



Crossing in the dark: Investigating the effect of vehicle kinematics and eHMI on older pedestrians' crossing behavior in a virtual reality experiment

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ABSTRACT

Introduction: There has been a surge in interest in evaluating new forms of communication for Automated Vehicles (AVs), namely external human-machine interfaces (eHMIs). However, much of the research has focused on younger pedestrians' crossing behavior and experience while interacting with AVs and in daytime conditions with optimum visibility. Given that the AVs will interact with pedestrians of all ages, and at all times, there are still key knowledge gaps that need to be addressed. **Method:** Using a cave-based pedestrian lab, this study investigated the effect of AV kinematics (i.e., deceleration, speed, time gaps) and eHMI (a Slow Pulsing Light Band) on the crossing behavior of younger adult pedestrians (18–35 years old) and older pedestrians (64–77 years old), in both daytime and nighttime virtual environments. **Results:** Results showed that older pedestrians adopted a different crossing strategy than younger pedestrians. If they decided to cross in the non-deceleration trials, they compensated for their longer crossing duration by initiating their crossing earlier than younger pedestrians. However, if they decided to wait until the deceleration was more prominent, they waited longer than the younger pedestrians. Generally, pedestrians reported feeling less safe and behaved more cautiously during nighttime crossings (i.e., less likely to cross, longer crossing initiation time (CIT) when there was no eHMI). eHMI decreased CIT for both age groups but was interpreted and used differently between younger and older pedestrians. Finally, an eHMI failure trial mainly affected younger pedestrians. **Conclusions and practical applications:** This knowledge should inform the design of effective communication for AVs for younger and older pedestrians.

1. Introduction

Automated vehicles (AVs) with higher levels (i.e., Levels 4 and 5; SAE International, 2021) of automation will be required to interact with other road users in mixed traffic conditions. While many previous studies have shown that road users rarely used explicit communication, and mainly focus on vehicle kinematics while making a crossing judgement (i.e., Ackermann, Beggiano, Bluhm, Löw, & Krems, 2019; Dey & Terken, 2017; Lee et al., 2021; Petzoldt et al., 2018; Sucha et al., 2017; Uttley et al., 2020; Várhelyi, 1998; Wang et al., 2014), some studies have found that road users may also communicate with each other by using hand/head gestures, facial expressions, and/or eye contact (Mahadevan et al., 2018; Rasouli et al., 2017; Sucha et al., 2017). This has led designers and researchers to propose various external Human-Machine Interface (eHMI) prototypes to communicate AVs' intentions, aiming to enhance interactions between pedestrians and AVs. Indeed, many

previous studies have shown the usefulness of these additional communications. For example, eHMI that communicated yielding intention was found to decrease the mean decision-making time when deciding to cross in a button-pressing task (Chang et al., 2017), increase willingness to interact with AVs in a Head-Mounted Display (HMD) study (Deb et al., 2018), improve understanding of AVs' intentions and increase willingness to cross (Dey et al., 2020), and decrease crossing initiation time (CIT) in an HMD study; while also improve feelings of comfort, trust, acceptance, and perceived safety (Holländer et al., 2019; Bindschadel et al., 2021).

Given that previous studies have found that road users mainly rely on implicit communication to help make crossing decisions in current, everyday crossing, recent studies investigated the combined role of eHMI and vehicle kinematics in more depth, providing a better understanding of the conditions in which eHMI affects pedestrian crossings. Using a cave-based pedestrian simulator, Lee et al. (2022) showed that

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eHMIs led to earlier crossings, but only when the vehicles were approaching at lower speeds and time gaps, and only if pedestrians were familiar with the eHMI. Another recent study found that an unfamiliar eHMI decreased Crossing Initiation Time (CIT), but only in uncertain conditions (i.e., where there was no pedestrian crossing markings present; Madigan et al., 2023). Thus, it would appear that the effect of eHMI on pedestrian crossing behavior is closely linked to vehicle movement patterns and roadway environment.

The results presented thus far show that we now have some knowledge of how eHMI can impact pedestrian behaviors. However, there are two major gaps in the research conducted to date. First, the majority of studies have been conducted during daytime conditions, and there is limited knowledge of how vehicle kinematics and/or eHMIs are perceived at night. Secondly, there has been very little investigation into how more vulnerable groups such as older pedestrians are likely to interact with AVs, and knowledge of how their behavior might differ from younger people is important to ensure the development of inclusive communication solutions.

1.1. The effect of time of day

Understanding the effect of time-of-day on road users' behavior is important, but very few studies have investigated pedestrian-AV interactions during nighttime.

Research conducted with conventional vehicles provides some insights into how lighting conditions may impact pedestrian actions. Research by Wood et al. (2005) found that drivers recognized only 5% of pedestrians in low beams, black clothing, and glare conditions during nighttime. Another study conducted by Kalatian and Farooq (2022) showed that drivers were more likely to make incorrect predictions about other road users' behaviors in nighttime conditions. This could lead to pedestrians being extra cautious while crossing in nighttime conditions. This conclusion is supported by interview evidence from another HMD study where participants experienced a bright daytime virtual environment or a rainy and foggy nighttime environment, and reported a more cautious approach during low visibility conditions (Pillai, 2017).

On the other hand, research has also shown that when good lighting conditions are provided (i.e., headlights), approaching vehicles can be more perceivable during nighttime than daytime conditions, showing that the contrast between bright lights and the dark environment may also play a role (Lee & Sheppard, 2018). One could deduce that under good visibility conditions, this could lead to pedestrians being able to detect the eHMI earlier, and potentially leading to early crossings (Lee et al., 2022). For example, using HMD and a data-driven deep survival model approach, Kalatian and Farooq (2022) showed that pedestrians had shorter wait times in the nighttime scenarios. In addition, this study also found that older pedestrians were more conservative in nighttime scenarios.

There have also been studies that found no effect of the time of day. For example, a video-based study to investigate the impact of speed, deceleration rate, deceleration onset, and daylight (morning, dusk, and evening) on pedestrians' reaction time to detect the deceleration onset of a vehicle, found no effect of daylight on pedestrians' reaction time (Ackermann et al., 2019). Another study investigating pedestrians' crossing behavior using a large-screen pedestrian simulator, found no difference between daytime and nighttime groups on the number of gaps seen before crossing, the probability of taking a gap, the timing of road entry, or crossing time. However, there was a marginal effect on the safety margin, which was found to be higher during nighttime than daytime (Subramanian et al., 2022).

To our knowledge, only two studies have explored the effect of external communications in relation to the time of day. Zandi et al. (2020) conducted a survey with 130 participants from six countries on the importance of communication with AVs. They found that the importance of communication was independent of the time of day,

traffic density, and number of pedestrians. Using an HMD, Bindschadel et al. (2021) investigated the effect of four eHMI designs and time of day on crossing behavior. The study found a higher CIT, lower walking speed and lower safety ratings for the eHMI during nighttime. Overall, these studies point to a need to explore the effects of time of day on perceptions of eHMI in more detail.

1.2. The effect of age

Lighting and time of day are not the only factors that could affect pedestrian perception. Many studies have investigated the impact of degradations in physical and perceptual capabilities during aging on pedestrian crossing strategies. For example, using a cave-based pedestrian simulator, Lobjois and Cavallo (2007) investigated the effects of age, vehicle speed, and time constraints on gap acceptance. The study found that, with no time constraint, older pedestrians accepted shorter and shorter time gaps as speed increased, putting them at a higher risk at high speeds (similar findings in Oxley et al., 2005).

However, there is evidence of older pedestrians trying to compensate for their decline in physical mobility and information processing. For example, another study by Lobjois and Cavallo (2009) demonstrated that older adults initiated their crossing sooner than younger pedestrians as an attempt to compensate for the longer time needed to cross the road. Similar findings were shown in a recent study by Nicholls et al. (2024), who found that older adults (age 65–85) could make safe crossing decisions and were more cautious than younger adults (age 18–24), even in high cognitive load situations. Older participants increased their head movements to compensate for poorer attention switching and support safe decision-making. Taken together, these studies suggest older pedestrians may have a different strategy while making crossing decisions compared to younger pedestrians.

