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

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Research over the past few years suggests that displays on the exterior of the car, known as eHMIs, can be effective in helping a pedestrian cross the road safely. This study examines a new application of eHMIs, namely the provision of direction information to pedestrians in scenarios where the pedestrian is almost hit by a car. In an experiment, car drivers and pedestrians interacted in the same virtual world, where the pedestrian had to cross the road as the car driver approached. The results showed that the directional eHMI caused pedestrians to step back and produced a tendency towards fewer crashes compared to no eHMI. The eHMI increased the pedestrians' self-reported understanding of what the car was going to do, although some pedestrians did not notice the eHMI. In conclusion, there is potential in 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 • Virtual reality • Laboratory experiments • Transportation

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

1 INTRODUCTION

Worldwide, 1.3 million fatal traffic crashes occur every year, 22% of which concern pedestrians [1, 2]. Factors contributing to pedestrian-car collisions include 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]. Besides the vehicle, the pedestrian also has a possible role in preventing accidents by deciding not to cross or stepping away in time. However, there is a risk that a 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 may often be 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, presumably 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 intention or provide advice to pedestrians. Various major 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 an arrow. Rettenmaier et al. [16], for example, used an eHMI in which arrows indicated whether or not an approaching road user could first go 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's signals. 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 they have been detected and instructed by the vehicle about what action they should 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].

Investigating the effectiveness of an eHMI in near-collision scenarios during a field test is ethically challenging. For that reason, we used a virtual simulator. Our experiment involved a participant in the role of a pedestrian who interacted with another participant acting as the driver of a manual 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. Different near-collision scenarios were created that were visually and temporally demanding via the inclusion of cars and buildings blocking the participants' views or acting as a distraction. 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 several characteristics of the participants. The research was approved by the Human Research Ethics Committee of the Delft University of Technology, and all participants provided written informed consent.

2.2 Hardware and Software

Two desktops were used, a host for running 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.

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 suit and was visible to the driver and the pedestrian. The driver drove a 1.6-m wide Smart Fortwo. 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: 1 100–1000: 8 1000–5000: 7 5000–10000: 3 More than 10000: 1	0–100: 7 100–1000: 5 1000–5000: 7 5000–10000: 0 More than 10000: 1
Car driving frequency in the past 12 months	Every day: 1 4–6 days/week: 1 1–3 days/week: 4 1 day per month–1 day per week: 10 Less than 1 day per month: 4 Never: 0	Every day: 0 4–6 days/week: 0 1–3 days/week: 4 1 day per month–1 day per week: 8 Less than 1 day per month: 3 Never: 5
Frequency of traffic participation as a pedestrian in the past 12 months	Every day: 7 4–6 days/week: 7 1–3 days/week: 5 Less than 1 day/week: 1	Every day: 13 4–6 days/week: 3 1–3 days/week: 3 Less than 1 day/week: 1
Worn virtual-reality goggles before	Yes, multiple times: 7 Yes, once: 7 No: 6	Yes, multiple times: 5 Yes, once: 5 No: 10

Figure 1: Left: Driver, Middle: Pedestrian with motion suit, Right: Pedestrian during a trial, with an experimenter monitoring safety.

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 placed 15 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 blocked by a building and a parked car.

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. Additionally, an automated car came from the pedestrian's right.

