The working of a directional External Human-Machine Interface in near-collision tested with a coupled simulator

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***Abstract*— Drivers nowadays are able to communicate to pass on awareness and show intent to pedestrians. Extensive research has been conducted into external Human-Machine Interfaces (eHMIs), which could potentially automate this communication. In the majority of previous studies, participants had enough time to see and process the eHMI. The usefulness of eHMIs in scenarios with a short time to react, such as cases of near-collision, is yet unknown. A directional eHMI with blue arrows and a pedestrian symbol was here chosen to investigate the effect in near-collision scenarios between pedestrians and vehicles. In a Unity based coupled simulator, a virtual reality near-collision scenario was tested with 40 participants, of which 20 as drivers and 20 as pedestrians. Each duo conducted 20 trials, consisting of scenarios with non-yielding vehicles and yielding vehicles with and without eHMI, in a randomized order. Results suggest the use of this eHMI increases the subjective understanding of the behaviour of the vehicle. Whether this type of directional eHMI should be used in near-collision scenarios remains to be investigated.**

Keywords: Virtual Reality; eHMI; pedestrians; near-collision; decision making

I. Introduction

Nearly 26 000 fatal road accidents happen in Europe every year [1]. According to the European Commission (EC) [2], almost a quarter of these people participated in traffic as pedestrians. If nothing changes, road traffic injuries will be the fifth leading cause of death in the world by 2030 [3]. In Europe, that is already the case [4].

Human error is responsible for 94% of all road accidents [5]. Reducing the human factor in traffic could be one of the solutions to reduce vehicle accidents. Automated vehicles (AV's) are capable of doing such by driving without involvement of humans. For several years Google[1] and Uber[2] have been testing their AV's on public roads, with a growing number of safe operations [6] [7].

In traffic, some negotiations happen naturally without formal rules. A driver's hand gesture towards a pedestrian, for example, might mean that it is possible to cross the street while no rule applies for that. Because it is possible that in future traffic, there will be no driver behind the wheel or that the person behind the wheel is preoccupied with a non-driving task, nonverbal communication like eye gaze, gestures and facial expression, which can reassure the pedestrian that the driver is aware of their existence [8] [9] [10], might become the way of the past. Therefore, another form of communication is needed.

II. Related work

A solution for the communication gap between AV's and pedestrians could be an external Human-Machine Interface (eHMI). Various types of eHMIs have been proposed in the literature, including symbols or text. As an example, De Clerq et al. [11] investigated the crossing behaviour of pedestrians when an eHMI is shown. Five eHMIs were displayed on different vehicles and participants had to indicate whether they felt safe to cross in the case a vehicle was driving towards them. The authors concluded that eHMIs increase the efficiency of the crossing decision relative to a condition without eHMI, meaning that the presence of an eHMI decreased the decision time (i.e., the time between seeing the eHMI and deciding to cross the street) in the interaction between pedestrian and AV. As another example, by means of a survey, Bazilinksyy et al. [12] investigated which properties make an eHMI clear and understandable. It was concluded that respondents regarded egocentric text-based eHMIs as clearest. However, this finding

[1] https://waymo.com

[2] https://www.uber.com/blog/pennsylvania/new-wheels/

does not imply that such eHMIs should be used in real traffic. As stated in the paper: “Further research in dynamic environments and naturalistic context is required before conclusions can be drawn about the optimal design principles for eHMI’s” [12].
In the majority of previous studies, participants had enough time to see and process the eHMI. The usefulness of eHMIs in scenarios with a short time to react, such as cases of near-collision, is yet unknown. Near-collision is in this research defined as a situation in which an evasive manoeuvre of the vehicle is necessary in order to avoid collision with the pedestrian. In a study of interactions between pedestrian and manual drivers, Ren et al. [11] argued that eye contact is important in the passing on of awareness of a pedestrian in near-collision scenarios. A problem herein is that this way of communication does not relevel the intent of the manual vehicle. Near-collision might be avoided or become less dangerous if a pedestrian knows that he or she is seen by the vehicle and is made aware of what the vehicle will do. If the pedestrian knows towards which direction the vehicle is going to move, the vehicle can be easier avoided and collision might be mitigated.