All the above-mentioned studies were based on gap acceptance in response to non-decelerating conventional vehicles. However, in recent times, there have been a small number of investigations into older pedestrians' interactions with AVs, along with the impact of vehicle deceleration on older pedestrians' decision-making. Dommes et al. (2021) focused on the effect of age, time gaps and speed on two-lane crossings in front of AVs that always decelerated and stopped, versus conventional vehicles (CVs) that never decelerated. This study found that older pedestrians were more likely than younger pedestrians to cross the street at shorter time gaps when AVs gave way to them in the near lane, even when there were non-decelerating CVs approaching in the far lane, thus demonstrating risky behavior. Finally, in a video-based study conducted by Hensch et al. (2022), pedestrians were asked to evaluate their subjective experience (i.e., trust, acceptance, perceived safety, vigilance) towards AVs with an eHMI. The study showed that generally, older pedestrians showed more positive experiences towards AVs with eHMIs and had less of a decrease in acceptance than younger pedestrians after encountering a malfunctioning eHMI. On a relevant note, Subramanian et al.'s (2024) latest study has demonstrated that children (8–12 years old) behaved differently compared to the young adults while interacting with AVs, which showed different deceleration kinematics and eHMI onsets. This study demonstrated the importance of studying pedestrians with varying age groups in an AV and pedestrian interaction context.

1.3. Current study

While studies by Subramanian et al. (2022) and Bindschadel et al. (2021) have investigated the effects of time of day and eHMI on gap acceptance behaviors, neither study manipulated the vehicle's kinematic behaviors. This is an important consideration, as research in daytime environments has shown that the vehicle's traveling speed and the time gap available are crucial factors in determining how interactions will play out, with the effect of eHMI only emerging in lower speeds and time gaps (Lee et al., 2022). It is not yet clear if vehicle

kinematics will play a similar role at night-time, where it may be more difficult for pedestrians to detect differences in vehicle speed or deceleration. Thus, it is important to gain an understanding of whether time of day has an impact on pedestrians' interpretation of, and response to kinematic behaviors and eHMI in decelerating and non-decelerating conditions. This will also provide an understanding of the full benefits and potential negative effects of eHMI at different times of day. In addition, previous studies investigating the different strategies deployed by older and younger adult pedestrians have mainly focused on gap acceptance in non-decelerating vehicles. With [Dommes et al. \(2021\)](#) showing potential risky behaviors of older pedestrians while interacting with AVs, it would be beneficial to understand how age, time of day and the presence of an eHMI play a role in crossing behavior under different kinematics circumstances.

Thus, the aim of this study was to investigate the crossing behavior of different age groups of pedestrians in daytime and nighttime environments. Kinematic cues (i.e., speed, time gaps, deceleration) and the presence of explicit communication (i.e., a Slow Pulsing Light Band eHMI vs no eHMI) were also manipulated to understand how these factors influence crossing decisions, and whether this varies depending on pedestrian age.

2. Method

2.1. Participants

A total of 46 participants were recruited for this study via the University of Leeds Driving Simulator database and social media posts. Recruitment criteria included either being 18–35 years old or above 65 years old, and participants were required to have been in the UK for more than a year. The demographic information for each age group is shown in [Table 1](#). The study lasted approximately 1.5 h, and participants received £20 as a token of appreciation. Ethical approval was obtained from the University of Leeds Research Committee (Ref: 0536).

2.2. Apparatus and virtual environment

The experiment was conducted in the University of Leeds Highly Immersive Kinematic Experimental Research (HIKER) laboratory, which is a controlled and safe environment ([Fig. 1](#)). HIKER is an advanced cave-based pedestrian simulator that provides walking space to pedestrians in a 9-metre-long by 4-metre-wide physical space. It also incorporates an array of 4 k projectors, providing an immersive Virtual Reality (VR) environment.

The virtual environment was created using the Unity cross-platform game engine (unity.com) ([Fig. 2](#)).

2.3. Design

The main task of each participant was to cross the road between two approaching vehicles – as shown in [Fig. 3](#), if they felt comfortable to do so. The vehicle approach speeds and time gaps were adapted from [Lee et al. \(2022\)](#). A mixed between-within subjects design was used, with five within-participant variables: (i) the speed of the approaching vehicles (25/30 mph); (ii) the time gap between the vehicles (3/5 s); (iii) the deceleration behavior of the second vehicle (deceleration/no deceleration); (iv) the presence of eHMI while decelerating (present/absent); and (v) the time of day (daytime/nighttime); and one between-

Table 1
Demographic information for the participants.

Groups	N	Age Range	Age		Years spent in the UK		
			M	S.D	Range	M	S.D
Younger	14 M, 15F	18–35	25	4.71	2–29	14.79	9.03
Older	9 M, 8F	64–77	69.53	4.13	45–77	68.06	9.75



Fig. 1. The Highly Immersive Kinematic Experimental Research (HIKER) laboratory at The University of Leeds.



Fig. 2. The participant waiting to cross the road between the two approaching vehicles in the virtual environment.

participant variable: participants' age (younger/older).

[Table 2](#) shows the range of behaviors, time of day and eHMI combinations experienced by the two age groups. Each of these was presented at both speeds and both time gaps, leading to four kinematic variations in total. The kinematic variations were repeated twice for the non-decelerating trials, to achieve an even number of decelerating and non-decelerating trials. This was so that the crossing decisions were not biased toward a condition that was more likely to happen. Each participant experienced two repetitions of each trial, resulting in 32 trials in the daytime block and 32 trials in the nighttime block. The order of these 32 trials was randomized differently per participant within each block. The order of the day/night blocks was counterbalanced across participants using the Latin square approach. A 'failure trial' was added at the end of each block, where participants were presented with a non-decelerating approaching vehicle displaying an eHMI traveling at 30 mph, with a 3 s time gap between the approaching vehicles. Participants had been informed that the presence of the eHMI was supposed to indicate a stopping intention (see [Section 2.4](#)). This led to a total of 33 trials in each block. The effect of these independent variables on crossing behaviors, such as crossing decisions and crossing initiation time, was analyzed.

a. eHMI and vehicle behaviors.

The vehicle behavior and eHMI used in this study were the same as [Lee et al. \(2022\)](#). Light-based eHMIs are commonly seen on vehicles (i.e., turn indicators, warning lights, and brake lights), and are considered the most appropriate form of eHMI as they avoid the issues of visibility

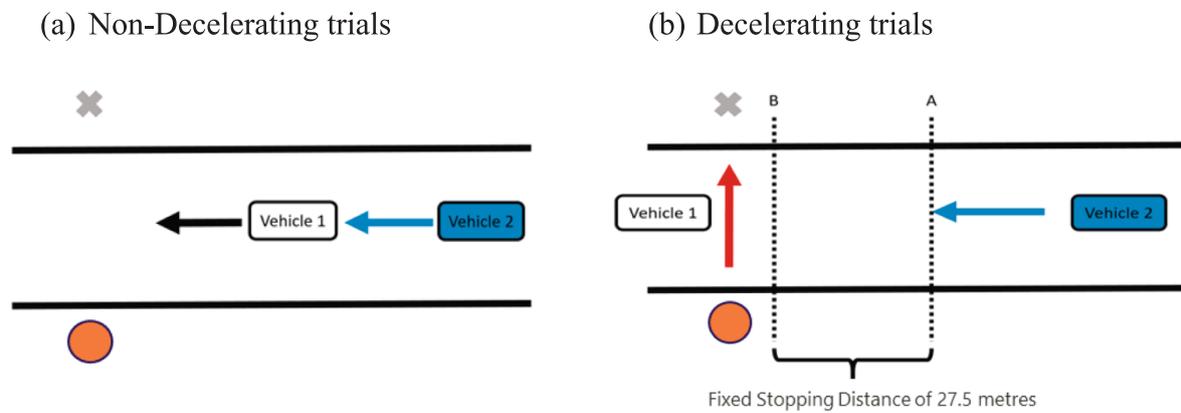


Fig. 3. A schematic of the deceleration procedure used in this study. The orange dot depicts the pedestrian standing at the edge of the road, waiting to cross between the approaching vehicles (Vehicle 1 and Vehicle 2). The grey X indicates bollards which guide pedestrians during their intended crossing, a path depicted by the red arrow. During the decelerating trials, Vehicle 2 started to decelerate at Point A, 30 m from the crossing path and stopped at Point B, 2.5 m from the crossing path. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

The combination of deceleration behavior/eHMI/time of day was presented to the two age groups.

Initial conditions and repetitions	Daytime block Behavior		Nighttime block Behavior	
	Behavior	eHMI	Behavior	eHMI
2 speeds x 2 gaps x 2 repetitions = 8 trials	Decelerating	Present	Decelerating	Present
2 speeds x 2 gaps x 2 repetitions = 8 trials	Decelerating	Absent	Decelerating	Absent
2 speeds x 2 gaps x 4 repetitions = 16 trials	Non-Decelerating	Absent	Non-Decelerating	Absent
The 33rd trial	Non-Decelerating	Present	Non-Decelerating	Present
	Decelerating		Decelerating	

that arise with text or icon-based eHMIs on a fast-moving vehicle (Clamann et al., 2017). The eHMI, a slow pulsing light band (SPLB), was developed as part of the interACT project (Weber et al., 2019), consisted of a 360° cyan light band placed around the windscreen and top of the vehicle (see Fig. 4), and presented at a pulsation rate of 0.4 Hz.

