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The ‘invisible gorilla’ during pedestrian-AV interaction: Effects of secondary tasks on pedestrians’ reaction to eHMIs

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ABSTRACT

In road traffic, mental overload often leads to a failure to notice new and distinctive stimuli. Such phenomenon is known as ‘inattention blindness’. Safe and efficient interaction between automated vehicles (AVs) and pedestrians is expected to rely heavily on external human-machine interfaces (eHMIs), a tool AVs are equipped with to communicate their intentions to pedestrians. This study seeks to explore the phenomenon of ‘inattention blindness’ in the context of pedestrian-AV interactions. Specifically, the aim is to understand the effects of a warning eHMI on pedestrians’ crossing decisions when they are engaged in a secondary task. In an experiment study with videos of pedestrian crossing scenarios filmed from the perspective of the crossing pedestrian, participants had to decide the latest point at which they would be willing to cross the road in front of an AV with an eHMI vs. an AV without an eHMI. Participants were also asked to predict the future behavior of the AV. 125 female and 9 male participants aged between 18 and 25 completed the experiment and a follow-up questionnaire. It was found that the presence of a warning eHMI on AVs contributes to a clearer understanding of pedestrians’ inferences about the intention of AVs and helps deter late and dangerous crossing decisions made by pedestrians. However, the eHMI fail to help pedestrians avoid such decisions when they face a high mental workload induced by secondary task engagement.

1. Introduction

1.1. Pedestrian-AV interaction and eHMIs

Automated vehicles (AVs) will gradually enter public roads in the next few decades, and it is likely that they will need to interact with human road users such as pedestrians. Currently, pedestrians and drivers use a range of explicit (e.g., hand gestures, eye contact) or implicit (e.g., vehicle movement) communication to indicate their intentions to each other in order to negotiate priority during traffic interactions, especially in situations where no formal traffic rules apply (Dey, & Terken, 2017; Palmeiro et al., 2018). In the future, AVs will be expected to drive completely autonomously without any intervention from a human driver, therefore requiring AVs to be capable of such communication on their own.

Researchers in this field have proposed the use of external human-machine interfaces (eHMIs) to transmit AVs’ intentions to pedestrians. This includes vehicle lights, symbols, text messages, and other signals that are visible and understandable for human road users, and are presented on the front or the side of an AV (Ackermann et al., 2019a; Bazilinskyy et al., 2019; Li et al., 2018; Habibovic et al., 2018; De Clercq et al., 2019). Although discrepancies exist in findings regarding the actual impacts of those eHMIs on pedestrians’ crossing behaviors, many studies have concluded that eHMIs could indeed improve pedestrians’ understanding of AVs’ intention, perceived safety, trust, and comfort, which may facilitate their crossing decisions (Chang et al., 2017; Deb et al., 2018; Hudson et al., 2018; Ackermans et al., 2020). Conversely, pedestrians may be confused about the AV’s behavior if the vehicle’s intention is not communicated clearly, and such confusion may further induce stress and low trust among pedestrians (Faas et al., 2021;

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Papadimitriou et al., 2022).

Within this body of research, the effects of a variety of messages transmitted by eHMIs have also been studied, including indications of the vehicle's state (e.g., driving autonomously or manually), situational awareness (e.g., pedestrians detected), the vehicle's current action (e.g., decelerating), advice to pedestrians (e.g., safe to cross), etc. (Dey et al., 2020). Among these messages, only few authors mentioned the importance of sending warnings to pedestrians (Li et al., 2018). In a review article, Dey et al. (2020) found that only 6 out of 70 eHMI concepts used warning messages. Meanwhile, providing eHMI warnings to pedestrians could be vital to ensuring safe pedestrian-AV interactions, especially in the event of a technical failure of the AV. More generally, such warnings seem critical given that pedestrians sometimes engage in risky behaviors when crossing roads. For example, pedestrians sometimes ignore traffic signals, cross the roads at non-designated locations because doing so is more convenient (Chandra et al., 2014), and run across the roads at the last minute without paying attention (Zhuang, & Wu, 2011). Moreover, in the AV context specifically, recent studies suggest that the presence of AVs on the roads can magnify these risky pedestrian behaviors, possibly because pedestrians perceive an elevated sense of safety around AVs (Millard-Ball, 2018; Zhao et al., 2022). Considering all of this, it is arguably even more important for AVs, compared to human-driven vehicles (HDVs), to communicate the danger of risky road crossing behaviors to pedestrians. And the role of eHMI warnings in preventing risky pedestrian crossing behaviors – especially late crossings, which are understudied in prior research on the effects of eHMIs – deserves further examination.

In the light of this, one of the objectives of the current study is to evaluate the impact of an eHMI warning on pedestrians' late crossing decisions. As there is not a consensus on the best way to use and design eHMIs to date, we designed and used a symbol-based eHMI warning based on a universal pedestrian signal for its familiarity and understandability (Ackermann et al., 2019a). Past research has suggested that properly constructed symbol-based eHMIs are clear and can be perceived from a farther distance (Rettenmaier et al., 2020). Symbol-based eHMIs can also avoid the misinterpretations that language-based eHMIs can generate (Eisele & Petzoldt, 2022).

1.2. Possible effects of high mental workload on the effectiveness of eHMIs

The effectiveness of eHMIs is also dependent on the extent to which the information they transmit is being received and processed by pedestrians. Currently, much of the research into eHMIs has been carried out with the assumption that pedestrians are attentive when interacting with vehicles in traffic, ignoring the fact that they are, in fact, the most unpredictable group of road users. In recent years, pedestrians are increasingly observed to constantly use their mobile phones while walking on roads (Thompson et al., 2013), leading to unsafe crossing decisions and crashes (Osborne et al., 2020). Technology use related pedestrian injuries that contribute to a significant portion of overall road injuries have become a major concern of road safety globally (Nasar, & Troyer, 2013). In a survey study conducted O'Hern et al. (2020), using technology while walking was found to be the most frequently self-reported behavior among pedestrians. While technology use is a prevailing phenomenon on roads, limited studies have been conducted to identify how it may influence pedestrian-AV interactions, especially when it comes to the use of eHMI.

