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ADAPTING TO COMPLEXITY: LEARNING EFFECTS ON PEDESTRIAN PERCEIVED SAFETY AND UNDERSTANDING OF INTENTIONS DURING INTERACTIONS WITH DRIVERLESS VEHICLES

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ABSTRACT

The deployment of driverless vehicles in urban environments raises concerns about pedestrian safety due to the loss of traditional driver communication cues. This study investigated the subjective crossing experience of young and older adult pedestrians facing two different driverless vehicles in a shared space. In a virtual reality setting, 44 participants (24 young adults and 20 older adults) were asked to cross while a driverless car and a driverless shuttle approached. The complexity of the crossing was manipulated so that the two driverless vehicles either had the same behavior (i.e., both yielding or both passing) or different behaviors (i.e., one yielding, the other passing). Additionally, the two vehicles could both be equipped with an external Human-Machine Interface (eHMI) indicating their respective intention (i.e., to yield or to pass) using visual and sound signals, or had none. After each crossing, the participants rated their perceived safety and understanding of the vehicles' intentions using questionnaires. Semi-structured interviews were conducted post-experiment to gather qualitative feedback on the participants' crossings and the bimodal eHMI. Firstly, our results indicated that the older adults reported better understanding of both the cars and shuttle's intentions than the young adults, likely due to their broader integration of environmental cues. Moreover, a learning effect among the older adults was found, indicating improved understanding of the car's intentions over time when the two vehicles exhibited different behaviors, reflecting preserved learning abilities in normal ageing that support adaptation to complex traffic scenarios. Furthermore, both age groups reported an initial loss of perceived safety when the two vehicles behave differently, which diminished with repeated exposure, suggesting an adaptive learning process in complex traffic scenarios. Finally, the presence of the bimodal eHMI on driverless vehicles demonstrated a positive impact at different levels of the pedestrian crossing experience. These findings are further discussed.

KEYWORDS

Bimodal eHMI, Pedestrian, Ageing, Driverless Vehicle, Learning

1. INTRODUCTION

For many years, French authorities have promoted active transportation and urban sustainability through the development of shared spaces (Cerema, 2014). Shared spaces are urban zones with limited speed wherein vulnerable road users and vehicles move freely (Article R.110-2 of the French Highway Code). Indeed, all road users share space in the absence of sidewalks, pedestrian crossings, or traffic signals. Hence, drivers often express their intentions (e.g., to yield or to continue driving) to pedestrians through non-verbal communication cues such as eye contact or hand gestures for instance (Rasouli et al., 2017, Sucha et al., 2017).

Yet, due to their potential benefits for road safety, traffic flow, and accessibility (Sharma & Zheng, 2021), driverless vehicles (e.g., robotaxis, self-driving shuttles) are expected to become increasingly prevalent in urban traffic. However, the human drivers' social cues are set to disappear with this level of automation, increasing ambiguity in decision-making. Moreover, recent research has shown that even when a human is physically present in an automated vehicle, pedestrians may no longer rely on making eye contact with the passive human inside, highlighting a diminishing reliance on human non-verbal communication as vehicle automation advances (Sahaï et al., 2022). This poses strong risks for pedestrians in shared spaces with highly automated vehicles, given their vulnerability, the lack of formal traffic rules, and the uncertainty about driverless vehicles' intentions. Indeed, such interactions require pedestrians to rapidly assess risks, build accurate mental models of automated vehicle behavior, and maintain high situation awareness (Endsley, 1988).

Implementing external Human-Machine Interfaces (eHMIs) on driverless vehicles could bridge this gap by restoring communication with other road users (Bazilinskyy et al., 2019; De Clercq et al., 2019). However, there is no consensus about the best eHMI signal to emit so far (Dey et al., 2020), highlighting the challenge of designing intuitive and universally understandable signals that suit diverse populations and contexts. The effectiveness of these signals depends not only on their technical capacities but also on the pedestrians' ability to interpret them quickly and accurately, especially in dynamic, multi-vehicle settings.

Indeed, most eHMI research has involved interactions with a single automated vehicle (e.g., De Clercq et al., 2019; Feng et al., 2023; Sahaï et al., 2024) which may fail to reflect the complexity of real-world scenarios involving multiple vehicles. Moreover, individuals aged over 60 are expected to represent 22% of the global population by 2050 (WHO, 2024). As cities evolve to accommodate both automation and an aging population, understanding how these two trends interact becomes critical to creating inclusive urban spaces. Therefore, including older adults in studies of interactions between pedestrians and driverless vehicles is essential to ensure their specific needs are met. This is especially important as older adult pedestrians already face mobility issues due to perceptual and motor deficits (Tournier et al., 2016). In line with this, recent work has shown that aging impairs the ability to detect perceptual information specifying safe crossing, which in turn affects decisions about when and how to act in traffic environments (Stafford, 2021).

Despite the known challenges older adults face in traffic environments, empirical evidence on their interaction with multiple driverless vehicles remained limited. To date, only one study investigated the crossing behavior of young and older adult pedestrians facing two driverless vehicles (Dommes et al., 2021). The study revealed that the older adult participants took longer to cross in front of two yielding driverless vehicles in a virtual reality (VR) scenario compared to the young adults, suggesting greater hesitation in the former case (Dommes et al., 2021).

Moreover, the older adult participants anticipated this motor slow-down by initiating their crossing earlier than the young adults (Dommes et al., 2021). However, this strategy could be risky if driverless vehicles fail to yield. Notably, the driverless vehicles in Dommes et al.'s (2021) study were not equipped with eHMIs to signal their intentions to the pedestrians. This absence might have increased uncertainty about vehicle intentions and influenced pedestrian behavior. Additionally, the study did not consider how repeated exposure to driverless vehicles might affect pedestrians' adaptation over time.

