# Get Out of The Way! Examining eHMIs in Critical Driver-Pedestrian Encounters in a Coupled Simulator

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## Abstract

Past research suggests that displays on the exterior of the car, known as eHMIs, can be effective in helping pedestrians to make safe crossing decisions. This study examines a new application of eHMIs, namely the provision of directional information in scenarios where the pedestrian is almost hit by a car. In an experiment using a head-mounted display and a motion suit, participants had to cross the road while a car driven by another participant approached them. The results showed that the directional eHMI caused pedestrians to step back compared to no eHMI. The eHMI increased the pedestrians' self-reported understanding of the car's intention, although some pedestrians did not notice the eHMI. In conclusion, there may be potential for supporting pedestrians in situations where they need support the most, namely critical encounters. Future research may consider coupling a directional eHMI to autonomous emergency steering.

**CCS CONCEPTS** • Human-centered computing ~ Human computer interaction (HCI) ~ HCI design and evaluation methods ~ Laboratory experiments • Applied computing ~ Operations research ~ Transportation • Human-centered computing ~ Human computer interaction (HCI) ~ Interaction paradigms ~ Virtual reality

**Additional Keywords and Phrases:** External human-machine interfaces, Coupled virtual-reality simulator, Pedestrian safety, Decision-making

# 1 Introduction

Worldwide, 1.3 million fatal traffic accidents occur every year, 22% of which concern pedestrians [1, 2]. Besides the car driver, the pedestrian also has a possible role in preventing accidents by deciding not to cross or by stepping away in time. Factors contributing to pedestrian-car collisions include the pedestrian's misinterpretation of the car's intention, a wrong assumption that the driver has noticed the pedestrian, or a misconception that there is sufficient time to cross [3]. Most fatal pedestrian accidents occur in darkness [4], and about 30% of pedestrian-car collisions occur in situations with visual obstruction, such as when a pedestrian stands next to a parked car [5, 6].

Efforts to prevent pedestrian-vehicle collisions have resulted in autonomous emergency braking (AEB) and autonomous emergency steering (AES) [7]. However, there is a risk that the pedestrian responds in a way that the AES does not anticipate. In a pedestrian simulator study, Soni et al. [8] found that pedestrians responded to an imminent collision by walking faster, stepping back, or freezing (while safety systems are often programmed assuming that the pedestrian does not change walking speed). Similarly, in a study analyzing pedestrians' behavior when crossing at a red light, Jay et al. [9] found that 5 to 10% changed their walking pattern while crossing, either by stepping back or accelerating, possibly because they realized they had misestimated the time they had to cross.

For automated vehicles, external human-machine interfaces (eHMIs) are currently being developed to communicate the vehicle's intention or provide advice to pedestrians. Various car manufacturers, such as Daimler, BMW, Toyota, and Jaguar, have presented eHMIs for their concept cars (see [10, 11] for reviews). The research so far indicates that, compared to no eHMIs, eHMIs improve crossing behaviors in that they promote crossing when it is safe to cross or inhibit crossing when it is not safe to cross (e.g., [12–15]). An interesting topic in several recent studies concerns eHMIs that communicate an expected direction or action using arrows. Rettenmaier et al. [16], for example, used an eHMI in which arrows indicated whether or not an approaching road user could go first through a narrowing of the road.

In most previous studies, participants were given enough time (at least several seconds) to perceive and process the eHMI message. The usefulness of eHMIs in cases in which there is only a short time to react, such as in (near-) collisions, is yet unknown. The hypothesis is that collisions could be prevented if pedestrians know that they have been detected and informed by the vehicle about what action to take. On the other hand, it can be argued that pedestrians will be unable to process the eHMI's instructions as they focus on the looming hazard instead of the eHMI, similar to the weapon focus effect [17].

This study aims to investigate the effectiveness of eHMIs in near-collision scenarios using a virtual simulator. Our experiment involved a participant in the role of a pedestrian who interacted with a manually-driven car. It was reasoned that this multi-agent approach could allow some natural variability to occur in the trajectories of both participants, which in turn would provide a more meaningful test of the effectiveness of the eHMI as opposed to pre-programmed vehicle behavior. Different near-collision scenarios were created that were visually and temporally demanding for the pedestrian through the inclusion of cars and buildings blocking the view. We examined whether the presence of an eHMI showing the direction toward which the pedestrian should move would result in safer and more predictable interactions in near-collision scenarios compared to when the eHMI was off.

# 2 METHODS

## 2.1 Participants

Forty people participated in this research, 20 in the role of a driver and 20 in the role of a pedestrian. Table 1 shows a number of characteristics of the participants. All participants were living in the Netherlands, a right-hand-traffic country. The research was approved by the Human Research Ethics Committee of the Delft University of Technology, and all participants gave their written informed consent.

## 2.2 Hardware and Software

Two desktops were used: a host to run the simulation for the driver and a client for the pedestrian. The host and client desktops were Windows-based gaming PCs. The client desktop was wirelessly connected to the Xsens Link Motion Tracking Device [18] through a router. It recorded the pedestrian's motion using MVN Analyze software [19]. An avatar in the virtual environment received the motion data from MVN Analyze via C# scripts. The driver steered the car using a Logitech G27 steering wheel. The pedestrian and the driver wore an Oculus Rift CV1 head-mounted display (see Figure 1). No sound was used in the simulation, to keep the experiment manageable in terms of the required hardware. In addition, because of not using sound, participants had to rely only on visual information, which constitutes a purer experimental evaluation of our visual eHMI. A third reason for not using sound is that city traffic is often noisy and that pedestrian-vehicle conflicts are more likely when valid sound cues are unavailable.

The experiment was set up using an open-source multi-agent simulator [20]. The pedestrian was visualized as an avatar that used input from a motion. The avatar was visible to the driver and to the pedestrian him/herself. The driver drove a 1.6-m wide and 2.7-m long Smart Fortwo. The pedestrians were able to move in a lab space of 6 m x 2.8 m. Unity was programmed so that walking 6 m in real life corresponded to 10 m in Unity. In this way, the pedestrian could reach the other side of the road within the available lab space.

