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A distributed simulation study to investigate pedestrians' road-crossing decisions and head movements in response to different vehicle kinematics in mixed traffic

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Abstract

The impending deployment of automated vehicles (AVs) will lead to mixed traffic conditions, where pedestrians will be required to interact with both AVs and human-driven vehicles. For traffic flow to be safe and efficient, AVs' understanding of pedestrians' behaviour and intention is as important as pedestrians' perception of AVs' status and intent. To investigate pedestrians' road-crossing decisions and interactive behaviour in mixed traffic, a distributed simulation study was developed by linking a CAVE-based pedestrian simulator and a desktop driving simulator. Twenty-five pairs of pedestrians and drivers were recruited, and each pair experienced 32 trials, where pedestrians decided to cross (or not) before an approaching vehicle at an un-signalised, single-lane, road. The driving pattern of the approaching vehicle (controlled by either a predefined program or human driver) and braking mode (braking/non-braking) were manipulated. For the predefined vehicles, the braking pattern was subdivided into hard braking and soft braking to provide more kinematic variability. Human drivers were also instructed to yield, or not, in different trials. Pedestrians' road-crossing decisions and head movements were recorded and analysed. Results revealed a significant difference in head-turning patterns between crossing and non-crossing manoeuvres, demonstrating pedestrians' head movements as a valid indicator of their road-crossing intentions. Moreover, results identified a 'last moment check' behaviour before pedestrians' crossing initiation, with a significant increase in head-turning during the last 2 seconds. Finally, pedestrians made a similar percentage of road crossings and displayed a similar pattern of head movements, in response to human-driven and predefined vehicles, suggesting that the difference of implicit cues in the current mixed traffic setup does not impact their behaviour prior to road crossings. The findings from this study extend our knowledge of how pedestrians behave when crossing the road in mixed traffic, particularly in terms of their head-turning behaviour. We hope this information can be used by future AVs to better predict pedestrians' road-crossing intentions in urban settings.

Keywords: pedestrian; mixed traffic; automated vehicle; interaction; road-crossing; head-turning behaviour

Introduction

Automated vehicles (AVs) promise to improve traffic efficiency, safety, and mobility of all users, especially the elderly and disabled, and are expected to become commercially available and widely deployed in the next ten to twenty years (Fagnant & Kockelman, 2015; Milakis et al., 2017). Once deployed, AVs and other road users, such as drivers of conventional vehicles (CVs), cyclists, powered two-wheelers, and pedestrians, will need to share the same road space in a mixed-traffic environment. In this case, pedestrians, one of the most vulnerable road users, will be required to interact with both AVs and CVs, which could lead to behavioural uncertainty or unsafe situations for pedestrians because AVs could, for example, behave differently to CVs, in terms of the way they negotiate the road and their kinematic conduct (Razmi Rad et al., 2020).

Pedestrians' interpretation of vehicle's intention

When studying the communication and interaction of actors in such mixed traffic environments, Markkula et al. (2020) describe an interaction as: "*a situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future*". Several recent studies in this context have indicated that when pedestrians are interacting with approaching vehicles, they interpret the intention of vehicles and base their crossing decisions on a combination of elaborate communication cues. These include implicit cues from the vehicle, such as its speed, distance, and time-to-arrival (TTA) (Ackermann et al., 2019; Dey & Terken, 2017; Lee et al., 2020; Sucha et al., 2017); and explicit information, such as traffic and road-based signals, sound- and light-based signals of approaching vehicles, as well as the body language of the driver (Mahadevan et al., 2018; Razmi Rad et al., 2020; Sucha et al., 2017). However, such interpretations are context dependent. For example, pedestrians can assume that an approaching vehicle will yield at signalised road sections, such as traffic lights or zebra crossings. By contrast, when crossing at an un-signalised location, where the right of way is more ambiguous, pedestrians are exposed to a higher risk if they choose to cross. Here, pedestrians may rely on other cues, such as vehicle kinematics or driver-initiated cues (Guéguen et al., 2015; Lee et al., 2020; Madigan et al., 2023).

The role of implicit cues for pedestrian-AV interaction

With the impending deployment of AVs, especially at SAE Level 4 or 5 (SAE International., 2021), where the human driver is no longer in charge of the driving task, the opportunity for interaction and communication between humans inside the AV and other road users is removed. To compensate for this lack of explicit communication, many recent studies have investigated external human-machine interfaces (eHMIs) as a potential solution for mitigating the uncertainty that might arise for pedestrians interacting with these AVs in a mixed traffic environment (Dey et al., 2020; Lee et al., 2022; Schieben et al., 2019). Some studies have demonstrated the value of eHMIs for resolving ambiguity and increasing pedestrians' perceived trust and safety towards AVs (de Clercq et al., 2019; Holländer, Colley, et al., 2019; Holländer, Wintersberger, et al., 2019), whilst other studies have found no significant effect of eHMIs on pedestrians' decisions (Clamann, 2017; Moore et al., 2019). Overall, there seems to be a consensus that implicit cues (e.g., speed-, distance-, or TTA- based information) have precedence over explicit cues in conveying AVs' intention, and assisting pedestrians' crossing decisions (Dey & Terken, 2017; Holländer et al., 2019; Rasouli & Tsotsos, 2020). For example, a recent study by Dey et al. (2020) investigated the contributions of eHMI and vehicle braking patterns (gentle/early/aggressive) in communicating the AV's intention to pedestrians, and demonstrated a secondary influence from eHMIs, with pedestrians' preference for gentle, rather than aggressive, braking.

Although the role of implicit cues (especially braking profiles) from AVs has been emphasised by many studies in AV-pedestrian interaction, few have explored whether differences in kinematic cues in mixed traffic influence pedestrians' decision-making and behaviour when crossing the road (Taima & Daimon, 2023). Wizard-of-Oz and 'ghost driver' studies (Dey et al., 2019; Rodríguez Palmeiro et al., 2018; Rothenbucher et al., 2016), which hide the driver in some way, creating a 'driverless' vehicle, have failed to show any differences in response from pedestrians to vehicles of different appearances or sizes, or those that clearly do not have a human in the driver's seat. These studies suggest that external appearance as a cue has limited effects on pedestrians' interactions with AVs and CVs, with more to be understood about the value of implicit cues (such as yielding patterns and braking profiles). However, the challenge with Wizard-of-Oz studies is that they are controlled by humans, and implicit traits such as driving and braking patterns are difficult to create in a repeated and controlled manner. Thus, an important research gap is to understand whether pedestrians respond differently to system-controlled vehicles and human driven vehicles in mixed traffic, approaching with different implicit characteristics, such as different yielding intentions and braking patterns.

AVs' recognition of pedestrians' intention

While it is important for pedestrians to understand the intentions of AVs when interacting with them in mixed-traffic environments, it is also important for future AVs to have some understanding of pedestrians' crossing intentions. As drivers, we use a range of cues from pedestrians to identify this intention. Although relatively rare (Lee et al., 2020), drivers are found to yield to pedestrians if they display hand gestures, leg and head movements (Chen et al., 2019; Crowley-Koch et al., 2011; Schmidt & Faerber, 2009; Zhuang & Wu, 2014) or achieve simple eye contact, or display a smile (Guéguen et al., 2016). On the other hand, pedestrian intention recognition for AVs is generally taken as a tracking problem, when using various models or algorithms. In general, these models use pedestrians' motion and pose and movements of the legs and upper body, within multiple consecutive image frames (Koehler et al., 2013; Volz et al., 2019), to create a trajectory representation. One major drawback of these models is that they may function inferiorly when pedestrians stop (Rasouli et al., 2018), for example if they are waiting at the curb or looking at approaching vehicles. In addition, these body pose- or dynamics-based models may fail when it comes to a more diverse range of pedestrians or scenarios, such as pedestrians with a crutch or in a wheelchair (Singh et al., 2019) or those partly occluded by other obstacles. For this reason, a number of researchers have incorporated head movements into their pedestrian-intention-recognition models, showing that the inclusion of head information could lower the estimation error rate (Varytimidis et al., 2018) and bring forward prediction time (Cao et al., 2022). However, little is known about the precise patterns of head movements in these cases, particularly in the AV context. In addition, few studies have included a baseline comparison of pedestrian head-movements in situations where they do not cross. Thus, it is important to gain a deeper understanding of pedestrian head movements in both crossing and non-crossing situations, to understand whether, and how, these differ. This understanding can be used to inform AV intention recognition algorithms.