To our knowledge, no study has investigated the crossing experience of young and older adult pedestrians in front of multiple driverless vehicles equipped with an eHMI. In this context, we aimed to explore the impact of eHMI signals from two driverless vehicles on the crossing experience of young and older adult pedestrians in a shared space. To overcome the limited legibility of text- or pictogram-based eHMIs from afar, a colored LED-strip-based eHMI was implemented in the present study as visual communication for pedestrians. Moreover, recognizing that sensory limitations such as age-related vision or hearing loss could reduce the effectiveness of unimodal cues, the eHMI was designed to be bimodal by incorporating sound signals alongside the visual signals. By supporting the principle of redundancy gain (Bastien & Scapin, 1993), this multimodal design aimed to increase the likelihood that the intended messages sent by the vehicles were perceived.

The present study addressed two key research questions: (RQ1) whether young and older adult pedestrians differed in their ability to perceive safety and understand two different driverless vehicles' intentions, and (RQ2) whether repeated exposure to the driverless vehicles improved the pedestrian perceived safety and understanding of vehicle intentions across age groups.

2. METHODS

2.1 Participants

Forty-four participants were recruited via a dedicated recruitment agency. They were divided into two age groups: young adults (N = 24) and older adults (N = 20). The young adult group consisted of 13 women (mean age = 26.08 years, SD = 4.42 years, range 21–34) and 11 men (mean age = 27.64 years, SD = 4.70 years, range 21–35). The older adult group consisted of 10 women (mean age = 72.60 years, SD = 2.17 years, range 70–76) and 10 men (mean age = 73.20 years, SD = 5.03 years, range 70–82). All participants had normal or corrected-to-normal vision, could walk 100 meters without difficulty, and met the simulator-related requirements (height:1.60–1.90 m, weight < 110 kg). For safety reasons, pregnant women or those who had given birth within the past three months were not included in the experiment. None of the participants required a walking aid to get around or had medical conditions affecting perception, decision-making, or mobility.

All participants gave their informed consent before participating in the experiment. Participants received a financial reward of €50 at the end of the experiment. The present study was not submitted to an ethics committee, as it was not required under current institutional and national guidelines for non-invasive behavioral research.

2.2 Materials

2.2.1 Virtual Environment

The experiment was conducted on a treadmill (KatWalk Premium) with the participants wearing a VR headset (Vive Pro Eye) (see Cherni et al., 2021). Harnesses kept the participants secure and centered on the treadmill. Moreover, rubber overshoes with slipping pads enabled the participants to slide onto the treadmill, sending walking signals to the simulation. The headset had a 2880×1600-pixel resolution, a 90 Hz refresh rate, and a 110° field of view. Moreover, the headset had an eye tracker with a frequency of 120 Hz.

The pedestrian crossings occurred in a virtual shared space wherein a bus shelter was located in front of the participants' starting point (see Figure 1). Buildings on both sides of the participants' starting point obstructed their visibility, causing vehicles approaching from either side to be perceived late. A road sign indicated the shared space with a speed limitation defined at 20 km/h. This virtual environment was developed using Unity 3D.

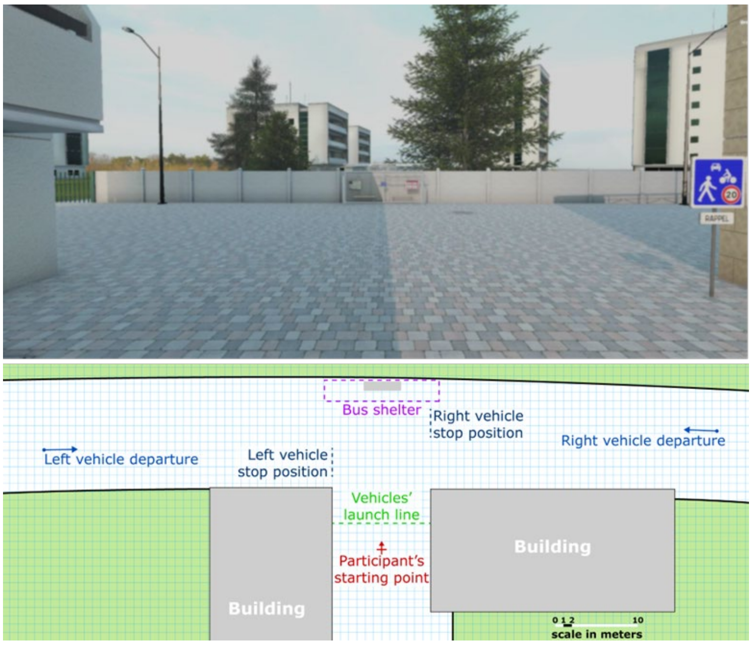


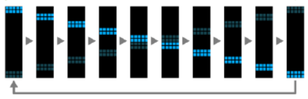
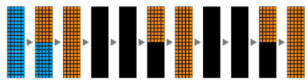
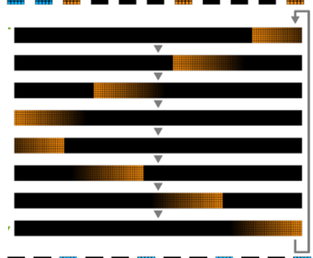
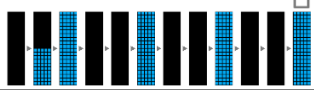
Figure 1. Front view (top) and schematic top view (bottom) of the shared space

Moreover, during the testing phase of the experiment, each participant systematically encountered two driverless electric vehicles: a car (Renault Zoé) and a shuttle (EasyMile EZ10), shown in Figure 2. Both were fitted with artificial sounds to mimic engine and tire noise, respectively proportional to acceleration and speed. The driverless vehicles could be equipped with a bimodal eHMI composed of visual and sound signals to indicate their intention to yield or to continue driving to the pedestrians.