**Table 1: Characteristics of the participants**

| | Drivers | Pedestrians |
|---|---|---|
| Males / Females | 10 / 10 | 10 / 10 |
| Mean age (SD) (years) | 21.5 (1.4) | 21.6 (2.2) |
| Lenses / Glasses | 2 / 2 | 4 / 0 |
| Nationality | 20 Dutch | 17 Dutch, 2 Belgian, 1 Irish |
| Driver's license: Yes / No | 20 / 0 | 15 / 5 |
| Mileage in the past 12 months (km) | 0–100: 1<br>100–1000: 8<br>1000–5000: 7<br>5000–10000: 3<br>More than 10000: 1 | 0–100: 7<br>100–1000: 5<br>1000–5000: 7<br>5000–10000: 0<br>More than 10000: 1 |
| Car driving frequency in the past 12 months | Every day: 1<br>4–6 days/week: 1<br>1–3 days/week: 4<br>1 day per month–1 day per week: 10<br>Less than 1 day per month: 4<br>Never: 0 | Every day: 0<br>4–6 days/week: 0<br>1–3 days/week: 4<br>1 day per month–1 day per week: 8<br>Less than 1 day per month: 3<br>Never: 5 |
| Frequency of traffic participation as a pedestrian in the past 12 months | Every day: 7<br>4–6 days/week: 7<br>1–3 days/week: 5<br>Less than 1 day/week: 1 | Every day: 13<br>4–6 days/week: 3<br>1–3 days/week: 3<br>Less than 1 day/week: 1 |
| Worn virtual-reality goggles before | Yes, multiple times: 7<br>Yes, once: 7<br>No: 6 | Yes, multiple times: 5<br>Yes, once: 5<br>No: 10 |

**Figure 1: Driver (left top), pedestrian during a trial with an experimenter monitoring safety (left bottom), and pedestrian with motion suit (right).**

## 2.3 Experimental Design

The experiment was of a within-subjects design with two independent variables: Scenario (1 or 2) and eHMI (on or off).

In Scenario 1 (Figure 2), the pedestrian had to cross a 10-m long crosswalk positioned 15.5 m from a corner on the pedestrian's left. The driver came around the corner at 30 km/h. Additionally, an automated car came from the pedestrian's right and stopped in front of the crosswalk. The participants' views of each other were initially blocked by a building and a parked car.

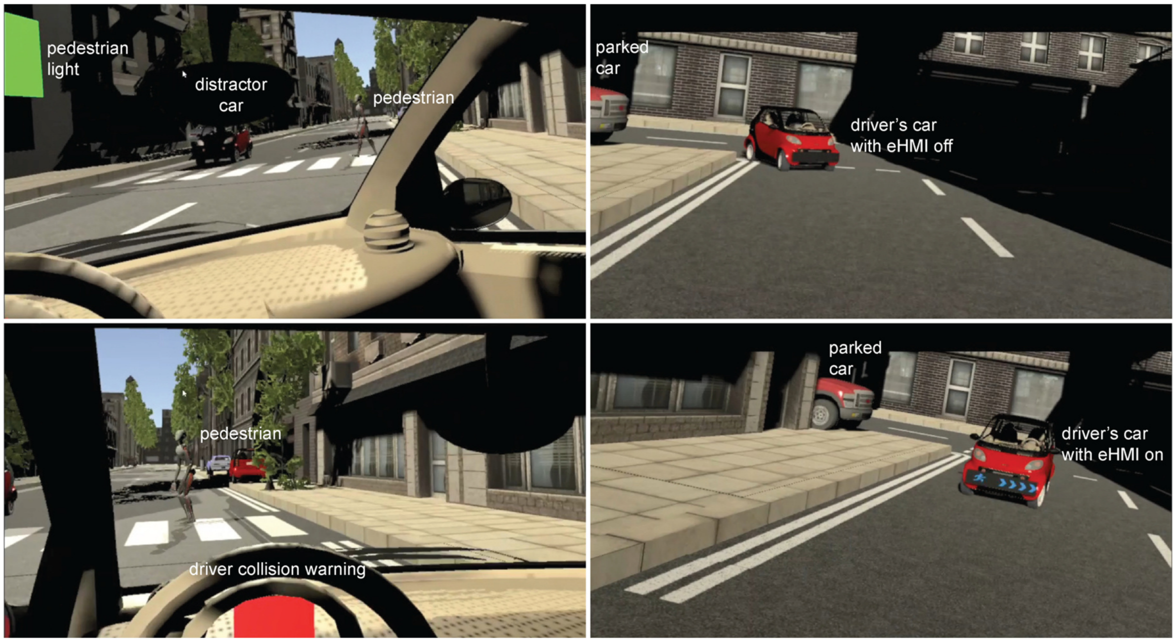


**Figure 2: Scenario 1. Screenshots from the driver's (left) and pedestrian's (right) perspective at the moment the driver collision warning switches on (top) and the eHMI switches on (bottom).**

In Scenario 2 (Figure 3), the pedestrian had to cross a 10-m long crosswalk. A truck driving 30 km/h drove through a curve from the pedestrian's left side and stopped in front of the crosswalk. Slightly behind the truck and in the left lane, the participant's car approached at 30 km/h and maintained speed, thus overtaking the truck. Additionally, an automated car came from the pedestrian's right. The participants' views of each other were initially blocked by the truck.

The eHMI was either off during the entire trial or switched on before reaching the pedestrian. When on, it depicted the icon of a walking pedestrian accompanied by arrows pointing leftward or rightward, depending on the position of the driver's car on the road. The eHMI was based on Othersen et al. [21], who tested a similar eHMI in a pedestrian simulator, but not in a critical scenario and only with rightward-pointing arrows. It can be reasoned that text-based eHMIs, which have been found to be easily understood [10, 22], are less suitable in stressful scenarios, as they may require the pedestrian to use foveal vision and read the text message. eHMIs indicating the car's intention might not be suitable either, as such eHMIs require the pedestrian to translate the information about the car to their own perspective [23]. Previous research concurs that in conditions of time pressure or visual ambiguity, warnings that indicate the escape direction produce more effective steering responses and higher user satisfaction ratings than warnings that indicate the location of the danger [24–26].