Head movement cues for AV-pedestrian interaction

Some studies have demonstrated that pedestrians' head movements are a strong indicator of their crossing intention (Hollands et al., 2002; Rasouli et al., 2018; Rehder et al., 2014), closely linked to their situation awareness, and visual attention before a crossing initiation (Kooij et al., 2014). For example, Rasouli et al. (2017) and Lee et al. (2020) have shown that in approximately 90% of crossings at un-signalised locations, pedestrians' heads were oriented towards approaching cars, prior to and during the road crossing. Research from naturalistic observation studies suggests that when performing risky tasks in a complex environment (e.g., road crossing), humans tend to turn their heads to expand their scanning area, to compensate for a limited oculomotor range (±55°) (Avineri et al., 2012). In addition, head rotation helps to re-centre the head on the torso as a new reference point for the next movement (Hollands et al., 2002), which is fundamental for a road crossing manoeuvre, where frequent redirection of attention is commonly required. Pedestrians are also seen to display different head movement patterns at various stages of a road crossing manoeuvre. For example, observation studies have shown that, when crossing in front of a vehicle approaching from the right, participants were found to turn their heads to the left before stepping off the curb, and then turn their heads to the right as they crossed the street (Geruschat et al., 2003). These authors also found an increase in head-turning frequency during the last 4 s before a crossing initiation, with the frequency being greatest during the last second (Hassan et al., 2005). In another observation study (Kalantarov et al., 2018), pedestrians initiated a crossing with their head and shoulder moving first (0.82s before ankle movement, which was defined as the beginning of the crossing), followed by the elbow (0.62s before ankle movement). These studies provide us with knowledge of the importance of pedestrian head movements as part of the information gathering process for pedestrians prior to crossing the road. By understanding the impact of variations in vehicle kinematic behaviours on these head movements, we can gain detailed information on how these vehicle behaviours are likely to impact pedestrian road crossing decisions in future mixed traffic with AVs.

Research aims and questions

Based on the above knowledge gap, the aim of this study was to investigate pedestrians' road-crossing decisions and patterns of head movements in mixed traffic. In particular, the study investigated head movements: (1) in crossing versus non-crossing manoeuvres, to validate head movement as a potential cue for road-crossing intention; and (2) in response to vehicles with different implicit kinematics (e.g., human-driven versus predefined patterns: soft braking versus hard braking).

Given the limited availability of AVs (SAE Level 3 or above) on roads and regarding safety concerns in pedestrian-vehicle interaction experiments, this study developed a distributed simulation platform, which integrates a CAVE-based pedestrian simulator and a desktop driving simulator, enabling the real-time interaction between pedestrians and human driven / predefined system-controlled vehicles in a VR environment. Within such a high-fidelity virtual environment, a range of road-crossing scenarios were developed, and pedestrians' road-crossing decisions and head movement were captured and investigated.

Method

Participants

Using the University of Leeds driving simulator database and social media adverts, 50 participants (25 pedestrians and 25 drivers) were recruited and matched randomly into 25 driver-pedestrian pairs for this study. Participants' demographic information is provided in Table 1. To be eligible for the study, drivers were required to have a UK/EU driving licence and at least three years of driving experience. All pedestrian participants were required to have lived in the UK for at least one year. The driver and pedestrian participants self-reported to have normal or corrected-to-normal vision, and be free from any head or upper/lower limb diseases that could lead to impairments in driving/walking. Due to the length of time taken to prepare for and complete the study, drivers and pedestrians were rewarded with £10 and £15, respectively, for their participation. Ethical approval was obtained from the University of Leeds Research Ethics Committee (Ref: LTTRAN-113). All participants provided written informed consent to take part in the study.

Table 1. Demographic information of participants

Participant	Gender		Age (years)	
	Male	Female	M (SD)	Range
Driver	13	12	43.36 (13.29)	21 - 64
Pedestrian	12	13	32.64 (9.97)	20 - 57

Apparatus and Virtual Environment

The experiment was conducted at the University of Leeds Virtuocity centre, which houses a set of human-in-the-loop, connected, Virtual Reality simulators to study road user interactions with vehicles on the road. For this study, the Highly Immersive Kinematic Experimental Research (HIKER) lab, a CAVE-based pedestrian simulator (see https://uolds.leeds.ac.uk/facility/hiker-lab/) was integrated with a desktop driving simulator, to create a distributed simulation environment for driver-pedestrian pairs (see Figure 1).

The HIKER lab provides walking space in a 9 m × 4 m room, formed by three glass panel walls and a wooden floor, which present the virtual road environment and respond to the pedestrians' position, using a set of body trackers and a lightweight pair of glasses with integrated reflective trackers. The glasses provide appropriate visual cues of the stereo virtual environment that can be adjusted to the pedestrians' height, and track their head movements over time. The Unity 3D software was used to incorporate the vehicle parameters and pedestrian state into the virtual environment.

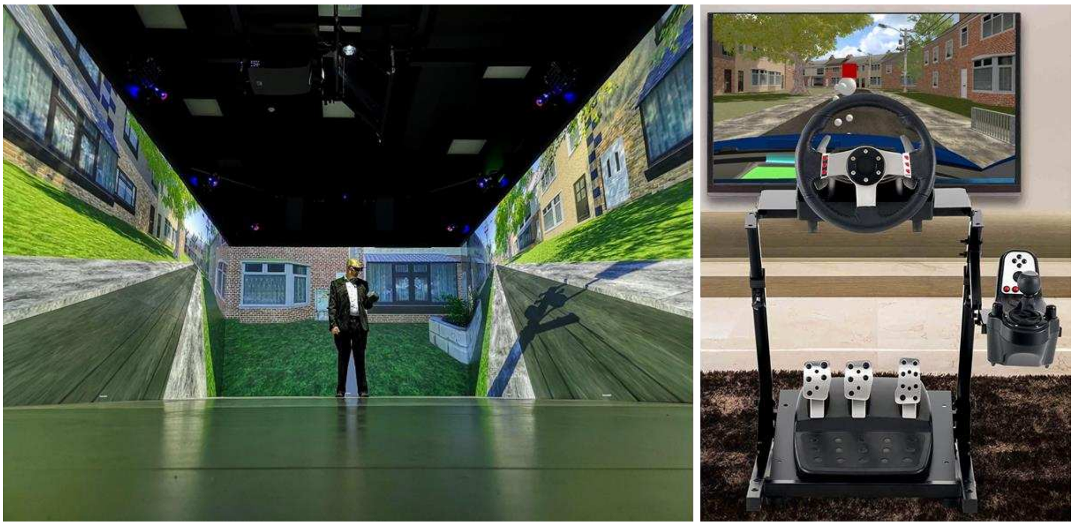

Figure 1. The HIKER lab (Left) and the desktop driving simulator (Right) at the University of Leeds, displaying the driver's view of the pedestrian.

For this experiment, an un-signalised, single-lane, urban road was used for the virtual environment, visible to both the pedestrian and the driver. The 4.2 metre-wide (UK standard) road depicted a residential setting during daylight hours (see Figure 2). From the drivers' perspective, the pedestrian was presented as a set of graphical components, which corresponded to the reflective trackers worn by the participant, and represented pedestrians' main body elements and head (see Figure 2). Due to technical limitations, the reflective trackers could become occluded while the pedestrian was walking, leading to a sense for the driver that the pedestrian was missing body parts when a human-like avatar was displayed. Therefore, to avoid potential driver discomfort, while still accurately representing pedestrian walking behaviour, this graphical visual representation was used instead of a more human-like agent. The drivers were notified that they were interacting with real pedestrians as depicted by those graphical components. The desktop simulator was placed behind one of the HIKER's walls, and the driver was not visible to pedestrians, who could only see the vehicle in the virtual environment.

Figure 2. Pedestrian's view of approaching vehicles (Left) vs driver's view of the crossing pedestrian (Right)

Experimental Design

A within-participant design was used in this study, in which each pair of participants experienced 32 trials, presented in a preselected randomised order. In each trial, the pedestrian interacted with a vehicle that was either controlled by a predefined driving (PD) program or a human driver (HD). In addition to the driving mode, the yielding behaviour of the vehicle was manipulated for both the PD and HD conditions: braking and non-braking (see Table 2). At the start of each trial in all conditions, the vehicle began driving in a predefined mode, travelling at 30 mph, which is the designated speed limit on many UK urban roads. For the PD braking trials, the braking pattern was subdivided into hard braking (PDHB) and soft braking (PDSB), to generate more kinematic variability and study the effect of these two braking patterns on pedestrian crossing behaviour. The initial travelling speed, deceleration rate, braking distance, and yielding behaviour of the PD vehicle were informed by previous studies in this context (Dey et al., 2020; Lee et al., 2022). The driver was made aware of the driving mode at the start of each trial, i.e., whether the vehicle was PD or HD, and also whether the trial was a braking or non-braking trial. A simple dashboard-mounted HMI was used to ask drivers to take over when prompted in the HD trials. Further information about the experimental design is provided in Table 2.