Figure 2. Front, lateral and three-quarter views of the car (left) and the shuttle (right), equipped with the bimodal eHMI (LED strips + sound signals)

When the driverless vehicles were equipped with the bimodal eHMI, LED strips located at the front of the vehicles emitted a cyan animated visual signal during the drive of the vehicles, with no eHMI sound signal. If a driverless vehicle intended to yield to a pedestrian, the LED strips shifted from cyan to amber through three successive vertical sweeps during deceleration, coupled with a sound signal composed of three descending F notes to indicate slowing down. Once the vehicle came to a complete stop and intended to wait, the LED strips displayed a looping amber horizontal sweep. This was paired with a sound signal composed of two quick D notes repeated five times with a 2-second interval, followed by four higher E notes, and ending with four repeated higher F notes to indicate the end of the stop period. When the vehicle intended to restart, the LED strips displayed a cyan vertical sweep followed by three cyan flashes. This was paired with a sound signal that gradually rose from F# to D, and upon reaching the pitch of A, continued with six successive beeps on that note. Finally, once the vehicle resumed driving, the LED strips returned to a cyan animated visual signal with no eHMI sound signal (see Table 1 for a summary).

Table 2. Visual and sound signals of the bimodal eHMI regarding the intentions of the driverless vehicles

Intention	Visual signal	Sound signal
Driving		None
Decelerating		Descending notes
Waiting		Progressive accelerating and rising notes
Restarting		Rising notes + beeps

Because green and red colors can lead to misinterpretation among pedestrians (Bazilinskyy et al., 2020), cyan and amber colors were chosen for the visual component of the bimodal eHMI. Cyan was an emerging trend in automated vehicle communication (Dey et al., 2020), while amber was aligned with existing vehicle interfaces such as turn signals. Moreover, all the sound signals implemented in the bimodal eHMI were pre-tested against alternative sound signals among an independent sample of 12 participants. The final sound signals were selected based on the participants' consistent and intuitive associations with an intended vehicle's intention (e.g., decelerating, waiting, restarting), ensuring clear auditory communication. The decelerating and restarting sound signals were designed to span more than one octave to be easily perceived in noisy environments.

2.2.2 Questionnaires

Two pre-experiment questionnaires were used. The **socio-demographic and walking habits** *ad hoc* questionnaire was in the form of a Word document to be completed. The first section required the participants to give socio-demographic information while the second section asked the participants about their walking habits. The **technophilia** questionnaire (Agarwal & Prasad, 1998) was also in the form of a Word document to be completed. It consisted of four items measuring individuals' attitudes towards new technologies to be rated on a six-point Likert scale ranging from 1 – "Strongly disagree" to 6 – "Strongly agree".

Moreover, two post-trial questionnaires were used. The **vehicles' intentions understanding** *ad hoc* questionnaire consisted of two items: "I have understood the intention of the car" and "I have understood the intention of the shuttle". The **feeling of safety** *ad hoc* questionnaire consisted of a single item "I felt safe during my crossing". These three items were stated orally to the participants during the experiment, and they were asked to rate each item on a six-point Likert scale ranging from 0 – "Not at all" to 5 – "Completely", by reporting their answer orally to the experimenter.

2.3 Procedure

Prior to the experiment, the participants completed the technophilia and the socio-demographic and walking habit questionnaires and were requested to send them back to the recruitment agency. The participants also received the consent form to participate in the experiment and were asked to read it carefully.

On the experiment day, the participants were requested to sign the informed consent form. Then, they read an instruction sheet outlining the experiment's three phases: **familiarization**, **testing**, and **semi-structured interview**. The participants could ask questions to the experimenter at any time and the experimenter ensured all instructions were understood before starting. The participants were then invited to go to the VR treadmill.

After being presented with the equipment, the participants received instructions on navigating on the treadmill, and the eye calibration steps with the VR headset. They were then fitted with overshoes to facilitate walking on the treadmill. After this, the participants were safely installed on the treadmill, with the harnesses and the VR headset adjusted. The eye calibration was then completed, followed by the familiarization part.

The **familiarization** part included two tasks. During the first task, the participants had to walk in a virtual environment depicting a tiled area to reach an orange-lit cylinder, twice. This task enabled the participants to become familiar with navigating in the simulator. During the second task, the participants were standing at a starting point and had to cross a shared space in order to reach a bus shelter while different types of vehicles (automated or not) approached from both sides at 20 km/h. The participants were instructed to carefully look left and right before crossing. After completing their crossing, the participants received an instruction reminder, and the testing part began.

During the **testing** part of the experiment, the participants had to cross the same shared space as in the second familiarization task, 32 times. However, only two vehicles were present: a car and a shuttle, both driverless (see Figure 2). These vehicles always traveled at 20 km/h on separate paths, ensuring one vehicle approached from the left and the other from the right, in a counterbalanced order. The participants had to initiate their crossings when they judged it safe. The vehicles' behavior congruency was manipulated in a counterbalanced order during the crossings: in congruent conditions, both vehicles either yielded or continued driving when the participants arrived at the intersection; in incongruent conditions, one vehicle yielded while the other vehicle continued driving when the participant arrived at the intersection. Yielding vehicles stopped 6 meters from the scene center, approximately 13 seconds after the participants had passed the vehicles' launch line. Buildings on either side of the participants prevented them from early vehicle detection, hindering the understanding of the vehicles' intentions from kinematics. Moreover, during half of the crossings (N = 16) and in a counterbalanced order, both vehicles were equipped with a bimodal eHMI indicating their respective intention, that is, to yield or to continue driving. The messages sent by the bimodal eHMIs of the vehicles were always consistent with their actual behaviors. Importantly, the meaning of these eHMI signals was not explained to the participants prior to the experiment.

