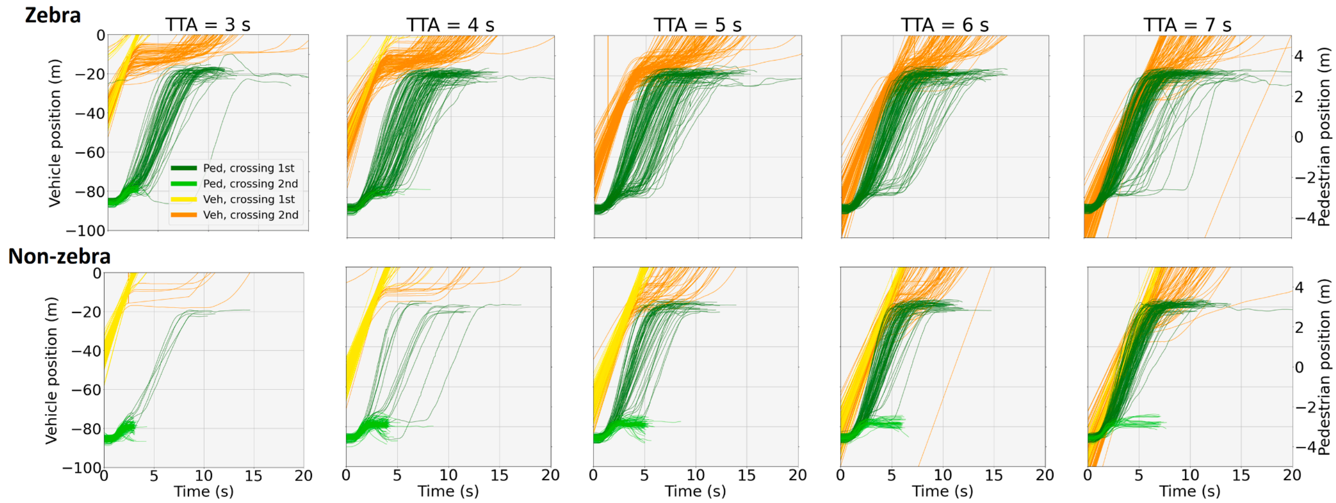

Fig. 3. Pedestrian and vehicle position measured as distance to the centre of the crossing as a function of time, for all trials, separated into panels by initial time gap (columns) and crossing type (rows). Time zero is at the auditory cue to the pedestrian, and all lines end at the time the vehicle passed the centre of the crossing. The y-axis on the left and right indicate the position of the vehicle and pedestrian, respectively. Orange and dark green lines show the vehicle and pedestrian position, respectively, in trials where the pedestrian crossed first, and yellow and light green lines show the same agents' positions in trials where the vehicle passed first.

Table 2
Results for mixed-effects logistic regression of interaction outcomes (1 = pedestrian crossed first, 0 = waited).

		Estimate	Std. Error	z value	Pr(>|z|)	95 % CI	
						L	U
(Intercept)		−0.553	1.737	−0.319	0.000	−3.958	2.851
Time gap		**1.855**	**0.135**	**13.723**	**0.000**	1.590	2.119
Crossing type (Non-zebra)		**−5.077**	**0.369**	**−13.755**	**0.000**	−5.801	−4.354
Δ*AISS*		**−0.079**	**0.032**	**−2.469**	**0.01**	−0.142	−0.016
Δ*SVO*		0.007	0.023	0.326	0.74	−0.039	0.054
Age		−0.087	0.071	−1.230	0.21	−0.227	0.052
Gender (Male)		1.111	0.680	0.632	0.10	−0.223	2.445
Waiting time		**−0.052**	**0.006**	**−7.494**	**0.000**	−0.064	−0.038
AIC	BIC	logLik	Deviance	df.resid	ICC	Observations	
662.2	708.6	-322.1	664.2	1270	0.43	1279	

time gaps. For the no-zebra conditions, the probability of crossing at the highest time gap (7 s) was just above 0.8. Fig. 3 shows that many pedestrians crossed at the no-zebra locations when the time gap was 6 s or more, probably because they had more than enough time to cross the road.