Pedestrians need to have a continuous perception of road traffic (situation awareness) in order to coordinate their motor activity to cross the roads, and this requires the identification and analysis of important information cues in the traffic environment (Cœugnet et al., 2019). In certain cases, however, pedestrians fail to notice important cues in traffic, causing risky crossing decisions. Such phenomenon can be explained by the concept of 'inattention blindness' (IB), a cognitive phenomenon that humans fail to notice a distinct visual stimulus while

engaging in tasks involving information processing by their working memory (Hyman et al., 2010).

Simons and Chabris (1999) illustrated this phenomenon in their famous "invisible gorilla" experiment. In this experiment, participants watched a video and were asked to count how many times a ball was being passed around by a circle of people. Many of the participants failed to notice a man in a gorilla suit in the video. In the context of traffic safety, IB among pedestrians has been quite commonly observed on roads as a result of technology use. For example, an earlier study found that pedestrians who were talking on the phone while walking had difficulty recognizing important information cues in their surroundings and failed to see a unicycling clown on their walking path (Hyman et al., 2010).

When AVs join normal road traffic in the near future, the eHMIs on AVs may be perceived as a new and unfamiliar stimulus, and thus pedestrians may not intentionally search for the eHMI on AVs as an information cue while making crossing decisions. As such, IB may occur if pedestrians are engaged in technology use while walking in the sense that eHMIs can be easily ignored. In addition, eHMIs may create an additional information load on pedestrians (Mahadevan et al., 2018; Moore et al., 2019). This additional information in an already complex traffic environment might lead to mental overload among pedestrians, leading poor decision-making performance (Tapiro et al., 2020). In such cases, eHMIs that add additional mental workload to pedestrians who are already overloaded with other tasks could result in even more dangerous situations. Despite the importance of these issues for safe pedestrian-AV interactions, past studies have yet to test the effectiveness of eHMIs when pedestrians are experiencing high mental workloads.

1.3. Study aim

In the light of the above discussion, the current study aims to understand pedestrians' crossing decisions when interacting with an AV under different levels of mental workload. Specifically, we seek to answer the following questions: (1) How does engagement in a secondary task influence pedestrians' mental workload and, subsequently, their road crossing decisions? And do these decisions differ when pedestrians are crossing in front of an AV vs. an HDV? (2) How does a warning eHMI used by AVs impact pedestrians' crossing decisions when they are under low vs. high mental workloads? To answer these questions, a video-based experiment was developed in which participants watched videos, taken from the perspective of a pedestrian, of an approaching vehicle. The individual and interaction effects of the vehicle type (AV vs. HDV), presence of warning eHMI (eHMI present vs. eHMI absent), and task demand (simple task vs. dual task) on pedestrians' crossing decisions were investigated.

2. Method

2.1. Apparatus

This study, in line with Dey et al. (2019), utilized a video-based experiment to study pedestrians' road crossing decisions. In total, 13 pedestrian-vehicle interaction videos were recorded on a sunny day on an empty one-way road without the presence of any other road users. Each of the videos was taken from the viewpoint of a pedestrian standing on the side of the road waiting to cross. An automated/human-driven vehicle approached the crossing location from different directions. The selected crossing locations include the mid-block of the road, where a vehicle approached from the near lane in one scenario, and from the far lane in another scenario, at the speeds of 30 km/h, 40 km/h and 50 km/h; at a T junction, where the vehicle turned left in one scenario, and right in another scenario, at the speeds of 30 km/h, 40 km/h and 50 km/h; and at a roundabout, where the vehicle exited the roundabout at the speed of 15 km/h. Around the time of data collection, a new traffic law was just passed, to reduce the speed limit in the Paris city area from 50

km/h to 30 km/h (Le Conseil de Paris (2021)). Because of the sudden change, many drivers and pedestrians were still confused and in the process of adapting to the new law. Thus, we decided to include both the new and older speed limits in our study. There was no formal pedestrian crosswalk in all the crossing locations depicted in the video, and the approaching vehicle did not yield to the pedestrian in all scenarios. All videos were then edited to end one second before the vehicle arrives at the crossing location, and each video lasted about 10 s to 20 s. During the experiment, the videos were presented on the wall using a projector so that the vehicles appear to be real-life size (see Fig. 1). Participants were instructed to stand one meter away from the wall during the experiment and used a small handheld keyboard to record their crossing decisions.

To create a ‘Wizard of Oz’ AV (Habibovic et al., 2016; Palmeiro et al., 2018) in the videos, the actual driver of the vehicle controlled the vehicle from the passenger seat. Thus no one appears behind the wheel in the driver seat inside the vehicle. A warning eHMI that simulates a ‘no crossing’ signal was designed and used in the experiment. The warning eHMI was edited onto the front of the vehicle using video-editing software (see Fig.2). The warning eHMI appears when the vehicle is 50 m away from the pedestrians’ crossing location.

2.2. Experimental design and procedure

A between-subject 2 (vehicle type: AV vs. HDV) * 2 (task demand: simple task vs. dual task) experimental design was employed, resulting in four experimental conditions. After controlling for gender and handedness, all participants were randomly assigned to one of the four experimental conditions where they watched videos of either an AV or a HDV approaching the crossing location and completed either the simple task or dual task described below.