In sum, there were 2 levels of vehicle arrival side (left, right) × 2 levels of congruent vehicles' behaviors (both yielding, both continue driving) × 2 levels of incongruent vehicles' behaviors (the car yielding while the shuttle continued driving, *vice versa*) × 2 levels of eHMI presence (yes, no) × 2 repetitions, leading to 32 crossings. After each crossing, the participants completed the vehicles' intentions understanding and feeling of safety questionnaires. The items were read aloud to the participants, who responded verbally; their answers were then transcribed into a dedicated interface. The participants could also provide open feedback. A break was set after the 16th crossing, creating two experimental blocks. Once the final crossing and questionnaires were completed, the participants exited the simulator and the equipment was removed.

Finally, an audio-recorded **semi-structured interview** collected the participants' impressions about their crossings and the bimodal eHMI. Then, the participants were thanked and the experiment ended.

2.4 Data Analysis

One older adult discontinued early due to suspected cybersickness, and data from three participants were lost during the testing part of the experiment due to technical issues, resulting in a final sample of 23 young adults and 17 older adults. All statistical analyses on the participants' vehicles' intention understanding scores and feeling of safety scores were performed using R software. The significance threshold was set at $\alpha = .05$.

Main effects were analyzed using Wilcoxon tests (due to non-normal data distributions, all $ps < .10$). Interaction effects were examined using mixed ANOVAs with the participants' age group (young adult, older adult) as a between-participants factor, and the presence of the eHMI on the vehicles (yes, no), the vehicles' behavior congruency (congruent, incongruent) and the experimental block (1, 2) as within-participants factors. Although normality assumptions were not met, ANOVAs were conducted given their robustness to violations of normality (Blanca

Mena et al., 2017). The vehicle arrival side was set for experimental control and was not included in further analysis. Moreover, vehicles' behaviors within the same congruency condition were considered together during analysis.

Post-hoc analyses aimed to investigate differences between factor modalities across the two experimental blocks. Pairwise comparisons were performed using Wilcoxon tests and applying the Bonferroni correction.

Moreover, to characterize learning effects, a temporal analysis was conducted using locally estimated scatterplot smoothing (LOESS) regressions. Specifically, these regressions modeled the participants' vehicle intention understanding scores and feeling of safety scores, respectively, as a function of trial number. Each analysis was performed on a specific data subset identified as relevant based on significant interaction effects from the mixed-design ANOVAs. Thereby, for each variable, two key phases were identified across trials: the learning phase and the stabilization phase. The start of the learning phase was defined as the first trial where the slope of the LOESS regressions sustained a positive acceleration, indicating the onset of consistent learning. The end of the learning phase was defined as the last trial during which the acceleration remained positive. Besides, to assess learning stability, the slope values of the LOESS regressions at each trial after the learning phase were extracted and averaged. The mean slopes were then compared against zero using the Wilcoxon signed-rank test (due to non-normal data distributions, all $ps < .10$) to assess whether learning gains were maintained across subsequent trials.

Finally, the participants' responses from the semi-structured interviews about their preference for communicating driverless vehicles were coded into binary categories (yes/no). The proportions of "yes" responses were compared between the young and the older adults using a chi-square test. For the open-ended questions (e.g., environmental cues used beyond the eHMI signals, feedback on the bimodal eHMI) a thematic analysis was conducted, and the proportion of participants reporting each theme was calculated separately by age group. Since participants could mention multiple cues, the total proportions within an age group could exceed 100%.

3. RESULTS

3.1 Place of Residence and Walking Habits

Most young adults (67%) and older adults (53%) reported living in an urban city center. The remaining participants indicated residing in a suburban area. Moreover, 83% of young adults and 68% of older adults reported walking daily or nearly daily for trips lasting over 15 consecutive minutes.

3.2 Level of Technophilia

The Wilcoxon test revealed no significant main effect of the participants' age group on the participants' global technophilia scores ($W = 163$, $p = .10$, $r = -.07$, mean = 5.10, SD = .54). **Thus, no difference in technophilia levels was found between the young adults and the older adults prior to the experiment.**

3.3 Vehicle's intention Understanding

3.3.1 The car

The Wilcoxon test revealed a significant main effect of the participants' age group on the participants' understanding scores of the car's intention, indicating higher intention understanding scores among the older adults compared to young adults (W = 107, p = .01, r = -.39, mean $_{young}$ = 3.95, SD $_{young}$ = .62, mean $_{older}$ = 4.40, SD $_{older}$ = .46). **Thus, the older adults reported overall a better understanding of the car's intention compared to the young adults.**

Moreover, the Wilcoxon test revealed a significant main effect of the eHMI presence on the participants' understanding scores of the car's intention, indicating higher intention understanding scores when the eHMI was present compared to when it was absent (W = 167.5, p = .002, r = -.35, mean $_{eHMI}$ = 4.35, SD $_{eHMI}$ = .58, mean $_{no\ eHMI}$ = 3.93, SD $_{no\ eHMI}$ = .81). **Thus, the participants reported a better understanding of the car's intention when both driverless vehicles were equipped with the bimodal eHMI indicating their respective intention compared to when the vehicles were not equipped with the device.**

No other significant main effects were found on the participants' understanding scores of the car's intention (ps > .05). However, the mixed ANOVA revealed a significant age group × vehicles' behavior congruency × experimental block interaction on the participants' understanding scores of the car's intention (F(1,38) = 9.46, p = .004, ηp^2 = .20, see Figure 3). Specifically, when the car and the shuttle had incongruent behaviors, the older adults reported higher intention understanding scores during the second experimental block compared to the first experimental block (p = .007). However, no significant difference was observed on the young adults' intention understanding scores when the car and the shuttle had incongruent behaviors between the first and the second experimental block (p = .90). Moreover, when the car and the shuttle had congruent behaviors, no significant difference was found on the participants' understanding scores between the first and the second experimental block, neither among the young adults (p = 1) nor among the older adults (p = 1). **Thus, when the car and the shuttle had different behaviors, the older adults reported better understanding of the car's intention during the second part of the experiment compared to the first part of the experiment.** This difference between experimental blocks was not observed among the young adults. Moreover, no such difference was found when the car and the shuttle displayed the same behavior, among both age groups.