Table 2. Detailed information about the experimental variables

Vehicle controller	Braking Mode	Abbreviation	Description	Number of trials
Predefined driving (PD)	Braking	Predefined driving, soft brake (PDSB)	PD vehicle started braking at a distance of 40 m from pedestrians at a rate of 2.5 m/s^2 and stopped at a distance of 4 m from the pedestrian	4

		Predefined driving, hard brake (PDHB)	PD vehicle started braking at a distance of 40 m from pedestrians at a rate of 3.2 m/s^2 and stopped at a distance of 12 m from the pedestrian	4
	Non-braking	Predefined driving, non-braking (PDNB)	PD vehicle did not brake and maintained a speed of 30 mph	8
Human Driver (HD)	Braking	Human driver, brake (HDB)	At 80 m from the pedestrian, the dash turned yellow, alerting drivers to 'get ready to take over control'. At 60 m from the pedestrian, the dash turned red, asking drivers to take over control. The HD was instructed to brake and allow pedestrians to cross the road.	8
	Non-braking	Human-driven, non-braking (HDNB)	At 80 m from the pedestrian, the dash turned yellow, alerting drivers to 'get ready to take over control'. At 60 m from the pedestrian, the dash turned red, asking drivers to take over control. The HD was instructed to carry on driving and not yield to the crossing pedestrian.	8

The decision to start each trial in a predefined mode was to generate the same initial speed, distance, and time-gap between the manipulated vehicle and the lead vehicle until the pedestrian appeared. This was to ensure that, from the pedestrian's perspective, the initial gap between the lead vehicle and the target vehicle was the same in both the PD and HD trials. To mitigate against any effects of takeover, for HDB, the drivers were informed to take over control at 60 m to the pedestrian, compared to 40 m for the PD trials, where the vehicle began to decelerate in PDSB and PDHB. Following a series of pilot studies, the earlier takeover and extended margin aimed to enable the drivers to adjust to their "normal driving", and they were instructed to drive normally and yield when they normally would for the pedestrian in HDB condition or not yield in the HDNB condition.

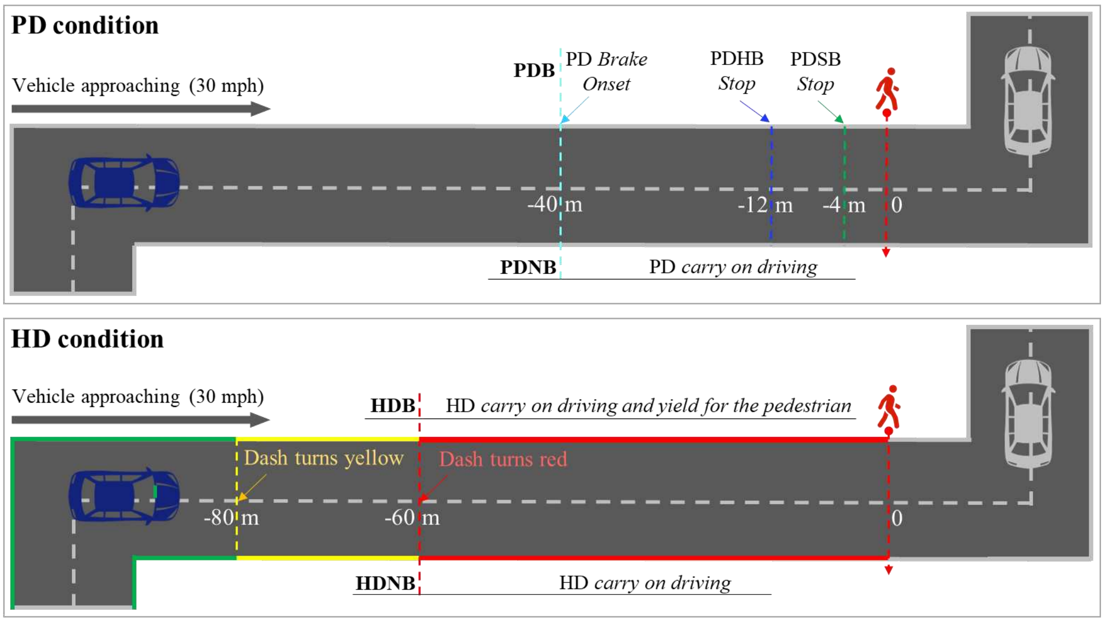

Figure 3. Depiction of the experimental design

Procedure

The experiment lasted between 60 and 75 minutes, respectively, for each pair of participants. The pedestrian participant was asked to attend the lab around 15 minutes earlier to prepare for the study, which involved fitting the trackers and the glasses. Upon arrival, the driver and pedestrian participants were greeted separately, and instructed to read and sign the information sheet and consent form about the experiment and had the opportunity to ask questions.

Drivers were briefed on how to operate the simulator and told to interact with the pedestrians as they would typically do when they are in control of a conventional vehicle in real traffic. They were asked to follow the instructions on the dashboard monitor of the driving simulator, which would display the manipulation of the vehicle mode (PD/HD) and braking mode (Braking/Non-braking) of the impending trial. If the vehicle mode was HD, the driver needed to get ready to take over control of the vehicle at 80 m from the pedestrian (indicated by a green-to-yellow change of HMI on the dashboard). After resuming control at 60 m to the pedestrian, the driver carried on driving normally and needed to brake for the pedestrian in the HDB condition (as they would in real traffic), but not brake in the HDNB conditions. However, they had the discretion to brake if the pedestrian stepped onto the road in non-braking trials and they felt uncomfortable driving on. When in the PD condition, drivers were asked to simply observe the predefined driving patterns. Drivers were equipped with a headset to hear the engine sound of the vehicle.

Pedestrians began by standing at a designated point at the edge of the road in the HIKER lab. Two cars approached the pedestrian from their right, with a white vehicle followed by a blue one (see Figure 3). The pedestrians’ task was to naturally cross the road (or not) between the approaching vehicles when they felt safe. Pedestrians were informed that although the second vehicle always looked the same, it could either be driven by a predefined program or a human driver. They were not informed about the identity of the driver (PD or HD), for individual trials. If they crossed the road in a particular trial, they needed to return to the starting position after the blue vehicle had passed, to get ready for the subsequent trial.

The experiment started with a 5-minute practice session for each pair of participants to familiarise them with the tasks and the virtual environment. Following the practice session, the experimental session, consisting of 32 trials, began. Once the experimental session was completed, the driver and pedestrian were each asked to complete a short questionnaire that included demographic information and questions about their subjective experience of the entire experiment.

Data collection and exclusion

As the head movement profiles of pedestrians are considered to be a powerful indicator of crossing intention and visual search (Hollands et al., 2002; Rasouli et al., 2018; Rehder et al., 2014), this paper focused on investigating pedestrians’ head movements in response to a range of implicit cues displayed by approaching vehicles. The head movement data of pedestrians were recorded at 50 Hz in quaternion format, which was then converted into Euler angle for ease of analysis (see Figure 4 for an illustration). The left/right head-turning behaviour reflects the switch of pedestrians’ visual attention between traffic elements, such as the road ahead and vehicles approaching from left or right. Therefore, the horizontal head-turning pattern around the torso (yaw axis) was analysed for this study, as left/right head-turns are considered more informative than looking up/down or tilting left/right for a road crossing task (Rhee et al., 2019).

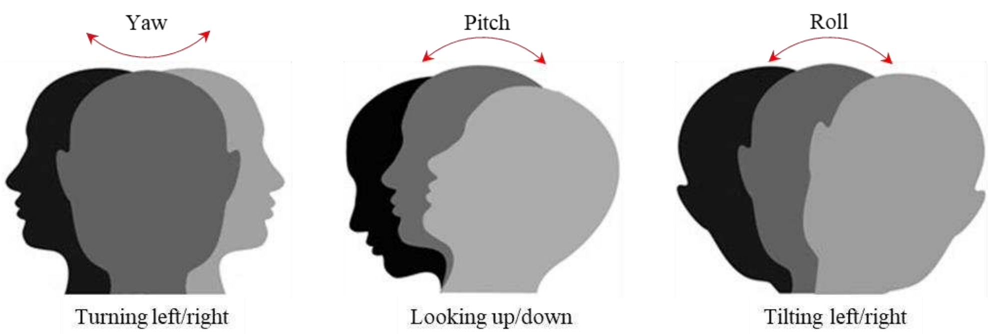

Figure 4. Scheme of head movement around yaw, pitch, and roll axes

The data analysed included results from 461 crossing trials and 290 non-crossing trials. 49 trials were excluded from analysis for two reasons: (1) pedestrians crossed the road before the first vehicle (not following the instructions given), and (2) head-tracking data was missing due to technical issues. Table 3 provides a detailed list of trials included and excluded in each condition.