After signing an informed consent form that stated that the study’s object is to understand pedestrians’ behaviours on urban roads, participants in the AV conditions were told that the vehicle in the videos is automated, while those in the HDV conditions were told that the vehicle in the videos is electric. Accordingly, participants in the AV conditions first read an introduction of AVs as follows: “A fully automated vehicle is driven by technology and not by a human. A fully automated vehicle uses a wide range of technologies such as radar and cameras to navigate the roads. With these technologies, a fully automated vehicle can sense its environment, and drive without any intervention of a human driver. Since human drivers will not be involved in the driving task, AVs in the future may use an external human-machine interface (eHMI) to communicate their intentions to pedestrians”. The participants in the AV condition were then presented with a photo representation of the eHMI



Fig. 1. Experimental set-up.

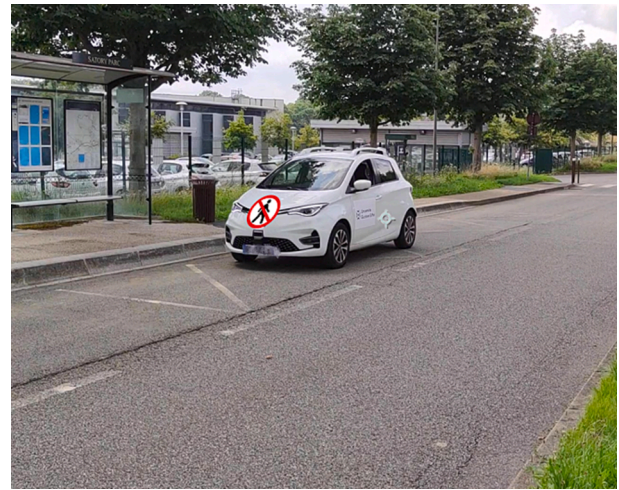


Fig. 2. The warning eHMI on the AV.

used in this study and were told that the eHMI means ‘be careful, the vehicle may not be able to stop’. To ensure participants in HDV conditions receive the similar time exposure to the introduction materials, participants in the HDV conditions read an introduction of electric vehicles as follows: “An electric vehicle is a vehicle that is propelled by electric motors and powered by batteries. The first practical electric vehicles were produced in the 1880s. However, it was not until the late 2000 s that electric vehicles began to gain popularity among consumers. The typical charging time for an electric vehicle can range from 30 min and up to more than 12 h. On average, a fully charged electric vehicle is capable of driving between 150 and 200 miles”.

Then, participants in both HDV and AV conditions were introduced to their experimental tasks. For participants that were assigned the simple task conditions, the task was to watch each video clip and imagine themselves as the pedestrian in the video waiting to cross the road to go to a bus station. While watching the video, the participants were instructed to press a key on a handheld keyboard to indicate the last moment that they would be willing to cross the road in front of the vehicle. This approach measures their critical gap acceptance (Palmeiro et al., 2018). Participants in the dual task conditions were asked to complete the simple task while also engaging in a secondary task. The secondary task was adopted from Karthaus et al. (2020). Specifically, participants were presented with stimuli that consisted of words starting with a vowel (e.g., interesting) and consonants (e.g., school). These stimuli were presented either visually as a sign on the bottom of the screen or acoustically via a speaker. The stimuli were presented for 1 s, with 0.5 s intervals in between them. On average, 8–15 stimuli were presented during one video clip. The participants’ task was to respond, as soon as possible, to words that both started with a vowel and were an adjective by orally repeating those words (and not any other words). Their responses were audio recorded.

Following the introduction session, all participants were instructed to practice several trials to familiarize themselves with the experimental tasks. After ensuring the participants correctly understood their tasks, the researcher asked participants to complete the formal experiment trials for two experimental blocks. Each experimental block contains 26 trials that were randomly presented to all participants in each condition. Table 1 presents an overview of the trials in each experimental condition. After each experimental block, participants were asked to rate their mental workload using the Raw NASA-TLX (RTLX) on a 100-point scale (Hart, & Staveland, 1988; Hart, 2006). In the end, all participants completed a post-experiment questionnaire.

Table 1
Experimental conditions.

Experimental conditions	Vehicle type	Task demand	eHMI status	No. of trials (videos)
1	AV	Simple task	eHMI present	13*2
			eHMI absent	13*2
2	AV	Dual (audio) task	eHMI present	13
			eHMI absent	13
		Dual (visual) task	eHMI present	13
			eHMI absent	13
3	HDV	Simple task	n/a	13*4
4	HDV	Dual (audio task)	n/a	13*2
		Dual (visual) task	n/a	13*2

2.3. Measures

Critical gap acceptance: This dependent variable is adapted from an earlier experiment on pedestrian-AV interactions conducted by [Palmeiro et al. \(2018\)](#). In the experiment, participants watching the video of an approaching vehicle were instructed to indicate the last moment that they would be willing to cross the road in front of the approaching vehicle. Their response time was recorded, and the critical gap was calculated in terms of vehicle time-to-arrival (TTA): the time before the vehicle reaches the crossing location when pedestrians made the crossing decision.

Self-reported prediction of the vehicle’s future behaviour: Adapted from [Vlakveld et al. \(2020\)](#), a single item was employed (“To what extent did you think the vehicle is going to stop and let you cross first?”). After watching each video clip in the experiment, participants were asked to rate this question on a 7-point Likert scale, ranging from 1 being extremely unlikely to 7 being extremely likely.

Perceived mental workload: The most commonly used measurement of subjective mental workload, raw NASA-TLX ([Hart, & Staveland, 1988; Hart, 2006](#)) was employed. After each of the two experimental blocks, participants were instructed to provide ratings on a scale ranging from 0 to 100 for each of the six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration level.

Perceived impact of eHMIs: At the end of the experiment, participants in the two AV conditions were presented with a photo of the eHMI again and asked the question: “How often did you see the symbol in front of the vehicle? How many times did you see it among the 52 videos? (From 1 to 52 times)” and the subsequent question “To what extent does the symbol influence your decision to cross? (From 1 meaning not at all to 7 meaning to a large extent)”. Then, they were asked to rate their agreement with the statement “I clearly remember what the symbol means (from 1, meaning I completely forget, to 7, meaning I remember 100% what it means).” Finally, participants were asked to describe how exactly their crossing decisions were (or were not) influenced by the eHMI.