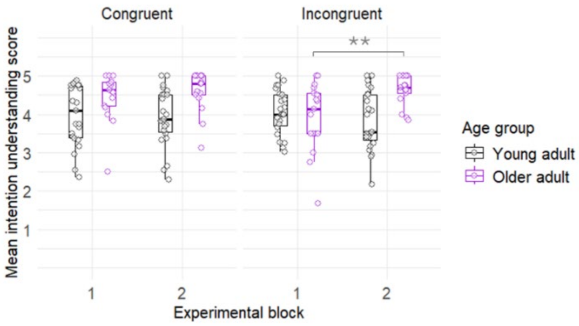


Figure 3. Three-way interaction on the participants' intention understanding scores of the car's intention, **: $p < .01$

Additionally, the LOESS regressions of the participants' intention understanding scores across trials under the incongruent condition (see Figure 4) provided a more detailed visualization of the significant interaction observed in the mixed ANOVA. The slope analyses of the older adults' curve revealed a reliable learning effect over time. The onset of the learning phase was identified at trial 14, marked by a sustained increase in slope and positive acceleration in the older adults' vehicle intention understanding scores. The learning phase ended at trial 18, when the acceleration ceased to be positive. Furthermore, the estimated average slope of the older adults' curve from trial 18 to trial 32 was equal to .001 and did not significantly differ from zero ($W = 51$, $p = .64$), suggesting that no substantial changes occurred in the participants' intention understanding scores after the learning phase. However, no definitive plateau was detected, indicating that some variability remained in performance. Taken together, these findings suggested a learning effect in the older adults' understanding of the car's intention under the incongruent condition, emerging toward the end of the first experimental block, followed by a stabilization of performance throughout the second experimental block

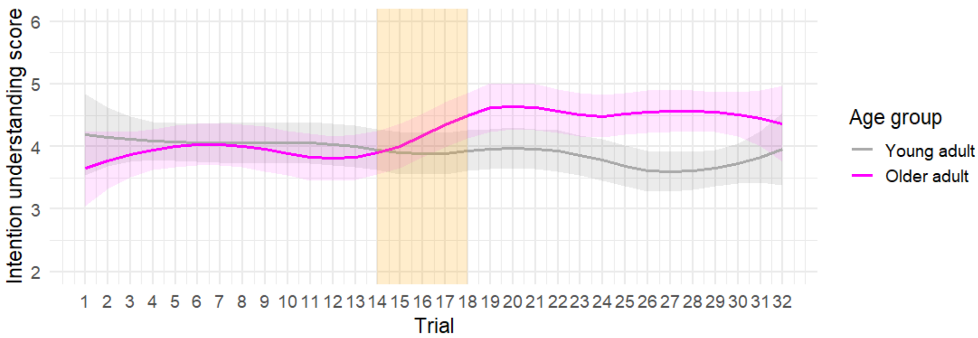


Figure 4. LOESS-smoothed curves of the participants' understanding scores of the car's intention under the incongruent condition by age group, as a function of trials. The shaded areas represent 95% confidence intervals. The orange area represents the trial range (14–18) during which a reliable growing performance was observed among the older adults' scores

3.3.2 The Shuttle

The Wilcoxon test revealed a significant main effect of the participants' age group on the participants' understanding scores of the shuttle's intention, indicating higher intention understanding scores among the older adults compared to the young adults ($W = 90$, $p = .004$, $r = -.45$, mean $_{young}$ = 3.89, SD $_{young}$ = .64, mean $_{older}$ = 4.48, SD $_{older}$ = .32). **Thus, the older adults reported overall a better understanding of the shuttle's intention compared to the young adults.**

Moreover, the Wilcoxon test revealed a significant main effect of the eHMI presence on the participants' understanding scores of the shuttle's intention, indicating higher intention understanding scores when the eHMI was present compared to when it was absent ($W = 127$, $p < .001$, $r = -.42$, mean $_{eHMI}$ = 4.36, SD $_{eHMI}$ = .55, mean $_{no\ eHMI}$ = 3.92, SD $_{no\ eHMI}$ = .80). **Thus, the participants reported a better understanding of the shuttle's intention when both driverless vehicles were equipped with the bimodal eHMI indicating their respective intention compared to when the vehicles were not equipped with the device.**

No other significant main effects were found on the participants' shuttle's intention understanding scores (*ps* > .05). Moreover, the mixed ANOVA revealed no significant interaction effect on the participants' shuttle's intention understanding scores (*ps* > .05).