Table 3. Detailed information about trials excluded and included for each condition

Item	HDB	PDSB	PDHB	HDNB	PDNB	Sum
Total trials	200	100	100	200	200	800
Trials – invalid crossing (before 1st vehicle)	10	6	3	10	13	42
Trials - data missing	0	1	5	1	0	7
Trials - valid non-crossing	6	1	0	134	149	290
Trials - valid crossing	184	92	92	55	38	461
Percentage of crossing	92%	92%	92%	27.5%	19%	57.63%

Analysis of head movements

Pedestrians' head movements were analysed for each crossing trial, for the period immediately before and after their crossing initiation. Figure 5 provides an example plot of a single trial, to illustrate how the pedestrian turned their head throughout the road crossing process. Due to the experimental setup, which included a one-way single-lane road, pedestrians were aware that the vehicle would approach from the right, and thus, they were facing this way most of the time. However, as the gap for crossing opened (i.e., the rear of the first vehicle passed the pedestrian's position), or the pedestrian was about to initiate a crossing, they exhibited more head-turns, as shown by the spikes of the black curve in Figure 5.

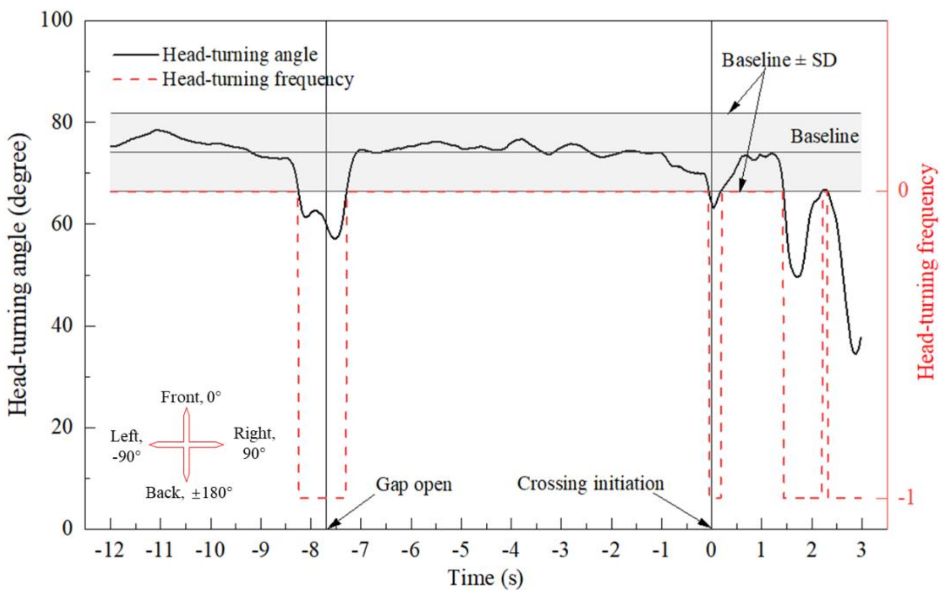

Figure 5. Example plot of a pedestrian's head-turning behaviour around crossing initiation (Pedestrian #1

Trial #29 in HDB condition)

To understand the effect of the vehicle's implicit cues on pedestrians' crossing behaviour, a target window was selected to investigate pedestrians' interactions with the vehicle. For the crossing trials, this window was selected based on pedestrians' crossing initiation time (CIT, i.e., the time elapsed from the crossing gap opening until the pedestrian stepped off the curb) and crossing duration time. In 455 out of 461 trials (98.70%), pedestrians initiated a crossing within 12 s after the crossing gap was open. Thus, the head-tracking data for the 12 s before a crossing initiation was selected as the first part of the target window. To avoid the inclusion of head-turning noise generated after they had crossed the road, the minimum of their crossing duration time (3 s) was selected as the end of this target window. For the non-crossing trials, a 12 s window before the second vehicle passed the pedestrian's location was chosen, for ease of comparison with head-turning behaviour in crossing trials. Two metrics were adopted within the predefined windows, to study pedestrians' head-turning behaviour while making road-crossing decisions: head-turning frequency and head-turning rate. For head-turning frequency, the mode and standard deviation of the head-turning angle were computed for the 15 s window and served as the baseline and threshold for head-turning detection, respectively. As shown in Figure 5, one head turn was counted if the head-turning angle was beyond the grey detection area (mode ± standard deviation, Baseline ± SD), with four head turns seen for this particular trial. Head-turning rate was provided and calculated as the difference in head-turning angle between the current frame and the next frame. A higher head-turning rate denotes that the pedestrian displayed larger head turns between the two adjacent frames. The head-turning rate was observed to fluctuate around 0 degrees, where positive values indicate that the pedestrians turned their heads towards the right. To avoid the positive and negative values cancelling each other out, the negative values were transformed into absolute values. In the subsequent analysis, an average value of head-turning rate was calculated every 0.5 s, to reduce the overall volume of data.

Descriptive statistics were used to check the effect of the experimental variables on the two head-turning metrics. For head-turning frequency, non-parametric tests were used when assumptions of parametric tests were violated. Particularly, a Mann-Whitney U test was performed when the factors consisted of two sampled groups (e.g., HDNB vs PDNB in non-braking conditions). If there were three or more sample groups for a single variable (e.g., HDB, PDSB, and PDHB in braking conditions), the Kruskal-Wallis test was performed. For the head-turning rate, Generalised Estimating Equation (GEE) was used.

Results

Based on the predefined research goals, we first report pedestrians' head movements for crossing versus non-crossing manoeuvres, followed by head-turning behaviour under different vehicle kinematics. Particularly, due to a notable difference between the speed patterns of the braking and non-braking conditions, which might induce different behavioural responses by pedestrians (Dey et al., 2019), results for these two conditions are presented separately.

Head movements for the different road-crossing decisions

Table 3 provides a comprehensive summary of the experimental trials, consisting of 800 trials in total, equally distributed between braking and non-braking scenarios. Pedestrians crossed the road in 461 trials, of which 79.83% stemmed from the braking conditions. In contrast, pedestrians refrained from crossing the road in 290 trials, with 97.59% of these instances occurring in the non-braking conditions. Pedestrians' head-turning metrics were subjected to analysis and comparison across different road-crossing decisions. Within the 12-second windows, the Mann-Whitney U test revealed a significant discrepancy in head-turning frequency between crossing and non-crossing pedestrians ($U(461,290) = 9.139*10^4$, $z = 9.137$, $p < .001$). The median head-turning frequency for the crossing and non-crossing incidents was 2 and 1, respectively, despite both of their mean values being very close to 0.9 during this time period.

Figure 6 presents the head-turning rate within the designated time window for the different road-crossing decisions, as indicated by the solid lines. The temporal point 0 marks the commencement of road-crossing, and the termination of the road-crossing task for non-crossing trials as this was when the second vehicle passed the location of the stationary pedestrian). The GEE test demonstrates a significant distinction in head movements between crossing and non-crossing trials ($Wald\ \chi^2(2) = 13.476$, $p < .001$), as well as across different time intervals ($Wald\ \chi^2(2) = 482.998$, $p < .001$). This disparity is illustrated in Figure 6, where pedestrians exhibited a significant increase in head-turning rate from time -2 s onwards, significantly surpassing their earlier head turnings. The GEE analysis also unveiled a significant interaction effect between road-crossing decisions and time intervals ($Wald\ \chi^2(2) = 41.056$, $p = .012$). Post-hoc analysis, with Bonferroni corrections, revealed that from 2 seconds prior to road-crossing decisions, the head-turning rate for crossing manoeuvres increased more rapidly and was significantly higher than that for non-crossing events, as depicted by the shaded area in Figure 6.