The aim of this paper is to understand the influence of a directional eHMI on pedestrian behaviour in a near-collision scenario with a vehicle. Othersen et al. [14] investigated, which eHMI leads to the shortest crossing decision time of a pedestrian and found that, among the tested eHMIs, an eHMI with four blue arrows and the symbol of a pedestrian (Fig. 1) resulted in the shortest time. Specifically, Othersen et al. reported a five times faster crossing decision time with the aforementioned eHMI as compared to without (M = 0.15 s, SD = 1.10 s and M = 1.07 s, SD = 0.99 s, respectively). Accordingly, we chose the eHMI with four blue arrows and the symbol of a pedestrian from Othersen et al. for our research.

Fig. 1. Directional eHMI used in this study.

Research in a near-collision scenario where participants interact with real vehicles is not safe and thus not ethically acceptable. For that reason, we will test the eHMI in a virtual reality (VR) world. A participant in the role of a pedestrian will meet in the simulated world with another participant in the driving seat of a manual driven vehicle equipped with eHMI. The driver is responsible for the steering input, whereas the speed is constant.

In order to answer the research question, the following hypotheses were tested:

H1 *More pedestrians move away from the vehicle in near-collision when the vehicle communicates through a directional eHMI compared to a vehicle without an eHMI.*

H2 *The minimum distance between the vehicle and the pedestrian is larger in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*

H3 *The feeling of safety is rated higher in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*

H4 *The ability to predict the behaviour of a vehicle is rated higher in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*

III. Experimental

A. Participants

Forty people participated in this research, twenty as a driver and twenty as a pedestrian. The participants (20 females, 20 males) were between 18 and 28 years old (M = 21.6, SD = 1.9). Only people living in right-hand side driving countries were allowed to participate. Participants had three different nationalities: 37 Dutch, 2 Belgian and 1 Irish. All the participants were living in the Netherlands at the time of the experiment. All participants who participated as a driver had a driving license; 15 of the 20 participants who participated as pedestrian had a driving license. From the drivers, one reported driving 0-100 km/year, eight reported 100-1000 km/year, seven reported 1000-5000 km/year, two reported 5000-10000 km/year and two reported more than 10000 km/year. From the pedestrians, 13 reported to participate in traffic as a pedestrian every day, three reported 4-6 days/week, three reported 1-3 days/week and one reported less than 1 day/week. During the experiment six participants wore contact lenses and two wore glasses. One participant, who was driver, reported to be colour-blind.

B. Simulator for the driver-pedestrian interaction

To test the effect of the behaviour of the pedestrian of the eHMI (Fig. 1) in near-collision scenarios, in which the vehicle has to perform an evasive manoeuvre in order to avoid a crash, a Unity based Virtual Reality (VR) coupled simulator is used [15]. The eHMI advises the pedestrian to move to the specific direction. In this coupled simulator, participants encounter each other in the same VR-world. The pedestrians were able to move in an area of 6 m x 2.8 m.

C. Hardware

The setup used during this research is described in Bazilinskyy et al. [15]. This setup consisted of:

- Netgear GS724T Switch.
- Two DrPhone 1Gbps Cat 6 Ethernet cables.
- Computer to run the pedestrian on, Dell Aurora R8 Desktop with an Intel Corei7-8750H CPU (@4.1 GHz) processor, 16 GB RAM, NVIDIAGeForce RTX 2080 8GB graphics card, and a Windows 10 Home64-bit operating system.
- Two Oculus Rift CV1, for the visual feedback of the pedestrian and driver.
- Xsens motion suit to let the pedestrian walk in the environment as seen in Fig. 2.
- Computer to run the driver on, a Dell AuroraR6 Desktop with Intel Core i5-7400 CPU (@3.0 GHz) processor,16GB RAM, NVIDIA GeForce GTX 1070 8GB graphics card, and a Windows 10 Enterprise 64-bit operating system.
- Logitech G27 Racing Wheel to control the vehicle.

Fig. 2. A pedestrian participant wearing the Xsens motion suit and Oculus Rift in the experiment surrounding.