3.4 Feeling of Safety

The Wilcoxon test revealed a significant main effect of the presence of the eHMI on the participants' feeling of safety scores with higher feeling of safety scores when the eHMI was present on the vehicles compared to when it was absent ($W = 168.5$, $p = .002$, $r = -.34$, mean $_{eHMI}$ = 4.10, SD $_{eHMI}$ = .62, mean $_{no\ eHMI}$ = 3.76, SD $_{no\ eHMI}$ = .85). **Thus, the participants reported feeling safer during their crossings when both driverless vehicles were equipped with the bimodal eHMI indicating their respective intention compared to when the vehicles were not equipped with the device.**

Moreover, the Wilcoxon test revealed a significant main effect of the vehicles' behavior congruency on the participants' feeling of safety scores with higher feeling of safety scores for congruent vehicles' behavior compared to incongruent vehicles' behavior ($W = 102.5$, $p < .001$, $r = -.42$, mean $_{congruent}$ = 4.04, SD $_{congruent}$ = .68, mean $_{incongruent}$ = 3.82, SD $_{incongruent}$ = .71). **Thus, the participants reported feeling safer during their crossings when the car and the shuttle had the same behavior compared to different behaviors.**

No other significant main effects were found on the participants' feeling of safety scores (*ps* > .05). However, the mixed ANOVA revealed a significant vehicles' behavior congruency × experimental block interaction on the participants' feeling of safety scores ($F(1,38) = 8.70$, $p = .01$, $\eta p^2 = .19$, see Figure 5). Specifically, when the car and the shuttle exhibited incongruent behaviors, the participants' feeling of safety scores were lower during the first experimental block compared to the second experimental block ($p = .02$). In contrast, when the driverless vehicles exhibited congruent behaviors, no significant difference was observed on the participants' feeling of safety scores between the first and the second experimental block ($p = 1$). **Thus, when the car and shuttle had different behaviors, the participants reported feeling less safe during their crossings during the first part of the experiment compared to the second part of the experiment. This difference in perceived safety between experimental blocks was not present when the car and the shuttle had the same behavior.**

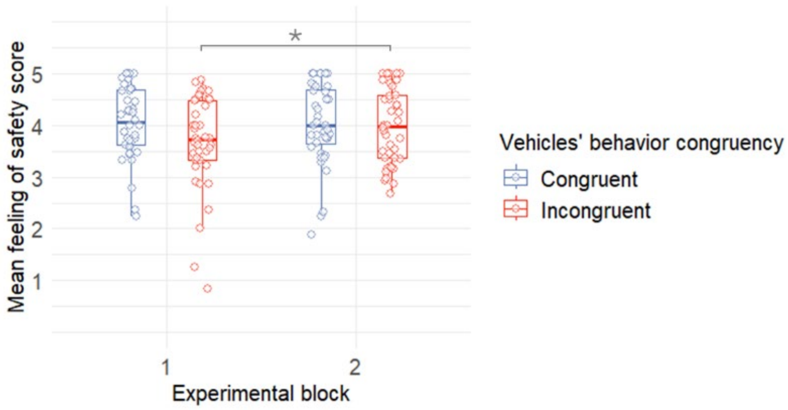


Figure 5. Two-way interaction on the participants' feeling of safety scores, *: $p < .05$

Additionally, the LOESS-smoothed curves of participants' feeling of safety scores across trials by vehicles' behavior congruency (see Figure 6) provided a more detailed visualization of the significant interaction observed in the mixed ANOVA. The slope analyses of the incongruent curve revealed a reliable learning effect over time. The onset of the learning phase was identified at trial 15, marked by a sustained increase in slope and positive acceleration in the participants' feeling of safety scores. The learning phase ended at trial 19, when the acceleration ceased to be positive. Furthermore, the estimated average slope of the incongruent curve from trial 19 to trial 32 was equal to .02 and did not significantly differ from zero ($T(13) = 1.67$, $p = .12$), suggesting that no substantial changes occurred in the participants' feeling of safety scores after the learning phase. However, no definitive plateau was detected, indicating that some variability remained. Taken together, these findings suggested a learning effect in the participants' perceived safety under the incongruent condition, emerging toward the end of the first experimental block, followed by a stabilization throughout the second experimental block.

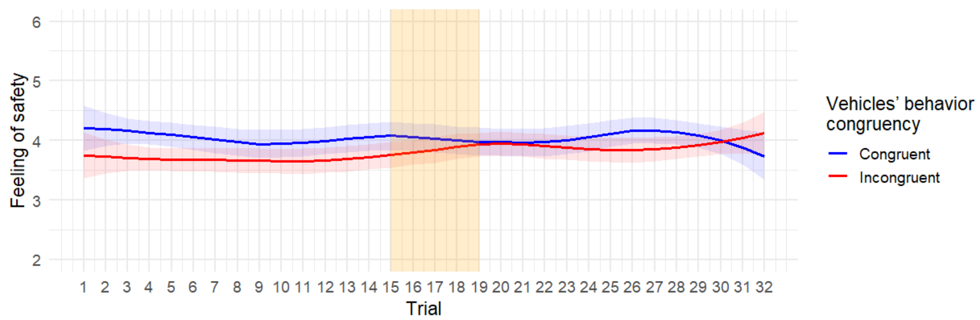


Figure 6. LOESS-smoothed curves of the participants' feeling of safety scores, by congruency as a function of trials. The grey areas represent 95% confidence intervals. The orange area represents the trial range (3–9) during which a reliable difference between congruency conditions was observed

3.5 Feedback on the Bimodal eHMI

During the semi-structured interviews, 88% of the young adults and 79% of the older adults reported preferring to cross in front of the driverless vehicles equipped with the bimodal eHMI, rather than without it. The chi-square test results revealed no significant difference between the young adults and the older adults ($\chi^2(1) = .57$, $p = .45$). Thus, both young and older adults showed a similar preference for crossing in the presence of vehicle signals. Participants explained that **the bimodal eHMI made them feel safer and more reassured, as it confirmed the vehicle's behavior and replaced human communication.**