The participant pairs completed 20 trials: 6 with the eHMI on (3 in Scenario 1, 3 in Scenario 2) and 6 with the eHMI off (3 in Scenario 1, 3 in Scenario 2). The remaining 8 were filler trials (5 in Scenario 1, 3 in Scenario 2), included to reduce predictability for the pedestrian. In the filler trials, an automated car approached and stopped in front of the zebra crossing. The order of the 20 trials was randomized. In the eHMI on and off trials, the speed of the driver's car was fixed and the driver only had to steer. In the filler trials, the pedestrian crossed the road, whereas the driver had no task other than to observe.


**Figure 3: Scenario 2. Screenshots from the driver's (left) and pedestrian's (right) perspective at the moment the driver collision warning switches on (top) and the eHMI switches on (bottom).**

## 2.4 Triggers

- At the start of the trial, the driver was about 22 s from the crosswalk. The driver's car started at zero speed and automatically accelerated to 30 km/h.
- In Scenario 1, the distractor car stopped in front of the crosswalk 5 to 10 s before the driver arrived, whereas, in Scenario 2, the distractor car stopped in front of the crosswalk about 5 s after the driver arrived. The distractor car was added to encourage the pedestrian to look left and right before crossing the road and to not focus on one side of the road only.
- The pedestrians were instructed to start crossing when a red light turned green (see Figure 4). The green light was triggered when the driver was about 5.5 s from the pedestrian in Scenario 1 and about 8.2 s from the pedestrian in Scenario 2. The green light trigger was set so that when crossing at a typical walking speed, a conflict between the pedestrian and the driver would arise.
- The driver received a collision warning in the form of a red rectangle on the dashboard (see Figure 2 and Figure 3) when the driver's car hit an invisible box collider [27] placed approximately 15 m from the pedestrian.
- Two 4.65-m wide invisible box colliders were placed on the road, acting as triggers for the eHMI. If the driver's car hit the left box, the eHMI with arrows to the left from the pedestrian's viewpoint was activated, whereas if the driver's car hit the right box, the eHMI with arrows to the right from the pedestrian's viewpoint was activated (Figure 5). Within a trial, the eHMI could be triggered only once, i.e., it did not switch state. The distance from the front edge of the box collider to the pedestrian was 9.2 m in Scenario 1 ($x$ = 9.2 m; see Figure

5) or 8.1 m in Scenario 2, which at a speed of 30 km/h corresponds to a time budget for the pedestrian of 1.1 or 1.0 s.

## 2.5 Procedure

Participants read and signed the informed consent form and completed a brief intake questionnaire. Next, they were informed that the experiment concerned the interaction between pedestrians and cars in near-collision scenarios. The participants were shown a picture of the car with the eHMI. It was mentioned that in the role of a pedestrian, they would sometimes see this eHMI if a car is in a near-collision with them, that this would be an indication that the car must swerve to not collide with them, and that they should follow the direction of the arrows on the eHMI to stay safe. Subsequently, participants were assigned the role of either pedestrian or driver while striving for a similar gender distribution across the two groups. Participants without a driver's license were always assigned to the role of the pedestrian.

The pedestrians were informed that their aim would be to cross the road via the crosswalk and instructed what to do depending on the color of the projected rectangle (Figure 4). The drivers were informed that the car was driving with cruise control and that they could only steer. They were also informed about the collision warning on their dashboard and that the eHMI would switch on automatically.

Before the experiment, participants completed a practice session. The drivers performed an evasive maneuver after the collision warning appeared on the dashboard. The pedestrians walked around to get used to virtual reality. During the practice session, drivers and pedestrians were not able to interact with each other.

Next, the experiment started. During each trial, an experimenter stayed in the vicinity of the pedestrian to monitor safety (Figure 1). After each trial, the participants were taken out of the Unity environment and returned to the Oculus Rift menu in order to be placed in the next scenario in Unity. Pedestrians were verbally asked how safe they had felt during the previous trial on a scale of 1 (*very unsafe*) to 7 (*very safe*), if they had seen the eHMI (*yes*, *no*), if they had followed the eHMI's advice (*yes*, *no*), and if they had understood what the car was planning to do on a scale of 1 (*no understanding*) to 7 (*understanding*). Additionally, pedestrians and drivers were enquired about their well-being through the single-item misery scale (MISC) [28]. The experiment would be terminated if participants reported a value of 4 or higher. Before starting the next trial, the pedestrian walked back to the starting position.

After the experiment, the pedestrians completed a questionnaire asking how realistic their behavior in the environment felt on a scale from 1 (*extremely artificial*) to 7 (*super realistic*) and what they thought of the eHMI from 1 (*not sensible*) to 7 (*very sensible*). The drivers were asked how realistic the simulation had felt. Finally, pedestrians and drivers had the opportunity to type comments about the experiment.

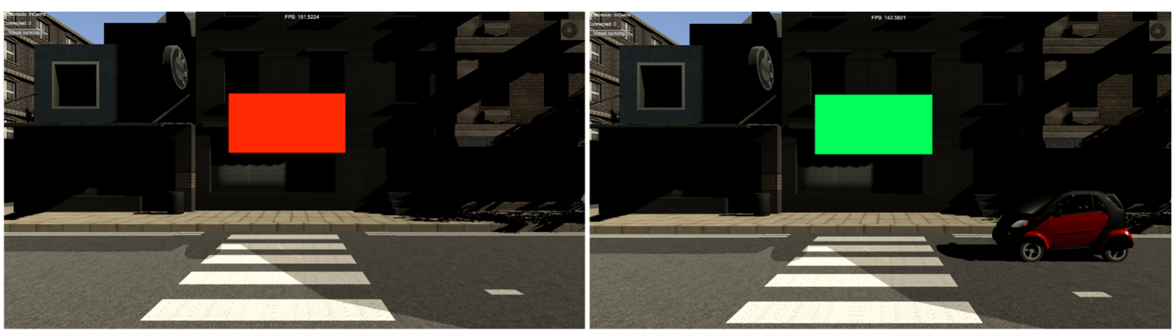

**Figure 4: Projected rectangle for indicating to pedestrians that they had to wait (left) or start crossing (right). The onset of the green rectangle was timed in such a way that a collision course with the driver's vehicle (always approaching from the left) was likely. The car depicted in the right image is the distractor car. The environment in both images is that of Scenario 1.**

## 2.6 Analyses

The pedestrian's $x$ and $y$ coordinates, as obtained from the motion suit, were filtered using a low-pass filter with a cut-off frequency of 10 Hz, whereas the driver's $x$ and $y$ coordinates were filtered with a cut-off frequency of 1 Hz. Next, the pedestrian's velocity was calculated by taking the derivative of the pedestrian's $y$-coordinate and subsequently applying a low-pass filter with a cut-off frequency of 1 Hz.