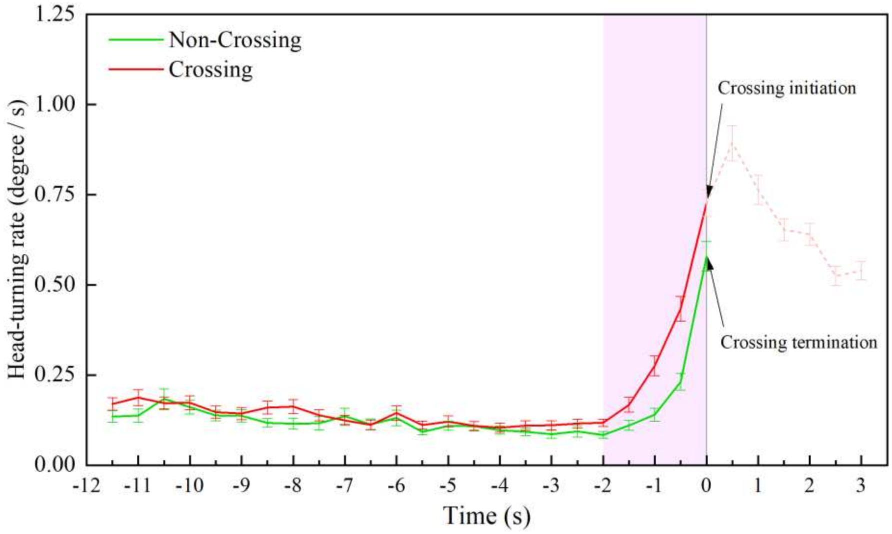

Figure 6. Head-turning rate of pedestrians under different road-crossing decisions. The error bar depicts standard error.

Head movements in braking conditions

In the braking conditions, regardless of driving mode or braking conditions, pedestrians completed an equal percentage of crossing (~92%) for the HDB, PDHB and PDSB trials ($\chi^2(2) = 3.80$, $p = .150$) (see Table 3). A Kruskal-Wallis H test was used to examine whether the different braking characteristics of the predefined and human-driven vehicles influenced pedestrians' head-turning frequency before and after their crossing initiation. There were no significant differences in head-turning frequency in response to the approaching HDB, PDSB, and PDHB, before crossing initiation ($H(2) = 1.084$, $p = .582$). However, after the pedestrians started to cross, there was a significant difference in head-turning frequency, between the three braking conditions ($H(2) = 13.318$, $p = .001$). Post-hoc analysis with Dunn's test showed that pedestrians' head-turning frequency in response to the PDSB was significantly lower than that of PDHB ($z(91) = 48.402$, $p < .001$) and HDB ($z(91) = 28.592$, $p = .014$), as shown in Figure 7.

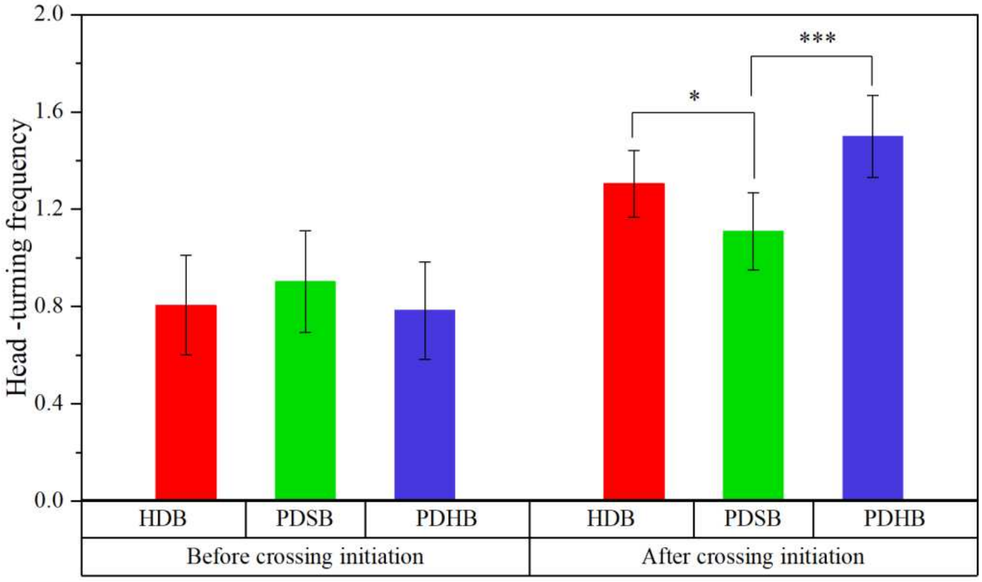

Figure 7. Head-turning frequency in braking conditions. The error bar depicts standard error. (* indicates $p < .05$, *** indicates $p < .001$)

A GEE analysis was used to check the effect of braking conditions on pedestrians' head-turning rate in the 15s window around their crossing initiation. Results showed that there was a main effect of time (*Wald* $\chi^2(24) = 2.935*10^3$, $p < .001$). The head-turning rate increased steadily from about 2 s before pedestrians' crossing initiation, reaching its peak value immediately after they commenced a crossing (see Figure 8). Post-hoc analysis, with Bonferroni corrections, showed that from around 0.5 s before the crossing initiation, pedestrians' head-turning rate was significantly higher than that of the previous waiting period, reaching its peak around 0.5 s after the crossing was initiated, and then steadily decreasing. There was no significant effect of braking conditions on head-turning rate (*Wald* $\chi^2(2) = 3.298$, $p = .192$). However, there was a significant interaction between time and braking conditions (*Wald* $\chi^2(28) = 1.740*10^{12}$, $p < .001$). Post-hoc analysis, with Bonferroni corrections, found that the head-turning rate was significantly higher when participants were crossing in response to the HDB, compared to the PDSB, at 0 s, 0.5 s, and 1 s after crossing initiation (see the shaded area in Figure 8).

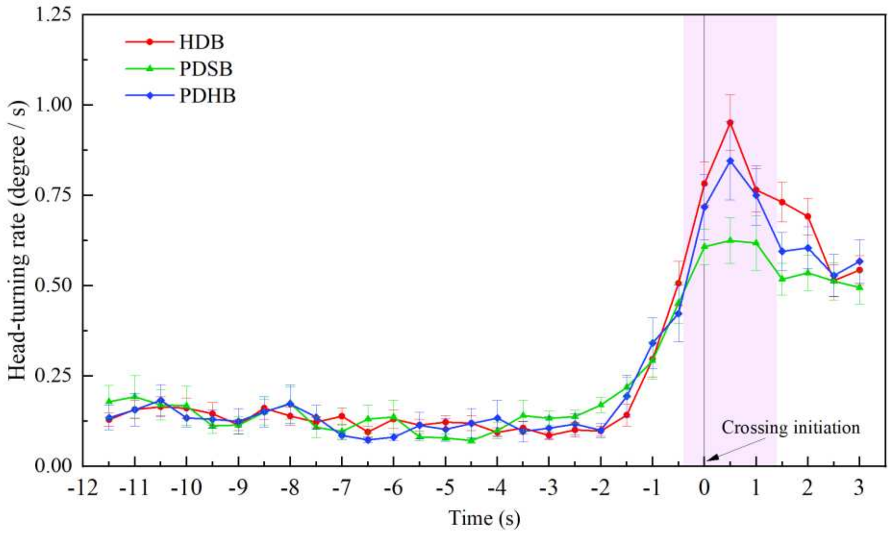

Figure 8. Head-turning rate of pedestrians in braking conditions. The error bar depicts standard error.

Taken together, the results from head-turning frequency and head-turning rate metrics show a consistent and complementary pattern. For all conditions, head-turning increased around 2 seconds before the crossing initiation, with no significant difference between the different driving or braking conditions. However, after pedestrians started crossing the road, there was a substantial increase in both head-turning frequency and head-turning rate. There was also a clear difference in head-turning behaviour during the crossings, in response to the different vehicle kinematics portrayed by the three conditions, with pedestrians displaying the lowest head-turning frequency, and head-turning rate in the PDSB condition, compared with the HDB and PDHB conditions. To understand this behaviour further, we provide information about kinematic states (including approaching speed and distance) of the manipulated vehicle at pedestrians' crossing initiation for each condition in Table 4.

Table 4. Kinematic state of 2nd vehicle at pedestrians' crossing initiation for each braking condition

Braking Mode	Pedestrians' CIT (s)	Distance to pedestrian (m)		Speed (mph)	
	M (SD)	M (SD)	Range	M (SD)	Range
HDB	4.33 (2.99)	-40.77 (23.46)	-104.06 ~ -3.15	9.08 (12.45)	0 ~ 30.12
PDSB	6.72 (4.22)	-20.66 (30.27)	-97.96 ~ -1.93	8.94 (13.51)	0 ~ 30.08
PDHB	5.58 (3.52)	-26.99 (25.86)	-96.89 ~ -10.83	8.86 (12.85)	0 ~ 30.11

Note: the minus sign before 'Distance to pedestrian' denotes that the vehicle is approaching the pedestrian from their right side.