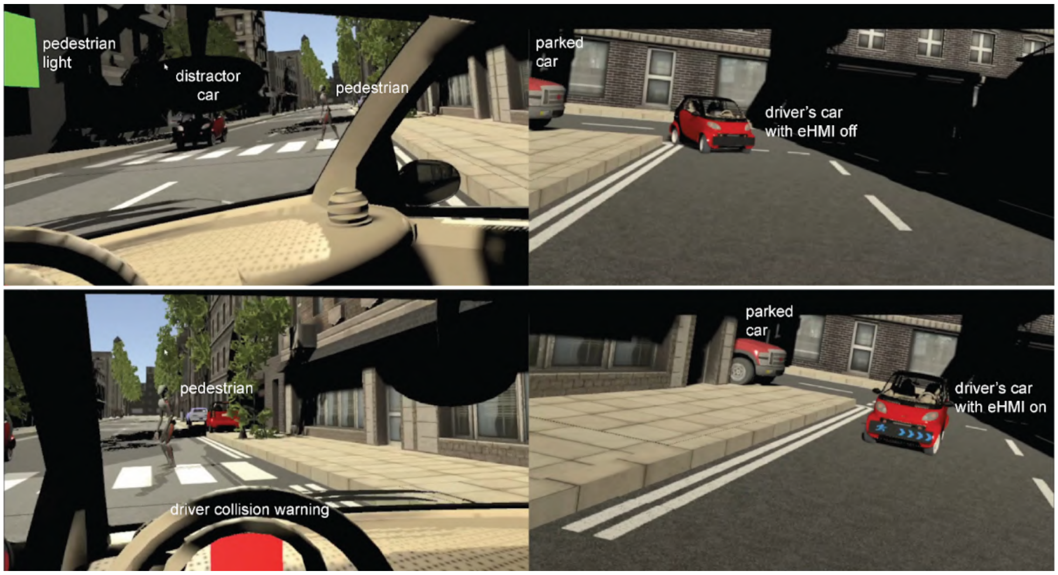

Figure 2: Scenario 1. Screenshots from the driver's (left) and pedestrian's (right) perspective at the moment the driver collision warning switches on (top) and the eHMI switches on (bottom).

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).

The eHMI was either off during the entire trial, or switched on at the trigger point. 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.

The participant pairs completed 20 trials: 6 trials with the eHMI on (3 in Scenario 1, 3 in Scenario 2) and six trials with the eHMI off (3 in Scenario 1, 3 in Scenario 2). The remaining 8 trials were filler trials (5 in Scenario 1, 3 in Scenario 2), included to reduce the 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.

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 at the crosswalk 5 to 10 s before the driver arrived, whereas, in Scenario 2, the distractor car stopped before the crosswalk about 3 s after the driver arrived. The reason for adding the distractor car was to encourage the pedestrian to look left and right before crossing the street, and to make sure the pedestrian did not have to 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 5.6 s from the crosswalk in Scenario 1 and 8.7 s from the crosswalk in Scenario 2. The green light trigger was heuristically 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 Figures 2 and 3) when the driver's car hit an invisible box collider [22] placed 15.5 m from the center of the crosswalk.
- Two 4.7-m wide invisible box colliders were placed on the road, acting as triggers for the eHMI. If the driver drove through the left box, the eHMI with arrows to the left from the pedestrian's viewpoint was activated, whereas if the car drove through the right box, the eHMI with arrows to the right from the pedestrian's viewpoint was activated (Figure 5). The boxes were placed with a 2.1-m gap in between them. Within a trial, the eHMI could be triggered only once, i.e., it did not switch state. The distance from the box collider to the center of the crosswalk was 8.5 m, which at a speed of 30 km/h corresponds to 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, you would sometimes see this eHMI if a car is in a near-collision with you, that this would be an indication that the car must swerve to not collide with you, and that you should follow the direction of the arrows on the eHMI to stay safe. Next, participants were allocated the role of either driver or pedestrian. Participants without a driver's license were assigned 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 back into 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 preceding trial on a scale of 1 (*very unsafe*) to 7 (*very safe*), whether they had seen the eHMI (*yes*, *no*) and whether they had followed the eHMI's advice (*yes*, *no*), and whether they had understood what the car was planning to do on a scale from 1 (*no understanding*) to 7 (*understanding*). Additionally, pedestrians and drivers were enquired about their well-being through the single-item misery scale (MISC; [23]). 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.