In addition to the results of the questionnaires, the following measures were calculated per trial from the simulator data:

- *Pedestrian y-coordinate (m).* This measure describes the pedestrian's $y$-coordinate as the driver passed the crosswalk (i.e., $x = 0$; see Figure 5). The higher the pedestrian's $y$-coordinate, the farther the pedestrian had walked; see Figure 5 for a definition of the y-coordinate.
- *Absolute pedestrian-car distance (m).* This measure describes the absolute difference between the $y$-coordinate of the center of the car and the $y$-coordinate of the pedestrian at the moment the driver passed the crosswalk. It is a measure of pedestrian-driver conflict severity.
- *Collision (0 = no, 1 = yes).* A collision was defined as an absolute pedestrian-car distance along the $y$-coordinate smaller than 1 m. The 1-m margin was based on half the width of the car (1.6 m / 2 = 0.8 m) plus an estimated pedestrian radius of 0.2 m. Note that collisions did not materialize; the car could simply drive through other objects.
- *Pedestrian velocity (m/s).* This measure concerns the derivative of the pedestrian's $y$-coordinate at the moment the driver passed the crosswalk. A positive value means that the pedestrian was walking forward; a negative value means that the pedestrian was walking or stepping backward (i.e., towards the starting position).
- *Negative pedestrian velocity (0 = no, 1 = yes).* This measure describes whether the pedestrian walked/stepped backward at the moment the driver passed the crosswalk.

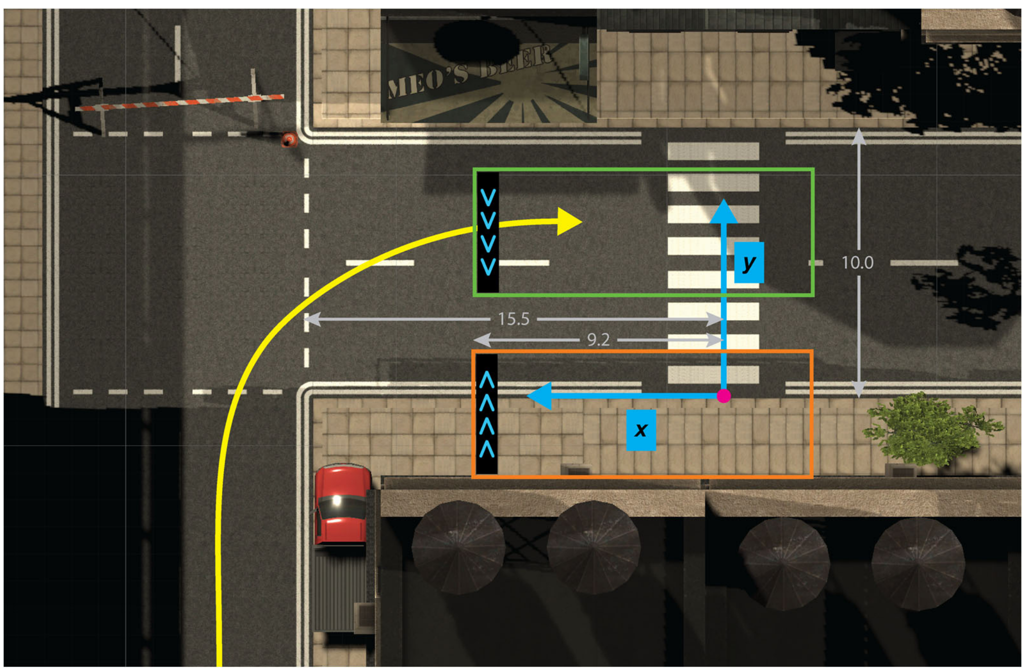


**Figure 5: Definition of the $y$-coordinate in Scenario 1. The $y$-coordinate corresponds to the driver's lateral position in the lane and the pedestrian's walking distance on the crosswalk. Also shown are the locations of the left (green) and right (orange) eHMI triggers, with the corresponding arrow directions of the eHMI. The yellow line represents a possible path of the driver. The magenta circle represents the starting position of the pedestrian.**

Mean differences between eHMI on and eHMI off in each of the two scenarios were compared using paired-samples *t*-tests. An alpha value of 0.05 was used.

Additionally, the pedestrian's and driver's *y*-coordinates in the virtual world as a function of elapsed time, with markers depicting the moment the driver passed the crosswalk, were plotted per trial. Furthermore, the pedestrian's velocity and the difference between the pedestrian's and car center's *y*-coordinate at the moment the driver passed the crosswalk were represented in boxplots.

# 3 Results

A total of 400 trials (20 participant pairs × 20 trials) were performed, of which 120 eHMI-on trials, 120 eHMI-off trials, and 160 filler trials. Fifteen of the 240 eHMI on/off trials had to be excluded because of an incorrect data recording. More specifically, the subjective and objective data for one participant pair were excluded entirely (12 trials), and 3 more trials of Scenario 2 were excluded. For the post-experiment questionnaire, the results for all 20 participant pairs were retained. The experiment was never terminated due to a high MISC score, as none of the participants reported a score higher than 3, where 3 corresponds to 'some' symptoms.