This data shows that at pedestrians' crossing initiation, the average speed of the approaching vehicle was around 9 mph for the three braking conditions: HDB, PDSB, and PDHB. However, the average distance from the vehicle to the pedestrian's position varied substantially from ~21 m in PDSB to ~41 m in HDB. Moreover, in the HDB condition, most drivers started braking immediately (~60m) after they took over control of the vehicle, compared to the designated braking onset for PDSB and PDHB, which was at 40m to the pedestrians. Therefore, it seems that the distance from the vehicle to the pedestrian played a dominant role, not only in determining pedestrians' crossing initiation time but also in their head-turning behaviour. More specifically, a shorter distance from the vehicle to the pedestrian was related to less head-turning behaviour during the crossing, although this resulted in a later crossing (a larger CIT).

Head movements in non-braking conditions

Pedestrians crossed the road for nearly 30% and 20% of trials in the HDNB and PDNB conditions, respectively (see Table 3). This proportion of crossings for the non-braking conditions is much less than that for the braking conditions (92%). A Mann-Whitney U test was adopted to compare the effect of HDNB and PDNB on pedestrians' head-turning frequency in the predefined 15 s window. There was no significant difference in head-turning frequency in response to the different driving modes, either before ($U(55,38) = 1146$, $z = -.827$, $p = .408$), or after crossing initiation ($U(55,38) = 970$, $z = -.621$, $p = .535$)).

For the head-turning rate, the GEE did not yield a significant main effect of non-braking modes, or any interaction effect. However, there was a main effect of time on the head-turning angle ($Wald\ \chi^2(16) = 5.071*10^{12}$, p <.001). As shown in Figure 9, pedestrians started to show a larger and increasing head-turning rate for the last 1 s before their crossing initiation in the non-braking scenarios.

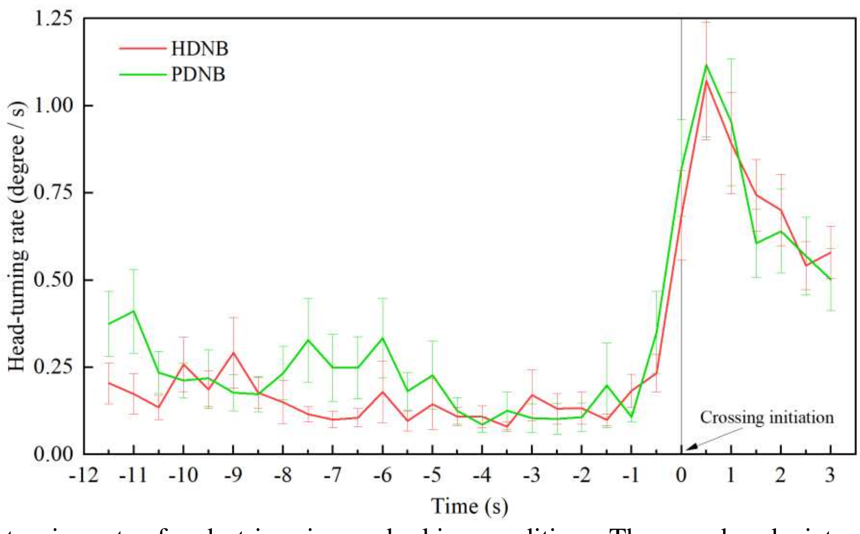

Figure 9. Head-turning rate of pedestrians in non-braking conditions. The error bar depicts standard error.

Overall, a significant increase in head-turning behaviour was observed just before, and particularly around the crossing initiation, for those pedestrians who commenced a crossing in the non-braking conditions. However, results showed no significant difference in head-turning frequency, or head-turning rate, between the HDNB and PDNB trials. This is likely because of the high similarity of kinematic features between the two non-braking conditions. The kinematic information for the manipulated and leading vehicles at the time of pedestrians' crossing initiation is provided in Table 5. As demonstrated by Table 5, while pedestrians were about to cross the road in non-braking conditions, the metrics, including the CIT and the speed and distance of the 1^{st} and 2^{nd} vehicle were very similar and comparable between HDNB and PDNB conditions. Therefore, for these two conditions, pedestrians initiated a road-crossing immediately (within approximately 1 s) after the 1^{st} vehicle had passed their standing location, when the 2^{nd} vehicle was about 70 m away. Thus, it seems that the observed head-turning behaviour was more related to tracking and checking the leading vehicle, to initiate an early and quick crossing, rather than focusing on the 2^{nd} approaching vehicle's behaviour.

Table 5. Kinematic state of 1^{st} and 2^{nd} vehicle at pedestrians' crossing initiation for each non-braking condition (M (SD))

Non-braking Mode	Pedestrians' CIT (s)	1^{st} vehicle (leading)		2^{nd} vehicle (manipulated)	
		Distance to pedestrian (m)	Speed (mph)	Distance to pedestrian (m)	Speed (mph)
HDNB	1.11 (1.60)	+10.34 (9.39)	29.82 (0.19)	-70.36 (22.74)	26.84 (8.30)
PDNB	0.62 (0.42)	+8.39 (5.59)	29.84 (0.17)	-70.40 (18.67)	29.62 (0.26)

Note: '-'/'+' before the value for Distance to the pedestrian denotes that the vehicle is on the right/left side of the pedestrian.

Finally, to understand the influence of vehicle yielding patterns on head-turning behaviour further, pedestrians' head-turning frequency for braking and non-braking conditions was compared using the Mann-Whitney U test. Head-turning frequency in the non-braking conditions was found to be significantly more frequent than in the braking conditions, both before ($U(368,93) = 14649.50$, $z = -2.306$, $p = .021$) and after the crossing initiation ($U(368,93) = 14383.50$, $z = -2.702$, $p = .007$). Furthermore, as illustrated from the head-turning rate plots in Figure 8 and Figure 9, in non-braking conditions, pedestrians produced later and higher head-turning behaviour while they were about to cross, compared with head movements in the braking conditions.

Discussion

The aim of this distributed simulation study was to investigate pedestrians' crossing decisions and head-turning patterns in response to different kinematics of approaching vehicles, at an un-signalised crossing location in VR. Pedestrians' head movements for different road-crossing decisions, and in response to different kinematic profiles were analysed, and compared.

Results indicated a significant difference in pedestrians' head-turning behaviour between crossing and non-crossing decisions. Pedestrians exhibited higher head-turning frequency and rate of head turns when they initiated a crossing, compared to trials that did not result in a crossing. This finding provides clear evidence that, for this type of scenario, pedestrians' head movements can serve as a valuable indicator for identifying road-crossing intentions. This result concurs with previous observation studies in this context (Hollands et al., 2002; Rasouli et al., 2018; Rehder et al., 2014). Our results also showed that the difference in head movement patterns for crossing trials was apparent 2 s before crossing initiations. This finding offers insights into behavioural explanations for studies that use head information as input features for pedestrians' intention recognition. For example, Varytimidis et al. (2018) reported that supplementation of head orientation on the basis of motion information decreased the estimation error rate from 60.5% to 25.3%. Cao et al. (2022) found that the incorporation of head movement feature advanced the prediction time from 0.13 s to 0.56 s before pedestrians' crossing initiation. Our results provide further insights into why this is the case, showing the exact head movements pedestrians engage in while making and enacting their crossing decisions. Therefore, with optimized algorithms and extended features, the incorporation of head movements information could benefit future AVs in earlier recognition of pedestrians' road-crossing intents.

For the braking conditions, results showed that from around 2 s before the pedestrians commenced a crossing, they increased their head-turning behaviour, which reached a peak value at the crossing initiation. This 'last moment check' behaviour has also been reported by other studies (Hassan et al., 2005; Tom & Granié, 2011), with Hassan et al. (2005) reporting an increase in the number of head turns in the last 4 s before a crossing initiation, and head-turning frequency being highest in the last 1 s. This difference in timing between our VR study and Hassan et al.'s (2015) data may be due to the different experimental setups, with our study involving a one-way single-lane road, compared to the real-world study used by

Hassan et al. (2005), which included one-way traffic across two lanes and incorporated more complex settings, such as intersections and roundabouts, and a higher volume of traffic. The length of our VR set up in the CAVE-based simulator may have also contributed to this difference in results.