Each trial involved the approach of two vehicles from the participant’s right (white, followed by blue), at two different speeds, and two different time gaps (Fig. 3a). For the non-decelerating trials, the second vehicle did not decelerate, and the two approaching vehicles continued to drive past the pedestrian, at their initial speed of 25 or 30 mph. For the decelerating trials, the second approaching vehicle started to

decelerate when it was 30 m away from the pedestrian (Point A in Fig. 3b) and stopped 2.5 m away from the pedestrian (Point B in Fig. 3b). This created the same stopping distance for all trials, with a deceleration rate of 2.3 and 3.3 m/s², for the 25 and 30 mph conditions, respectively. When the eHMI was present, it was activated at the same time as the vehicle started decelerating.

b. Daytime and Nighttime The daytime stimuli in the current study were the same as the ones created by Lee et al. (2022), with the ‘Global Illumination’ within Unity set at 12:00 pm. The nighttime environment was created by setting the ‘Global Illumination’ in Unity to 12am, and switching ‘On’ the streetlights and the cars’ headlights.

2.4. Procedure

On arrival, participants were provided with a written description of their task in the information sheet and the opportunity to ask any questions. They then signed the consent form indicating that they were willing to take part in the study (Fig. 5.).

Before the experiment, participants were equipped with eye and head trackers, which were calibrated. Their comfortable walking speed without the influence of the approaching vehicle was collected at the beginning and the end of the experimental crossing blocks. One trial was collected in the daytime environment and one in the nighttime environment, to allow an investigation of any mobility change between the beginning and end of the experiment, for each individual and age group

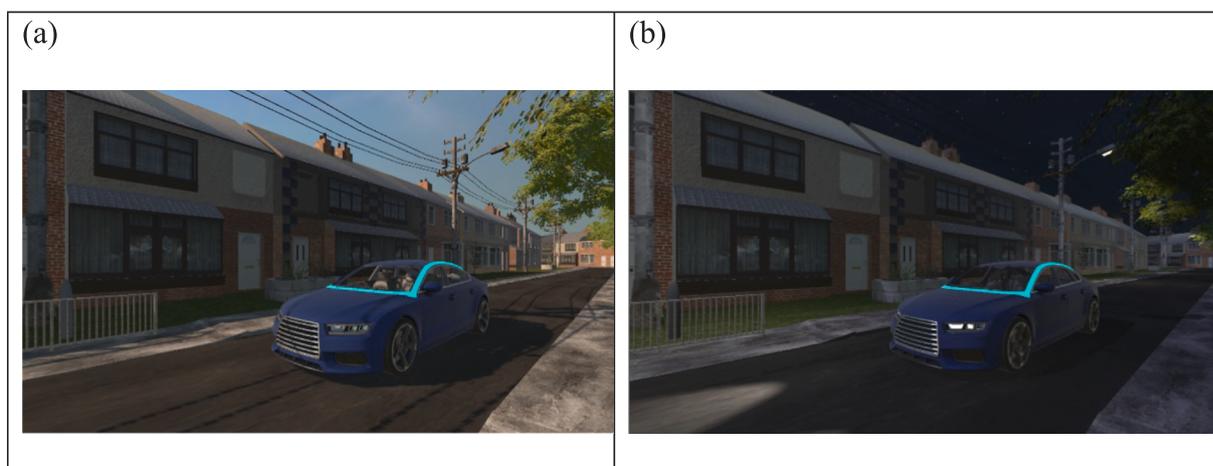


Fig. 4. A vehicle equipped with a Slow Pulsing Light Band in the daytime (a) and the nighttime (b) environment.

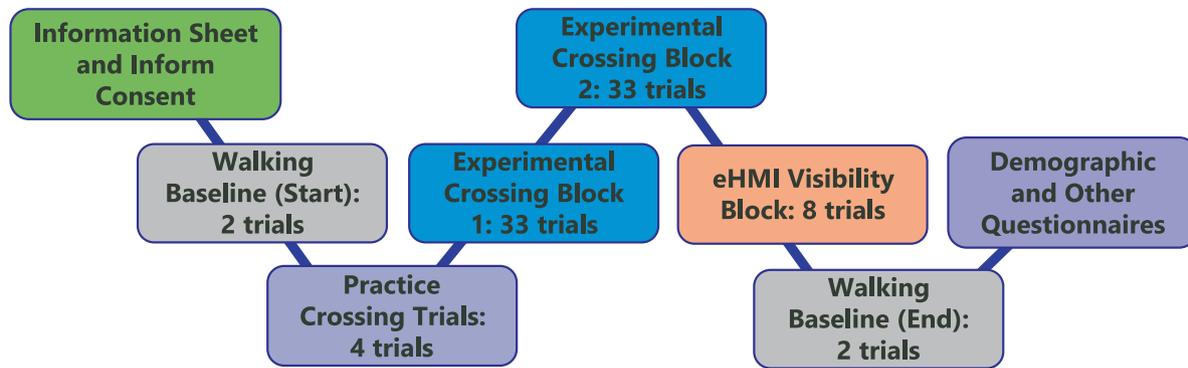


Fig. 5. A schematic of the procedure.

(see Wang et al., 2024 for more information).

A practice block with both daytime and nighttime environments was also presented to ensure that participants understood the task instructions and to familiarize them with the virtual environment. The practice block and the experimental block had the exact same task description, which was written in the Information Sheet as follows:

‘You will begin by standing at the edge of the road when you are ready, and you will have to press a button on the controller to trigger the trial. You will then see two cars approaching from the right. Your task is to cross (or decide not to cross) between the two approaching cars (pictures were provided). Please cross naturally when you feel comfortable to do so, such as you would in real traffic. If you cross the road before the second car arrives, we will want you to rate afterwards how safe this road crossing situation felt to you.’

In this study, they were informed that the presence of the cyan color SPLB indicated that the approaching vehicle was providing the message ‘I am yielding.’

If participants crossed the road between the approaching vehicles, they were asked to give their perceived safety rating from 1 to 4, to indicate their agreement with the following statement: ‘I felt safe during this road crossing situation, both while standing and walking,’ where 1 = ‘Disagree,’ 2 = ‘Mostly disagree,’ 3 = ‘Mostly agree,’ and 4 = ‘Agree.’ They then walked back to the starting point and triggered the next trial. If they did not cross the road, they were asked to press the button to trigger the next trial. Each block took approximately 15 min to complete, with a short break between the blocks.

After the experimental crossing block, another block was added to investigate the visibility of eHMI in the simulated daytime and nighttime environments. In this block of trials, the vehicles again approached participants at two speeds, with two time gaps, in both daytime and nighttime environments. Instead of crossing the road, participants were asked to press a button on the hand-held controller as soon as they saw the eHMI. The distance of the approaching vehicle to the pedestrian was recorded when the button was pressed.

Finally, a questionnaire was administered, asking for demographic information (i.e., age, gender, years living in the UK) and questions about the experiment, such as what information they used to decide to cross, and whether and how the time of day and eHMI affected their crossing.

2.5. Dependent variables

Similar to the previous studies (e.g., Lee et al., 2022), both objective measures and subjective measures were included as dependent variables in the experimental design. To understand pedestrians’ crossing behaviors, this study specifically investigated participants’ crossing decisions, with the binary outcome of cross or not cross. In addition, to investigate how long it took participants to initiate crossing in each condition, participants’ Crossing Initiation Time was also included in the analyses. Finally, to investigate participants’ perceived safety in each

crossing trial, they provided their rating from 1 to 4 indicating how safe they felt.

3. Results

A total of 3,036 trials (46 participants x 66 trials) were conducted across the experimental blocks. The 33rd trial of each day and night block, in which eHMI was presented on a non-decelerating approaching vehicle, was excluded from the analyses under Sections 3.1 and 3.2, but is presented in 3.3. Therefore, 2,944 trials were analyzed to investigate participants’ crossing decisions, crossing initiation time, and their perceived safety in trials where they crossed. The decelerating and non-decelerating trials were analyzed separately.

3.1. Non-decelerating condition

a. Crossing Decision

As the crossing decision measure was a binary dependent variable (cross vs. not cross), a Generalised Linear Mixed Model with binomial link function (glmer() package in R) was used to analyze the data (Stroup, 2012). This type of model is also suitable here due to its ability to handle repeated measures (Stroup, 2012). In this GLMM, the fixed effects were Age Group (young/old), Time of Day (day/night), Time Gap (3 s/5 s), and Speed (25 mph / 30 mph), whereas participant ID was included as a random effect variable (Table 3).