D. Simulating near-collision with pedestrians

Two environments (i.e., an area in the Unity world) were created to simulate near-collision scenarios, so the pedestrian does not directly predict what is going to happen during multiple trials. The created virtual environments were residential areas. For the experiment, it was important that the pedestrian and driver would not be able to see each other before the vehicle was within stopping distance from the pedestrian, where stopping distance is defined as the sum of the physical braking distance and distance travelled during the reaction time of the driver. By doing this, the vehicle would not be able to stop in time, meaning that an evasive manoeuvre would be necessary to avoid a collision. To achieve a near-collision scenario a suitable timing would be required, regarding the position of the vehicle with respect to the position of the pedestrian. For that reason, the speed of the vehicle was kept constant and the driver was not able to brake. Because the simulated environments were residential areas, the constant speed of the vehicle was set to 30 km/h. This means that the stopping distance of the vehicle with a reaction time of the driver of 1 second was 12.67 m. [16]

Similar to the Unity based coupled simulator of Bazilinkskyy et al. [15], three different vehicles (a Smart fortwo[3], a BMW[4], and a Ford[5]) were available. In the experiment of Bazilinkskyy the participant had to push a button when he or she felt safe to cross. The pedestrians felt the most safe with the Smart fortwo. To get as little influence of external factors as possible, such as size of the vehicle, the Smart fortwo was chosen for this research (Fig. 3).

E. Testing the effect of the eHMI

Three scenarios were created within each environment. In one of the scenarios, the driver was driving in a Smart equipped with an eHMI. In the second scenario within the same environment the driver was driving in the same Smart without eHMI. The driver did not know whether the eHMI was on or not. In the third scenario a programmed Smart stopped before the crosswalk. This means that in the first two scenarios the vehicle was manually driven, whereas in the last scenario the vehicle was programmed.

To study the effect of the eHMI, the evasive manoeuvre had to be initiated at the same distance from the pedestrian in the first and second scenario of both environments. To make sure of this, a collision warning was shown on the dashboard at 15.5 m from the pedestrian (Fig. 4). This warning was an indication for the driver to initiate the manoeuvre.

In the first environment, as seen in Fig. 5, the pedestrian had to cross a crosswalk on a corner (Fig. 8 a). A vehicle came from the right and stopped before the crosswalk (Fig. 8 b). The vehicle came around the corner while the pedestrian was crossing the road walking on a crosswalk (Fig. 8 c). The crosswalk was placed 13 m from the corner and is 10 m long across the street. Unity was programmed in a way that walking 6 m in real life was walking 10 m in Unity. In this way, it was possible for the pedestrian to reach the other side of the road within the room. Due to the fact that the buildings on the corner of the road were blocking the driver's view, the driver would only be able to see the pedestrian after the stopping distance had passed.

In the second environment (Fig. 5) the pedestrian had to cross a crosswalk on a two-lane road (Fig. 9 a). Traffic was coming from the left side of the pedestrian. To block the pedestrian's view, a truck stopped on the first lane (Fig. 9 b) the lane closest to pedestrian. Behind this truck, the manual steered Smart was driving on the second lane (Fig. 9 c).

In both scenarios a stopping vehicle from the opposite side, meaning the right side of the pedestrian, was added to act as a

[3] https://www.smart.com/nl/nl#220
[4] https://bit.ly/36QScaB
[5] https://www.ford.nl/

Fig. 3. Driveable Smart with eHMI to the right in the experiments' VR world

Fig. 4. Collision warning in Smart in the experiments' VR world

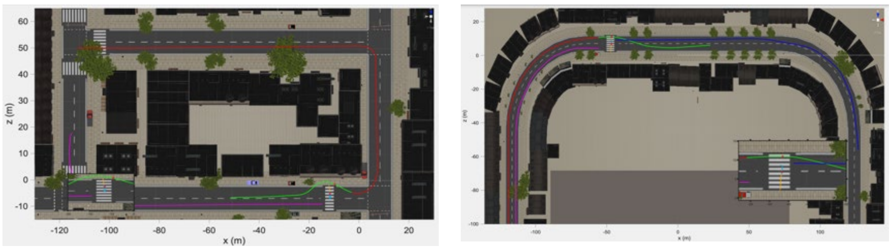

Fig. 5. Environments 1 (left) and 2 (right). The red line is the path of the driver when the eHMI was still off and turned green when the eHMI is put on. The orange line is the path of the pedestrian when the eHMI was still off and turned light blue when the eHMI is put on. The pink line describes the path of the stopping vehicle and truck, respectively. The blue line is the other stopping vehicle. A zoom box is depicted to have a better view of the crossing section situation.