Figure 6 shows the pedestrians' walking distance as a function of elapsed time. The graphs illustrate that the experiment successfully elicited critical encounters, with a portion of the pedestrians crossing before the driver (magenta markers) and a portion of the pedestrians crossing behind it (blue markers). Pedestrians walked a greater distance in Scenario 2 than in Scenario 1, which is explained by the fact that the encounter in Scenario 2 took place on the left side of the road (see Figure 3).

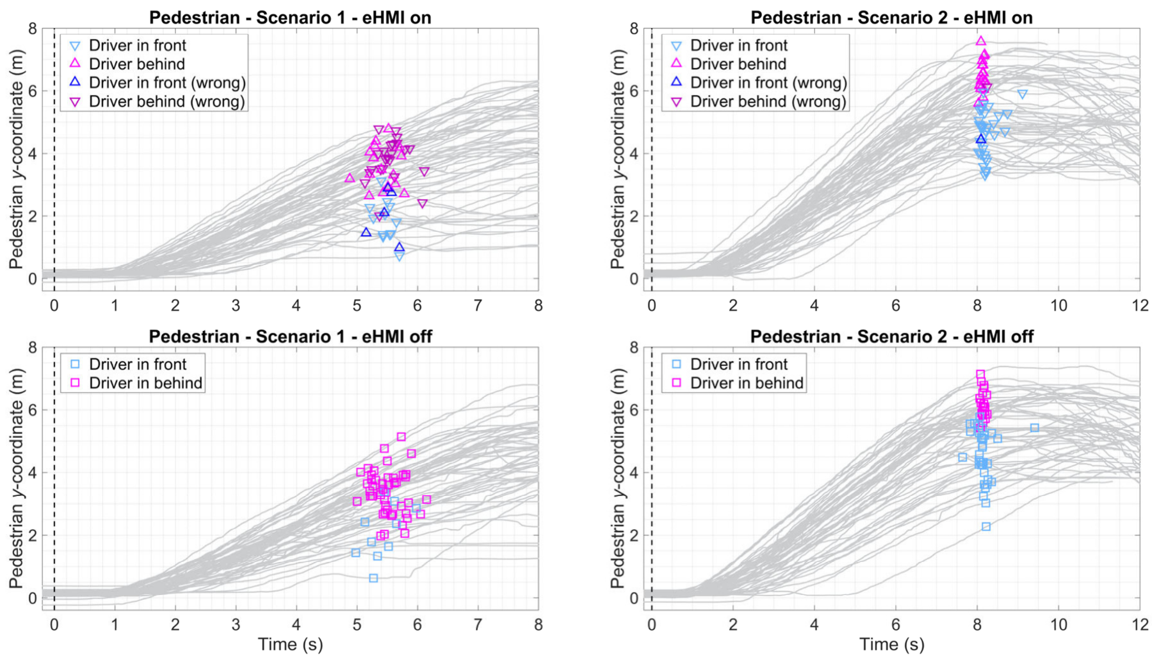


**Figure 6: Pedestrians' *y*-coordinate for the four conditions. The vertical line at time = 0 s is the moment the pedestrian was presented with the green light. Magenta markers represent the moment the driver passed the pedestrian behind; blue markers represent the moment the driver passed the pedestrian in front. Dark blue/magenta markers (28 of 57 trials in Scenario 1 - eHMI on; 2 of 56 trials in Scenario 2 - eHMI on) represent trials in which the pedestrian received eHMI feedback in the wrong direction (see Discussion). The tip of triangular markers points in the direction of the eHMI's message.**

Figure 7 shows corresponding results for the driver's lateral position. Note that the driver was unaware of whether the eHMI was on or off and could not brake. In Scenario 1, drivers often steered to the right onto the sidewalk, signified by the negative *y*-coordinate values. A possible reason is that the pedestrian had not stepped far onto the road and that the distractor car approached in the other lane, making evading to the left relatively difficult or dangerous. It can also be seen that drivers sometimes steered onto the left sidewalk, signified by *y*-coordinate values greater than 10 m.