Post-experimental questionnaire: The post-experimental questionnaire first collected the demographic information of participants such as age and walking habits. Then, participants were asked to rate how realistic the experiment was using a short experimental realism scale ([Woodman et al., 2019](#)). This scale contained five questions (e.g., how well did the tasks hold your attention?). Answers were given on a 7-point Likert scale, from 1 meaning not at all to 7 meaning to a large extent. Finally,

pedestrians in the two AV conditions were asked about their level of knowledge of AVs (see [Appendix A](#)).

2.4. Participants

Ethical clearance was approved by the Ethics Review Committee of the Queensland University of Technology (QUT) as an overseas data collection project in partnership with Université Paris Cité (Approval Number: 4530). The study was conducted on a university campus in Paris, France. All participants were university students recruited through flyers distributed on campus and a Student Participant Pool. Prior to the experiment, participants were introduced to the research project and gave their consent to participate in this study. Participation time in the experiment was approximately one hour. Participation was on a voluntary and anonymous basis without any monetary reward. Participants’ consents were confirmed again at the end of the experiment, and they were made aware that they were able to withdraw their data at any time prior to the data analysis stage of this project.

In total, 149 university students participated in the study. Of these, 15 participants were excluded from the sample because they provided incomplete answers with more than half of responses missing or because they indicated that they did not understand clearly the experimental task at the end of the experiment. The final sample consists of 134 participants, who were randomly assigned to four experimental conditions: 32 in the AV-dual task condition, 33 in the AV-simple task condition, 35 in the HDV-dual task condition, and 34 in the HDV-simple task condition. The participants ranged in age from 18 to 25 (M= 19.42, SD=1.56) and are mostly female. All participants reported having normal or corrected-to-normal vision and hearing. Participants’ demographics and walking habits in the four experimental conditions are described in [Table 2](#). Overall, there is little variability among all participants in their demographic information.

3. Results

3.1. Experimental realism

Participants reported that the experimental tasks held their attention quite well (M = 5.23, SD = 1.14), that they were quite focused on the tasks (M = 5.63, SD = 1.16), and that they were actively engaged in the tasks, rather than passively experiencing them (M = 5.1, SD = 1.37). Participants also indicated that the experimental scenarios were similar

Table 2
Demographic information of participants in four experimental conditions.

	HDV-simple task	HDV-dual task	AV-simple task	AV-dual task
Age	M=19.67, SD=1.73	M=19.21, SD=1.27	M=19.53, SD=1.95	M=19.25, SD=1.22
Gender (% of females)	91.2	91.4	90.9	90.6
Main walking area (% of those walking mainly in urban area)	79.4	85.7	75.8	78.1
Daily walking time (% of those walking less than 60 min per day)	85.3	80	84.8	81.3
Purpose of walking (% of those walking for daily commute to work/university)	85.3	88.6	81.8	90.6
Technology use	M=4.35, SD=1.63	M=4.51, SD=1.4	M=4.45, SD=1.42	M=4.63, SD=1.16
Level of knowledge of AVs	n/a	n/a	M=2.33, SD=0.48	M=2.13, SD=0.75

to real-world situations ($M = 5.68, SD = 1.42$), and believed that their decision in the experiment would be relatively consistent with what they would do in the real world ($M = 4.57, SD = 1.57$). Results from a series of one-way ANOVA show there is no significant difference between the four experimental groups in all dimensions of experimental realism (all $p >.1$).

3.2. Mental workload

First, pedestrians' ratings of their mental workload depending on whether they were engaged in a simple vs. dual task were analyzed. A series of 2 (vehicle type: AV vs. HDV) * 2 (task demand: simple task vs. dual task) ANOVA on all dimensions of NASA-TLX scores and the overall score were conducted. Significant difference between tasks were found in the overall score, $F(3, 269) = 30.41, p <.001, \eta^2 = 0.10$. The overall workload of the dual task condition is significantly higher ($M = 289, SD = 81.11$) than the simple task condition ($M = 235.36, SD = 80.02$). In particular, the main differences appeared in the "effort" and "performance" dimensions (see Fig. 3). Participants in the dual task conditions ($M = 45.08, SD = 20.14$) were less satisfied with their level of performance than those in simple task conditions ($M = 62.64, SD = 20.98$), $F(3, 269) = 49.74, p <.001, \eta^2 = 0.16$. Participants in the dual conditions ($M = 60.67, SD = 19.03$) also reported that they undertook more effort to achieve their level of performance than those in the simple task conditions ($M = 37.54, SD = 22.43$), $F(3, 269) = 85.06, p <.001, \eta^2 = 0.24$.

Even though participants had a slightly lower mental workload when interacting with an AV ($M = 258.17, SD = 85.79$) than an HDV ($M = 265.75, SD = 83.98$) in the simple task condition, the main effect of the vehicle type is not significant, $F(3, 269) = 0.63, p = .42$. There is no significant interaction effect between vehicle type and task demand, $F(3, 269) = 0.52, p = .47$. And further analysis shows no difference in participants' mental workload when engaging in different secondary tasks (visual vs. auditory), $F(1, 32) = 0.04, p = .84$.