Waiting time had a negative relationship with pedestrian crossing

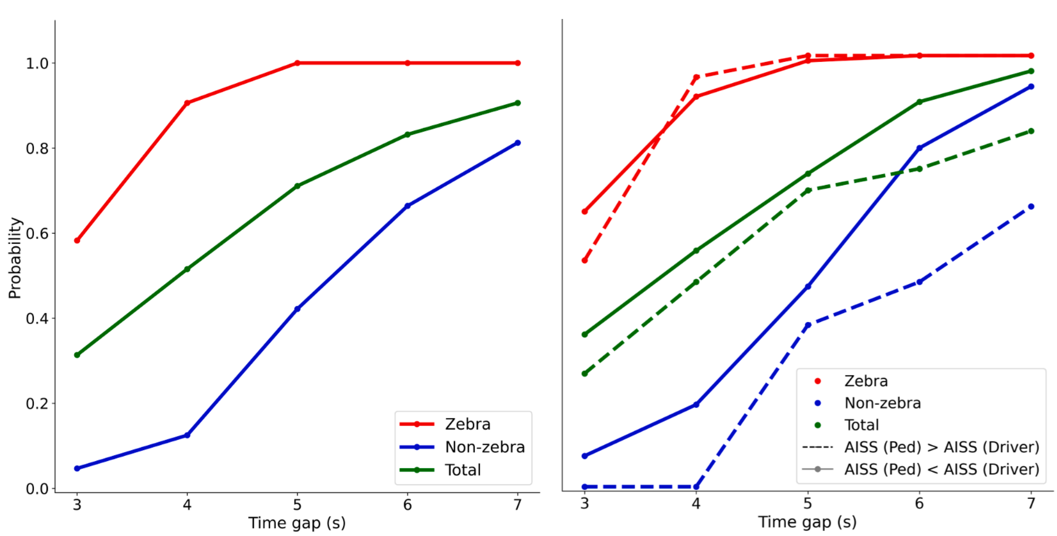

Fig. 4. The probability of pedestrian crossing first as a function of time gap and location (left) and for AISS groups (right).

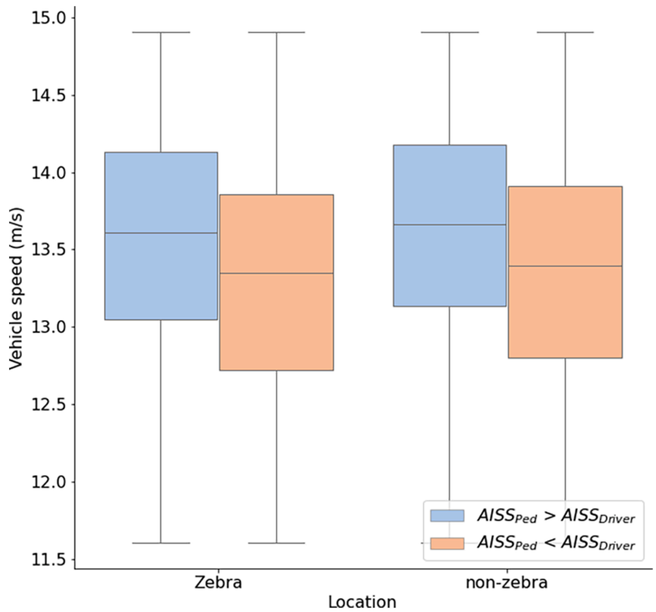

Fig. 5. Box plots of vehicle speed for the AISS groups.