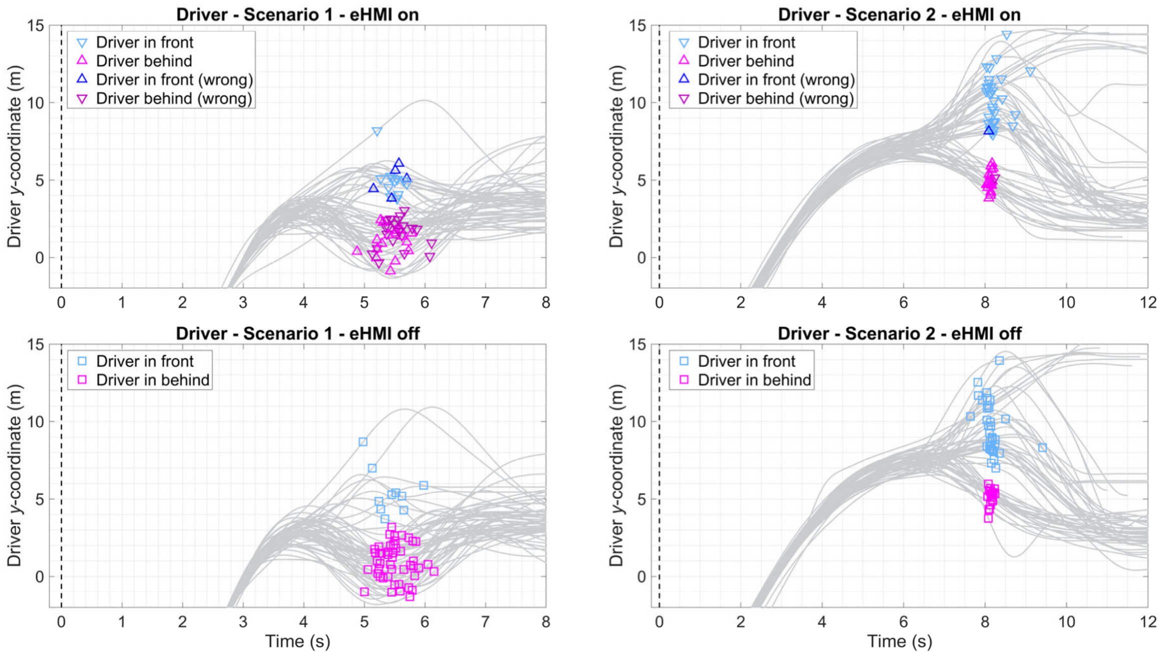


**Figure 7: Drivers' *y*-coordinate for the four conditions. Negative *y*-coordinate values upon approach are caused by the right corner (Scenario 1) or curve (Scenario 2) that preceded the straight. The vertical line at time = 0 s is the moment the pedestrian was presented with the green light. Magenta markers represent the moment the driver passed the pedestrian behind; blue markers represent the moment the driver passed the pedestrian in front. Dark blue/magenta markers (28 of 57 trials in Scenario 1 - eHMI on; 2 of 56 trials in Scenario 2 - eHMI on) represent trials in which the pedestrian received eHMI feedback in the wrong direction (see Discussion). The tip of triangular markers points in the direction of the eHMI's message.**

In Figure 6, it appears that in the eHMI-on trials, pedestrians sometimes stepped back, as seen from the negatively sloping lines when the driver passed. This may be an indication that these pedestrians responded to the eHMI. Figure 8 shows boxplots for the pedestrian's velocity along the *y*-axis at the moment the driver passed the crosswalk. In Scenario 1, pedestrian velocities were mostly positive, while in Scenario 2, pedestrian velocities were closer to zero, which may be explained by the fact that pedestrians in Scenario 2 had reached the end of the walking range or had stopped walking because they saw the driver's car approaching (from a farther distance as compared to Scenario 1). Figure 8 also shows that, with eHMI on, velocities were negative in a higher proportion of trials compared to eHMI off (see also the statistically significant effects shown in Table 2). It can also be seen that the incidences of the pedestrian walking back (i.e., negative velocities) occasionally occurred when the driver still passed behind (magenta markers), which points to a conflict between driver and pedestrian (i.e., pedestrian walking back with the car driver steering to the right).

The questionnaire results show that the eHMI did not significantly affect perceived safety (Table 2). However, it did help improve the pedestrian's understanding of the intentions of the car in Scenario 2. There were no significant differences in collision rates between eHMI on and eHMI off. Figure 9 illustrates that drivers and pedestrians mostly evaded each other. However, in Scenario 2, some collisions occurred. These are cases where the driver steered to the right to pass the pedestrian behind. Although there were no significant differences in collisions, there were significant effects in that the eHMI made it more likely that the pedestrian would step back (21% vs. 5% in Scenario 1, 47% vs. 18% in Scenario 2), as could also be recognized from Figure 6.

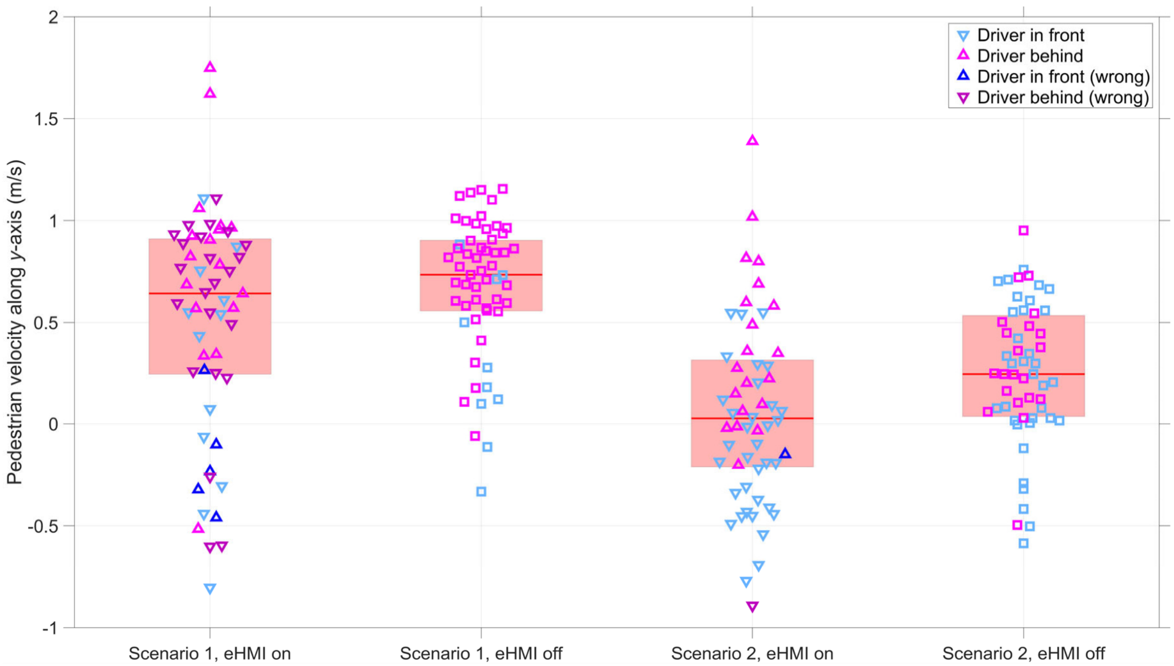


**Figure 8: Pedestrians' walking velocity along the *y*-axis at the moment the driver passed. Magenta markers represent the driver passing the pedestrian behind; blue markers represent the driver passing the pedestrian in front. Dark blue/magenta markers (28 of 57 trials in Scenario 1 - eHMI on; 2 of 56 trials in Scenario 2 - eHMI on) represent trials in which the pedestrian received eHMI feedback in the wrong direction (see Discussion). The tip of triangular markers points in the direction of the eHMI's message.**

In the post-experiment questionnaire, participants rated the perceived fidelity of the virtual environment relatively low on the seven-point scale (pedestrians: $M = 3.90$, $SD = 1.52$; drivers: $M = 4.15$, $SD = 1.14$). Pedestrians found the eHMI moderately sensible, with a mean score of 4.60 ($SD = 1.27$) on a scale from 1 to 7.