3.3. Pedestrians' crossing decisions: Critical gap and self-reported prediction of vehicle future behavior

3.3.1. Impact of secondary task

The aim of this part of the analysis was to further understand the effects of task demand on pedestrians' crossing decisions, and whether the effects are different depending on the type of vehicle (AV vs. HDV) they interact with. Repeated measures ANOVA were conducted with between factors vehicle type (AV vs. HDV) and task demand (simple task vs. dual task) on pedestrians self-reported predictions of vehicle intention and critical gap acceptance in the 13 interaction scenarios.¹

First, no significant difference in pedestrians' self-reported predictions of vehicles' future behavior was found between groups, indicating that neither vehicle type ($F(1, 264) = 0.02, p = .88$), nor task demand ($F(1, 264) = 0.35, p = .55$) influenced such predictions. The interaction effect was also not significant ($F(1, 264) = 2.84, p = .09$). However, as shown in Fig. 4, significant differences in pedestrians' critical gap choice were found between those who engaged in only a simple crossing task vs. those who engaged in dual tasks, $F(1, 257) = 31.16, p <.001, \eta^2 = 0.11$. Pedestrians accept smaller crossing gaps when engaging in dual tasks ($M = 5381.58, SD = 1870.53$), compared to when they are not ($M = 6869.17, SD = 2409.35$). No significant main effect of the vehicle type was found ($F(1, 257) = 0.61, p = .43$). However, a small interaction effect between vehicle type and task demand was found, $F(1, 257) = 4.67, p = .03, \eta^2 = 0.02$. The impact of task demand was larger when pedestrians interact with an HDV, $F(1, 129) =$

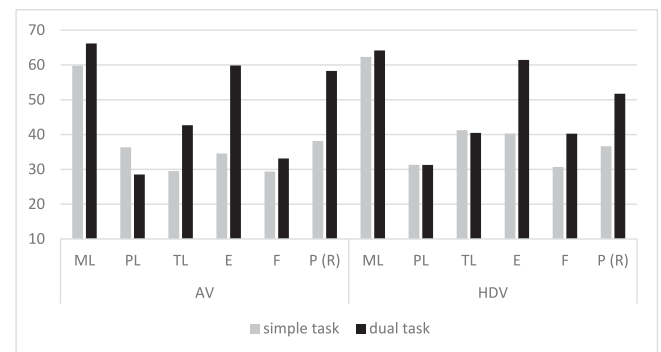


Fig. 3. Mean NASA-TLX scores. ML = Mental load, PL = Physical load, TL = Temporal load, E = Effort, F = Frustration, P(R) = Performance (reverse scored).

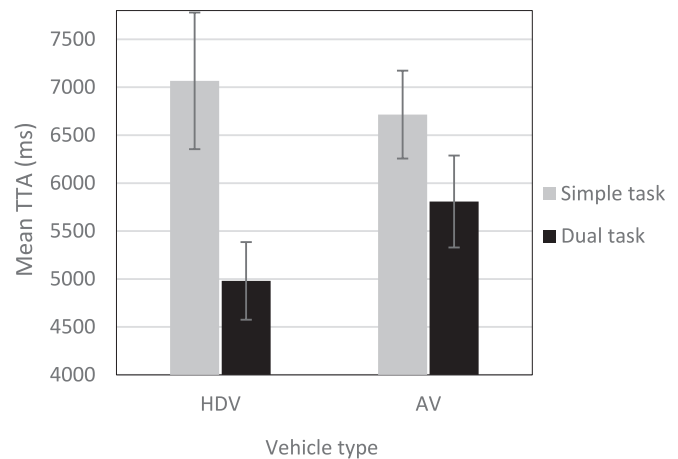


Fig. 4. Mean TTA in four experimental conditions.

$25.36, p <.001, \eta^2 = 0.16$, compared to when pedestrians interact with an AV ($F(1, 128) = 7.18, p = .008, \eta^2 = 0.05$). Further analysis found no effect of the secondary task type (visual or auditory) ($F(1, 31) = 0.0, p = .9$).

3.3.1.1. Impact of eHMI. Participants in simple task and dual task conditions were asked three questions about the eHMI they saw, and their responses were compared between groups. For responses to the first question(s) "How often did you see the symbol in front of the vehicle? How many times did you see it among the 52 videos?", significant between-group differences were found using independent t test. While the eHMI was presented a total of 26 times in the 52 videos, the results showed that the average time participants noticed the eHMI in the simple task condition ($M = 25.79, SD = 10.81$) was significantly higher than in the dual task condition ($M = 18.75, SD = 10.28$), $t(1, 63) = 2.69, p = .009$. For the second question, "I clearly remember what the symbol means." and the third question, "To what extent does the symbol influence your decision to cross?", results of Mann-Whitney U tests showed that there was no significant difference between the groups in their responses ($U = 490, p = .58; U = 388.5, p = .06$).

Next, we investigated the effectiveness of the eHMI and if there were different crossing decisions when pedestrians were or were not engaged in the secondary task. To do this, a repeated measures ANOVA was conducted for the 13 interaction scenarios with the within-group factor eHMI (i.e., with eHMI vs. no eHMI) and the between-group factor task demand (i.e., simple task vs. dual task) on pedestrians' predictions of vehicle intention and critical gap acceptance. In terms of participants' predictions of vehicle intention, the main effect of eHMI was significant. Participants were less likely to believe that an AV is going to stop and

¹ Since the effect of the interaction scenario is not the focus of the current study, only the main and interaction effects of between factors are described in the results.

give way to them when the eHMI is present ($M = 4.79$, $SD = 1.23$), compared to when the eHMI is absent ($M = 3.89$, $SD = 1.53$), $F(1, 128) = 65.41$; $p < .001$; $\eta^2 = 0.34$.

In terms of critical gap acceptance, as shown in Fig. 5, there was a significant main effect from the presence of a warning eHMI, $F(1, 128) = 38.05$; $p < .001$; $\eta^2 = 0.23$. Pedestrians chose larger crossing gaps when the warning eHMI is present ($M = 6464.84$, $SD = 2004.93$) than when the eHMI is absent ($M = 6071.98$, $SD = 2016.24$). The main effect of task demand was marginally significant, $F(1,128) = 7.18$, $p = .008$, $\eta^2 = 0.05$. The interaction effect of eHMI*task demand was also significant, $F(1,128) = 17.64$, $p < .001$, $\eta^2 = 0.12$. This indicates that the effectiveness of the warning eHMI differs depending on whether pedestrians engage in a secondary task or not. While the eHMI significantly increased participants' critical gap size in the simple task condition ($F(1, 65) = 48.42$, $p < .001$; $\eta^2 = 0.43$), it did not influence pedestrians' gap selection in the dual task condition ($F(1,63) = 2.2$; $p = .14$). Further analysis found no effect of secondary task type (visual or auditory) ($F(1,31) = 0.42$, $p = .52$).