However, 23% of participants claimed that it would have **been more suitable for vehicles to emit an amber light signal when it was not advisable for pedestrians to cross** (i.e., while driving) and a cyan light signal when yielding to them. For example, P30 (older adult) said "*As a driver, the orange traffic light is clearly an alert. It signals that I need to be ready to stop, not go. But here, it was the opposite.*"

Moreover, 25% of young adults reported **difficulty identifying which vehicle was emitting the eHMI sound signal**. For example, P42 (young adult) said "*If the car arrives first from the left and I start to cross, I am unsure if the other vehicle is stopping or not, creating a brief wait. The issue is that we can't really tell where the sound is coming from. I cannot tell if it is the car that has stopped that is emitting the sound, or if it is the shuttle that is making the sound and thus will stop.*"

Additionally, 13% of young adults and 16% of older adults mentioned that **the acceleration of the sound signal during the vehicle's stop period was stressful and, for some, confusing**. For example, P34 (older adult) said "*Because the sound signal increases, it's stressful. It really increases. Well, you don't know if you should hurry, if the car is going to restart. And I think that since the light signal remains steady, we have time to cross. Otherwise, maybe it could cause some confusion.*"

3.6 Other Cues Used in the Crossing Decisions

Beyond the eHMI signals sent by the driverless car and shuttle, during the semi-structured interviews, **the older adults reported using a wider variety of environmental cues when making their crossing decisions than the young adults** (see Figure 7).

Among the young adults, the most frequently other cue used in their crossing decision was the slowing down of the vehicles, with 67% of participants reporting having used this cue. The second most used cue was the complete stop of the vehicles, mentioned by 50% of them.

Among the older adults, the most frequently other cue used in their crossing decision was the complete stop of the vehicles, reported by 58% of participants. The second most used cue was the vehicles slowing down, reported by 47% of older adults. Another important cue for this age group was that the vehicles had already passed, mentioned by 37% of the older adults.

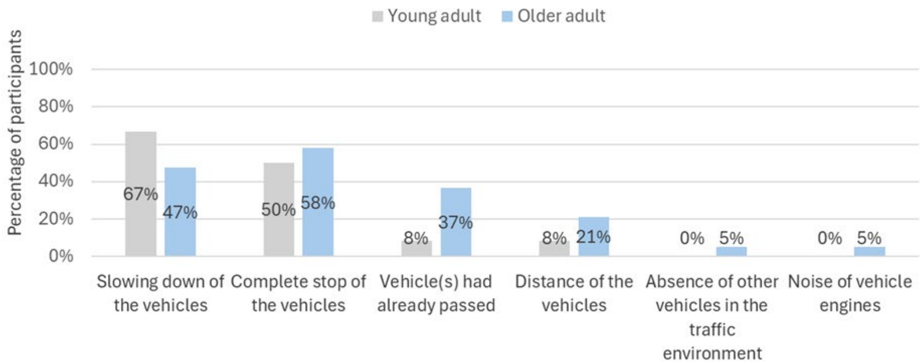


Figure 7. Environmental cues used in the participants' crossing decisions, other than the eHMI signals of the vehicles

4. DISCUSSION

In the present study, age-related differences in the pedestrians' ability to understand driverless vehicles' intentions (e.g., to yield or to continue driving) were highlighted. Indeed, addressing the first research question (RQ1), we found that the older adults reported overall better understanding of the intentions of the car and the shuttle than the young adults. Consistently, our findings indicated that the older adults actively drew on a richer set of environmental cues compared to the young adults when making crossing decisions. This broader integration of contextual information may have enabled the older adults to develop a more accurate understanding of the vehicles' intentions. Indeed, the possession of such mental models has been identified as a major element for building effective cognitive skills (Pacherie & Mylopoulos, 2020), which likely enabled the older adults to develop a more accurate understanding of the vehicles' intentions. However, this effect appeared specific to the context of interacting with two driverless vehicles, as previous research with a single self-driving car found that during daytime, young and older adults relied primarily on similar cues when making crossing decisions (Sahaï et al., 2024). These findings suggested that increased environmental complexity in multi-vehicle scenarios might engage older adults' compensatory cognitive strategies, promoting broader cue integration, whereas single-vehicle contexts elicit more uniform processing across ages. Yet, both age groups reported comparable levels of perceived safety when crossing in front of the two driverless vehicles, indicating that the differences in the processing of vehicle intentions did not directly translate into variations in the pedestrians' emotional experience of safety in multi-vehicle crossing scenarios.

Furthermore, addressing the second research question (RQ2), we found that when the car and shuttle exhibited different driving behaviors, the older adults showed improved understanding of the car's intention after repeated crossings, pointing out a learning effect for this age group in complex crossing scenarios. A complementary analysis indicated that this improvement emerged from the 14th pedestrian crossing to the 18th pedestrian crossing and persisted thereafter. This sustained improvement suggested that the older adults recognized and retained reliable behavioral patterns of the driverless vehicles over time. Accordingly, this sustained improvement reflects preserved learning abilities in normal ageing, enabling better adaptation to complex traffic environments.

Nevertheless, this learning effect observed among the older adults was not observed for the understanding of the shuttle's intention, pointing out different mechanisms for interpreting the car's and the shuttle's behavioral intentions. These differences could be explained by bottom-up processes, whereby the participants' perception of vehicle speed was influenced by low-level features such as the physical characteristics of the vehicles, notably size. Top-down processes may also have played a role, involving the participants' mental representations of each vehicle, with the shuttle being more readily associated with a driverless vehicle and the car more readily associated with a human-driven vehicle, which may have influenced the perception of the driving behavior of the vehicles. Further research is needed to clarify the relative influence of these processes.