Interestingly, despite the different yielding behaviours adopted in the three experimental conditions (HDB, PDHB, PDSB), there was no main effect of braking condition on pedestrians' head movements prior to a crossing. Instead, it would appear that the distance between the manipulated vehicle and the pedestrian was a dominant factor in influencing pedestrians' head-turning behaviour (see Table 4). This is in line with the finding from a number of previous real-world observation studies (Oxley et al., 2000; Zito et al., 2015). The largest CIT, shortest distance-gap, and least head-turning behaviour were observed in PDSB conditions, whilst the opposite was seen for the HDB conditions. The early crossers in the HDB condition turned their head more frequently to seek further information and check the environment, likely as a result of their quick and somewhat risky decisions, but perhaps also to ensure that vehicle would not start moving again. This is supported by the findings of Kalantarov et al. (2018) and (Yang et al., 2024), who found pedestrians exhibiting more head and body movements, during less safe crossing opportunities, such as for earlier crossing events . By contrast, for the PDSB conditions, the late crossers who waited for a longer time to begin crossing, and crossed when the vehicle was closer, showed less head turning behaviour, in line with a more confident crossing, perhaps because it was clear that the approaching vehicle had definitely yielded for them. This inverse relationship between head-turning behaviour and CIT was particularly strong in the non-braking trials, with very short CIT of around 1 s associated with a high frequency of head turns. Thes results show clearly that a high head-turning frequency is likely to lead to an imminent road crossing, particularly for those earlier crossers who base their decisions mainly on crossing immediately after the passing of the first approaching (lead) vehicle in this study, rather than examining the behaviour of the second approaching vehicle. Future AVs can use this sudden increase in head movement as a cue for yielding to crossing pedestrians.

Finally, a post-experiment interview with the pedestrian participants (not reported here due to space constraints), found that they could not distinguish between human-driven and predefined driving vehicles, if based solely on the yielding profiles adopted. Thus, it would appear that pedestrian head movements in relation to crossing decisions are likely to remain constant when interacting with AVs in future mixed traffic scenarios (at least with a similar parameter setup to the current study). Thus, the incorporation of current patterns of head movement data into AV prediction models for pedestrian crossing is likely to be successful. However, more research is needed to understand if varying the appearance of the AV compared to conventional vehicles would lead to a change in these behaviours.

Limitations and Future Research

The current study has two major limitations. First, this study involved a relatively simple, fixed traffic scenario involving an un-signalised, single-lane, urban road. This may mitigate pedestrians' perception of traffic risk and reduce their use of head movements for information-seeking purposes, particularly when they were required to complete a series of road-crossing tasks from a fixed point, involving similar scenarios across trials. Second, this study controlled explicit cues of the manipulated vehicles to spotlight the influence of implicit cues. However, future AVs may differ from conventional vehicles in exterior appearance, for example, with labels marking their AV identity, or by including eHMIs to display their intention. This may influence pedestrians' road-crossing decisions or behavioural patterns, particularly when they have little prior experience with AVs.

Based on the above limitations, future work should use more complex traffic scenarios, such as two-way traffic, crossroads, and multiple lanes, to further investigate the effect of these on pedestrian crossing behaviour and head movements. In addition, understanding how explicit cues that distinguish AVs from conventional cars, or indeed how externally presented messages affect this behaviour should be considered. Finally, understanding if this behaviour is also observed in other pedestrian groups, such as young adults or older pedestrians will be relevant to ensure a more inclusive development of future algorithms for AVs in this context.

Conclusions

The main goal of the current study was to determine pedestrians' road-crossing decisions and head movement patterns in response to vehicles with predefined yielding patterns and decelerating profiles, compared to human-driven vehicles, using a CAVE-based pedestrian simulator linked to a desktop driving simulator. Results showed that pedestrians' head movements can be a valid indicator of their road-crossing intention, with a significant increase in head-turns during the last 2 seconds before a crossing. This information could be beneficial for the early recognition of pedestrians' road-crossing intention, in future AVs, following more data with a wider range of scenarios and pedestrians. The comparable road-crossing percentage and head-turning patterns of pedestrians in response to the predefined and human-driven vehicles (for both braking and non-braking conditions) before a crossing initiation was made, demonstrates the significance of existing research on pedestrians' head movements and intention recognition for future AV-pedestrian interaction. Finally, the position of the yielding vehicle exhibited quite different head movement patterns when a crossing was made, information which can be used to infer pedestrians' uncertainty, information gathering, and risk taking behaviour, all of which can be used for the design of more informative kinematic behaviour of future AVs interacting in such mixed traffic urban settings.

Author contributions

Conceptualization: W.L., Y.M., R.M., and N.M.; Data curation: W.L., C.U., and J.P.; Formal analysis: W.L., Y.M., R.G., and N.M.; Funding acquisition: N.M.; Methodology: W.L., Y.M., C.U., R.G., R.R., and N.M.; Project administration: N.M.; Resources: N.M.; Supervision: N.M.; Roles/Writing - original draft: W.L.; Writing - review & editing: Y.M., R.M., and N.M.

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Declarations of interest

The authors declare no conflict of interest.

References

Ackermann, C., Beggiato, M., Bluhm, L. F., Löw, A., & Krems, J. F. (2019). Deceleration parameters and their applicability as informal communication signal between pedestrians and automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*, 757–768. https://doi.org/10.1016/j.trf.2019.03.006

Avineri, E., Shinar, D., & Susilo, Y. O. (2012). Pedestrians' behaviour in cross walks: The effects of fear of falling and age. *Accident Analysis and Prevention*, *44*(1), 30–34. https://doi.org/10.1016/j.aap.2010.11.028

Cao, H., Huijie, S., Xiaolin, S., Mingjun, L., Dai, H., & Huang, Z. (2022). Prediction of Pedestrian Intention and

Trajectory Based on Multi-feature Fusion. *China Journal of Highway and Transport*, *35*(10), 308–318. https://doi.org/10.19721/j.cnki.1001-7372.2022.10.027

Chen, W., Zhuang, X., Cui, Z., & Ma, G. (2019). Drivers' recognition of pedestrian road-crossing intentions: Performance and process. *Transportation Research Part F: Traffic Psychology and Behaviour*, *64*, 552–564. https://doi.org/10.1016/j.trf.2019.07.004

Clamann, M. (2017). Evaluation of Vehicle-to-Pedestrian Communication Displays for Autonomous Vehicles. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *57*(3), 407–434.

Crowley-Koch, B. J., Van Houten, R., & Lim, E. (2011). Effects of pedestrian prompts on motorist yielding at crosswalks. *Journal of Applied Behavior Analysis*, *44*(1), 121–126.

de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. (2019). External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. *Human Factors*, *61*(8), 1353–1370. https://doi.org/10.1177/0018720819836343

Dey, D., Martens, M., Eggen, B., & Terken, J. (2019). Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, *65*, 191–205. https://doi.org/10.1016/j.trf.2019.07.027

Dey, D., Matviienko, A., Berger, M., Pfleging, B., Martens, M., & Terken, J. (2020). Communicating the Intention of an Automated Vehicle to Pedestrians: the Contributions of eHMI and Vehicle Behavior. *Information Technology*, *63*(2), 123–141. https://doi.org/10.1515/ITIT-2020-0025

Dey, D., & Terken, J. (2017). Pedestrian interaction with vehicles: Roles of explicit and implicit communication. *AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings*, *August 2018*, 109–113. https://doi.org/10.1145/3122986.3123009

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Geruschat, D. R., Hassan, S. E., & Turano, K. A. (2003). Gaze behavior while crossing complex intersections. *Optometry and Vision Science*, *80*(7), 515–528. https://doi.org/10.1097/00006324-200307000-00013

Guéguen, N., Eyssartier, C., & Meineri, S. (2016). A pedestrian's smile and drivers' behavior: When a smile increases careful driving. *Journal of Safety Research*, *56*, 83–88. https://doi.org/10.1016/j.jsr.2015.12.005

Guéguen, N., Meineri, S., & Eyssartier, C. (2015). A pedestrian's stare and drivers' stopping behavior: A field experiment at the pedestrian crossing. *Safety Science*, *75*, 87–89. https://doi.org/10.1016/j.ssci.2015.01.018

Hassan, S. E., Geruschat, D. R., & Turano, K. A. (2005). Head movements while crossing streets: Effect of vision impairment. *Optometry and Vision Science*, *82*(1), 18–26. https://doi.org/10.1097/01.OPX.0000150186.96888.E8

Holländer, K., Colley, A., Mai, C., Häkkilä, J., Alt, F., & Pfleging, B. (2019). Investigating the influence of external car displays on pedestrians' crossing behavior in virtual reality. *Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services*, 1–11. https://doi.org/10.1145/3338286.3340138

Holländer, K., Wintersberger, P., & Butz, A. (2019). Overtrust in External Cues of Automated Vehicles : An Experimental Investigation. *11th International Conference on Automotive User Interfaces and Interactive*