3.4. Qualitative analysis of pedestrians' opinions about eHMIs

At the end of the experiment, participants in the AV conditions were asked one open-ended question about how eHMIs influenced (or not) their crossing decisions. Data from the 65 participants assigned to the AV conditions was included in the analysis. There was a large variance in their responses. Overall, three types of participants were identified. The first type, consisting of 13 participants, are the "risk avoiders" – those who are cautious when it comes to interacting with AVs. All the participants belonging to this group indicated that they decided to cross the road as soon as or even before the eHMI was visible. While some participants indicated that they are always quite risk-averse, a few specifically mentioned their concerns about interacting with AVs. They indicated that they are "more vigilant" and "more cautious than they would be when interacting with a vehicle driven by a human". Interestingly, by contrast, two participants claimed that they would be riskier when interacting with the AV than they would with a HDV, because they assumed that they would be safe in front of the AV before the eHMI appeared.

Most participants (35) belong to the second group – "the conformists." This group stated that their crossing decisions were largely influenced by the eHMI. They claimed that they decided to cross "sooner than usual", "immediately after seeing the eHMI", and "questioned their ability to cross safely" because "it would be riskier if wait(ing) for too long" and were "not sure if the AV will be able to stop". Interestingly, several participants who mentioned that they initially complied with the eHMI and made earlier crossing decisions were less influenced by the eHMI later on as they believed that the "warning eHMI sometimes were

presented quite early".

Finally, 17 participants belong to the group "the challengers", that is, people who were not influenced by the eHMI to a large extent. As stated by one participant, "it didn't really influence me, I was still thinking as usual with my own experiences and beliefs about a car stopping". This group of participants seems to trust their own judgement more than the suggestions of the eHMI. Moreover, some also have more confidence that the AV would stop for them: "I don't really pay attention to the symbol (eHMI) on the car...I'm confident that the radar technology will detect me. I have mostly ignored the symbol or not seen it".

4. Discussion

The current study set out to investigate the impact of secondary task engagement on pedestrians' crossing decisions when interacting with AVs. We further compared whether the impact differs depending on if the vehicle is an HDV vs. an AV. In addition, because future AVs will likely use eHMIs to communicate their intentions to pedestrians, we tested the effectiveness of a warning eHMI on reducing late crossing decisions by pedestrians. We also explored the impacts of secondary task engagement on the effectiveness of the eHMI.

Overall, we found that engaging in a secondary task while making crossing decisions led to higher perceived mental workload experienced by pedestrians during the experiment. Specifically, the subjective ratings of the NASA-TLX indicated that "effort" and "performance" dimensions were mostly impaired by dual tasking. Correspondingly, participants in the dual task condition were found to select significantly smaller and less safe critical crossing gaps in comparison to participants in the simple task condition. This finding is in accordance with earlier research suggesting that pedestrians who are under high mental workloads tend to pay less attention to traffic and take greater risks while crossing roads with HDVs (Schwebel et al., 2012; Chen et al., 2017; Osborne et al., 2020).

The current study extends existing literature by evaluating the impact of secondary task engagement on pedestrians' crossing decisions in front of an approaching AV vs. an HDV. Our results show that the impact of secondary task engagement is smaller in the AV conditions compared to the HDV conditions. While engagement in the secondary task on average reduced participants' critical gap acceptance by more than 2 s in HDVs conditions, only less than 1 s of difference were observed in AV conditions. This means pedestrians were more cautious when it comes to interacting with an AV under dual task conditions, as they chose larger crossing gaps in front of an approaching AV.

This finding can be partially explained by low trust in AVs among participants incurred by high mental workload. In an earlier study conducted by Karpinsky et al. (2018), participants were asked to monitor automation in dynamic multitasking environment. The authors found that participants' trust declined significantly as the task demanded more attention. In addition, pedestrians may also experience uncertainty regarding the future behavior of AVs in situations that provide no additional information about the vehicles' intentions (i.e., areas that are not regulated by formal traffic rules). Here, pedestrians may not be able to obtain enough information from the vehicle to reduce uncertainty and as a result will become more cautious when crossing (Jayaraman et al., 2019). By contrast, pedestrians are more comfortable crossing in front of AVs amidst regulated traffic conditions, such as a crossing facility (Jayaraman et al., 2019; Zhao et al., 2022).

In contrast with most of the past research that focus on eHMIs that encourage crossing, the current study evaluated whether a warning eHMI could help to prevent late crossing decisions by pedestrians. When the warning eHMI is present, participants were less likely to believe that the vehicle is going to stop and yield to them, and thus chose larger and safer crossing gaps. In many traffic situations, the right-of-way rules tend to be ambiguous, and pedestrians were found to sometimes misunderstand the right-of-way rules, which causes potential conflicts (Hatfield et al., 2007). In this case, warnings transmitted by AVs could

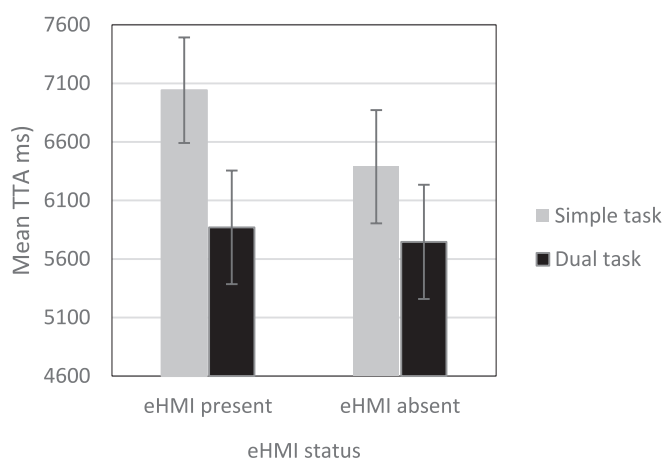


Fig. 5. Mean TTA in FAV conditions when eHMI is present vs. absent.