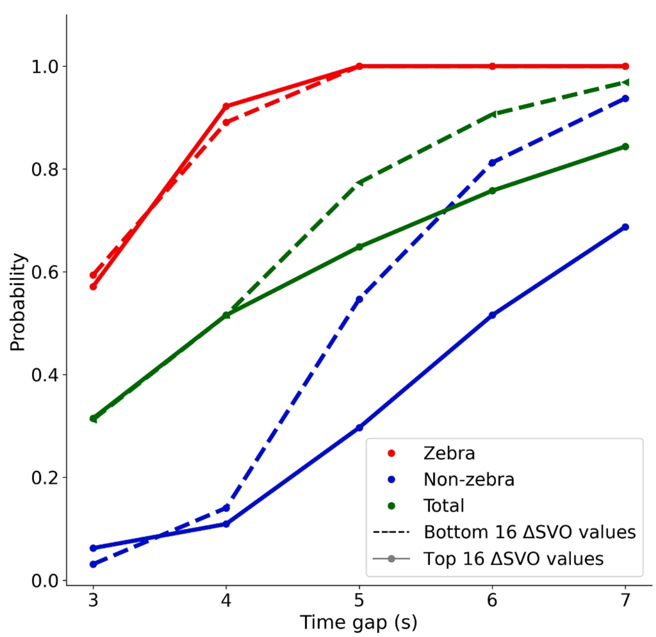

Fig. 6. Pedestrian's probability of crossing first as a function of the time gap, dichotomised by 16 highest (top) and lowest (bottom) values of ΔSVO.

decisions, suggesting that pedestrians who had waited longer since their previous crossing had a lower probability of crossing before the vehicle. Finally, $\Delta AISS$ was found to have a negative relationship with the pedestrian's choice to cross first. As shown in the right panel of Fig. 4, interestingly, when pedestrians had lower SS scores compared to drivers, they crossed first more often, especially at non-zebra which seems counterintuitive to the reported role of SS in risky traffic behaviours. However, higher vehicle speed has been found to increase pedestrian tendencies of accepting smaller gaps (K. Tian et al., 2022). Therefore, we checked the vehicle's speed distribution as a function of crossing type and AISS groups to see if there was any difference between the groups. Fig. 5 shows the box plots of the vehicle's speed based on the crossing types and the two groups of AISS: when the AISS scores for the pedestrians were higher than the drivers (higher values, n = 10, denoted by $AISS_{Ped} > AISS_{Driver}$) and when it was the other way around (lower values, n = 21, denoted by $AISS_{Driver} > AISS_{Ped}$). The figure shows that the average vehicle speed was higher for the first group, suggesting that this might have a stronger effect than $\Delta AISS$ on the interaction outcome. It is worth noting that speed outside the interaction time interval, i.e. from the time the auditory tone was triggered to the time the vehicle passed the centre of the crossing, had an average of 13.47 m/s (SD = 1.72 m/s) for all trials. Within the interaction time interval, the average vehicle speed was 8.59 m/s (SD = 5.29 m/s).

Although ΔSVO was not significant in the model, due to the strong previous interest in SVO as a potential factor in road user interactions (Crosato et al. 2021), we conducted a follow-up analysis: Fig. 6 shows the probability of pedestrian crossing first as a function of time gap and crossing type for the top and bottom 16 values of ΔSVO (i.e. the participant pairs were dichotomised into two groups by ΔSVO). As shown in Fig. 6, while the impact of ΔSVO at zebra crossings was negligible, at non-zebra crossings with time gaps of 3 s or higher, there was a trend of higher probabilities of pedestrian crossing first when ΔSVO was low, i.e. when the driver was more altruistic than the pedestrian.

3.3. *Crossing initiation time*

Table 3 shows that time gap had a negative effect on CIT meaning that, with increasing time gap, CIT decreased, i.e. pedestrians were less hesitant to start their crossing behaviour. Moreover, they had lower CITs at non-zebra compared with zebra crossings. These two findings can be seen visually in Fig. 7. Finally, ΔSVO also had a significant positive effect on CIT, suggesting that for more positive ΔSVO, i.e. when pedestrians tended more toward altruism than the drivers, they spent more time screening the situation before crossing.

3.4. *Crossing duration*

Table 4 shows the results of the mixed-effects modelling for the crossing duration. As shown in Table 4, crossing type had an effect on

Table 3
Results for linear mixed-effects modelling of CIT.

