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Deceleration parameters as implicit communication signals for pedestrians' crossing decisions and estimations of automated vehicle behaviour

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ABSTRACT

Society greatly expects the widespread deployment of automated vehicles (AVs). However, the absence of a driver role results in unresolved communication issues between pedestrians and AVs. Research has shown the crucial role of implicit communication signals in this context. Nonetheless, it remains unclear how pedestrians subjectively estimate vehicle behaviour and whether they incorporate these estimations as part of their crossing decisions. For the first time, this study explores the impact of implicit communication signals on pedestrians' subjective estimations of approaching vehicle behaviour across a wide range of experimental traffic scenarios and on their crossing decisions in the same scenarios through a comprehensive analysis. Two simulator tasks, namely a natural road crossing task and a vehicle behaviour estimation task, were designed with controlled time to collision, vehicle speed, and deceleration behaviour. A novel finding is that the correlation between crossing decisions and vehicle behaviour estimations depends on the traffic scenario. Pedestrians' recognition of different deceleration behaviour aligned with their crossing decisions, supporting the notion that they actively estimate vehicle behaviour as part of their decision-making process. However, if the traffic gap was long enough, the effects of vehicle speed were the opposite between crossing decisions and estimations, suggesting that vehicle behaviour estimation may not directly impact crossing decisions when the time gap to the vehicle is large. We also found that pedestrians crossed the street earlier and estimated yielding behaviour more accurately in early-onset braking scenarios than in late-onset braking scenarios. Interestingly, vehicle speed significantly affected pedestrians' estimations, with pedestrians tending to perceive low vehicle speed as yielding behaviour regardless of whether the vehicle yielded. Finally, we demonstrated that visual cue $\dot{\tau}$ is a practical indicator for controlling the vehicle deceleration evidence in the experiment. In conclusion, these findings reveal in detail the role of deceleration parameters as implicit communication signals between pedestrians and AVs, with implications for road crossing safety and the development of AVs.

1. Introduction

Automated vehicles (AVs), equipped with sensors, cameras and radars, use intelligent detection and motion planning algorithms to mitigate human operational errors and have become one of the most promising solutions to current traffic issues (El Hamdani et al., 2020). However, the absence of a driver or the driver's inattention to driving in AVs may significantly alter the conventional communication methods between vehicles and vulnerable road users (VRUs). For example, communication methods like eye contact or hand gestures may become obsolete, and pedestrians may have to rely solely on the movements of vehicles to assess the situation (de Clercq et al., 2019). Recent studies revealed that communication breakdowns between AVs and VRUs, such as pedestrians, could lead to traffic dilemmas and additional safety concerns (El Hamdani et al., 2020; Millard-Ball, 2018). This issue has therefore prompted extensive research across multiple fields, including road user behaviour research (Lee et al., 2022), computational

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modelling (Pekkanen et al., 2022), external human–machine interface research (eHMI) (de Clercq et al., 2019) and more.

1.1. Explicit and implicit communication signals

When pedestrians communicate with vehicles, the signals can be categorised as explicit or implicit. Explicit signals usually refer to road user behaviour that provides information to other road users without affecting the communicator's own movement or perception. In contrast, implicit signals refer to road user behaviour that affects the communicator's own movement but can also be interpreted as cues about their intention or movement by other road users (Markkula et al., 2020). In conventional traffic scenarios, eye contact, hand gestures, and light signals are the most commonly observed explicit signals. There is strong evidence supporting the role of eye contact in pedestrian–vehicle interactions (Markkula et al., 2020; Nathanael et al., 2018; Rasouli and Tsotsos, 2019; AlAdawy et al., 2019). Pedestrians seek eye contact to ensure that they have been seen by drivers or to request the right of way, which may increase their perceived safety (Onkhar et al., 2022). Hand gestures and light signals are relatively less likely to be observed compared to eye contact (Lee et al., 2021; Nathanael et al., 2018). In future traffic scenarios that involve AVs, conventional explicit signals are compromised, and eHMIs may act as a remedy to make up for missing communications and help reduce uncertainty in pedestrian behaviour. As road traffic can be viewed as a social system where continuous reciprocal communication between road users is necessary (Ackermann et al., 2019), the smooth integration of AVs in society requires them to clearly signal their intentions and movements to all other road users, making eHMIs critical in improving social acceptance of AVs (Carmona et al., 2021). Researchers proposed different eHMI prototypes to convey explicit signals to pedestrians, including textual messages (Nissan, 2015), light signals (Lee et al., 2022), anthropomorphic symbols (Semcon, 2016), and more. In addition to these AV-based eHMIs, recent studies also explored the effectiveness of infrastructure-based eHMIs, such as flashing in-curb LEDs and beacons, which could encourage drivers to decelerate (Lantieri et al., 2021; Lingam et al., 2023).

However, different opinions exist regarding the effectiveness of explicit communication and eHMIs. Firstly, the reliability of eHMIs was scrutinised due to their susceptibility to weather conditions (Kooijman et al., 2019), light conditions (Rasouli and Tsotsos, 2019), and traffic situations (Dey et al., 2021). In addition, studies suggested that pedestrians rarely communicate through explicit signals in their daily lives, preferring implicit signals (Dey and Terken, 2017; Lee et al., 2021). The presence of explicit signals might not significantly improve the quality of pedestrian crossing behaviour, as reasonable implicit signals were sufficient for pedestrians to interact safely with Autonomous Vehicles (AVs) (Moore et al., 2019; Palmeiro et al., 2018; Sripada et al., 2021). Furthermore, recent studies demonstrated that the impact of eHMIs on pedestrians was itself influenced by implicit signals, such as vehicle deceleration and distance (de Clercq et al., 2019; Dey et al., 2021).

Implicit signals are generally considered more reliable than explicit ones since they are directly related to the vehicle's movements and intentions. Pedestrian road-crossing behaviour in road-crossing scenarios is influenced by various implicit signals depending on traffic scenarios. At uncontrolled crossings, pedestrian crossing behaviour is typically influenced by driver/AV adjustments to vehicle kinematics, such as speed, distance, and time to collision (TTC) (Tian et al., 2022a). For instance, some drivers may accelerate to signal that they have the right of way and intend to go first (Rasouli et al., 2018).

In most cases, drivers/AVs can reduce their speed or stop the vehicle to give way to pedestrians (Sucha et al., 2017; Ghasemi et al., 2022). Studies showed that the deceleration behaviour of drivers, as a critical implicit signal, significantly affected pedestrian behaviour (Ackermann et al., 2019; de Clercq et al., 2019; Lee et al., 2022). Pedestrians required less time to understand the behaviour of an approaching vehicle when the driver braked early and lightly and pitched strongly (Dietrich et al., 2019; Ackermann et al., 2019). According to Zimmermann and Wettach (2017), vehicle deceleration behaviour was correlated with pedestrians' emotions and affected their decisions. Pedestrians were likely to feel comfortable and initiated crossing quickly when approaching vehicles slowed down early and braked lightly. Conversely, late and harsh braking led to pedestrian avoidance behaviour (Dey et al., 2021; Risto et al., 2017). In addition, shortening the lateral distance to pedestrians while yielding to them helped them understand the vehicle's yielding behaviour (Sripada et al., 2021).

1.2. Visual cues in pedestrian-vehicle interactions

Until now, all the above-mentioned findings have supported the crucial role of implicit signals. However, from a more general and psychological perspective, research suggested that humans might not base their crossing decisions on direct estimation of absolute speed, TTC, distance, or deceleration rates (Lee et al., 2019; Petzoldt, 2014; Sun et al., 2015). Instead, pedestrians might estimate the movement of approaching vehicles from visual cues such as visual angle, its change rate, and more (DeLucia, 2015; Lee, 1976). These visual cues, based on optical flow field theory, provided a more realistic description of perceived collision risk (DeLucia, 2015; Lee, 1976). Specifically, the visual angle represents the image size of objects on the observer's retina, while its change rate describes the expansion rate of the image, which is linked to the perception of approaching objects. It has been found that pedestrian crossing behaviour is strongly correlated to the change rate of visual angle in scenarios where vehicles do not yield to pedestrians (Tian et al., 2022a). Moreover, τ, the ratio of the visual angle to the change rate of visual angle, specifies the TTC to approaching vehicles (Lee, 1976). If the change rate of τ is greater than -0.5, it means that the deceleration rate of the approaching object is sufficient to stop it in front of the observer, avoiding a collision event (Lee, 1976; Bardy and Warren, 1997). A detailed demonstration of visual cues in crossing scenarios is in Appendix A. Based on the above discussion, it would be valuable to investigate the correlation between visual cues and pedestrian crossing decisions.