Results showed that pedestrians were more likely to cross when the approaching vehicles were traveling at 30 mph than 25 mph, $p < 0.001$ (OR = 2.23, 95% CI [1.43, 3.47]). Pedestrians were more likely to cross in the 5-second time gap than in the 3-second time gap condition, $p < 0.001$ (OR = 480, 95% CI [183.66, 1254.29]). They were also more likely to cross in the daytime than nighttime conditions, $p = 0.022$ (OR = 0.60, 95% CI [0.39, 0.93]). However, age group was not a significant predictor of crossing decision, $p = 0.625$ (OR = 2.30, 95% CI [0.08, 64.36]).

b. Crossing Initiation Time.

Crossing Initiation Time (CIT) was measured as the time taken for

Table 3
Crossing Decision for non-decelerating trials.

	Estimate	Std. Error	p-value	
Intercept	-6.46	1.457	< 0.001	
Age Group	0.832	1.701	0.625	
Speed	0.801	0.226	< 0.001	*** 25 mph (32.88%); 30 mph (37.36%)
Time Gap	6.174	0.49	< 0.001	*** 3-second (14.40%); 5-second (55.84%)
Time of Day	-0.51	0.223	0.022	* daytime (36.55%); nighttime (33.70%)

participants to start crossing the road after the rear end of the first vehicle had passed the crossing point (Lee et al., 2022; Lee et al., 2019; Lobjois & Cavallo, 2007; Lobjois & Cavallo, 2009). Due to CIT being a continuous variable, a Linear Mixed Model (lmer) package in R) with a Gaussian identity link was used to investigate factors that predict CIT. Age group, Time of Day, Time Gap, and Speed were included as fixed effects, and participant ID was included as a random effect. Given that Age Group and Time of Day were the main variables of interest in this study, two-way interactions between Age Group and all other variables, and Time of Day and all other variables were also included in the model (Table 4). The conditional R-squared was 0.75, showing that the fixed and random effects together explained 75% of the variance.

Older pedestrians showed a significantly shorter CIT than younger, $p = 0.018$ (OR = 1.27, 95% CI [1.05, 1.53]). Pedestrians showed shorter CIT when the approaching vehicles traveled at 25 mph than at 30 mph, $p < 0.001$ (OR = 1.13, 95% CI [1.08, 1.19]), and shorter CIT at a 3-second time gap than at a 5-second time gap, $p < 0.001$ (OR = 1.30, 95% CI [1.21, 1.40]). No other significant effects were found.

c. Perceived Safety.

The same model that was used to investigate CIT was deployed for Perceived Safety (PS) ratings (Table 5). The conditional R-squared was 0.69, showing that the fixed and random effects together explained 69% of the variance. Older pedestrians felt significantly safer than younger pedestrians, $p = 0.011$ (OR = 0.47, 95% CI [0.27, 0.83]). Pedestrians felt safer crossing at a 5-second time gap than at a 3-second time gap, $p < 0.001$ (OR = 4.57, 95% CI [3.44, 6.07]). There was an interaction between Age Group and Time Gap, $p = 0.03$ (OR = 1.42, 95% CI [1.04, 1.95]). As can be seen in Fig. 6a, there was a bigger discrepancy in perceived safety between younger and older pedestrians in the 3-second time gap condition than in the 5-second time gap condition. There was also an interaction between Age Group and Time of Day, $p = 0.029$ (OR = 1.29, 95% CI [1.03, 1.62]): Fig. 6b shows a difference in perceived safety between day and night for younger pedestrians, but not for older pedestrians. Conversely, the discrepancy between younger and older pedestrians in perceived safety was more prominent in daytime conditions than in nighttime.

3.2. Decelerating condition

In the decelerating trials, pedestrians crossed 100% of the time because the vehicles waited indefinitely. Therefore, in this section, the focus is on analyzing Crossing Initiation Time and Perceived Safety

Table 4
Crossing Initiation Time of non-decelerating condition.

	Estimate	Std. Error	p-value	
Intercept	0.173	0.08	0.036	
Age Group	0.237	0.096	0.018	* younger (M = 0.50, SD = 0.24); older (M = 0.44, SD = 0.24)
Speed	0.124	0.027	< 0.001	*** 25 mph (M = 0.44, SD = 0.26); 30 mph (M = 0.50, SD = 0.28)
Time Gap	0.264	0.036	< 0.001	*** 3-second (M = 0.38, SD = 0.24); 5-second (M = 0.56, SD = 0.28)
Time of Day	-0.04	0.038	0.3	
Age Group x Speed	-0.031	0.029	0.287	
Age Group x Time Gap	-0.064	0.04	0.11	
Age Group x Time of Day	-0.015	0.029	0.61	
Time of Day x Speed	-0.016	0.027	0.566	
Time of Day x Time Gap	-0.007	0.034	0.835	

Table 5
Perceived Safety of non-decelerating condition.

	Estimate	Std. Error	p-value	
Intercept	2	0.243	< 0.001	
Age Group	-0.756	0.288	0.011	* younger (M = 2.46, SD = 0.77); older (M = 3.72, SD = 0.96)
Speed	0.034	0.108	0.75	
Time Gap	1.519	0.145	< 0.001	*** 3-second (M = 1.84, SD = 0.87); 5-second (M = 3.35, SD = 0.86)
Time of Day	-0.213	0.155	0.169	
Age Group x Speed	0.174	0.116	0.134	
Age Group x Time Gap	0.352	0.161	0.03	* Fig. 6a
Age Group x Time of Day	0.253	0.116	0.029	* Fig. 6b
Time of Day x Speed	0.101	0.11	0.361	
Time of Day x Time Gap	-0.207	0.139	0.137	

rating. Similar to previous studies, a bimodal crossing pattern emerged in decelerating conditions (e.g., Lee et al., 2022; Giles et al., 2019; Lee et al., 2019; Markkula et al., 2020) (Fig. 7). As presented in Fig. 7, a higher density can be observed in the first peak of crossing at higher time gaps (5 s), and this effect is more pronounced at 30 mph.

Due to the bimodality, the CIT analyses for the scenarios with deceleration were done separately for the first peak (early crossing) and the second peak (late crossing). Early crossing was defined as any crossing initiated before the vehicle had decelerated to two-thirds of its initial speed. This point in time is indicated with black dotted vertical lines in Fig. 7. As can be seen, this criterion works well for separating the two clusters of crossing initiation across all four kinematical variations of the decelerating scenario.

a. Crossing Initiation Time.

When analyzing CIT in these early and late crossings, the same fixed effects variables, random effects, and two-way interactions were included as in the non-deceleration analysis, with the presence of eHMI as an additional fixed effects variable, and Age Group x eHMI and Time of Day x eHMI as additional two-way interactions. The conditional R-squared for the early crossing and late crossing models were 0.60 and 0.71, respectively, showing that the fixed and random effects together explained 60% and 71% of the variance, respectively.

Table 6 provides a summary of the results on early and late crossing.

For early crossing, CIT was significantly shorter at a 3-second than at a 5-second time gap, $p < 0.001$ (OR = 1.26, 95% CI [1.15, 1.39]). CIT was also shorter at 25 mph than at 30 mph, $p < 0.001$ (OR = 1.14, 95% CI [1.06, 1.22]).

For late crossing, younger pedestrians showed significantly shorter CIT than older pedestrians, $p = 0.002$ (OR = 0.37, 95% CI [0.20, 0.68]). CIT was also shorter at a 3-second than a 5-second time gap, $p < 0.001$ (OR = 7.61, 95% CI [5.97, 9.71]). CIT was significantly shorter in daytime than nighttime, $p < 0.001$ (OR = 1.62, 95% CI [1.25, 2.10]); and also shorter with the presence of eHMI than without, $p < 0.001$ (OR = 0.65, 95% CI [0.52, 0.81]).

In addition, there was a significant interaction between Age Group and Speed, $p < 0.001$ (OR = 1.53, 95% CI [1.21, 1.94]). Fig. 8a shows that vehicle speed affected younger pedestrians' CIT but not older pedestrians. Finally, there was a significant interaction between the Time of Day and eHMI, $p = 0.011$ (OR = 0.74, 95% CI [0.59, 0.93]). Fig. 8b shows that CIT was higher for nighttime than daytime only when there was no eHMI.