The participants were allowed to comment on the experiment in the last section of the questionnaire. Nineteen of the 40 participants responded (10 pedestrians, 9 drivers). Six participants mentioned that they liked aspects of the experiment. Six participants (2 pedestrians, 4 drivers) commented on recognizing or getting used to the scenarios, e.g., '*At some point I recognized the situations, so it became predictable*' and '*Steering took some getting used to in the beginning; that might be made a little easier.*' Two drivers noted that the pedestrian light was visible to them, making it obvious when/whether the pedestrian was walking. Three pedestrians commented that the eHMI could be helpful, but two indicated that it sometimes indicated an incorrect escape direction.

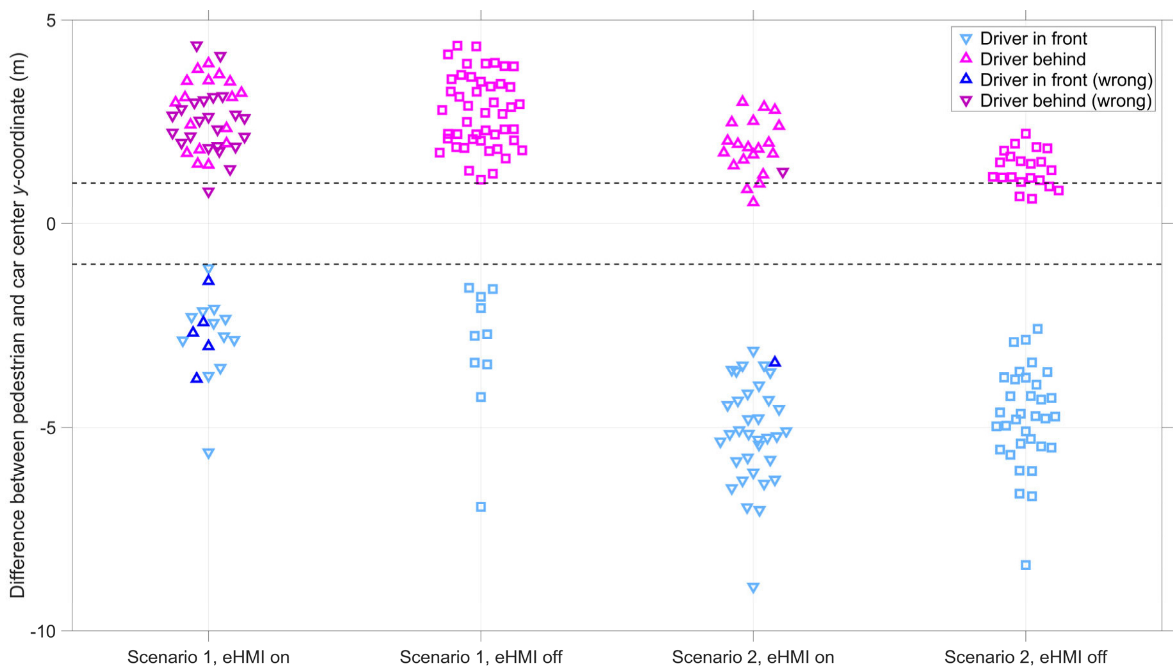


**Figure 9: Difference between pedestrian and car center *y*-coordinate at the moment the driver passed. Magenta markers represent the driver passing the pedestrian behind (positive values); blue markers represent the driver passing the pedestrian in front (negative values). Dark blue/magenta markers (28 of 57 trials in Scenario 1 - eHMI on; 2 of 56 trials in Scenario 2 - eHMI on) represent trials in which the pedestrian received eHMI feedback in the wrong direction (see Discussion). The tip of triangular markers points in the direction of the eHMI's message. A collision was defined as occurring when a marker fell between the two horizontal lines, at 1 and -1 m, respectively.**

**Table 2: Means of dependent variables and results of paired-samples *t*-tests (*df* = 18)**

| | Scenario 1 | | Scenario 2 | | Scenario 1 | | Scenario 2 | |
|---|---|---|---|---|---|---|---|---|
| Measure | eHMI on | eHMI off | eHMI on | eHMI off | t | p | T | p |
| Q. Safety (1 = very unsafe, 7 = very safe) | 3.98 | 4.07 | 4.26 | 4.00 | -0.29 | .775 | 1.28 | .216 |
| Q. Seen the eHMI (0 = no, 1 = yes) | 0.70 | | 0.84 | | | | | |
| Q. Followed the eHMI (0 = no/other, 1 = yes) | 0.42 | | 0.63 | | | | | |
| Q. Understanding (1 = no, 7 = yes) | 3.58 | 3.00 | 4.09 | 3.21 | 1.26 | .224 | 2.49 | **.023** |
| Q. MISC pedestrian (0 = no problems, 9 = retching) | 0.16 | 0.18 | 0.12 | 0.19 | -1.00 | .331 | -1.17 | .259 |
| Q. MISC driver (0 = no problems, 9 = retching) | 0.12 | 0.14 | 0.18 | 0.19 | -0.44 | .667 | -1.00 | .331 |
| S. Pedestrian position (m) | 3.14 | 3.15 | 5.31 | 5.15 | -0.01 | .994 | 1.01 | .325 |
| S. Abs. pedestrian-car distance (m) | 2.66 | 2.80 | 3.89 | 3.53 | -0.68 | .505 | 1.22 | .238 |
| S. Collision (0 = no, 1 = yes) | 0.02 | 0.00 | 0.05 | 0.07 | 1.00 | .331 | -0.44 | .667 |
| S. Pedestrian velocity (m/s) | 0.51 | 0.68 | 0.06 | 0.23 | -2.31 | **.033** | -1.61 | .125 |
| S. Negative pedestrian velocity (0 = no, 1 = yes) | 0.21 | 0.05 | 0.47 | 0.18 | 2.67 | **.016** | 2.50 | **.022** |

Questionnaire measures are marked with a 'Q'. Measures obtained from the simulator data are marked with an 'S'. *p*-values smaller than 0.05 are marked in boldface.