		Estimate	t value	P-value	95 % CI	
					L	U
(Intercept)		2.391	3.078	**0.004**	0.868	3.914
Time gap		**−0.146**	**−7.287**	**<0.001**	−0.186	−0.107
Crossing type (Non-zebra]		**−0.145**	**−2.417**	**0.01**	−0.263	−0.027
ΔSVO		**0.018**	**1.996**	**0.04**	0.003	0.03
$\Delta AISS$		0.020	1.609	0.11	−0.004	0.04
Age		0.052	1.862	0.07	−0.002	0.107
Gender (Male)		0.399	1.503	0.14	-0.121	0.920
Waiting time		0.002	1.784	0.07	−0.000	0.005
Marginal R^2	Conditional R^2	ICC	N	Observations		
0.189	0.555	0.45	32	836		

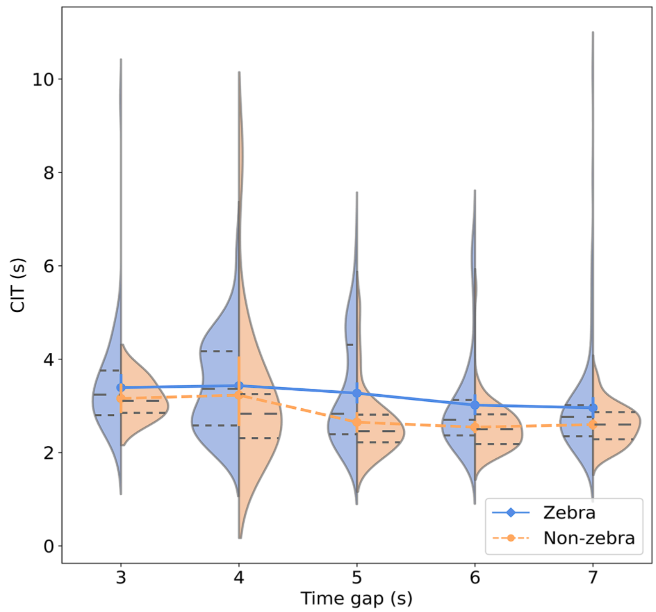

Fig. 7. Violin plots of CIT: The connected dots show the means for each category and the dashed lines show the quartiles.

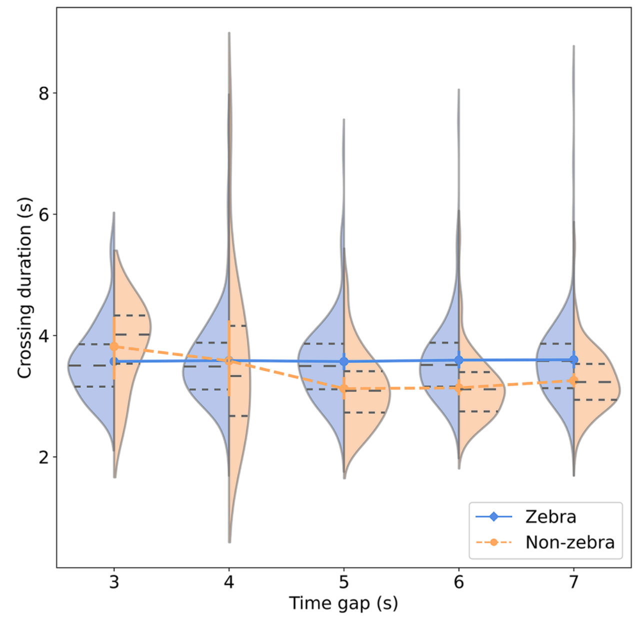

Fig. 8. Violin plots of crossing duration.

the crossing duration in which longer crossing durations were observed at zebra crossings. This effect can be seen in Fig. 8, where the distribution of this variable is depicted and the means of crossing duration are higher for zebra except for time gap 3 s. Also, men had longer crossing durations than women.

3.5. *Vehicle delay*

Table 5 shows the results of the mixed-effects modelling for the vehicle delay. From the table, it can be seen that both time gap and non-zebra location had negative relationships with the vehicle delay. This suggests that with a rise in time gap and while interacting at non-zebra crossings, the driver waited less for the pedestrian to cross the road. These findings can be confirmed in Fig. 9 where the means of vehicle delay at the zebra crossing are more than those for non-zebra except for time gap 3.