To explore this further, we conducted an LMM to investigate the

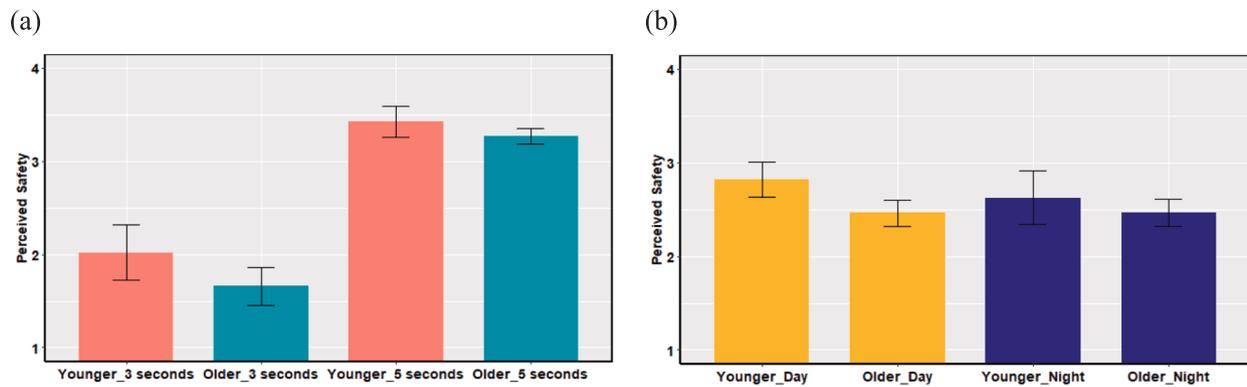


Fig. 6. (a) Interaction between Age Group and Time Gap on Perceived Safety for Non-decelerating condition. (b) Interaction between Age Group and Time of Day on Perceived Safety for Non-decelerating condition.

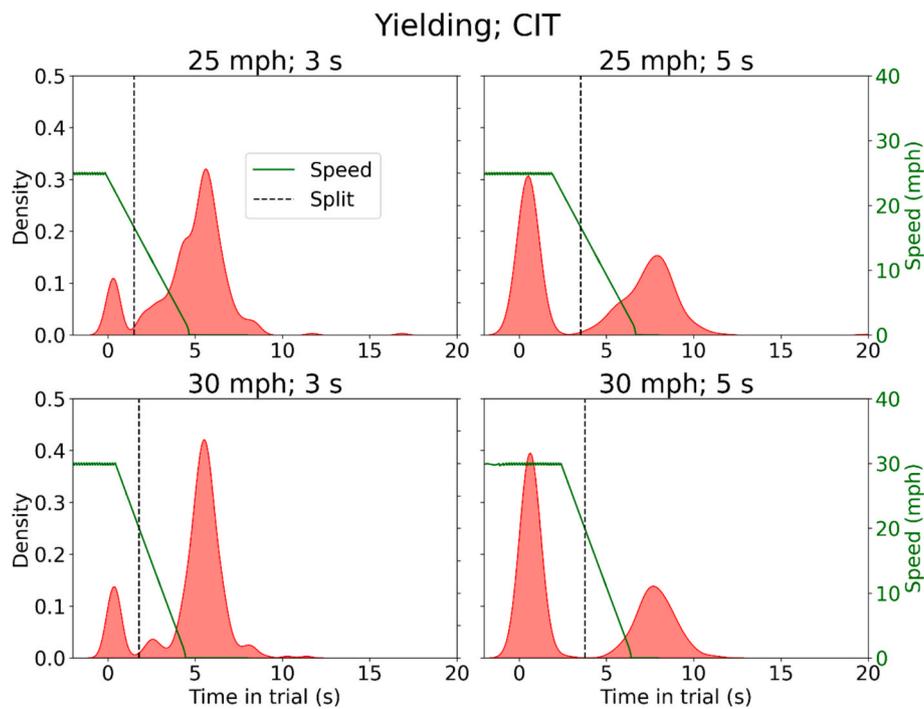


Fig. 7. The bimodal crossing patterns for each speed and time gap combination.

distance at which eHMI became visible in the simulated daytime and nighttime environment for younger and older pedestrians. The model showed no significant effect of age group ($p = 0.638$), time of day ($p = 0.264$), or interactions between both ($p = 0.939$), suggesting that eHMI visibility is not the cause of any group differences in CIT.

b. Perceived Safety.

Perceived Safety (PS) ratings were investigated using the same models that were used to investigate CIT (Table 7). The conditional R-squared for the early crossing and late crossing models were 0.59 and 0.66, respectively, showing that the fixed and random effects together explained 59% and 66% of the variance, respectively.

For early crossing, PS was significantly higher when pedestrians crossed at a 5-second time gap ($M = 3.44$, $SD = 0.82$) than at a 3-second time gap ($M = 2.60$, $SD = 0.84$), $p < 0.001$ (OR = 3.72, 95% CI [2.83, 4.90]). There was also an interaction between the Time of Day and Time Gap, $p < 0.001$ (OR = 0.61, 95% CI [0.46, 0.80]). Fig. 9a shows a bigger PS discrepancy between 3 and 5-second time gaps during daytime than nighttime.

For late crossing, PS was significantly higher for daytime crossing ($M = 3.51$, $SD = 0.78$) than nighttime crossing ($M = 3.29$, $SD = 0.92$), $p <$

0.001 (OR = 0.75, 95% CI [0.65, 0.87]). There was a significant interaction between Age Group and Time of Day on PS, $p = 0.046$ (OR = 1.15, 95% CI [1.00, 1.31]). Fig. 9b shows that older pedestrians felt less safe, especially during nighttime conditions.

3.3. Inaccurate eHMI trials

Each pedestrian underwent one trial in each daytime and nighttime block where the approaching vehicle presented an eHMI, but did not decelerate (33rd trial of each block). To understand the impact of this inaccurate eHMI trial, we explored the number and percentage of collisions under different conditions. Fig. 10 shows pedestrians' position (jitter dots) in relation to the road (highlighted in grey) when the vehicle arrived at the crossing path, across non-decelerating trials, where vehicles traveled at 3-second time gaps and 30 mph. The orange-highlighted area shows the car's area, and overlaps between the jitter dots and the orange-highlighted area indicate a collision. There was one collision (0.18%) in the older pedestrian with no eHMI condition, compared to no collision in the eHMI condition; there were four collisions (0.43%) in the younger pedestrian with no eHMI condition,

Table 6
Crossing Initiation Time of decelerating condition for early and late crossing.

	Early Crossing				Late Crossing			
	Estimate	Std. Error	p-value		Estimate	Std. Error	p-value	
Intercept	0.183	0.083	0.03		5.904	0.254	< 0.001	
Age Group	0.104	0.099	0.297		-1.005	0.314	0.002	** younger (M = 6.13, SD = 1.04); older (M = 7.21, SD = 1.36),
Speed	0.127	0.036	< 0.001	*** 25 mph (M = 0.40, SD = 0.48); 30 mph (M = 0.48, SD = 0.29)	-0.052	0.111	0.643	
Time Gap	0.233	0.049	< 0.001	*** 3-second (M = 0.32, SD = 0.25); 5-second (M = 0.56, SD = 0.30)	2.03	0.235	< 0.001	*** 3-second (M = 5.48, SD = 1.26); 5-second (M = 7.86, SD = 1.14)
Time of Day	-0.002	0.057	0.969		0.484	0.132	< 0.001	*** daytime (M = 6.59, SD = 1.11); nighttime (M = 6.75, SD = 1.29)
eHMI	0.008	0.036	0.835		-0.434	0.111	< 0.001	*** eHMI (M = 6.38, SD = 1.23); no eHMI (M = 6.96, SD = 1.17)
Age Group x Speed	-0.008	0.039	0.833		0.428	0.12	< 0.001	*** Fig. 8a
Age Group x Time Gap	0.096	0.055	0.081		-0.086	0.137	0.53	
Age Group x Time of Day	-0.05	0.039	0.205		-0.093	0.12	0.438	
Age Group x eHMI	-0.025	0.039	0.522		0.002	0.12	0.989	
Time of Day x Speed	0.022	0.038	0.567		-0.113	0.116	0.329	
Time of Day x Time Gap	-0.038	0.049	0.441		-0.135	0.123	0.269	
Time of Day x eHMI	-0.035	0.038	0.35		-0.296	0.116	0.011	* Fig. 8b

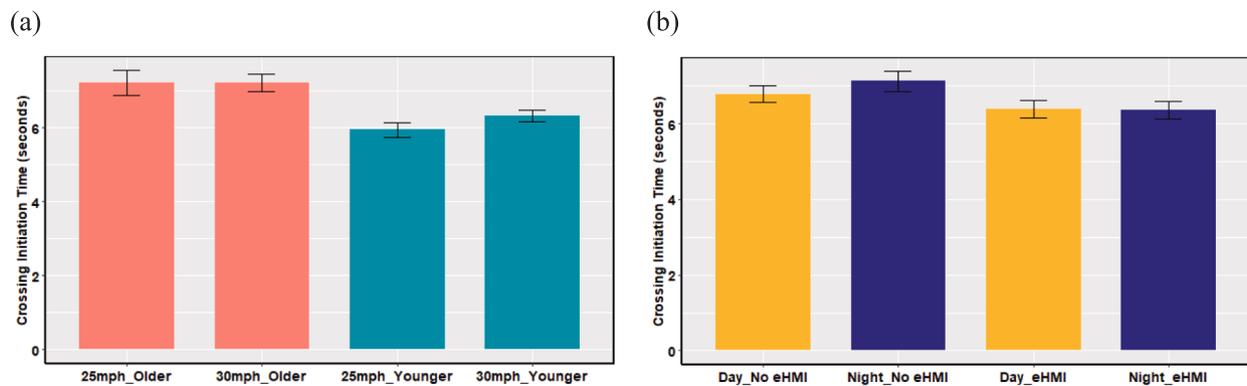


Fig. 8. (a) Interaction between Age Group and Speed on Crossing Initiation Time for Late Crossing. (b) Interaction between Time of Day and eHMI on Crossing Initiation Time for Late Crossing.

compared to one collision (1.72%) in the eHMI condition.