# 4 DISCUSSION

## 4.1 Main Findings

This study aimed to discover whether an external human-machine interface (eHMI) can be useful in preventing collisions between a car and a pedestrian. A noteworthy aspect of the experiment is that two participants inhabited the same virtual world (for similar approaches, see [29–33]). While one might reason that the role of the driver could have been fulfilled by an experimenter, the use of human participants generated variability in terms of trajectories and decisions (i.e., sometimes passing in front of and other times behind the pedestrian), which approximates a real interaction better than an experimenter's premeditated maneuvers. Although an approach not taken in the current study, multi-user simulations like ours also allow studying the interaction between agents, for example through a cross-correlation analysis [34, 35]. While our experiment was conducted with a manually controlled car, we expect the same principles to apply to automated driving and AES, in which the steering wheel is decoupled from driver input (e.g., [36]).

Another unique aspect of this study is that it investigated the effectiveness of eHMIs in time-critical conditions. Most eHMI research has been conducted in non-critical scenarios where the car arrives from tens of meters away and the pedestrian is standing safely on the sidewalk (e.g., [22]), but in our study, there was only one second for the pedestrian to respond to the advice of the eHMI.

These collision rates between the eHMI on and eHMI off conditions were not statistically significant, perhaps because of too few subjects and because collisions were rare (most participants had zero collisions). However, it turned out that the eHMI had a statistically significant effect on the walking behavior of pedestrians compared to the absence of an eHMI. With the eHMI activated, more pedestrians walked backward as the car passed than without the eHMI, presumably in an attempt to follow its directional instructions. In addition to having an effect on behavior, the eHMI positively affected the pedestrians' self-reported understanding of what the approaching car would do. Overall understanding ratings were moderate (around the midpoint of the 7-point scale), suggesting room for improvement. Kunst et al. [37] found that the use of arrows on the car can cause confusion because it may not be clear to the pedestrian whether the car is giving instructions or projecting its next move (as the turn indicators do). It cannot be ruled out that such confusion also occurred in our experiment.

Pedestrians were explicitly informed about the eHMI and instructed that they were supposed to follow the signals from the eHMI. Nevertheless, in an overall 23% of trials, pedestrians did not notice the eHMI, even though the experiment consisted of repeated scenarios. In only 53% of the eHMI-on trials, participants indicated they followed the eHMI's advice. In reality, we expect pedestrians to be even more likely to overlook an eHMI. When in a near-miss situation, human perception and attention are drastically affected [38] so that one will no longer be able to respond adequately to a visual signal from an eHMI. On the other hand, in reality, the eHMI can perhaps be initiated earlier than one second before the conflict, depending on the quality of the vehicle's sensors and whether it relies on pedestrian-to-vehicle communication.

## 4.2 Limitations and Recommendations

The current study was conducted with a car that did not brake. Although braking is a common emergency maneuver, steering is more effective in some cases [39], such as when the time-to-collision is too short for safe braking. How the current conditions translate toward automated vehicles or vehicles equipped with AEB and AES deserves further consideration. It must also be realized that vulnerable road users may rely on the turn indicators to estimate better what action the approaching car will perform [40, 41]. In addition, there is a growing body of studies on internet-of-things-like systems, which, for example, use cameras, GPS, or wireless communication to provide timely warnings to pedestrians [42]. How the current eHMI concept should be integrated with other safety technologies needs further investigation.

Another limitation of our experiment was that the eHMI's directional signal (left vs. right) did not always correspond with the driver's steering behavior. In Scenario 1, the car passed behind the pedestrian in about two-thirds of the trials (see Figure 6 and Figure 7). However, in about half of those trials, the eHMI ordered the pedestrian to step back, which is a wrong signal (see Figure 6 and Figure 7). The explanation for this anomaly is that drivers came out of the corner in Scenario 1 (see Figure 2, right top) rather widely and touched the left box collider first. We expect that in reality, it can also happen that an eHMI gives an incorrect directional signal or that a driver may change his/her decision at the last moment. These problems may be solved by continuously linking the path planning of an automated vehicle to the eHMI. An alternative would be to use simple heuristics for eHMI communication, such as displaying messages only when the escape direction is unambiguous for both parties (e.g., when the pedestrian is within 1 meter from the sidewalk). Such basic decision rules may benefit the transparency of system functioning. In Scenario 2, wrong eHMI directional information was rare, which may explain why the comprehensibility of the situation with eHMI was higher in Scenario 2 than in Scenario 1 ($M = 4.09$ vs. 3.58 on the seven-point scale).

A final limitation is that the study participants were young students. It would be beneficial to conduct a follow-up study with participants of other age groups. Since older pedestrians process visual information and walk more slowly [43], they may be less able to take advantage of an eHMI in near-collision scenarios but may derive benefit from an eHMI to determine whether they should or should not cross. Furthermore, instead of a visual-only eHMI, auditory or visual-auditory eHMIs (e.g., [44–47]) may be considered to account for a greater diversity of pedestrians and traffic situations.

## 4.3 Conclusions

The aim of this study was to investigate whether eHMIs have added value in near-collision situations, i.e., in situations that are cognitively and temporarily demanding. It can be concluded that eHMIs may have some value in these situations, as pedestrians were found to be responsive to the eHMIs. At the same time, the eHMI did not prevent collisions in a statistically significant manner, arguably because the driver successfully avoided the pedestrian in most of the trials and because there was little time for the pedestrian to respond. Furthermore, some pedestrians overlooked the eHMI, and it also happened that the eHMI gave the wrong advice because the driver may have decided to steer in a different direction at the last moment. The results are therefore not uniformly positive, but at the same time, we recommend further research on how to support pedestrians in highly time-critical events. Critical situations as studied in this coupled-simulator experiment are precisely the situations in which accident reduction can still be achieved.


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## DATA AVAILABILITY

Questionnaires, raw data, videos, and MATLAB script used for analysis can be found at https://doi.org/10.4121/20224281. The repository with the version of the simulator used in the study is available at https://github.com/bazilinskyy/coupled-sim-evasive. A video demonstration of the experiment is available at https://youtu.be/CC4KMyK4fUw.

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