4. Discussion

In this study, we sought to investigate vehicle–pedestrian interaction by specifically showing the impact of crossing type, time gap, AISS and SVO on interaction outcome. This was done by conducting a distributed simulation study, where two actors (a driver and a pedestrian) interacted via two connected high fidelity simulators. Apart from the technical challenge of connecting the simulators to each other in these types of studies, there is also the matter of having the participants together at the same place at the same time, ideally with experimental control over the initial conditions, in a way which permits natural interaction behaviour. This methodology could be an important step for providing validation tools for the models of road user interaction like game-theoretic models in which variables should be controlled with a high degree of accuracy for determining exactly how to formulate the payoffs (Kalantari et al., 2022).

The results showed that time gap, location, waiting time and Δ*AISS* had a significant effect on pedestrians' probability of crossing first. In line with the current literature in this context, increasing the time gap led to higher probabilities of crossing which has been shown in both naturalistic (Theofilatos et al., 2021) and controlled studies (Dommès et al., 2021; Lee et al., 2022; Velasco et al., 2021).

Our findings for waiting time and ΔAISS were both interesting and unexpected. In this study, we investigated the effect of the total waiting time of the pedestrian on crossing decisions. According to the literature, the general belief is that the longer pedestrians wait at the kerb, the higher the chance of accepting lower time gaps (Theofilatos et al., 2021; W. Wu et al., 2019; Zhao et al., 2019). However, we observed the opposite behaviour in our study: by increasing the waiting time, pedestrians were less inclined to cross the road first. This may be because

Table 4
Results for linear mixed-effects modelling of crossing duration.

		Estimate	t value	P-value	95 % CI	
					U	L
(Intercept)		2.873	4.258	0.000	1.550	4.207
Time gap		−0.001	0.097	0.92	−0.020	0.020
Crossing type (Non-zebra)		**−0.288**	**−9.026**	**0.000**	−0.350	−0.230
Δ*AISS*		0.010	0.558	0.58	−0.020	0.030
Δ*SVO*		0.011	1.380	0.17	−0.020	0.030
Age		0.025	1.022	0.31	−0.020	0.070
Gender (Male)		**0.280**	**1.228**	**0.02**	−0.170	−0.740
Waiting time		−0.000	−0.700	0.48	−0.000	0.000
Marginal R^2	Conditional R^2	ICC	N	Observations		
0.130	0.706	0.66	32	836		

Table 5
Results for linear mixed-effects modelling of vehicle delay.

		Estimate	t	P-value	95 % CI	
					L	U
(Intercept)		7.379	3.398	0.000	3.121	11.640
Time gap		**−0.963**	**−20.000**	**0.000**	−1.059	−0.870
Crossing type (Non-zebra)		**−0.863**	**−6.212**	**0.000**	−1.135	−0.590
Δ*AISS*		0.023	0.681	0.68	−0.501	0.090
Δ*SVO*		0.507	1.934	0.06	−0.001	0.100
Age		0.086	1.103	0.27	−0.071	0.240
Gender (Male)		1.147	1.539	0.13	−0.321	0.269
Waiting time		0.003	1.034	0.30	−0.001	0.010
Marginal R^2	Conditional R^2	ICC	N	Observations		
0.326	0.686	0.53	32	836		

our definition of waiting time is not identical to that used in previous, naturalistic studies. In the previous studies waiting time is defined as the time that a pedestrian takes to wait for a gap size that is safe to cross while there is a stream of cars approaching and passing, suggesting that the pedestrians were actively and continuously looking for a chance to cross, which could lead to frustration after a while (Zhao et al., 2019). That said, our findings are consistent with (Yannis et al., 2013) who observed that pedestrians who had waited for a longer time, were more inclined to be cautious and less likely to engage in risk-taking by accepting smaller gaps.