Fig. 6. Zoomed view of Environments 1 (left) and 2 (right), with box colliders in light green. These boxes are used to activated the right or left eHMI when there is driven through them.

distraction. Consequently, the pedestrian was forced to look left and right before crossing the street and was not able to focus on one side of the road.

The timing of the manually steered Smart was set as such that the driver could only see the pedestrian after it passed the stopping distance. Therefore, an evasive manoeuvre was needed to avoid a collision with the pedestrian. To realize this timing, it was important that all pedestrians start walking at the same moment. Therefore, a red rectangle that turned green when the pedestrian was expected to start walking was shown in the scenarios (as seen in Fig. 10).

F. *Initiating the eHMI*

In order to activate the eHMI when the driver initiated the evasive manoeuvre, so-called box colliders were placed in Unity (Fig. 6). A box collider is a cuboid-shaped collision primitive within Unity that can be used to trigger events. [17] Therefore, the box collider could trigger the eHMI to be activated on the vehicle when the vehicle made contact with a box collider. If the vehicle drove through the left box meaning in front of the pedestrian (viewpoint of the driver), the eHMI with arrows to the left (viewpoint of the pedestrian) was activated, whereas if the vehicle drove through the right box meaning behind the pedestrian (viewpoint of the driver), the eHMI with arrows to the right (viewpoint of the pedestrian) was activated (see Fig. 7 for the graphical explanation). The boxes were placed in a way that only one box at a time could be triggered due to the empty distance between them. This empty distance between the boxes was 2.1 m and the width of the Smart was 1.6 m.

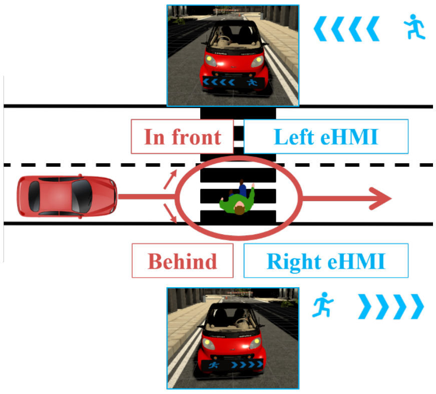

Fig. 7 Explanation of the naming of directions of driving with the eHMI to the side that is activated.

G. *Experimental procedure*

Prior to the experiment, the participants were asked to read and sign an informed consent and respond to some demographic questions. The informed consent and questions asked prior to the experiment can be found in *Appendix A* and *Appendix B* respectively. Next, the participants were verbally instructed on what to do during the experiment. The instructions were given by the same experimenter for all participants. At first, the experimenter informed the participants about the aim of the research. The meaning of the eHMI was explained to the pedestrian and driver in the instruction. A picture of the specific eHMI (Fig. 3) was shown with the explanation of required movement for the pedestrian The pedestrian was aware the eHMI would not always be visible on the front of the vehicle, but if it was, the eHMI should be followed. Once spawned in