To investigate whether crossing decisions in non-decelerating trials changed as a function of eHMI, age group, and time of day, a GLMM was performed, by including these factors as the fixed effects variables and participants as the random effect variable (Table 8. Crossing Decision for non-decelerating trials). To match the inaccurate eHMI trials, only non-decelerating trials in which the vehicles traveled at 30 mph with an initial time gap of 3 s were included in the model. Although the time of day was counterbalanced, to be thorough, we also included the ‘Block’ as a fixed effect and investigated its interaction with time of day in the model. Results revealed no significant main or interaction effects, showing that there was no significant effect of the inaccurate eHMI on pedestrian crossing decisions.

3.4. Questionnaires

a. What information did you use to cross in the experiment?

After completing the experiment, participants completed an open-ended questionnaire about their experiences during the experiment.

Firstly, they were asked about the information used when crossing. The percentage of participants who mentioned specific information was computed by dividing the number of younger/older pedestrians who mentioned each factor, over the total number of younger/older participants who took part in the study. Since participants could mention more than one piece of information, the total percentages for each group are larger than 100%. The five most common answers were Speed (N = 33: 22 younger, 11 older), Distance (N = 24: 17 younger, 7 older), Gap (N = 17: 11 younger, 6 older), Stop (N = 12: 8 younger, 4 older), and eHMI (N = 5: 4 younger, 1 older) (Fig. 11). In addition, there was some information mentioned by the younger participants only, such as Time to Arrival (TTA) (N = 3, 10.34%), the Bend in the scenario (N = 2, 6.90%), Yielding (N = 2, 6.90%), Time of Day (N = 1, 3.45%), and one participant mentioned that there was no driver in the car (N = 1, 3.45%). Finally, there was also some information mentioned by the older participants only, such as Intuition and Experience (N = 2, 11.76%), ‘Engine Wheel’ (N = 1, 5.88%), Zebra Crossing (in real life) (N = 1, 5.88%), and length of the road (N = 1, 5.88%).

b. Did the time of day affect your crossing?

Table 7
Perceived Safety of decelerating condition for early and late crossing.

	Early Crossing				Late Crossing		
	Estimate	Std. Error	p-value		Estimate	Std. Error	p-value
Intercept	2.145	0.235	< 0.001	3.435	0.178	< 0.001	
Age Group	-0.007	0.282	0.981	0.108	0.221	0.626	
Speed	0.06	0.105	0.57	-0.057	0.063	0.365	
Time Gap	1.315	0.14	< 0.001	0.067	0.071	0.345	*** 5-second (M = 3.44, SD = 0.82); 3-second (M = 2.60, SD = 0.84)
Time of Day	0.063	0.163	0.701	-0.287	0.075	< 0.001	*** daytime (M = 3.51, SD = 0.78); nighttime (M = 3.29, SD = 0.92)
eHMI	0.122	0.104	0.242	0.11	0.063	0.083	
Age Group x Speed	-0.023	0.114	0.842	-0.106	0.068	0.119	
Age Group x Time Gap	-0.085	0.158	0.593	-0.016	0.775	0.837	
Age Group x Time of Day	0.212	0.158	0.061	0.136	0.068	0.046	* Fig. 9b
Age Group x eHMI	0.047	0.113	0.679	-0.066	0.068	0.332	
Time of Day x Speed	0.103	0.11	0.346	0.059	0.065	0.37	
Time of Day x Time Gap	-0.502	0.141	< 0.001	-0.132	0.069	0.056	*** Fig. 9a (*)
Time of Day x eHMI	0.071	0.11	0.517	0.062	0.065	0.344	

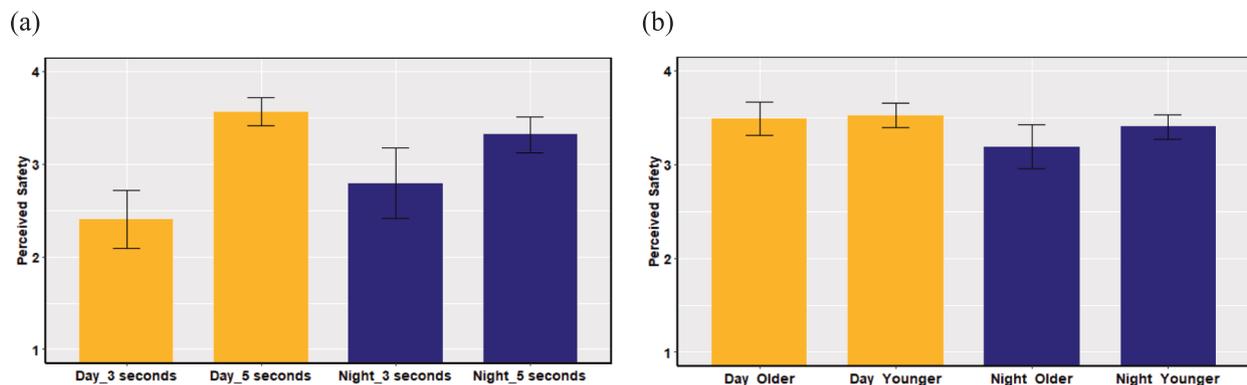


Fig. 9. (a) Interaction between Time of Day and Time Gap on Perceived Safety for Early Crossing. (b) Interaction between Time of Day and Age Group on Perceived Safety for Late Crossing.

Among the 29 younger participants, 11 (38%) answered ‘No’ and 18 (62%) answered ‘Yes.’ Among the 17 older participants, 7 (41%) answered ‘No’ and 10 (59%) answered ‘Yes.’

Two main reasons were provided by participants who felt that the time of day did not affect their crossings. First, they thought whether it was day or night did not affect their perception (N = 10). For example, they stated that they ‘can still see the car,’ it ‘was not that dark,’ it was ‘easy to judge because of the light,’ and ‘the information is the same.’ Secondly, they claimed that they mainly used other information to make crossing decisions (N = 3), such as ‘will cross only the car stop,’ ‘only cross when feel safe,’ and ‘depend on car.’

Three main reasons were identified by participants who felt that the time of day affected their crossing decisions. The most commonly given reasons linked to participants’ feelings of safety while crossing in the nighttime environment, which was mentioned by 16 participants (10 younger, 6 older). Quotes included ‘it’s safer in the daytime, not so much different in the end, adapt to the night,’ ‘more hesitation at night,’ ‘daytime is safer,’ ‘felt dangerous at night,’ ‘confident during day,’ and ‘more cautious during night.’ The second reason participants provided was that time of day affected their vision (N = 7: 5 younger, 2 older). Participants mentioned that ‘at night, it’s hard for the car to see pedestrians,’ ‘Day – see better, Night – driver cannot see well, thus walk

faster,’ and ‘better vision at day time.’ Finally, six participants (4 younger, 2 older) wrote about the effect of eHMI and lighting being clearer at night (e.g., ‘blue light clearer at night’), ‘almost same except the measure of eHMI,’ and ‘at start, light makes car more obvious at night, so more confidence.’

c. Did the eHMI affect your crossing?

Among the 29 younger participants, 10 (34%) answered ‘No’ and 19 (66%) answered ‘Yes.’ Among the 17 older participants, 7 (41%) answered ‘No’ and 10 (59%) answered ‘Yes.’

Three main reasons were provided by participants who answered no. The first was that they used kinematics/other information to decide on crossing instead (N = 6). For example, ‘Mainly depend on whether the car stop’ (similar statements provided by 5 participants) and ‘Depend on driver mostly.’ The other reason was that they did not trust the eHMI (N = 6), and they were not familiar with the eHMI (N = 3).