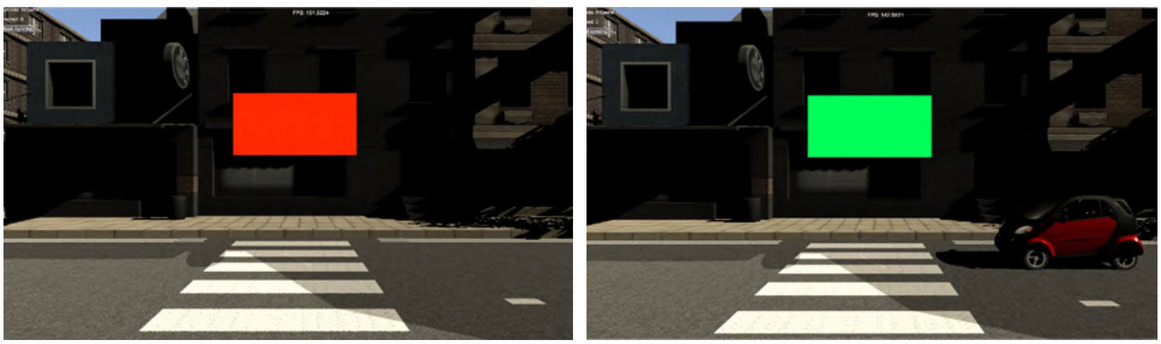

Figure 4: Projected rectangle for indicating to pedestrians that they had to wait or start crossing.

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 down comments about the experiment.

2.6 Analyses

Apart from the results of the questionnaires, the following measures were calculated per trial from the simulator data:

- *Pedestrian position (m).* This measure describes the pedestrian's y-coordinate at the moment the center of the driver's car passed the center of the crosswalk. The higher the pedestrian distance, 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 in the driver's and pedestrian's y-coordinate at the moment the center of the driver's car passed the center of 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 smaller than 1 m. The 1-m margin was based on half the car width (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 center of the driver's car passed the center of 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.

The pedestrian's and driver's *y*-coordinate in the virtual world over time, with markers depicting the moment the driver passed the pedestrian were plotted per participant pair. Means 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.

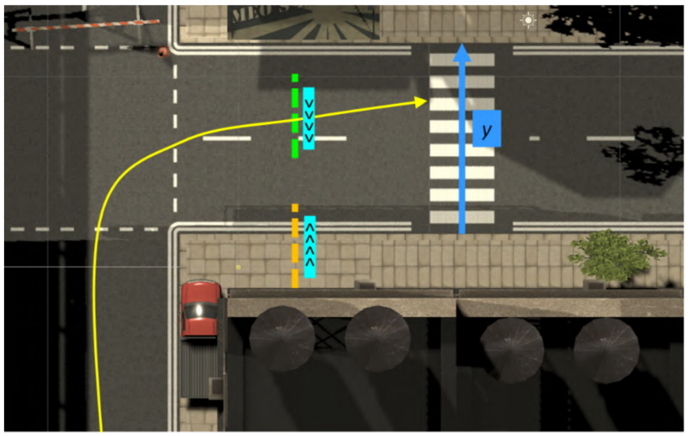

Figure 5: Definition of the *y*-coordinate in Scenario 1. The *y*-coordinate corresponds to the driver's lateral position in the lane and the pedestrian's walking distance on the crosswalk. Also shown are the approximate locations of the left (green) and right (orange) eHMI triggers, with corresponding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

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.

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 pedestrians crossing before the driver's car (magenta markers) and a portion of 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 of Scenario 2 took place on the left side of the road (see Figure 3).

Figure 6 also 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 driver position 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. In the same vein, drivers sometimes steered onto the left sidewalk, signified by lateral position values greater than 10 m.