Vehicular Applications (AutomotiveUI '19), 211–221. https://doi.org/10.1145/3342197.3344528

Hollands, M., Patla, A., & Vickers, J. (2002). "Look where you're going!": Gaze behaviour associated with maintaining and changing the direction of locomotion. *Experimental Brain Research*, *143*(2), 221–230. https://doi.org/10.1007/s00221-001-0983-7

Kalantarov, S., Riemer, R., & Oron-Gilad, T. (2018). Pedestrians' road crossing decisions and body parts' movements. *Transportation Research Part F: Traffic Psychology and Behaviour*, *53*, 155–171. https://doi.org/10.1016/j.trf.2017.09.012

Koehler, S., Goldhammer, M., Bauer, S., Zecha, S., Doll, K., Brunsmann, U., & Dietmayer, K. (2013). Stationary detection of the pedestrian?s intention at intersections. *IEEE Intelligent Transportation Systems Magazine*, *5*(4), 87–99. https://doi.org/10.1109/MITS.2013.2276939

Kooij, J. F. P., Schneider, N., Flohr, F., & Gavrila, D. M. (2014). Context-Based Pedestrian Path Prediction. *European Conference on Computer Vision*, 618–633. https://doi.org/10.1007/978-3-319-10599-4_40

Lee, Y. M., Madigan, R., Giles, O., Garach-Morcillo, L., & Markkula, G. (2020). Road users rarely use explicit communication when interacting in today ' s traffic : implications for automated vehicles. *Cognition, Technology & Work*, *23*(2), 367–380. https://doi.org/10.1007/s10111-020-00635-y

Lee, Y. M., Madigan, R., Uzondu, C., Garcia, J., Romano, R., Markkula, G., & Merat, N. (2022). Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrian' crossing behavior. *Journal of Safety Research*, *80*(December), 270–280. https://doi.org/10.1016/j.jsr.2021.12.010

Madigan, R., Mun Lee, Y., Lyu, W., Horn, S., Garcia de Pedro, J., & Merat, N. (2023). Pedestrian interactions with automated vehicles: Does the presence of a zebra crossing affect how eHMIs and movement patterns are interpreted? *Transportation Research Part F: Traffic Psychology and Behaviour*, *98*(July 2022), 170–185. https://doi.org/10.1016/j.trf.2023.09.003

Mahadevan, K., Somanath, S., & Sharlin, E. (2018). Can Interfaces Facilitate Communication in Autonomous Vehicle-Pedestrian Interaction? *13th Annual ACM/IEEE International Conference on Human Robot Interaction, HRI 2018*, 309–310. https://doi.org/10.1145/3173386.3176909

Markkula, G., Madigan, R., Nathanael, D., Portouli, E., Lee, Y. M., Dietrich, A., Billington, J., Schieben, A., & Merat, N. (2020). Defining interactions: a conceptual framework for understanding interactive behaviour in human and automated road traffic. *Theoretical Issues in Ergonomics Science*, *21*(6), 728–752. https://doi.org/10.1080/1463922X.2020.1736686

Milakis, D., Van Arem, B., & Van Wee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future research. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, *21*(4), 324–348. https://doi.org/10.1080/15472450.2017.1291351

Moore, D., Currano, R., G. Ella Strack, & Sirkin, D. (2019). The Case for Implicit External Human-Machine Interfaces for Autonomous Vehicles. *AutomotiveUI '19: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 295–307. https://dl.acm.org/doi/abs/10.1145/3342197.3345320

Oxley, J., Fildes, B. N., & Ihsen, E. (2000). Older pedestrian safety: The role of perceptual and cognitive factors and the ability to compensate for age-related changes. *Proceedings of the Australasian Road Safety Research, Policing and Education Conference*, *4*, 209–215.

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2017). Agreeing To Cross : How Drivers and Pedestrians

Communicate. *2017 IEEE Intelligent Vehicles Symposium (IV)*, *Iv*, 264–269. https://doi.org/10.48550/arXiv.1702.03555

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2018). Understanding Pedestrian Behavior in Complex Traffic Scenes. *IEEE Transactions on Intelligent Vehicles*, *3*(1), 61–70. https://doi.org/10.1109/TIV.2017.2788193

Rasouli, A., & Tsotsos, J. K. (2020). Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems*, *21*(3), 900–918. https://doi.org/10.1109/TITS.2019.2901817

Razmi Rad, S., Homem de Almeida Correia, G., & Hagenzieker, M. (2020). Pedestrians' road crossing behaviour in front of automated vehicles: Results from a pedestrian simulation experiment using agent-based modelling. *Transportation Research Part F: Traffic Psychology and Behaviour*, *69*, 101–119. https://doi.org/10.1016/j.trf.2020.01.014

Rehder, E., Kloeden, H., & Stiller, C. (2014). Head detection and orientation estimation for pedestrian safety. *2014 17th IEEE International Conference on Intelligent Transportation Systems, ITSC 2014*, 2292–2297. https://doi.org/10.1109/ITSC.2014.6958057

Rhee, Y.-E., Ryu, J.-K., & Hahn, S. (2019). *Gentlemen on the Road: Understanding How Pedestrians Interpret Yielding Behavior of Autonomous Vehicles using Machine Learning*. ArXiv. https://arxiv.org/abs/2005.07872

Rodríguez Palmeiro, A., van der Kint, S., Vissers, L., Farah, H., de Winter, J. C. F., & Hagenzieker, M. (2018). Interaction between pedestrians and automated vehicles: A Wizard of Oz experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 1005–1020. https://doi.org/10.1016/j.trf.2018.07.020

Rothenbucher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *25th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2016*, 795–802. https://doi.org/10.1109/ROMAN.2016.7745210

SAE International. (2021). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. SAE International.

Schieben, A., Wilbrink, M., Kettwich, C., Dodiya, J., Sorokin, L., Merat, N., Dietrich, A., Bengler, K., & Kaup, M. (2019). Testing external HMI designs for automated vehicles – An overview on user study results from the EU project interACT. *19 Tagung Automatisiertes Fahren*, 1–7.

Schmidt, S., & Faerber, B. (2009). Pedestrians at the kerb–Recognising the action intentions of humans. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(4), 300–310. https://doi.org/10.1016/j.trf.2009.02.003

Singh, B., Kumar, M., & Ubhi, J. S. (2019). Special Pedestrian and Head Pose Detection for Autonomous Vehicles. *Advances in Signal Processing and Communication*, 175–186. https://doi.org/10.1007/978-981-13-2553-3

Sucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*, *102*, 41–50. https://doi.org/10.1016/j.aap.2017.02.018

Taima, M., & Daimon, T. (2023). Differences in Pedestrian Behavior at Crosswalk between Communicating with Conventional Vehicle and Automated Vehicle in Real Traffic Environment. *Safety*, *9*(1), 2. https://doi.org/10.3390/safety9010002

Tom, A., & Granié, M. A. (2011). Gender differences in pedestrian rule compliance and visual search at signalized and unsignalized crossroads. *Accident Analysis and Prevention*, *43*(5), 1794–1801. https://doi.org/10.1016/j.aap.2011.04.012

Varytimidis, D., Alonso-Fernandez, F., Duran, B., & Englund, C. (2018). Action and Intention Recognition of Pedestrians in Urban Traffic. *Proceedings - 14th International Conference on Signal Image Technology and Internet Based Systems, SITIS 2018*, 676–682. https://doi.org/10.1109/SITIS.2018.00109

Volz, B., Mielenz, H., Gilitschenski, I., Siegwart, R., & Nieto, J. (2019). Inferring Pedestrian Motions at Urban Crosswalks. *IEEE Transactions on Intelligent Transportation Systems*, *20*(2), 544–555. https://doi.org/10.1109/TITS.2018.2827956

Yang, Y., Lee, Y. M., Madigan, R., Solernou, A., & Merat, N. (2024). *Interpreting pedestrians' head movements when encountering automated vehicles at a virtual crossroad*. https://doi.org/10.31234/osf.io/n98v2

Zhuang, X., & Wu, C. (2014). Pedestrian gestures increase driver yielding at uncontrolled mid-block road crossings. *Accident Analysis & Prevention*, *70*, 235–244. https://doi.org/10.1016/j.aap.2013.12.015

Zito, G. A., Cazzoli, D., Scheffler, L., Jäger, M., Müri, R. M., Mosimann, U. P., Nyffeler, T., Mast, F. W., & Nef, T. (2015). Street crossing behavior in younger and older pedestrians: An eye- and head-tracking study Psychology, psychiatry and quality of life. *BMC Geriatrics*, *15*(1), 1–10. https://doi.org/10.1186/s12877-015-0175-0

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