Results regarding ΔAISS showed that while no clear pattern was observed at zebra crossings, pedestrians with lower AISS scores than drivers crossed first more often, when interacting at non-zebra crossing locations. There are two possible explanations for this: First, although SS is seen to be associated with risky traffic behaviours (Jonah, 1997; Rosenbloom, 2006), it was not the strongest predictor of road crossing intentions in some studies (e.g. see Zhou & Horrey, 2010). Second, as shown in Fig. 5, this could be because the drivers of this group, on average, drove faster replicating the findings in the literature that pedestrians are more likely to accept smaller gaps when the speed of approaching vehicle is higher (S. Schmidt & Faerber, 2009; K. Tian et al., 2022; Velasco et al., 2019). This might be because pedestrians tend to overestimate a specific TTA in higher vehicle speed conditions compared to lower speeds (Hancock & Manster, 1997; Petzoldt, 2014).

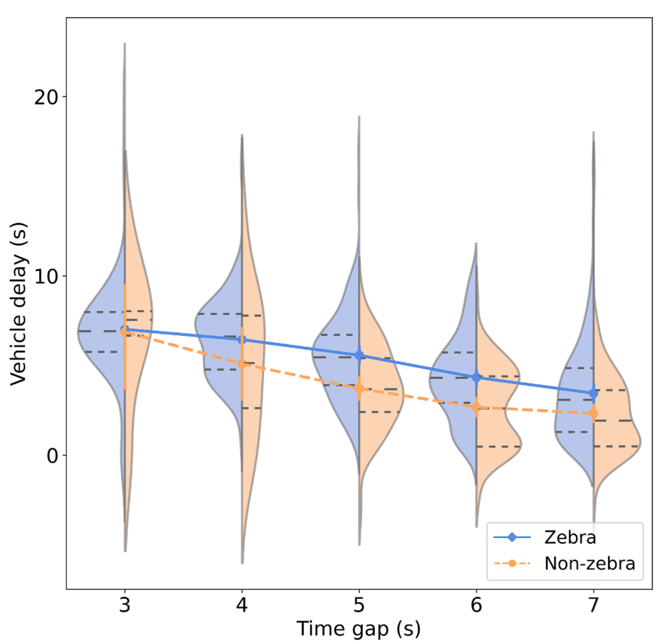

Fig. 9. Violin plots of vehicle delay.

Overall, this confirms the stronger role of kinematic cues for pedestrians when crossing the road. As mentioned in Methods, speed was not part of the study design, and since all drivers were expected to follow the same speed limit of 30 mph we did not include speed in our statistical models. However, it could be argued that natural variations in speed between drivers and trials may have affected the interaction outcomes (and indeed, we saw some possible indications of this in relation to AISS as discussed above). Therefore, we reran our mixed-effects models also including the vehicle's speed 1 s after the auditory tone (to allow time for the pedestrian to have reached the kerb), but did not find any statistically significant effect of this variable on interaction outcome. Other metrics such as the distance from the vehicle to the conflict point and pedestrian could help predict pedestrians' decisions to cross the road (Zhang & Fricker, 2021). Future studies could investigate the role of spatial distance, by including it as a controlled variable.

CIT results showed that pedestrians were less hesitant to cross the road at higher time gaps. This is in line with previous lab studies (Dommès et al., 2021; Velasco et al., 2021) and can be confirmed by looking at Fig. 3. CIT is reported to be an important factor for predicting pedestrians' perceived safety and trust, when crossing in front of AVs and conventional vehicles (Dommès et al., 2021) and also a good predictor for assessing the application of human–machine interface (Lee et al., 2022). Also, both CIT and crossing duration were found to be longer for the zebra crossing locations in this study. The longer CIT at zebra crossings was likely because there were more unresolved interactions suggesting that the incentive to save time and conform to the priority rules might put the two agents into a dilemma. This could happen also in real traffic: when a pedestrian is in hurry, they would expect the driver to yield to them at a marked crossing, while at the same time the driver wants to reach their destination sooner also as a matter of urgency, they both will be placed in a situation where the driver might at first slow down a little bit and when they see that the pedestrian might be a bit hesitant they accelerate shortly right after that or continue to approach the crossing with the same speed, making the pedestrian doubtful if their crossing will be safe or not; eventually, the driver decides to yield resulting in delays.