help pedestrians to understand the intentions of the vehicle and improve their safety. The results of this study illustrate that including an eHMI that warns of the danger of crossing is effective in reducing the likelihood of late and unsafe crossings initiated by pedestrians. This result is in line with previous research in this area which shows that eHMIs can, to some extent, influence pedestrians' crossing decisions (Bazilinsky et al., 2019; Dey et al., 2020). Nevertheless, eHMIs could also pose legal and ethical complications (Faas et al., 2020). This is particularly true if the eHMI fails to comply with relevant laws or respect pedestrians' autonomy. For example, an eHMI may warn pedestrians not to cross the road when pedestrians have the legal right-of-way. Given the importance of warning eHMIs in informing pedestrians about the danger in risky situations such as automation failure, the design requirements for eHMIs is worth further debate from a legal perspective.

Inattention blindness appeared among pedestrians who were engaged in a secondary task while making crossing decisions. While participants in the simple task condition were able to quite accurately estimate the frequency that the eHMI was present out of all interactions, participants in the dual task condition noticed the eHMI significantly less often (only 18 times out of the actual 26 times). Furthermore, while the eHMI significantly influenced the crossing decisions of pedestrians in the simple task condition, pedestrians in the dual task condition were not impacted by the eHMI. Our finding suggests that it is vital to consider inattention blindness when designing eHMIs for AV-pedestrian interactions. Moreover, this study was conducted in a controlled laboratory setting, and the secondary tasks were used to explore the effects of inattention blindness on crossing decisions. In real-world traffic, crossing a road itself can be a mentally demanding task (Dommes, 2019), especially if the crossing happens in a mixed traffic environment where the visual load is high (Tapiro et al., 2020). As such, inattention blindness may more commonly exist even when pedestrians are not engaged in a secondary task.

It is worth noting that we have used a symbol-based eHMI to show the warning intention of AVs in our study. This type of eHMI had a moderate impact on pedestrians' crossing decisions. Nonetheless, a symbol-based visual eHMI might not be the best option for pedestrians who experience high mental workloads. In these situations, visual eHMI alone may not be enough to attract pedestrians' attention, and pedestrians may take time to study and interpret the meaning of a symbol that they are not familiar with (Bazilinsky et al., 2019). As such, sound and haptic information would be more suitable than visual information when pedestrians are not looking at the road and the AV. In current road traffic with HDVs, previous research has already suggested several countermeasures for minimizing the negative consequences of technology use among pedestrians, such as sending warnings directly to the pedestrians' phones (Osborne et al., 2020). These countermeasures may also be helpful in designing a safer and a more efficient AV-pedestrian interaction strategy vis-à-vis eHMIs, especially in situations where pedestrians are distracted by technology.

Our final contribution lies in our qualitative analyses which revealed distinct individual differences in pedestrians' willingness to comply with warning eHMIs. The most problematic group of pedestrians we identified is the "challengers" of eHMIs, namely those who stated that their crossing decisions were not influenced by eHMIs. This group accounted for about 26% of the total participants in this study. Thus, it is vital to explore means to improve this group's compliance to eHMIs, and/or to consider using alternative vehicle-to-pedestrian communication means other than eHMIs. For example, previous literature suggests that the speed and the distance of vehicles play an important part in the decision-making of pedestrians (Wang et al., 2021; Lee et al., 2021). This is also confirmed in our qualitative data, where several participants stated that they prefer to cross the road based on their own judgement. Considering these points, we agree with Lee et al. (2022), who argue that a combination of vehicle kinematics and eHMIs seems to be a more optimal solution for AV-pedestrian communication as it fulfills the needs of different types of pedestrians. Furthermore, we found that certain

pedestrians become less compliant with eHMIs over time. One of the reasons for such behavior involves the timing of eHMIs. Pedestrians in our study preferred to rely on vehicle kinematics if the eHMI is inappropriately timed (i.e., too early). As very little is found in the literature on the timing of eHMIs in relation to vehicle kinematics (Dey et al., 2020), a next key step for eHMI design is to explore this question.

4.1. Limitations and future research

While the present study provides novel insights into pedestrians' interaction with AVs, it faces several limitations that should be addressed in future research. First, the sample of this study is rather homogeneous, consisting of mostly female university students residing in Paris, France. In an earlier study, women were found to feel more anxious about AVs than men (Hohenberger et al., 2016). This may limit the generalizability of our results to the general public. Thus, further study is needed considering different demographic samples.

Second, we conducted the experiment using video materials presented with a projector instead of an on-road experiment. The different field of view might potentially influence the perception of vehicle speed and time gap decisions. Video-based experiments have been an increasingly popular method to study pedestrian-vehicle interaction. Previous studies have used video-based experiments to explore pedestrians' gap acceptance (Beggiato et al., 2018), detection of vehicle movement (Ackermann et al., 2019b), willingness to cross (Dey et al., 2019; Colley et al., 2022), and preference for eHMIs (Ackermann et al., 2019a; Lau et al., 2022). Results from these studies suggest that participants are sensitive to the speed and deceleration of vehicles (Beggiato et al., 2018; Ackermann et al., 2019a), and are in general quite accurate in assessing TTA of oncoming vehicles (Petzoldt, 2014). Nonetheless, future research should further explore this phenomenon with on-road observations of pedestrians once AVs are on public roads.