For participants who answered yes, there were variations of how they interpreted the eHMI, despite having been told that it conveyed ‘I am yielding.’ Younger participants seemed to have a more direct interpretation of what the eHMI was conveying, such as ‘Will decelerate’ (N = 3), ‘Will stop’ (N = 8), and ‘Detecting me’ (N = 2). For older participants, their interpretations were more vague (N = 3), such as ‘Blue light gives information,’ ‘It is an indicator and helps judge the

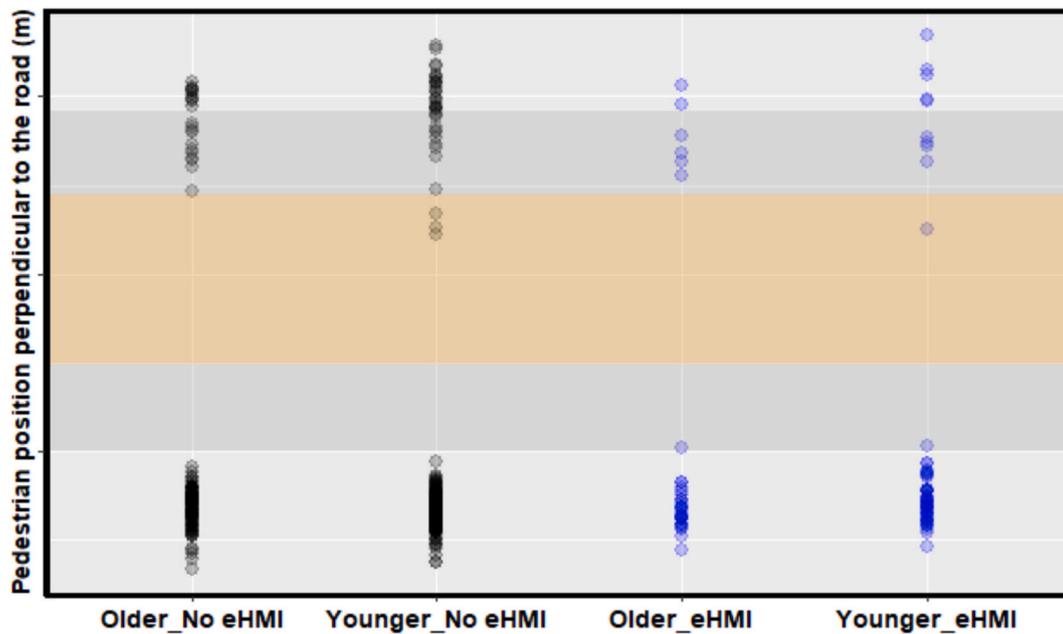


Fig. 10. Pedestrians’ position in relation to the road when the vehicle arrived at the crossing path, comparison between age group and the presence of eHMI, when the approaching vehicle travels without deceleration at 3-second time gaps and 30 mph. The grey highlighted area represents the road, and the orange highlighted area represents the area of the car. Jitter dots represent pedestrians in each trial; the bottom group are pedestrians who did not cross the road, and the upper group are pedestrians who did cross the road. Please note that there were uneven numbers of trials under each condition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 8

Crossing Decision for non-decelerating trials where vehicles travelled at 30mph with a 3-second initial time gap.

	Estimate	Std. Error	p-value
Intercept	-8.54	6.78	0.208
Age Group	0.048	1.75	0.978
eHMI	0.525	0.537	0.328
Time of Day	-9.699	12.15	0.425
Block	0.147	1.754	0.933
Time of Day x Block	2.527	3.451	0.464

second car,’ and ‘can give notice.’ Two participants mentioned that the blue light helps increase the visibility of the car, such as ‘See better →

judge distance’ and ‘visibility increase, but still depend on cars stop or not.’

Some participants also mentioned that they felt safer or more confident with the presence of eHMI (N = 5: 2 younger, 3 older), with one older participant elaborating further with ‘but not sure after light on but car not stop.’ Finally, there were some negative statements about the eHMI (N = 3: 1 younger, 2 older) such as ‘a little bit misleading,’ ‘distraction, don’t like it,’ and ‘when the blue light is on, I will decide not to cross if it is close to me.’

4. Discussion

In this study, we investigated the effect of time of day (daytime, nighttime), speed (25mph, 30 mph), time gap (3 s, 5 s), deceleration

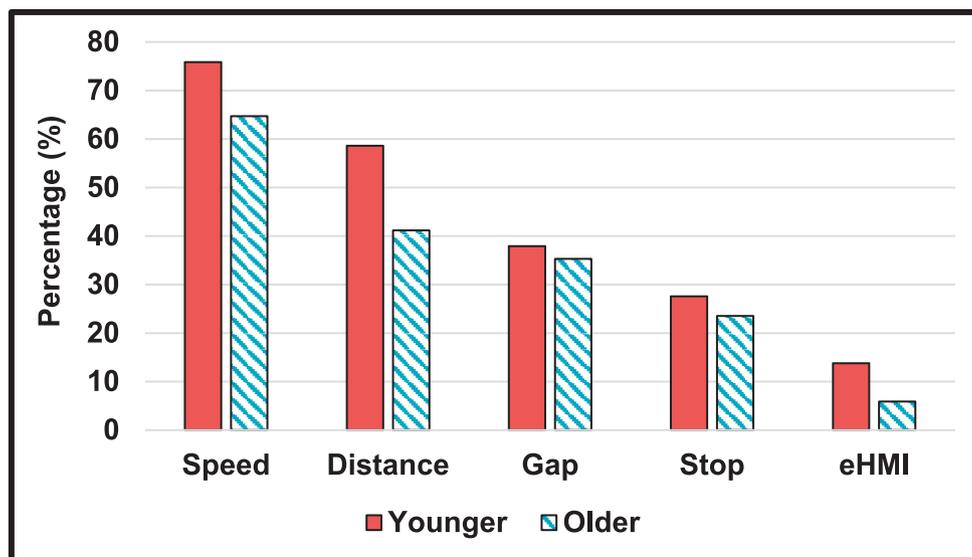


Fig. 11. The most common information used to make crossing judgment reported by younger and older pedestrians.

behavior (decelerating, non-decelerating), and presence of eHMI during deceleration (eHMI, no eHMI) on both younger and older pedestrians' crossing behaviors (i.e., crossing decision, crossing initiation time, perceived safety) in a cave-based pedestrian simulator.

This study replicated the effects of time gap and speed on crossing behavior. When AVs were not decelerating, the crossing percentage increased as a function of time gaps and speed (e.g., Lobjois & Cavallo, 2007; Lobjois & Cavallo, 2009; Dommes et al., 2021). Pedestrians initiated their crossing earlier if they crossed at smaller time gaps and at higher speeds, showing a compensation phenomenon (Dommes et al., 2021). Similar to previous pedestrian crossing studies, when the AVs were decelerating, a bimodal distribution crossing pattern was observed (e.g., Lee et al., 2022; Giles et al., 2019; Lee et al., 2019; Markkula et al., 2020).

4.1. Effects of time of day

Overall, our study demonstrated that pedestrians showed more cautious behavior in the nighttime than in the daytime environment. In line with Bindschadel et al. (2021), our results showed that when AVs were not decelerating, pedestrians were more likely to cross in the daytime than in the nighttime environment. Moving beyond most of the previous studies, we found that when AVs were decelerating, CIT was also shorter for daytime than nighttime. It is challenging to assess how much of this effect stemmed from the difficulty of interpreting kinematic cues at night, since such information may rely more on the saliency of vehicle headlights than on the vehicle body, as is typically the case during the daytime (Balasubramanian & Bhardwaj, 2018). Pedestrians reported feeling a sense of danger and being more cautious and hesitant in the nighttime, but feeling safer and more confident in the daytime. However, there were contradictory evaluations of the effect of time of day on participants' vision, with some participants claiming that the lighting provided in the nighttime environment helped their vision, while others reported that the general nighttime environment made it harder for them to see. These explanations support the mixed findings from previous studies (e.g., Lee & Sheppard, 2018; Kalatian & Farooq, 2022; Rasouli & Tsotsos, 2019; Ackermann et al., 2019; Subramanian et al., 2022; Bindschadel et al., 2021), and that the effects of time of day on behavior could boil down to individual differences in perception, as well as their everyday experience that leads to different attitudes toward the nighttime environment. The simulated virtual environment may not represent how vehicle lighting would appear in the real world, due to the rendered light sources (e.g., LEDs and headlights) being different on a computer screen (e.g., Ghosh et al., 2005). However, the results demonstrate that pedestrians were able to project their feelings and associate with the environment, showing the capability of such simulation.