1.3. Research gaps and questions

Understanding how pedestrians communicate with vehicles has significant implications for traffic safety and the development of AVs. The literature reviewed provides strong evidence to support the crucial role of implicit signals in pedestrian–AV interactions. Although previous studies have assumed that pedestrians recognise the intentions of approaching drivers/AVs based on the vehicle's behaviour, direct research on pedestrians' estimation of vehicle behaviour is limited (Predhumeau et al., 2021; Rasouli and Tsotsos, 2019). For example, while studies such as Sun et al. (2015) measured pedestrians' estimation of vehicle stopping distance and Ackermann et al. (2019) studied pedestrians' reaction time to detect the deceleration behaviour of an approaching vehicle, these measures were limited and did not provide detailed quantitative indications of pedestrian estimation of vehicle behaviour, such as the pattern changes during vehicle approach. Therefore, there is currently a lack of structured research on the aspects of approaching vehicle behaviour that determine how pedestrians estimate vehicle intentions and how the estimation changes over time. Additionally, it has not been clearly demonstrated that pedestrians incorporate subjective estimations of driver/AV intentions into their crossing decisions. In principle, pedestrians may directly rely on the momentary perceived collision risk indicated by visual cues, which could trigger crossing decisions without inferring vehicle intentions. Although Pekkanen et al. (2022) provided some model-based evidence supporting a separate process of behaviour estimation by pedestrians but did not collect any subjective estimation data. To the authors' knowledge, no previous study has collected both subjective estimation and objective crossing

Fig. 1. Apparatus and experimental environment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

data from pedestrians in the same scenarios to permit a comparison between the two. Given these research gaps, this study proposed two research questions:

- How do implicit signals of approaching vehicles affect the pedestrian estimation of vehicle behaviour and road crossing decisions?
- What is the relationship between pedestrians' subjective estimations of approaching vehicle behaviour and road crossing decisions?

2. Experiment

2.1. Participants

A simulated experiment was conducted to investigate the research questions, with the approval of the Ethics Committee of the University of Leeds (No. LTTRAN-145). Thirty healthy adults (17 males and 13 females) aged between 20 and 67 (M = 30.73, SD = 8.63) were recruited from the University of Leeds Virtuocity participant pool. All participants confirmed that they did not have any serious mobility issues or medical conditions such as epilepsy. In addition, the participants were required to have a normal or corrected-to-normal vision to ensure that they could accurately perceive traffic scenarios. Participants were also required to have resided in the UK within the last 12 months because their experience of road traffic could influence their road crossing behaviour. Prior to participation, participants provided written informed consent for procedures. Following participation, they received £15 as compensation for their time.

2.2. Apparatus

The Highly Immersive Kinematic Experimental Research (HIKER) lab at the University of Leeds was used to conduct the experiment. This pedestrian simulator is equipped with a CAVE-based simulated environment consisting of three glass wall projections and a floor projection, as illustrated in Fig. 1. A 9 m × 4 m walking space is provided for participants to move in the simulator. The scenario is projected by eight 4k projectors at a frequency of 120 Hz from behind the glass walls or above the floor. Tracking glasses on the participant's head is used to monitor the participant's head position, which enables the system to adjust the image to correspond to the participant's actual viewpoint. The virtual environment is established using Unity3D software, and the internal code automatically records the kinematics of vehicles and participants, including speed, position, and other parameters, at each time step.

2.3. Environment and traffic

The virtual road environment was a residential block in daylight with a 4.2 m wide one-lane road and an unmarked pedestrian crossing, as depicted in Fig. 1. A blue sedan automated vehicle was driven in the middle of the lane without a driver. Several variables of the approaching vehicle were varied in the traffic scenario, including its deceleration behaviour, initial TTC, and initial speed. Specifically, the vehicle approached the pedestrian with two types of deceleration behaviour (deceleration and mixed) and a constant driving behaviour, as well as three different initial speeds (25, 40, and 55 km/h) and two different initial TTCs (3 and 6 s). The driving behaviour was designed as follows:

- *Deceleration*: The vehicle decelerated at a constant deceleration rate from the beginning of the scenario until it stopped 2.5 m away from the participant. The detailed parameters of this driving behaviour are in Table 1.
- *Mixed*: Previous studies indicated that late-onset braking manoeuvre could negatively impact pedestrians, leading to a decreased willingness to cross (Dey et al., 2021). However, less is known about how this braking behaviour affects pedestrian crossing decisions and estimations. To investigate this, we introduced a mixed condition that included both constant speed and deceleration, serving as a comparison to the pure deceleration condition. In the mixed scenario, the vehicle maintained a constant speed for a period before slowing down and stopping 2.5 m from the participant. This condition was considered a late-onset braking behaviour compared to the deceleration condition. To ensure that the deceleration rate for each condition was greater than the corresponding condition in the deceleration condition, we applied a constant speed travel time of 1.5 s for 3 s initial TTC conditions and 3.4 s for 6 s initial TTC conditions, as presented in Table 1.
- *Constant speed*: The constant speed scenario was used as a baseline, where the vehicle maintained a constant speed throughout the scenario duration, as shown in Table 1.

2.4. Tasks and procedures

In this study, participants completed two tasks: a natural road crossing task and a vehicle behaviour estimation task.

For task one, participants were informed: "*If you decide to cross, please walk naturally as you would do in everyday life and stop before that wall. If you decide not to cross, just wait for the vehicle to pass*". Initially, they stood at a marked starting point located 57 cm from the edge of the pavement. To prevent obtaining traffic information prior to the start of the trial, a white rectangle obscured the road environment on their right-hand side (Fig. 2A). They were then presented with a message on a screen in front of them, which read, "*Please Look Here. Keep Looking*" (Fig. 2A). The message disappeared after looking at it for 1 s, at which point they were instructed to turn their heads towards the right to begin the trial. As they turned his/her head, the traffic scenario started, and the white rectangle was removed (Fig. 2B1). During the scenario, participants decided whether or not to cross (Fig. 2C1). If they chose to cross, the trial ended when they reached the opposite side of the road. Alternatively, if they rejected the crossing opportunity, the trial ended when the vehicle had passed. The first task comprised a practice session and an experimental session. The practice session consisted of 10 trials to familiarise participants with the task. The experimental session involved 18 experimental conditions (3 Behaviour × 2 TTCs × 3 Speeds), and each repeated once. This total of 36 trials was presented in a randomised order, different for each participant. Therefore, a total of 1080 trials of data were collected. Following the completion of the first task, participants were given a 10-minute break before beginning the second experimental task.

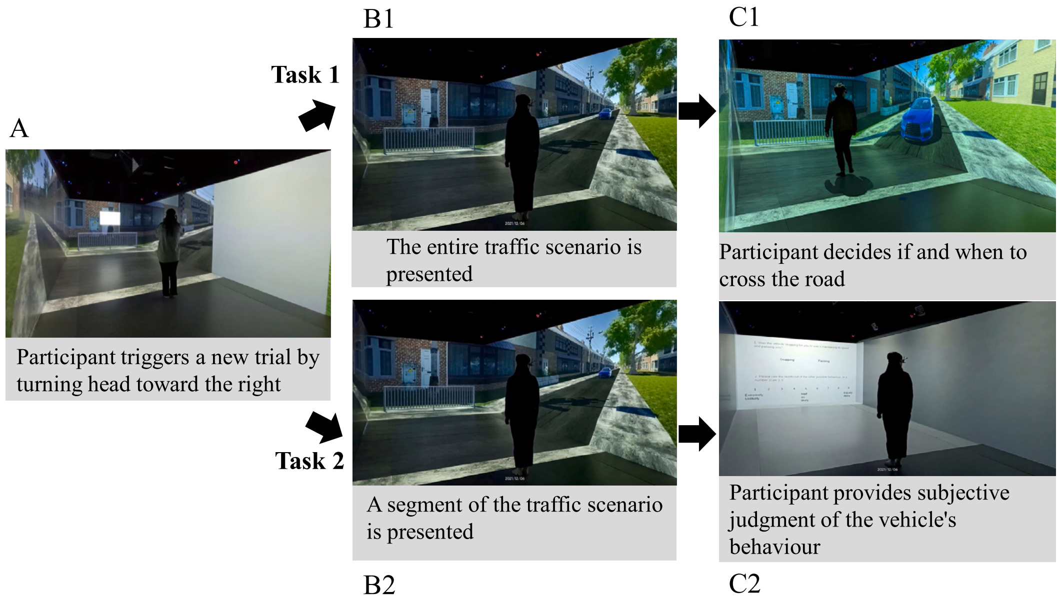

Fig. 2. Experimental tasks and procedures.

Table 1
Parameters of traffic scenarios.