Additionally, our findings revealed that during their first crossings in the shared space, the participants' feeling of safety was lowered when the car and the shuttle exhibited different behaviors compared to the same one. This might reflect pedestrians' vulnerability due to uncertainty about the appropriate behavior to adopt when vehicles act inconsistently. However, regarding the second research question (RQ2), we found that this decline in perceived safety in complex traffic scenarios faded after repeated crossings for all participants, indicating an adaptive learning process. A complementary analysis revealed that this learning effect emerged from the 15^{th} pedestrian crossing to the 19^{th} pedestrian crossing and persisted thereafter. This suggested that the participants were able to develop coping strategies in response to opposite driverless vehicle behaviors, leading to a convergence in safety perceptions across the two congruency conditions. This was supported by the experiential learning theory, which posits that individuals adapt through a cyclical process of direct experience, reflection, and conceptual adjustment in response to environmental complexity (Kolb, 2014).

Interestingly, we found that the presence of a bimodal eHMI on the two driverless vehicles improved both the participants' understanding of the vehicles' intentions and their feeling of safety during their crossings compared to scenarios without eHMI. These findings aligned with previous research showing that the pedestrian feeling of safety when deciding to cross in front of a single driverless vehicle was enhanced when the vehicle emitted eHMI signals to the pedestrian compared to when no eHMI signal was sent (De Clercq et al., 2019). However, our findings extended previous work (De Clercq et al., 2019), underscoring that the pedestrian feeling of safety benefits from an eHMI was not limited to the moment of the crossing decision-making but persisted throughout the entire crossing, even when two different driverless vehicles were present in the traffic.

Furthermore, a preference for an alternative eHMI color coding was suggested by 23% of participants, highlighting potential ambiguities in interpreting the visual signals of the bimodal eHMI. Indeed, the amber color, possibly associated with caution or danger, may be interpreted differently depending on whether pedestrians adopt an egocentric perspective (i.e., the amber signal is directed at them – they must not cross) or an allocentric perspective (i.e., the amber signal reflects the vehicle's behavior – the vehicle is warning a stopping). This perceptual ambiguity aligns with prior findings suggesting that light-band eHMIs, while promising in terms of visibility, are not always intuitive (De Clercq et al., 2019; Kaleefathullah et al., 2022). Yet, ISO guidelines discourage providing explicit guidance to vulnerable road users (e.g., a crossing advice) to avoid legal and safety issues, and recommend instead communication of vehicle state, understanding of the environment and intentions (ISO/TR 23049:2018).

In addition, difficulties in perceiving the sound signals of the eHMI were reported, with 25% of young adults struggling to identify the source of the sound. While this aspect was not explicitly verbalized by the older adults during the semi-directive interviews, it is possible that they also considered it during their crossings. Hence, considering the use of sound signals in bimodal eHMIs on driverless vehicles, it is crucial to select sound signals with acoustic properties that allow clear identification and minimize the risk of confusion with ambient noise to avoid informational masking. This phenomenon occurs when an auditory stimulus becomes difficult to detect within an environment of similar acoustic properties (Kidd et al., 2008; Veyrié et al., 2023). The use of a bimodal eHMI is nevertheless recommended, as participants reported preferring to cross in front of driverless vehicles equipped with such a communication system. Moreover, the bimodal nature of these eHMIs may promote accessibility and inclusivity by accommodating individuals with different sensory needs, such as those with blindness or deafness, as well as age-related sensory decline (Enam et al., 2024).

Despite these promising findings, several limitations of the present study must be acknowledged. Firstly, the relatively small sample sizes of participants for which the data were able to be analyzed (23 young adults and 17 older adults) might have limited the generalizability of the results and reduced the statistical power to detect more subtle effects. Secondly, this study was conducted in a VR environment which, although offering controlled conditions, might not fully capture the complexity and emotional impact of real-world street crossings. In particular, risk perception might be reduced, as the participants were aware that unlike in real life, they could not be physically hit by a vehicle. Moreover, pedestrians' crossing experience is closely dependent on individual factors such as social norms and culture (Pelé et al., 2019; Rasouli & Tsotsos, 2019). Thus, the results obtained here with French participants may not be directly transferable to pedestrian populations in other countries.

5. CONCLUSION

In the present study, the implementation of a bimodal eHMI on two different driverless vehicles demonstrated a positive impact on pedestrians' perceived safety and their understanding of vehicles' intentions. Participants also expressed a preference for the presence of such a communication system, emphasizing that it reassured them by confirming the vehicle's behavior and compensating for the absence of human communication.

Nevertheless, beyond the influence of the eHMI presence, a learning effect was observed among the older adults regarding their understanding of the driverless car's intention in complex crossing scenarios. Moreover, both the young and the older adults exhibited adaptive learning over time, enabling them to accommodate incongruent vehicle behaviors and subsequently report improved safety perceptions. These findings underscored the importance of designing eHMIs that reduce reliance on learning, supporting accurate interpretation of vehicle behavior and fostering a strong sense of safety from the pedestrians' very first encounter with driverless vehicles.

Moreover, to minimize ambiguity and improve intuitiveness, LED visual signals may avoid colors like amber, which may be subject to divergent interpretations depending on the pedestrian's egocentric or allocentric perspective. In addition, when incorporating sound signals into a bimodal eHMI, designers should avoid overly intrusive sounds or closely spaced loops, as these characteristics can lead to user confusion, annoyance, or rejection. Crucially, sound signals must be distinct, easily localizable, and resilient against masking by ambient noise to ensure effective and reliable pedestrian communication.

Taken together, these findings offer promising directions for the development of intuitive and inclusive communication systems between pedestrians and driverless vehicles, paving the way for safer interactions.

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