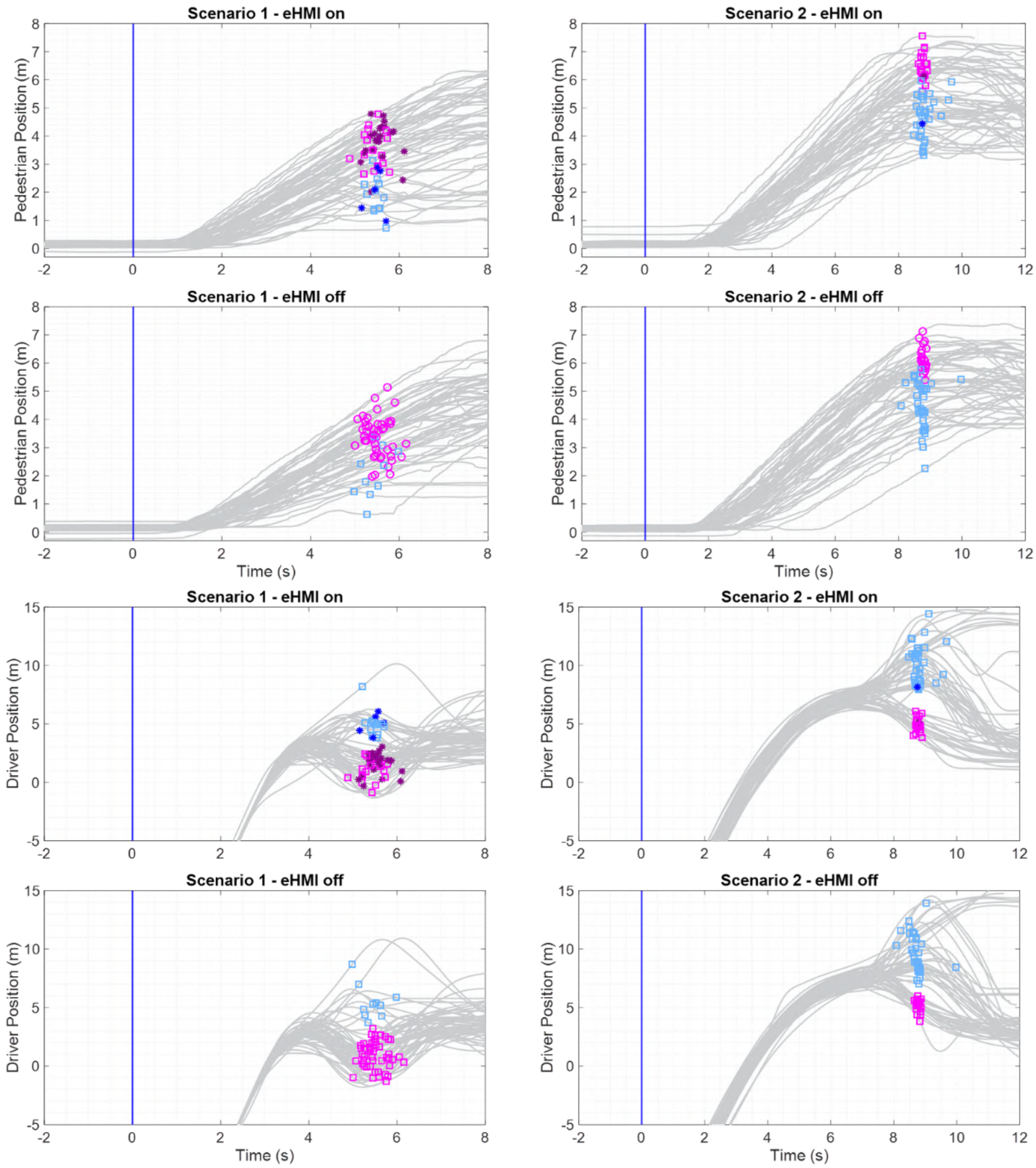

Figure 6: Pedestrians' (top four figures) and drivers' (bottom four figures) *y*-coordinate for the four conditions. Gray lines are the individual traces of pedestrians/drivers. The blue vertical line at time = 0 s is the moment the pedestrian was presented with the green light. Magenta markers represent the moment the driver passed the pedestrian behind; blue markers represent the moment the driver passed the pedestrian in front. Negative driver position values upon approach are caused by the right corner (Scenario 1) or curve (Scenario 2), which preceded the straight. Asterisk-shaped dark blue/magenta markers (28 of 57 trials in Scenario 1 - eHMI on; 2 of 57 trials in Scenario 2 - eHMI on) represent trials in which the pedestrian received eHMI feedback in the incorrect direction (see Discussion).