Behaviour	Initial TTC (s)	Initial speed (km/h)	Initial distance to pedestrian (m)	Decelerationrate (m/s^2)	Constant speed duration (s)
Deceleration (Early-onset braking)	3	25	20.75	−1.32	n/a
		40	33.21	−2.00	
		55	45.67	−2.69	
	6	25	41.61	−0.62	
		40	66.58	−0.96	
		55	91.55	−1.31	
Mixed (late-onset braking)	3	25	20.75	−3.05	1.5
		40	33.21	−4.36	
		55	45.67	−5.72	
	6	25	41.61	−1.55	3.4
		40	66.58	−2.34	
		55	91.55	−3.14	
Constant speed (Non-yielding)	3	25	20.75	n/a	3
		40	33.21		3
		55	45.67		3
	6	25	41.61		6
		40	66.58		6
		55	91.55		6

For task two, participants watched a segment of a traffic scenario (Fig. 2B2) and estimated whether the vehicle was giving way or maintaining a constant speed and passing them. Their subjective estimations were collected via a questionnaire consisting of two questions, namely "*Was the vehicle stopping for you, or was it maintaining its speed and passing you?*" and "*How confident are you in your previous answer?*". Participants answered either "stopping" or "passing" for the first question and selected their confidence level on a scale of 1 to 9 (1 being not confident at all and 9 being totally confident) for the second question. This paper analysed only data from the first question.

In the second task, participants were required to observe traffic scenarios and answer questions without moving from their position. Each trial began with the participants standing at the marked starting point, as in the first task. The traffic scenario was triggered in the same way as in the first task, after which a segment of the scenario was presented (Fig. 2B2). Once the segment ended, the entire environment was obscured, and the participants were presented with a questionnaire on the screen to answer (Fig. 2C2).

The scenarios (i.e., deceleration and mixed) were divided into segments based on different deceleration evidence intensities of the approaching vehicle to acquire participants' estimations. Specifically, each of the 12 traffic scenarios was clipped at specific timestamps corresponding to when the vehicle was at four different distances from the participants. The purpose of this manipulation was to include no or subtle vehicle deceleration cues in the first segment of the traffic scenario ($-1 \le \dot{\tau} \le -0.36$), with increasingly clear yielding evidence in the second and third segments ($\dot{\tau}$ was belonged to $[-0.36, -0.16]$ and $[-0.16, 0.99]$, respectively), and very clear stopping behaviour in the fourth segment. To achieve this, a logarithmic distance division method was applied, as the visual cues, $\dot{\tau}$, increase exponentially with decreasing distance, given by:

$$D_i = a^{5-i}; a = \sqrt[5]{D_{int}}, i = 1, \ldots, 3; D_4 = 2.5 \quad (1)$$

where D_i refers to the distance between the approaching vehicle and the pedestrian at the ith measuring point (Fig. 3). a is a logarithmic base based on the initial distance of the approaching vehicle, D_{int}. D_4 is always equal to 2.5 m, i.e., the final stopping distance from pedestrians (Fig. 3). The constant speed scenarios were also clipped to get four segments as comparisons with two yielding scenarios. The four measuring distances from participants were given as follows:

$$D_i = D_{int} - ai; a = \left(D_{int} - D_a\right)/4, i = 1, \ldots, 3; D_4 = 2.5 \quad (2)$$

During pilot testing, the method outlined above was deemed effective, except for the first segment of the constant speed scenario with 3 s

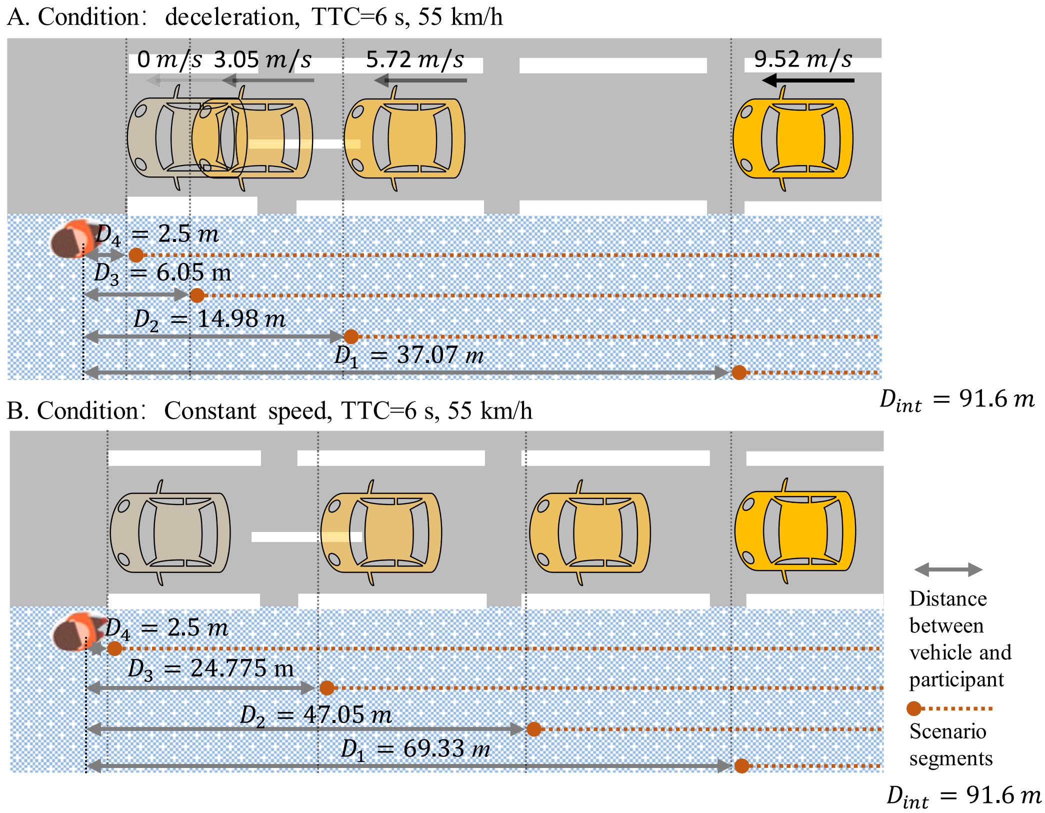

Fig. 3. Demonstration of the scenario division method. Two example scenarios (A: deceleration, TTC = 6 s, speed = 55 km/h and B: constant speed, TTC = 6 s, speed = 55 km/h) are divided into four segments.

initial TTC. This segment's brevity prevented meaningful observations, so its duration was extended to 1 s. Table B.2 displays the final parameters, demonstrating that the $\dot{\tau}$ ranges at the end of the first three segments were [−1, −0.36], [−0.36, −0.16], and [−0.16, 0.99], with a large $\dot{\tau}$ after the fourth segment, resulting in nearly complete separation of $\dot{\tau}$ between divisions. Consequently, the 18 experimental conditions' traffic scenarios were split into 72 segments (18 Conditions× 4 Segments). These segments were presented in an order that was fully randomised separately for each of the 30 participants, yielding 2160 trials of data for the second task. The task also consisted of a practice session and an experiment session, and the practice session provided participants with ten trials.

3. Results

3.1. Data processing and reduction

The participants' decisions to cross the road were recognised based on the following criteria: (a) the participant's longitudinal position exceeding the pavement edge; (b) the change in longitudinal position in one simulation time step of 120 Hz being greater than 0.003 m; and (c) the participant being at least 1.1 m away from the pavement edge after meeting the first two conditions for 2 second (Tian et al., 2022b). In literature, the crossing initiation time (CIT) is commonly used to analyse participants' crossing behaviour, referring to the time taken for participants to start crossing the road after the appearance of an approaching vehicle or the rear end of the previous vehicle passing the participants (Lee et al., 2022; Lobjois and Cavallo, 2007; Pekkanen et al., 2022). However, in this study, the CIT was not applicable because the durations from the start of traffic scenarios to vehicle stops in experimental conditions with the same initial TTCs and different initial speeds were different (Please see the duration of the 4th segments in Table B.2), which led to the fact that pedestrians' CITs based on vehicle yielding behaviour were not on the same time scale. For example, the duration of the deceleration condition with 6 s TTC and 55 km/h initial speed was 11.67 s, longer than the duration of the deceleration condition with 6 s TTC and 25 km/h initial speed, with a duration of 11.28 s. In Lee et al. (2022), researchers applied CIT in similar traffic scenarios. However, they analysed the difference in aggregate CIT between normal AV and AV equipped with eHMI conditions, which did not apply to our study. Instead, we applied Z_c, which was the distance between the participant and the vehicle when the pedestrian started crossing. Since our analysis of Z_c did not incorporate the temporal information of pedestrian crossing decisions, conducting an analysis based on time gaps or safety margins could provide valuable insights. However, using those time-based metrics is challenging in situations with low and zero speeds, such as in our scenarios with deceleration. Nevertheless, additional analyses of this nature were performed. The results from these analyses were in line with our analyses based on Z_c. Considering that the safety analysis was beyond the scope of our study and the results were replicated, these analyses were supplemented in Appendix C.

For the second task, participants' answers were binary data, where one indicated that the vehicle was stopping for the participant, and zero indicated that the vehicle was maintaining its speed.