In addition, we have only evaluated one type of eHMI in our study. Past research appears to provide few insights regarding optimal eHMI design solutions for AV's interaction with distracted pedestrians. More research is needed to examine various other types of eHMIs in terms of their cognitive demand to pinpoint the best designs for eHMIs. For example, a previous study on driver warnings showed that, in critical situations, warnings that include audio induced a shorter response time among drivers than visual warnings (Politis et al., 2015). Especially in the case of distracted pedestrians, visual eHMIs that are accompanied by sound (Mahadevan et al., 2018) may better attract pedestrians' attention away from their secondary tasks. Future studies should explore the design of combined visual and auditory eHMI for AVs. Further, in our study, we introduced the meaning of the eHMI before the start of the experiment and confirmed whether the participants remembered the meaning at the end of the experiment. However, it might not be possible to sufficiently educate all pedestrians about the meaning of eHMIs when AVs enter the roadway in the future. As such, pedestrians may experience high mental workload if they struggle to interpret the meaning of eHMIs. Thus, the learnability, and long-term adaptation of the eHMI should be further studied to explore the challenges associated with high mental workload.

Future studies should also explore the visibility of eHMIs in various traffic scenarios. In our study, we found that pedestrians tended to ignore eHMIs if they were under a high mental workload. There are also other scenarios, including light conditions (i.e., day and night), complex traffic (e.g. a busy intersection with multiple vehicles) that might have a negative impact on the visibility of eHMIs. For example, it was found that driver's visual exploration behaviors are reduced at night, which results in difficulties in hazard perception (Evans et al., 2022). Yet, vision and perceptual capabilities of pedestrians which are important for the interaction design of AVs have been rarely explored.

5. Conclusion

Overall, this study evaluated the extent to which mental workload influences pedestrians' interaction with AVs. When engaging in a secondary task, pedestrians tended to select larger and safer gaps to cross in front of an approaching AV compared to an HDV. A warning eHMI reduced late and unsafe crossing gaps selected by pedestrians. Furthermore, this study showed that the eHMI could be ignored and become less effective when pedestrians are engaged in secondary tasks while making crossing decisions. The qualitative analysis revealed strong individual differences in pedestrians' attitudes towards eHMIs. While the majority of pedestrians are willing to comply with eHMIs, a small group of people chose to disregard them for various reasons such as low-trust.

Insights from this study offer significant implications for the design of AV-pedestrian interactions. Although the warning eHMI can effectively reduce the likelihood of late and dangerous crossing gaps selected by pedestrians, it is vital to attract their attention to the eHMI in the first place. Thus, a successful eHMI design should minimise pedestrians' mental workload while attracting sufficient attention from pedestrians. In addition, as certain pedestrians may not comply with eHMIs, the idea of purely relying on eHMIs to communicate the intentions of AVs seems unrealistic. As such, AV manufacturers should consider using a combination of eHMIs and vehicle kinematics to transmit vehicle intentions to pedestrians. Finally, rather than treating all pedestrians as the same, optimizing eHMI design requires further exploration of the factors associated with challenging and non-complying behaviours of pedestrians.

CRedit authorship contribution statement

Xiaoyuan Zhao: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Xiaomeng Li:** Conceptualization, Methodology, Writing – review & editing. **Andry Rakotonirainy:** Project administration, Writing – review & editing. **Samira Bourgeois-Bougrine:** Writing – review & editing. **Dominique Gruyer:** Resources, Writing – review & editing. **Patricia Delhomme:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. . Questionnaire used in the study

Section 1 Demographic information.

1. What is your age?____
2. What is your gender?_____

3. On a normal day, how long do you spend walking on roads?
 - 0–30 min
 - 31–60 min
 - greater than60 min
4. For what reason do you walk most often?
 - commute to work/university
 - physical exercise
 - everyday chores (to the supermarket, restaurant, etc.)
5. In which areas do you walk most often?
 - urban area
 - rural area
 - suburban area
6. How often do you use phone while walking on roads, including but not limited to: write or read a message, use social media (e.g., TikTok, Instagram), access the Internet, talk on the phone, listen to music. (From 1 very infrequently to 7 very frequently or always)

Section 2 Experimental realism.

We are not only interested in your performance but also in your subjective experience during the experience. You will be evaluating the task(s) you did. There is no right answer, we just want your opinion. Please read each question carefully. Please indicate to what extent you agree or disagree with the following statements from 1 not at all to 7 to a large extent.

7. How well did the tasks hold your attention?
8. How focused did you feel on the tasks?
9. To what extent did you feel that the experimental tasks were something you were actively doing, rather than passively experiencing?
10. To what extent was the experimental situation similar to situations you are likely to encounter on the road?
11. To what extent do you think your decision was consistent with what you would do on the road?

Section 3 Perception of eHMI and AVs.

In the experiment you have just participated in, this symbol was placed on the vehicle in some of the videos. Please answer the following question about this symbol:

12. How often did you see the symbol in front of the vehicle? How many times did you see it among the 52 videos? (from 1 to 52)
13. I clearly remember what the symbol means. (From 1 I forgot completely to 7 I remember clearly)
14. To what extent did the symbol influence your decision to cross? (From 1 not at all to 7 to a large extent)
15. How did the symbol influence your decision to cross? For example, did you make a faster decision to cross once you saw it? (Open question)
16. How familiar are you with the concept of a fully automated vehicle? (from 1 to 5)
 1. I have never heard of a fully automated vehicle
 2. I have heard of fully automated cars once or twice
 3. I am quite familiar with the idea of fully automated vehicles.
 4. I follow the development of fully automated vehicles.
 5. I work in a field directly related to fully automated vehicles.

Appendix B. . Illustration of all crossing locations

Scenarios

Straight lane (far lane)



Straight lane (near lane)



T-junction (vehicle turn left)



T-junction (vehicle turn right)



Roundabout



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