From Figure 6, it seems that in the eHMI-on trials, pedestrians sometimes stepped back, as seen from the negatively sloping lines when the car passed. This may mean that these pedestrians responded to the eHMI.

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 car's intentions in Scenario 2. There were non-significant indications that the eHMI helped reduce collisions (2% vs. 5% in Scenario 1, 9% vs. 19% in Scenario 2). However, 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.

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.

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	3.02	4.09	3.21	1.22	.238	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	1.04	.310
S. Abs. pedestrian-car distance (m)	2.54	2.60	3.97	3.58	-0.28	.780	1.10	.284
S. Collision (0 = no, 1 = yes)	0.02	0.05	0.09	0.19	-1.46	.163	-1.84	.083
S. Pedestrian velocity (m/s)	0.51	0.68	0.06	0.23	-2.31	**.033**	-1.67	.112
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

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 [24–27]). What is also unique about this study is that it investigated the effectiveness of eHMIs in time-critical conditions; more specifically, there was only one second for the pedestrian to respond to the advice of the eHMI. Although 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., [28]).

The results showed that with eHMIs, the collision rate was half as low as without eHMI, both in Scenarios 1 and 2. However, these differences 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 an effect on the walking behavior of pedestrians. With the eHMI engaged, more pedestrians walked backward as the car passed than without the eHMI, presumably in an attempt to follow its directional instructions. In addition to an effect on behavior, the eHMI positively affected the pedestrians' self-reported understanding of what the approaching car would do. However, overall ratings of understanding were moderate (around the midpoint of the 7-point scale), suggesting room for improvements. Kunst et al. [29] found that using arrows on the car can cause confusion because it may not be clear to a pedestrian whether the car is giving instructions or projecting its next move (as 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. It can be expected that when one is in a near-miss situation, human perception and attention are drastically affected [30] so that one will no longer be able to respond adequately to a visual signal from an eHMI. On the other hand, perhaps in reality, the eHMI can 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.

A limitation of our experiment was that the eHMI's directional signal (left vs. right) did not always coincide 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). However, in about half of those trials, the eHMI ordered the pedestrian to step back, which is a wrong cue (see asterisk markers in Figure 6). The explanation of this anomaly is that drivers came out of the corner in Scenario 1 (see Figure 2, right top) rather widely and hence touched the left box collider first. We expect that in reality, it can also happen that an eHMI gives an incorrect directional signal. These problems may be solved by linking the path planning of an automated vehicle to the eHMI. In Scenario 2, wrong eHMI directional information was rare, which may explain that the comprehensibility of the situation with eHMI was higher in Scenario 2 than in Scenario 1 (4.09 vs. 3.58 on the seven-point scale).

The current study was conducted with a car that could not brake; how the current conditions translate towards vehicles where AEB and AES may be present deserves further consideration. It must also be realized that vulnerable road users currently rely on the turn indicators to estimate better what action the approaching car will perform [31, 32]. In addition, there is currently 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 [33]. How the current eHMI concept can possibly be integrated with other safety technology needs to be further investigated.

In conclusion, this study examined the use of directional eHMIs in highly time-critical situations. The results are encouraging and indicate that pedestrians are responding to the eHMIs. At the same time, some pedestrians overlook the eHMI, and it can also happen that the eHMI gives the wrong advice because the driver may decide to steer in a different direction at the last moment. The results are therefore not uniformly positive, but at the same time, we certainly recommend further research into how to support pedestrians in highly time-critical events. Most eHMI research has been conducted in non-critical scenarios where the car arrives from tens of meters away while the pedestrian is standing safely on the sidewalk (e.g., [34]). Critical situations as studied in this coupled-simulator experiment are precisely situations in which substantial accident reduction can potentially be achieved.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

Questionnaires, anonymized data, and MATLAB code used for analysis can be found at https://www.dropbox.com/sh/p5kj94me1evk8u3/AADcuB73_4QgW_eJfi1Dna7ga. 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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