3.2. Task one: Road crossing decisions across a range of traffic scenarios

3.2.1. Overall analysis

As depicted in Fig. 4, all pedestrians were observed to cross the road in deceleration and mixed conditions, while hardly any pedestrians crossed in constant speed conditions with 3 s initial TTC. In constant speed conditions with 6 s initial TTC, over half of the pedestrians took the opportunity to cross. A mixed-effects linear regression analysis was conducted with Z_c as the dependent variable and initial speed, initial TTC, and deceleration behaviour as independent variables. The model

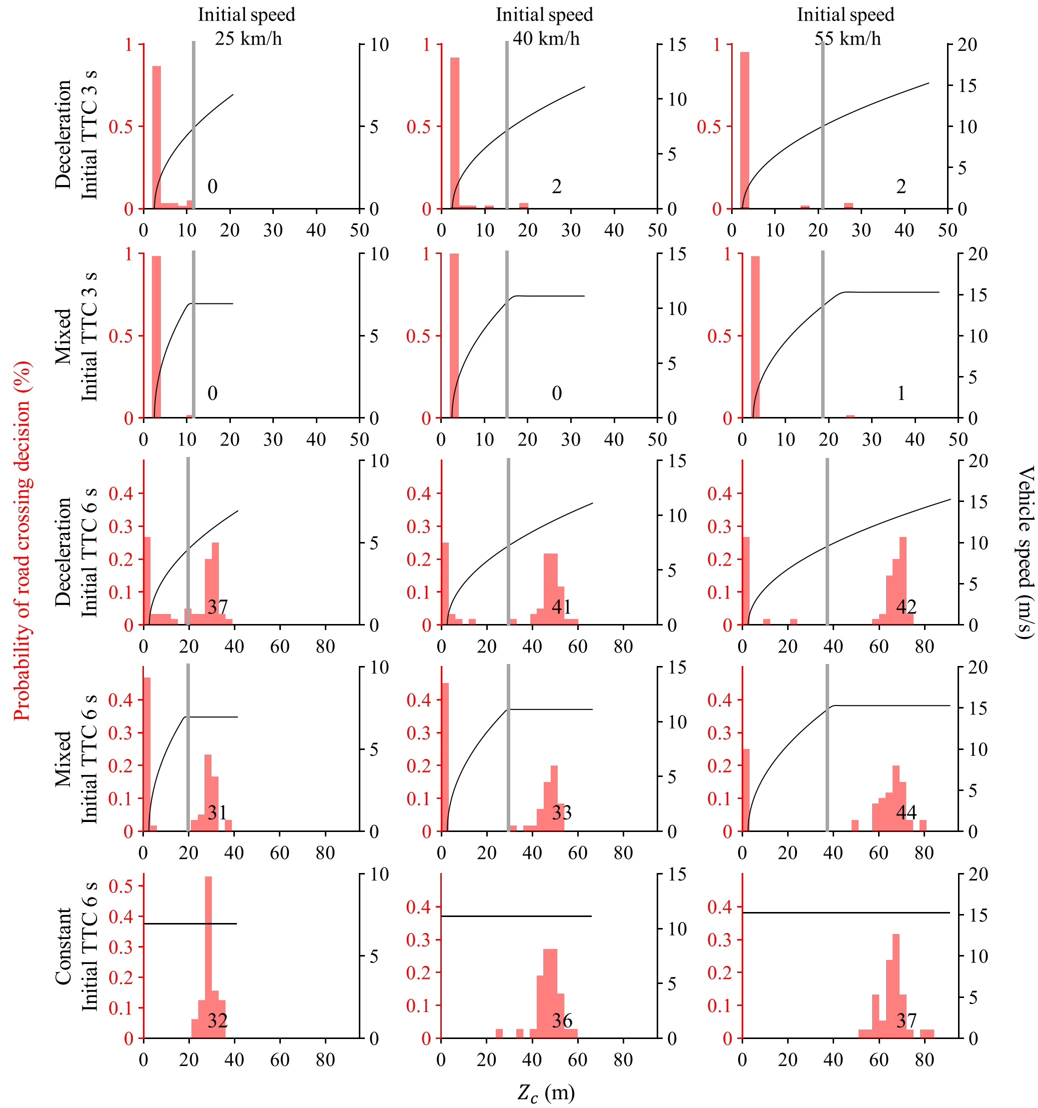

Fig. 4. Density functions of Z_c in the first task. The rows have identical initial TTC and the columns have identical initial speed. Corresponding vehicle trajectory is denoted using a black solid curve. As there were no pedestrians crossing the road in 3 s TTC and constant speed conditions, no data are available for these conditions. The data in deceleration and mixed conditions are separated into early and late crossings using thresholds (solid grey lines). The corresponding number of early crossings in each condition is plotted in the subfigure.

included random intercepts for individual differences. The analysis showed that pedestrians crossing decisions in deceleration and mixed conditions significantly differed from their decisions in constant speed scenarios ($Coef. = -11.00, z = -6.25,\ p < 0.001; Coef. = -12.80, z = -7.29, p < 0.001$) indicating that both types of deceleration behaviour facilitated pedestrian crossing decisions. Moreover, significant main effects of initial speed and initial TTC were found ($Coef. = 0.62, z = 14.47,\ p < 0.001; Coef. = 9.88, z = 26.66, p < 0.001$). Pedestrians crossed further away from the vehicle with an increase in the initial speed and TTC (Lee et al., 2022).

Moreover, as shown in subfigures in the third and fourth rows of Fig. 4, pedestrian crossing decisions in scenarios that involved vehicle deceleration and larger initial TTCs exhibited a bimodal distribution. Some pedestrians chose to cross shortly after the traffic scenario was triggered, while the others crossed after the vehicle had stopped or before it was about to stop, which was consistent with previous studies (Giles et al., 2019; Lee et al., 2022). Therefore, we categorised the crossing decisions in deceleration and mixed conditions into early and late crossings. The separation thresholds were the end distances of the first segments of the traffic scenarios in the second task (Table B.2), indicated with vertical grey lines in Fig. 4. Pedestrians were less likely to make crossing decisions based on vehicle deceleration behaviour before these thresholds because there were subtle or no deceleration cues in scenarios. If pedestrians crossed the road before the time threshold, these decisions were identified as early crossings, while others were identified as late crossings (Fig. 4). It can be found the patterns of early crossings were similar for the three different driving behaviours. For example, under deceleration and mixed conditions with 3 s initial TTC, almost no pedestrian crossed the road in the early phases of the scenarios. The same was true for the constant speed conditions with 3 s initial TTC. Moreover, for mixed conditions with 6 s initial TTC, the number of crossing decisions in the early phase was $31, 33$, and 44 at 25, 40, and 55 km/h. The corresponding numbers in the deceleration and constant speed conditions were $31, 43, 44$ and $32, 36, 37$, respectively (Fig. 4). A logistic regression was applied to pedestrians' early crossing decisions with initial speed, TTC, and driving behaviour as independent variables. There is no significant difference in the early crossing decision between vehicle behaviour conditions. Additionally, it was found that pedestrians appeared to adjust their decisions to the initial speed, and fewer pedestrians crossed the road early as the initial speed decreased ($Coef. = -0.02, Std.Error = 0.073, p < 0.01$). In line with previous studies (DeLucia, 2008; Giles et al., 2019; Pekkanen et al.,

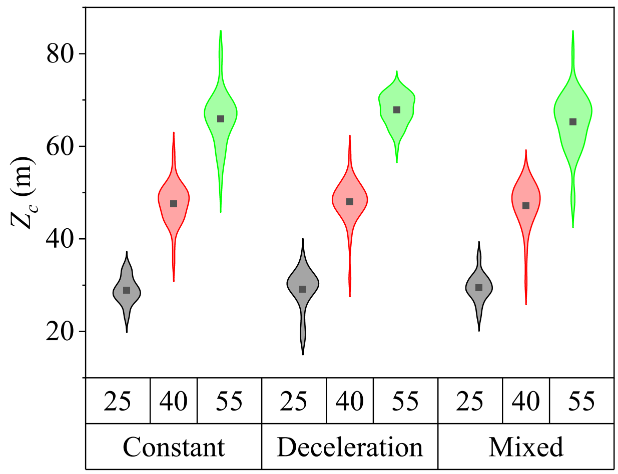

Fig. 5. Comparison of crossing decisions (in terms of the distance Z_c to the vehicle at crossing onset) across the scenarios with initial TTC of 6 s. Only those crossing decisions classified as early crossings (the rightmost modes in Fig. 3) are included here. Black squares represent average values.

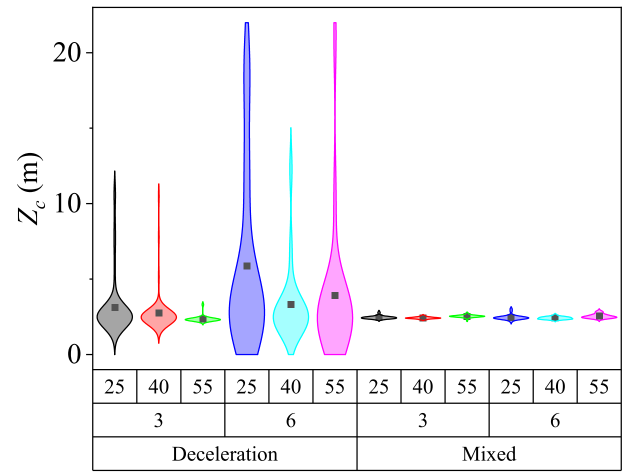

Fig. 6. Comparison of late crossing decisions (in terms of the distance Z_c to the vehicle at crossing onset) between deceleration and mixed conditions.