4.2. Effect of Age

Our results demonstrated that older pedestrians adopted different crossing strategies compared to younger pedestrians and generally felt less safe. When AVs were not decelerating, older pedestrians initiated their crossing earlier than the younger pedestrians. This finding is in line with Lobjois and Cavallo (2009), who also demonstrated that older adults initiated their crossing sooner than younger adults, attempting to compensate for their need for a longer time to make the crossing, known as the compensation phenomenon (see also Dommes et al., 2021). In addition, older pedestrians showed lower perceived safety ratings than younger pedestrians, especially when they crossed at the 3-second time gaps compared to 5-second time gaps. These low ratings were not affected by time of day. This shows that despite the presence of the compensation phenomenon, older pedestrians still felt less safe than younger pedestrians in both day and nighttime. There was a bigger discrepancy in perceived safety between age groups during daytime than at nighttime, showing that younger pedestrians provided much

higher safety ratings during the daytime than the older pedestrians.

Overall, our results showed that older pedestrians were more cautious than younger pedestrians. Similar to previous studies, in the AV deceleration trials, a bimodal crossing pattern was observed (e.g., Lee et al., 2022; Giles et al., 2019; Lee et al., 2019; Markkula et al., 2020), whereby pedestrians either crossed immediately once a gap became available or waited until it was very clear that the vehicle was coming to a stop. While there were no differences in the crossing initiation times of younger and older pedestrians who decided to cross the moment a gap became available in the deceleration trials, in the situations where pedestrians decided to wait until the deceleration/yielding intention became prominent, older pedestrians initiated their crossing later than younger pedestrians. The opposite occurred during the non-decelerating trials, showing that if older pedestrians decided to take a higher risk and accept a gap, they would compensate by initiating the crossing earlier, but if they decided to wait, they would take a more cautious approach than younger pedestrians (see also Nicholls et al., 2024), making sure the deceleration became very prominent before crossing.

Older pedestrians were also unaffected by speed, whereas younger pedestrians had a shorter CIT for 25 mph than 30 mph. Perhaps older pedestrians had difficulty calibrating their behavior according to the perception of speed information in decelerating trials (see Lobjois & Cavallo, 2009 on the effect of time gaps), or perhaps, once they had decided to wait, they preferred being more certain about their decision. Older pedestrians provided particularly low perceived safety ratings during nighttime crossings, showing the greater risks associated with nighttime walking for this group.

Overall, these findings provide new insights into the challenges that older pedestrians face, which were amplified by the nighttime environment. Future road safety interventions should help older pedestrians feel safer crossing, especially during nighttime. AV communication should be designed with inclusivity in mind, with research efforts focused on gathering the thoughts and taking into account the needs of older pedestrians, who are likely to be different from younger pedestrians.

4.3. Effect of eHMI

When AVs were decelerating, CIT was shorter with eHMI than without eHMI for the pedestrians who decided to wait until the deceleration became more prominent (late crossers). This finding was in line with previous studies, which showed that eHMI decreased CIT (e.g., Madigan et al., 2023; Lee et al., 2022; Bindschadel et al., 2021; Kaleefathullah et al., 2020; Holländer et al., 2019). Reduced CIT can be interpreted as either favorable or harmful to safety. When it provides an indicator that pedestrians understood the intention and trusted the AV, this could benefit efficiency, leading to a favorable outcome; whereas the potential for overreliance on eHMI leading to reduced caution in making safety judgments, can lead to a negative outcome (Petzoldt et al., 2018; Holländer et al., 2019; Kaleefathullah et al., 2020; Lee et al., 2022). The lack of interaction between eHMI and age group showed that the eHMI had the same effect on pedestrians, regardless of age. There were also no significant differences in the distance at which the eHMI became visible for younger and older pedestrians. However, the self-report data showed that younger and older pedestrians interpreted the eHMI very differently and had different opinions on how it affected their crossing decisions, despite being informed of what the eHMI was conveying at the beginning of the study. Older pedestrians interpreted eHMI more generally, suggesting that eHMI provided information and a visual aid to increase visibility. On the other hand, younger pedestrians interpreted eHMI with various 'incorrect' direct interpretations, such as 'Will stop' and 'Detected me.' It is challenging to determine the factors that contribute to such a difference in interpretation. Perhaps, it may be that older pedestrians are more cautious in their use of novel signals, whereas younger pedestrians are more confident and comfortable with new technologies (Brill et al., 2024).

This study also found that the presence of eHMI diminished the discrepancy in CIT between daytime and nighttime, showing the usefulness of eHMI in aiding crossing decisions, especially during nighttime. Although not reflected in the analysis of eHMI detection times during daytime and nighttime, participants' questionnaire responses stated that the eHMI became more prominent during nighttime, and helped with their crossing decisions. Evidence from previous studies showed an increase in subjective experience (e.g., perceived safety, acceptance) while crossing in front of AVs with eHMI (Holländer et al., 2019; Bindschadel et al., 2021). Although eHMI did not increase the perceived safety rating in this study, pedestrians generally felt less safe in the nighttime environment.

Although the findings were not significant, results showed that younger participants were more likely to be affected by an inaccurate eHMI, leading to a higher collision rate. Overall, the risks of the inaccurate eHMI were much lower than those obtained in previous studies (Kaleefathullah et al., 2020), suggesting future research is required to understand the impact of factors such as eHMI onset, visibility and crossing scenario.

This study had a few limitations or caveats. First, the older participants who took part in this study were capable of attending a 1.5-hour experiment that involved constant walking. Therefore, they may be considered a relatively fit group within the older population, and thus, caution should be taken when generalizing the findings. Second, given the number of participants and the complexity of the study design, the imbalance in numbers between the older and younger age groups may have affected the results. However, given the lack of research investigating the experiences of older road users, and the difficulties in accessing this group, the study provides some much-needed insights into the issues likely to be faced by this group when interacting with AVs. Finally, while controlled studies in VR offer valuable insights into causal relationships between variables and outcomes, questions remain regarding the realism of risk perception due to the absence of physical harm. Nonetheless, this study was conducted using one of the world's largest and highest-resolution CAVE-based pedestrian simulators, which has demonstrated good relative validity (Kalantari et al., 2023), though not identical to naturalistic datasets.

5. Conclusions and recommendations

This study extends our knowledge of how older pedestrians cross the road in front of an AV, in both daytime and nighttime, and how this is influenced by the presence of an eHMI. In summary, we found that if older pedestrians accepted a riskier time gap and speed, they compensated for their longer crossing duration by initiating their crossing earlier. However, if they decided to wait until the deceleration was more prominent, they would wait longer than the younger pedestrians. Generally, pedestrians reported feeling less safe and behaving more cautiously during nighttime crossings. This effect was more prominent for older pedestrians, especially when crossing at 3-second time gaps. Although eHMI was interpreted and used differently by younger and older pedestrians, eHMI decreased CIT in both age groups. Pedestrians also reported mixed feelings about how lighting affected their perceptions during daytime and nighttime, but despite there being no difference in objective measures of eHMI visibility at daytime and nighttime, eHMI did diminish the differences between daytime and nighttime crossings.

These results show the importance of taking older pedestrians needs into account to design safer crossing environments, even in current road infrastructure environments. Further research is needed to understand older pedestrians' perspectives on how road infrastructure can be improved to enhance their safety, and in turn improve quality of life and encourage independence. eHMI provides one potential solution, decreasing CIT for both age groups, and also particularly diminishing the time of day effect. However, it did not improve pedestrians' perceived safety ratings, suggesting it did not increase their comfort

around AVs. In addition, it also increased the percentage of crossings when AVs were not decelerating. This two-sided effect of eHMI, where it has the potential for both positive and negative consequences, seems to be emerging in many studies (e.g., Holländer et al., 2019; Kaleefathullah et al., 2020; Lee et al., 2022). Thus, it is important to critically determine the weight of the potential positive and negative impacts before implementing eHMI to communicate yielding.

Finally, it is important to note that the results of this study might be biased towards a more active group of older pedestrians who were able to participate in a 1.5 h crossing study. Future research should try to incorporate a wider range of capabilities in information processing and physical mobility (Nicholls et al., 2024), as these are likely to affect crossing strategies in the real world. A wider range of more complex scenarios should also be considered, including an investigation of cross-cultural differences. In addition, given that most of the previous studies have been focused on communicating yielding, the question remains as to whether there is a need to explicitly convey any other messages. This may be particularly important at night-time, when it may be difficult for pedestrians to interpret kinematic cues. Finally, research should consider the needs of other marginalized groups of pedestrians who may benefit from presenting eHMIs using different forms and modalities.

CRediT authorship contribution statement

Yee Mun Lee: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruth Madigan:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Yueyang Wang:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Jorge Garcia:** Writing – review & editing, Visualization, Software. **Hao Qin:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Aravinda Srinivasan:** Writing – review & editing, Supervision, Investigation. **Gustav Markkula:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Natasha Merat:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

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