Although we saw only limited effects of ΔSVO, there was an interesting trend for interaction outcome at non-zebra crossings at higher time gaps and its effect on the pedestrians' hesitation to cross the road. This is in line with the theory stating that larger differences in SVO values would usually lead to a situation where an agent with the higher SVO value shows more cooperative behaviour, and as a result, it is more likely for them to give the right of way to an agent with the lower SVO values (Schwarting et al., 2019). That would need confirmation in future studies by using larger and more inclusive datasets. One possible reason for the limited observed effect of SVO could be that our sample did not include more extreme SVO profiles, such as individualists and competitors. Research suggests prosocials (who were the extreme case of considering self-benefits in our study) exhibit more fairness and are less demanding compared to individualists and competitors who were absent in this study (De Dreu & Van Lange, 1995). Hence, to include a wider range of SVO categories in an experiment and see, for example, what would happen if competitor pedestrians and drivers interact with each other and also with other SVO categories, one might try non-probability sampling techniques such as purposive sampling. That said, while the inclusion of such profiles could lead to observing more substantial effects of SVO on interactions, these profiles are less common in the general population (Zhen et al., 2015). Thus, the applied importance of more extreme SVO profiles may still be limited.

Finally, vehicle delay which can be viewed as the amount of time added by the pedestrian to the vehicle's journey was higher at zebra crossings and lower time gaps. These findings can be explained by looking at the results of both CIT and crossing duration. As stated by (J. E. Domeyer et al., 2020) when it comes to 'Nonintersection encounters', the amount of waiting time for the driver is solely pedestrian-dependent, that is what we also observed in our study.

This study had several limitations: First, we did not include pedestrian approach phase, whereas past naturalistic studies (J. E. Domeyer et al., 2022; Gorrini et al., 2018; Varhelyi, 1998) suggest that interaction takes place already during this time, if the vehicle and pedestrian can see each other during the approach. Second, due to the size limit of the CAVE-based system, we could not account for multiple pedestrians to investigate the effect of group size on interaction outcome (head-mounted displays will be preferred in this instance). Third, we also did not account for the scenarios including encountering at least two vehicles from both directions as this seems to cause relatively different crossing behaviours (Dommès et al., 2021). Fourth, instead of using spheres to represent pedestrians and presenting the vehicle as an entity without a driver behind its wheels, having calibrated avatars of both agents would help to truly examine how drivers and pedestrians see each other in the virtual environment. This would help to further investigate aspects such as eye contact and gaze under different traffic scenarios, which could be an important aspect to address in future studies.

5. Conclusions

This study showed that, overall, distributed simulation can simulate scenarios where traffic agents interactively communicate with each other, demonstrating behaviours that are qualitatively in line with those observed in naturalistic studies. Some of these important observed patterns were the higher probability of pedestrians' crossing first at higher time gaps and also at marked crossings. The controlled nature of the study made it possible to draw the conclusion that these behavioural patterns are due to causal links between the independent and dependent variables, rather than spurious correlations. Our findings also showed that kinematic cues, including vehicle speed and time gap, had a stronger influence on pedestrians' crossing behaviours at unmarked crossings, than psychological traits such as AISS and SVO. The findings of this study could provide further insights into how to study a large number of vehicle–pedestrian interactions in a controlled manner, which is an essential part of the design and testing of AVs.

CRediT authorship contribution statement

Amir Hossein Kalantari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Yue Yang:** Conceptualization, Data curation, Investigation, Writing – review & editing. **Jorge Garcia de Pedro:** Conceptualization, Investigation, Methodology, Software. **Yee Mun Lee:** Conceptualization, Methodology, Writing – review & editing. **Anthony Horrobin:** Conceptualization, Data curation, Investigation, Methodology, Software. **Albert Solernou:** Investigation, Software, Writing – original draft, Writing – review & editing. **Christopher Holmes:** Conceptualization. **Natasha Merat:** Conceptualization, Methodology, Funding acquisition, Supervision, Project administration, Writing - review & editing. **Gustav Markkula:** Conceptualization, Methodology, Funding acquisition, Supervision, Project administration, Writing - review & editing.

Declaration 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.

Data availability

Data are available at https://data.mendeley.com/datasets/w9scvcckh4/1.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2023.107050.

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