2022), it is hypothesised that pedestrians may adopt different strategies to determine their crossing decisions when a decelerating vehicle is approaching, which is formally concretised as follows:

- In the early phase of a traffic scenario, pedestrians make crossing decisions mainly based on a traffic gap (e.g., distance or TTC of the approaching vehicle) and are not concerned with vehicle yielding behaviour. This strategy is also valid in constant speed scenarios.
- If pedestrians fail to cross at the early phase of a traffic scenario, pedestrians may tend to mainly focus on the speed and details of the behaviour of the approaching vehicle.

3.2.2. Early crossing decisions

To further investigate the above strategies, the mixed-effects linear regression analysis was applied to early and late crossings separately.

The results showed no difference in pedestrian crossing decisions for constant speed, deceleration, and mixed conditions in early crossings (Fig. 5). This indicated that early crossing decisions in vehicle-yielding scenarios followed a similar pattern to those in constant speed scenarios, supporting our assumption. Moreover, initial speed had a positive impact on pedestrian crossing decisions across all types of traffic scenarios ($Coef. = 1.22, z = 68.75, p < 0.001$).

3.2.3. Late crossing decisions

Since there were no late crossing data in constant speed conditions, only data in deceleration and mixed conditions were compared. The Z_c distributions for the late crossings are shown in Fig. 6. The regression results showed that initial speed, initial TTC, and braking behaviour had significant main effects. In deceleration conditions, as initial TTC increased, pedestrians crossed the road further away from the vehicle ($Coef. = 0.28, z = 4.34, p < 0.001$). However, the effect of speed was the opposite ($Coef. = -0.02, z = -2.40, p < 0.05$) (Fig. 6). Pedestrian decisions significantly differed between deceleration and mixed conditions ($Coef. = 0.78, z = 4.57, p < 0.001$). In mixed conditions, pedestrians tended to wait for the vehicle to come to a complete stop, while more pedestrians crossed before the vehicle stopped in deceleration conditions compared to mixed conditions (Fig. 6).

3.3. Task two: Vehicle behaviour estimation

3.3.1. Overall analysis

In the second task, we investigated pedestrian judgements of approaching vehicle behaviour using a mixed-effects logit regression model with pedestrian 'stopping' judgement as the dependent variable, initial speed, initial TTC, and driving behaviour as independent variables and participants' individual differences as a random intercept. Participants' individual differences were considered as a random intercept in the model. The results showed significant main effects of initial speed, initial TTC, and deceleration behaviour. The initial TTC had a positive effect on the 'stopping' judgement ($Coef. = 0.94, z = 7.84, p < 0.001$), indicating that pedestrians were more likely to believe the vehicle was yielding to them at longer initial TTC conditions (Fig. 7). However, the initial speed negatively affected the 'stopping' judgement ($Coef. = -0.06, z = -11.80, p < 0.001$), indicating that the lower the initial speed, the higher the proportion of 'stopping' judgements (Fig. 7). Pedestrian judgements also differed between driving scenarios, with those in deceleration and mixed conditions more likely to make a 'stopping' judgement (Fig. 7). Furthermore, there was a significant difference between judgements in deceleration and mixed conditions, indicating better judgement of yielding vehicle behaviour in deceleration conditions. ($Coef. = 3.39, z = 8.38, p < 0.001$). Due to the apparent differences in the judgement of different scenarios, we separately analysed data in respective scenarios with initial speed, initial TTC, and segment as independent variables, as described below.

3.3.2. Constant speed and deceleration conditions

For the constant speed scenario, pedestrians were more likely to make 'stopping' judgements at larger initial TTC and lower initial speed conditions ($Coef. = 2.99, z = 9.90, p < 0.001; Coef. = -0.10, z = -9.02, p < 0.001$). From the first to the fourth segment, 'stopping judgements' decreased ($Coef. = -1.18, z = -10.00, p < 0.001$), indicating that over time pedestrians could discern that the vehicle was maintaining a constant speed (Fig. 7c). Regarding deceleration conditions, the effects of initial TTC and initial speed were similar to those in constant speed scenarios ($Coef. = 1.40, z = 4.33, p < 0.001; Coef. = -0.05, z = -3.38, p < 0.001$). Additionally, $\dot{\tau}$ was included as an independent variable in the regression model (Table B.2). Larger $\dot{\tau}$ values were associated with an increased likelihood of judging that the vehicle was stopping ($Coef. = 4.70, z = 4.33, p < 0.001$), suggesting that as visual cues increased, the yielding behaviour of the approaching vehicle became more apparent to pedestrians (Fig. 7).

3.3.3. Mixed condition

Notably, the situation becomes somewhat more complicated in mixed conditions, as shown in Fig. 7b. The results of the mixed condition appear to be a combination of those from the first segment of the constant speed condition and those from the third to fourth segments

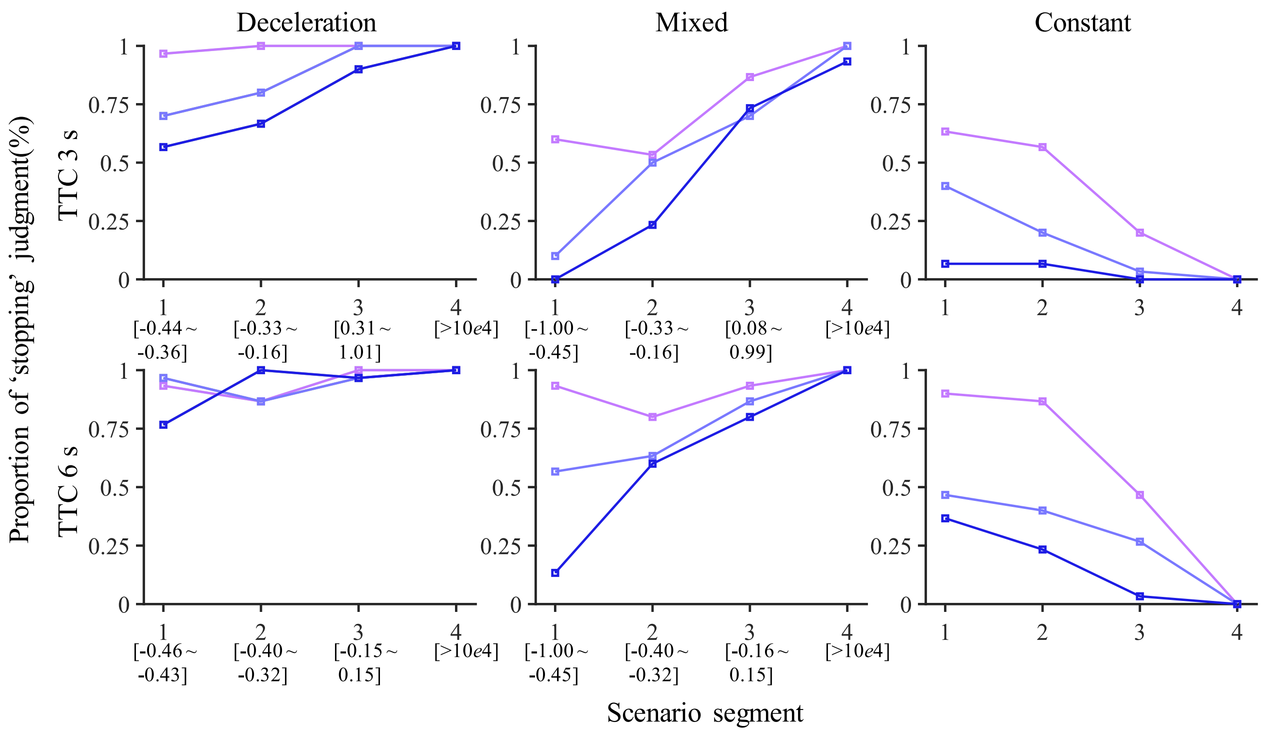

Fig. 7. Proportion of participants' 'stopping' judgements for segments of different traffic scenarios. The numbers 1 to 4 on the x-axis represent the four segments defined in Section 2.4. The gradient colours from light to dark denote the initial speed from 25 km/h to 55 km/h. The corresponding value range of $\dot{\tau}$ is plotted below the x-axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the deceleration condition. Therefore, we analysed the first segment and the other three segments separately.

We compared pedestrians' judgements on the first segments of the mixed and constant speed conditions were compared, and found no significant difference ($Coef. = -0.08, z = -1.64, p = 0.10$), suggesting that pedestrians used the same strategy to judge vehicle behaviour in these segments. We also compared the results of the other three segments in the mixed and deceleration conditions, and found a significant interaction effect between $\dot{\tau}$ and braking behaviour ($Coef. = -4.49, z = -4.36, p < 0.001$), indicating that as $\dot{\tau}$ increased, the proportion of pedestrians' 'stopping' judgements in the mixed condition increased more than that in the deceleration condition(Fig. 7). Although pedestrians' could better judge the yielding behaviour with increasing $\dot{\tau}$ in both scenarios ($Coef. = 0.27, z = 6.70, p < 0.001$), the rate of increase differed between the mixed and deceleration conditions, showing that at a similar level of $\dot{\tau}$, pedestrians could better anticipate the yielding behaviour in the deceleration condition than in the mixed condition ($Coef. = 0.13, z = 1.98, p = 0.047$). Additionally, a significant interaction effect was found between the initial TTC and segment ($Coef. = -0.21, z = -9.29, p < 0.001$). For instance, in the scenario with an initial TTC of 3 s and an initial speed of 25 mph, the proportion of 'stopping' judgements increased from approximately 60% to 100% as the segment changed from the first to the fourth. However, for the condition with an initial TTC of 6 s and an initial speed of 25 mph, the rate of 'stopping' judgements was high at the beginning (i.e., about 94%) and remained at this level. This indicates that pedestrians' initial 'stopping' judgements in the 3 s initial TTC condition were lower than those in the 6 s initial TTC condition.

4. Discussion

This study conducted an experiment to investigate pedestrian crossing decisions and their estimations of vehicle behaviour when interacting with an AV through two tasks, respectively. The primary aim was to explore the effects of deceleration parameters as implicit communication signals on pedestrian crossing behaviour and their subjective estimations of approaching vehicle behaviour in various traffic scenarios. In the first task, the influences of initial vehicle speed, initial TTC, and deceleration behaviour on pedestrian road crossing decisions were studied. In the second task, we investigated pedestrians' estimations of approaching vehicle behaviour in the same scenarios, and subsequently compared the results of the two experiments.

4.1. Impacts of implicit signals on road crossing decisions

Pedestrians tended to cross the road at a greater distance from the vehicle as the initial speed and initial TTC increased, a pattern observed across all scenarios. This finding is consistent with previous studies (Giles et al., 2019; Lee et al., 2022) that showed pedestrians preferred to cross in larger spatial or temporal traffic gaps in both yielding and non-yielding scenarios. The effects of initial vehicle speed and initial TTC had the same tendency across all scenarios, indicating that pedestrians crossed the road farther from the vehicle as speed and TTC increased. Consistent with previous studies, in yielding and non-yielding scenarios, pedestrians preferred to cross the road in larger spatial or temporal traffic gaps. This distance-dependent crossing decision suggests that pedestrians rely more on the distance to the approaching vehicle when deciding to cross, especially when there is a sufficient traffic gap available (Tian et al., 2022a).

We also analysed pedestrian early and late crossing decisions and found that there was no significant difference between yielding and non-yielding scenarios in early crossing decisions. This supports the hypothesis that pedestrians apply the same crossing decision strategy in the early phase of the traffic scenario, regardless of the vehicle's behaviour. In other words, pedestrians base their crossing decisions on the traffic gap, such as the distance or TTC of the approaching vehicle, without considering yielding behaviour (DeLucia, 2015; Pekkanen et al., 2022).

It was found that the braking behaviour of vehicles had a significant impact on pedestrian crossing decisions. In deceleration and mixed conditions, where vehicles gave way to pedestrians, more pedestrians

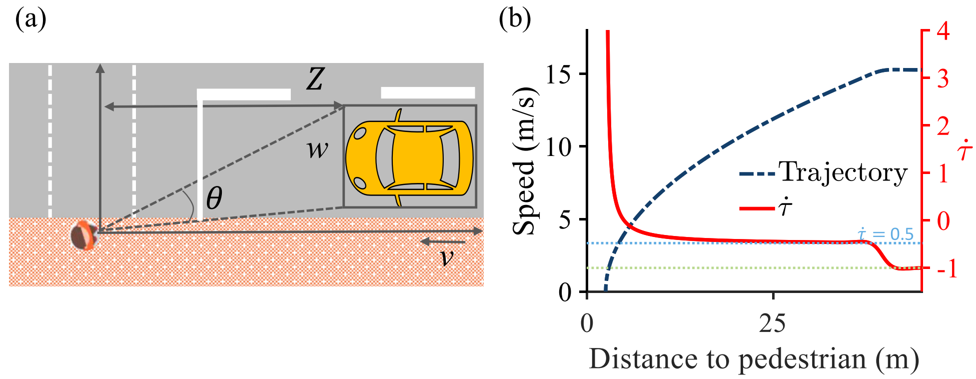

Fig. A.1. A Visual cue in road-crossing scenarios. (a) Diagram of the vehicle yielding scenario. (b) $\dot{\tau}$ curve and its corresponding vehicle trajectory.

crossed the road than in constant speed conditions. However, closer examination of pedestrian crossing initiation in yielding conditions revealed various patterns. Late crossing decisions in deceleration and mixed conditions were significantly different, with more pedestrians crossing the road before the vehicle stopped in deceleration conditions, indicating that pedestrians were more cautious in mixed conditions. Our findings were consistent with a previous study by Dey et al. (2021), which showed that the driving behaviour in the deceleration condition encouraged earlier pedestrian crossings due to a relatively early-braking style, while the relatively late-braking style in the mixed condition had the opposite effect, with pedestrians tending to cross the road after the vehicle had fully stopped. Moreover, the impact of initial speed on Z_c of late crossing decisions was opposite to that in early crossing decisions, indicating that pedestrians relied on different strategies or cues when crossing the road early versus late in vehicle-yielding scenarios (DeLucia, 2015; Pekkanen et al., 2022). Specifically, When the vehicle was far from pedestrians, crossing decisions were mainly based on the size of the traffic gap. Many studies reported that the tendency for gap acceptance increases with vehicle speed for a given time gap (Tian et al., 2022a; Lobjois and Cavallo, 2007). However, when the vehicle drove close, pedestrians' crossings were mainly based on the vehicle's driving behaviour. According to the hypothesis proposed above, pedestrians' decision-making difficulties arise when they transit from one strategy to the other one due to the contradictory relationships between cues for both strategies and collision risk (generally, the collision risk is negatively correlated to the traffic gap and positively correlated to vehicle speed), leading to the road crossing 'dilemma zone' (Pawar and Yadav, 2021). Therefore, pedestrians prefer to cross the road when one strategy or cue is apparently safer than the other (the traffic gap is big enough or the vehicle is about to stop). This tension may help explain why the distribution of pedestrian crossing initiations in front of a yielding vehicle is bimodal.

4.2. Links between road crossing behaviour and estimations

Although the deceleration rates in the mixed condition were more intense than in the deceleration condition, and we also controlled the level of visual cue, i.e., $\dot{\tau}$, for each segment of the traffic scenarios, we showed that pedestrians could better anticipate the yielding behaviour in the deceleration condition than in the mixed condition. This was consistent with the results in the first task that more pedestrians crossed the road before the vehicle had fully stopped in the deceleration condition compared to the mixed condition. Hence, both findings in the first and second tasks strengthen the conclusion that the early-onset braking style facilitates pedestrians to notice the yielding behaviour of vehicles and benefits their crossing decisions (Dey et al., 2021; Ackermann et al., 2019).

Another important finding of this study is that the initial speed had a negative effect on the proportion of 'stopping' judgements. Notably, pedestrians had a tendency to interpret low vehicle speed as yielding behaviour. For instance, under the constant speed condition with 6 s initial TTC and 25 km/h initial speed, nearly 90% of pedestrians felt that the vehicle gave way to them at the beginning. The value was still very high, i.e., 65%, for the condition with 3 s initial TTC and 25 km/h initial speed. Therefore, we suggest that pedestrians may rely on vehicle speed to estimate vehicle-yielding behaviour. It is very interesting to note that this result is in accordance with the pedestrian late crossing decision in the first task: as the initial speed decreased, more pedestrians crossed the road before the vehicle came to a complete stop.

However, as discussed above, this speed effect is precisely the opposite of the pattern in early crossings, where more pedestrians cross the road at higher initial speed conditions. This discrepancy between pedestrian early crossing behaviour and their estimations of vehicle behaviour further supports the hypothesis proposed above, whereby when the vehicle is far from pedestrians, pedestrian crossing decisions are mainly based on the size of the traffic gap rather than on estimations of vehicle-yielding behaviour. The finding is novel and significant. It provides evidence that vehicle behaviour estimation may not directly impact crossing decisions when the time gap to the vehicle is large. Crossing decisions and estimations of vehicle behaviour are correlated in late phases when vehicles drive close and yield. This notion highlights that pedestrian crossing decision-making strategy is highly contingent on the traffic scenario and vehicle kinematics.

4.3. Visual cue for road crossing

The visual cue $\dot{\tau}$ was found to have a significant correlation with the detection of yielding behaviour. As the $\dot{\tau}$ value increased, yielding behaviour became more noticeable to pedestrians. This finding is consistent with previous studies that have proposed $\dot{\tau}$ as a visual cue used by pedestrians to estimate vehicle yielding behaviour (Giles et al., 2019; Pekkanen et al., 2022). However, it is important to note that in the second task, we observed that pedestrians could better anticipate vehicle yielding behaviour in the deceleration condition than in the mixed condition, even though the values of $\dot{\tau}$ in both conditions were very close. This phenomenon can be explained by the evidence accumulation theory (Markkula et al., 2018), which suggests that pedestrian crossing decisions are not solely based on the immediate value of visual cues, such as $\dot{\tau}$, but rather their integration over time. In deceleration conditions, since the period of time for deceleration evidence accumulation is longer than the time in mixed conditions, pedestrians may be better able to anticipate vehicle yielding behaviour.

4.4. Implications

We see several ways in which the study's results could enhance traffic safety. Firstly, the findings suggest that pedestrians may interpret

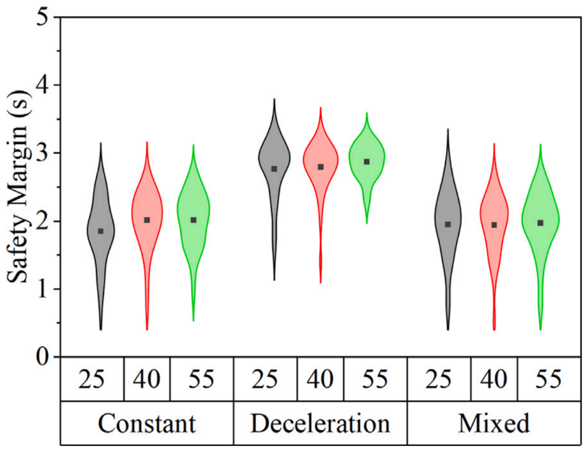

Fig. C.1. Pedestrian Crossing safety margins. Only those crossing decisions classified as early crossings are included here.

the slow-moving behaviour of a vehicle as a signal to give way, even when the vehicle does not actually yield. This may lead to confusion and misinterpretation in situations, potentially resulting in safety hazards. To address this issue in pedestrian–AV interactions, AV developers should be aware of this human behaviour and consider design strategies such as providing explicit yielding signals to pedestrians. This could improve their estimation accuracy in such situations. Additionally, the study's results reinforce the idea that early-onset braking behaviour not only helps pedestrians estimate vehicle behaviour but also encourages them to cross the road, which is conducive to road crossing safety. Finally, these results support the notion that pedestrians pay attention to different kinematic cues during the various phases of vehicle-yielding scenarios. This insight highlights the need to target different vehicle kinematic cues at different phases of a crossing scenario to enhance safety. For example, when the distance between pedestrians and vehicles is large, TTC and distance may have greater safety implications than driving behaviour.

Another significant aspect of these findings lies in aiding the understanding of pedestrian-AV interactions, which may also have practical implications for improving road safety. Specifically, the results highlight the impacts of deceleration parameters on pedestrian crossings, which can inform the design of AV driving behaviour in such interactions. To make AVs more understandable to pedestrians, they could be programmed to decelerate early at relatively large TTCs and avoid consistently approaching pedestrians at low speeds. Additionally, as discussed earlier, sending explicit signals to pedestrians through eHMI could facilitate their estimations and reduce the likelihood of misunderstanding. However, these results also suggest that pedestrians may not consider vehicle braking behaviour when the TTC is relatively large, which indicates that the design of eHMI should take into account the impacts of deceleration parameters. Finally, the identified correlation between visual cue $\dot{\tau}$ and pedestrian estimation of approaching vehicle behaviour has practical implications for future research on pedestrian-AV interactions. For example, $\dot{\tau}$ could be a practical indicator for controlling the vehicle deceleration evidence in experiments. Overall, this research deepens the understanding of the vital role of implicit signals in pedestrian crossing behaviour and has safety implications for multiple fields through improved knowledge of pedestrian-AV interactions.

4.5. Limitations and future directions

Given the complex and variety of braking behaviour in real-world traffic, it is impractical to exhaustively consider all possible driving scenarios. Therefore, this study focused on investigating two types of braking behaviours from various initial conditions. However, generalising these findings to other situations requires careful validation and potentially expanding upon the interpretations provided here. It is worth noting that there are limitations to our methodology, including participants verbally reporting their estimations during the second task, which may have introduced unknown cognitive biases (Te Velde et al., 2005). Additionally, τ is a contentious visual cue for human collision detection, and we did not specifically analyse the impact of τ and $\dot{\tau}$ on pedestrian crossing behaviour. As a result, we cannot conclude that τ is the only or primary visual cue used by pedestrians, and overinterpreting the related results should also be avoided. Finally, the simulated environment we used has the advantage of being safe and allowing for precise control over all experimental parameters. While the simulated environment was highly immersive, the virtual nature of the task may have produced unpredictable behaviour patterns.

Based on the aforementioned limitations, future research could consider designing complex pedestrian-AV interaction scenarios, such as approaching vehicles with varying deceleration rates, for pedestrian crossing tasks. Additionally, to better understand the potential cognitive biases introduced by verbal judgements, it would be worthwhile to investigate the relationship between verbal judgements and actual estimations. Finally, while conducting experiments in a simulated environment provides precise control over experimental parameters, replicating the experiment in a real-world test field may reveal new insights and help validate the findings.

5. Conclusions

This study investigated the impacts of deceleration parameters as implicit signals on pedestrians' subjective estimation of approaching behaviour across a wide range of experimental traffic scenarios and on their crossing behaviour in the same scenarios through a comprehensive analysis. The following conclusions were drawn to address the research questions:

- Regarding the first research question, the study finds that the initial speed has an effect on pedestrians' estimates. Pedestrians tend to interpret low vehicle speed as an indication of planning to stop, even if that low speed is constant. Moreover, the results support that the early-onset braking style helps pedestrians to notice the yielding behaviour of vehicles and benefits their crossing decisions.
- As for the second research question, the study reveals that pedestrians can distinguish between different vehicle braking behaviours. Their crossing decisions correspond to their subjective estimates, indicating that pedestrians actively estimate vehicle behaviour as part of their decision-making process. However, for large traffic gaps, the effect of vehicle speed on crossing decisions and estimations about vehicle behaviour changes, implying that the estimation of vehicle behaviour may not have a strong impact on crossing decisions at larger gaps. Furthermore, the correlation between crossing decisions and vehicle behaviour estimations is stronger in the late phases when the vehicle drives closer and yields.

These findings strengthen the argument for the crucial role of implicit signals in pedestrian–AV interactions and may need to be considered when designing human-friendly braking manoeuvres for AVs.

CRediT authorship contribution statement

Kai Tian: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Athanasios Tzigieras:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Chongfeng Wei:** Conceptualization, Writing – review & editing, Supervision. **Yee Mun Lee:** Writing – review & editing. **Christopher**

Holmes: Conceptualization, Writing – review & editing, Supervision. **Matteo Leonetti:** Conceptualization, Writing – review & editing, Supervision. **Natasha Merat:** Conceptualization, Writing – review & editing, Supervision. **Richard Romano:** Conceptualization, Writing – review & editing, Supervision. **Gustav Markkula:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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 will be made available on request

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Appendix A. Visual information for vehicle behaviour estimation

In the road crossing scenario (Fig. A.1a), the pedestrian acquires the vehicle's movement information through the optical variables that change on the retina, which usually refers to the 'optic flow field' (Gibson, 2014). As the vehicle drives close, its image on the pedestrian's retina grows continuously. This optical expansion variable and its first temporal derivative are correlated to the sensation of collision threat, and can be written as (Gibson, 2014; Lee, 1976):

$$\theta = 2\tan^{-1}\left(\frac{w}{2Z}\right) \Rightarrow \dot{\theta} = \frac{wv}{(Z)^2 + w^2/4} \tag{A.1}$$

where θ is the visual angle subtended by the approaching vehicle at the pedestrian's pupil. Its first temporal derivative is $\dot{\theta}$. Z, w denote vehicle distance from the pedestrian and its width. The ratio of visual angle to its first temporal derivative, τ, approximates the TTC of the approaching vehicle to the pedestrian, called Tau (Lee, 1976), and its rate of change over time is given by:

$$\tau = \frac{\theta}{\dot{\theta}} \Rightarrow \dot{\tau} = \frac{ZD}{v^2} - 1 \tag{A.2}$$

where D is the deceleration rate of the vehicle. Previous literature has demonstrated that $\dot{\theta}$ is correlated to the judgement of collision events in the course of vehicle yielding (Bardy and Warren, 1997), which can be a variable that pedestrians use to judge whether the deceleration rate is enough to stop the vehicle in front of them and avoid a collision. If the deceleration rate is enough to stop the vehicle in front of the pedestrian, the distance the vehicle will take to stop, $v^2/2D$, should be less than or equal to its current distance, Z, from the pedestrian:

$$\frac{v^2}{2D} \leq Z \Leftrightarrow \frac{1}{2} \leq \frac{ZD}{v^2} \tag{A.3}$$

Substituting from Eq. (A.2) into Eq. (A.3) we get the following condition of collision avoidance:

$$\frac{1}{2} \leq \dot{\tau} + 1 \Leftrightarrow \dot{\tau} \geq -\frac{1}{2} \tag{A.4}$$

Now, suppose a concrete example, as shown in Fig. A.1b, that a vehicle approaches the intersection, and a pedestrian intends to cross the road. The trajectory of the vehicle is given, i.e., the car maintains a constant speed, 55 km/h, for a while and then decelerates at a constant rate, -3.135 m/s^2, at a distance of approximately 40 m from the pedestrian and finally stops at a distance of 2.5 m from the pedestrian, as shown in Fig. A.1b. In the beginning, when the vehicle approaches at a constant speed, $\dot{\tau} = -1$ (for each second that passes, the apparent TTA of the vehicle decreases by one second), suggesting that the pedestrian cannot perceive any deceleration behaviour of the approaching vehicle. As the car decelerates, $\dot{\tau}$ quickly increases to -0.5, since the deceleration rate is enough to stop the vehicle in front of the pedestrian. As the vehicle comes close, $\dot{\tau}$ begins increasing approximately exponentially, since the vehicle is decelerating to stop with a small distance margin, rather than exactly at the pedestrian. This means that the closer the distance, the more obvious the collision avoidance cues become. Therefore, we then assumed that $\dot{\tau}$ might be the visual cue associated with pedestrian crossing decisions in vehicle-yielding scenarios.

Appendix B. Parameters of segments of traffic scenarios

See Table B.2.

Appendix C. Analysis on pedestrian safety margins

Additional analysis was conducted using safety margins as the dependent variable. Safety margin defines as Tgc – Tcz, where Tgc is the time gap between the participant and the vehicle when the pedestrian starts crossing, and Tcz is the time it takes for the pedestrian to leave the collision zone. As shown in Fig. C.1, the safety margins for pedestrians' early crossing decisions were significantly higher in the Deceleration condition compared to the other two conditions ($Coef. = 0.861, std = 0.054, p < 0.001$).

There was no significant difference between the Constant and Mixed conditions ($Coef. = 0.011, std = 0.056, p = 0.848$). Pedestrians' safety

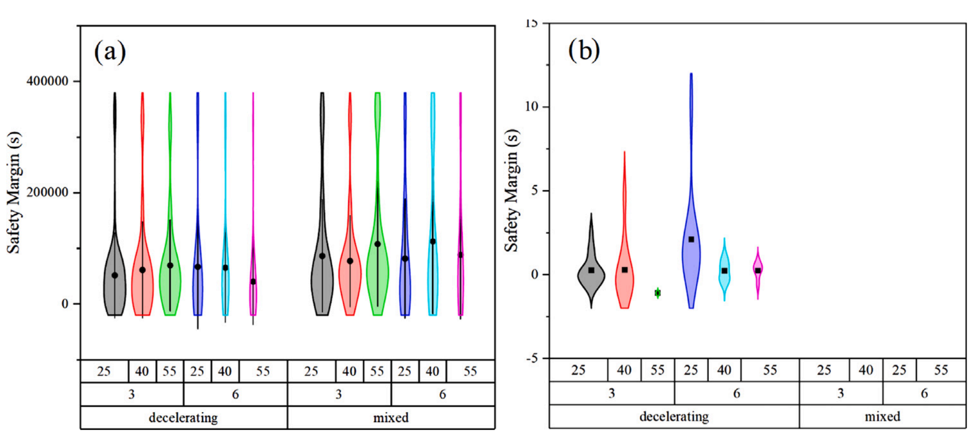

Fig. C.2. Pedestrian Crossing safety margins. Only those crossing decisions classified as late crossings are included here. Figure a includes all data points, while Figure b only includes the data point with safety margins of less than 12 s.

Table B.2
Parameters of segments of traffic scenarios. The duration of the segment, vehicle distance to the participant, and $\dot{\tau}$ are included. All parameters correspond exactly to scenarios at the end of segments.

Condition		1st segment	2nd segment	3rd segment	4th segment
Const_3s_25 km/h	Duration (s)	1.00	1.33	1.98	2.64
	Distance (m)	13.79	11.61	7.06	2.50
Const_3s_40 km/h	Duration (s)	1.00	1.39	2.08	2.78
	Distance (m)	22.06	17.83	10.17	2.50
Const_3s_55 km/h	Duration (s)	1.00	1.43	2.13	2.84
	Distance (m)	30.32	24.05	13.28	2.50
Const_6s_25 km/h	Duration (s)	1.42	2.83	4.23	5.64
	Distance (m)	31.80	22.03	12.27	2.50
Const_6s_40 km/h	Duration (s)	1.46	2.90	4.34	5.78
	Distance (m)	50.50	34.50	18.50	2.50
Const_6s_55 km/h	Duration (s)	1.47	2.93	4.38	5.84
	Distance (m)	69.20	46.97	24.73	2.50
Decel_3s_25 km/h	Duration (s)	1.62	2.92	4.16	5.28
	Distance (m)	11.29	6.15	3.32	2.50
	$\dot{\tau}$	−0.36	−0.16	1.01	>10e4
Decel_3s_40 km/h	Duration (s)	1.81	3.17	4.31	5.52
	Distance (m)	16.46	8.15	4.03	2.50
	$\dot{\tau}$	−0.41	−0.28	0.31	>10e4
Decel_3s_55 km/h	Duration (s)	1.93	3.33	4.43	5.61
	Distance (m)	21.31	9.86	4.03	2.50
	$\dot{\tau}$	−0.44	−0.33	0.15	>10e4
Decel_6s_25 km/h	Duration (s)	3.80	6.56	8.79	11.28
	Distance (m)	19.70	9.34	4.40	2.50
	$\dot{\tau}$	−0.43	−0.32	0.15	>10e4
Decel_6s_40 km/h	Duration (s)	4.16	7.01	9.12	11.55
	Distance (m)	28.73	12.39	5.33	2.50
	$\dot{\tau}$	−0.45	−0.37	−0.06	>10e4
Decel_6s_55 km/h	Duration (s)	4.40	7.30	9.34	11.67
	Distance (m)	37.07	14.98	6.05	2.50
	$\dot{\tau}$	−0.46	−0.40	−0.15	>10e4
Mixed_3s_25 km/h	Duration (s)	1.36	2.23	3.04	3.78
	Distance (m)	11.30	6.17	3.36	2.50
	$\dot{\tau}$	−1.00	−0.16	0.99	>10e4
Mixed_3s_40 km/h	Duration (s)	1.51	2.43	3.21	4.05
	Distance (m)	16.47	8.17	4.06	2.50
	$\dot{\tau}$	−0.65	−0.28	0.31	>10e4
Mixed_3s_55 km/h	Duration (s)	1.61	2.56	3.31	4.17
	Distance (m)	21.24	9.89	4.06	2.50
	$\dot{\tau}$	−0.45	−0.33	0.08	>10e4
Mixed_6s_25 km/h	Duration (s)	3.15	4.91	6.31	7.88
	Distance (m)	19.72	9.36	4.44	2.50
	$\dot{\tau}$	−1.00	−0.32	0.15	>10e4
Mixed_6s_40 km/h	Duration (s)	3.41	5.24	6.59	8.15
	Distance (m)	28.72	12.41	5.36	2.50
	$\dot{\tau}$	−0.67	−0.36	−0.06	>10e4
Mixed_6s_55 km/h	Duration (s)	3.57	5.44	6.76	8.27
	Distance (m)	37.06	15.02	6.09	2.50
	$\dot{\tau}$	−0.45	−0.40	−0.16	>10e4

margins generally increased with speed ($Coef. = 0.03, std = 0.013, p < 0.05$), supporting our analysis based on Z_c, i.e., that vehicle speed encouraged early crossing decisions across all types of conditions. The difference in safety margins between Deceleration and the other two conditions may be attributed to early-onset braking behaviour rather than a change in pedestrian crossing behaviour patterns.

Regarding late crossing decisions, as depicted in Fig. C.2a, no consistent pattern of impact of vehicle speed and time gap was found. Pedestrians in Mixed conditions appeared safer than those in Deceleration conditions. However, comparing two safety margin values that are both extremely large does not yield valuable information. To avoid the impact of large safety margins, We removed the late crossing decisions with safety margins greater than 12 s, thus enabling us to analyse pedestrian crossing decisions made in potentially risky situations, as shown in Fig. C.2b. Significant effects of speed and TTC were found. The safety margins decreased with speed ($Coef. = -0.065, std = 0.0235, p < 0.01$) and increased with TTC ($Coef. = 0.462, std = 0.1712, p < 0.01$). This speed effect on late crossing decisions was opposite to that on early crossing decisions, which aligned well with our analysis on Z_c. The above results were overall in line with our analyses based on Z_c.

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