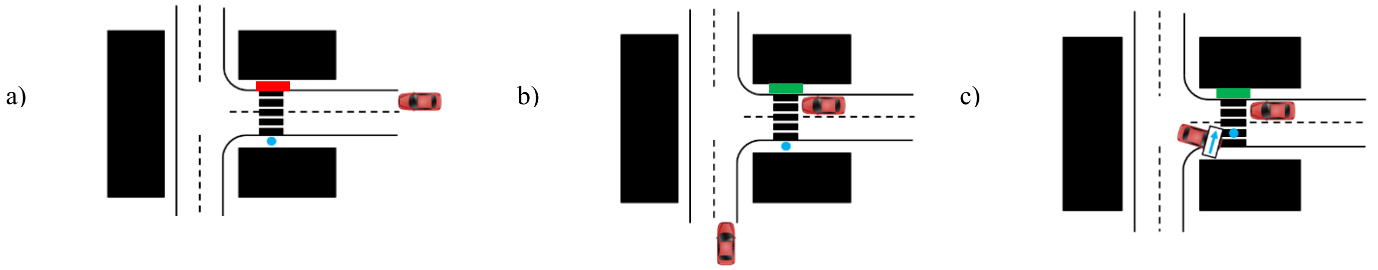

Fig. 8. Environment 1: graphical explanation scenario with eHMI. Symbols used: red vehicle = Smart, blue dot = pedestrian, blue arrow = eHMI, red rectangle = sign to wait for pedestrian and green rectangle = sign to start crossing for pedestrian. a) Pedestrian waits at crosswalk, a vehicle is coming from the right, red rectangle visible b) Vehicle stops for crosswalk, green rectangle visible, pedestrian starts crossing the road, c) Vehicle driven by driver participant comes around the corner, evasive manoeuvre is needed to avoid collision

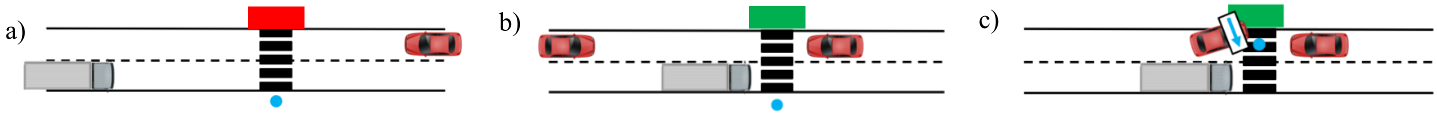

Fig. 9. Environment 2: graphical explanation scenario with eHMI. Symbols used: red vehicle from left = manual steered Smart, red vehicle from right = stopping Smart, white bigger vehicle = truck, blue dot = pedestrian, blue arrow = eHMI, red rectangle = sign to wait for pedestrian and green rectangle = sign to start crossing for pedestrian. a) Pedestrian waits at crosswalk, a truck is coming from the right, red rectangle visible, b) Truck stops for crosswalk, green rectangle visible, pedestrian starts crossing the road, vehicle driven by driver participant comes behind truck c) evasive manoeuver is needed to avoid collision.

the virtual environment, the pedestrian had to look at the red rectangle on the opposite side of the road (Fig. 10). Once the rectangle turned green (Fig. 10), the pedestrian had to start crossing the road while staying aware of the surroundings. The driver got the instruction to follow the road and evade the pedestrian once the collision warning (Fig. 4), as visible on a picture, was shown on the dashboard. The driver was not able to influence the speed, but has the ability to steer. The eHMI on front of the car was showing the opposite direction of the steering input. The instructions can be found in *Appendix C.*

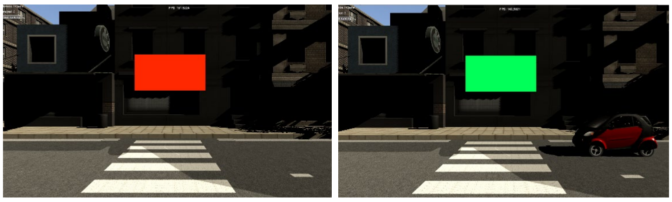

Fig. 10. The rectangles: on the left red, for when the pedestrians need to wait and on the right green, for when the pedestrians need to start walking

Before the actual experiment started, both the driver and the pedestrian did a practice session. The driver practiced by driving in the VR-simulator and to perform a correct evasive manoeuvre once the collision warning appears on the dashboard. The pedestrian practiced by walking around in one of the created environments to get used to the feeling of being in virtual reality.

During the experiment, the pedestrian had to cross the road twenty times, ten times in both environments. In each environment three different scenarios were tested (see section III.E). Each of the two scenarios with the manually driven vehicle was done three times, whereas the scenario with the programmed stopping vehicle was tested four times. The order of the scenarios was randomized for each participant. In this way, each participant got the same amount of each scenario, but in a different order. The randomization can be found in *Appendix D.*

After each trial, meaning twenty trials per pedestrian and driver, pedestrians were asked to rate how safe they felt on a scale from 1 (‘very unsafe’) to 7 (‘very safe’). Pedestrians were also asked whether they understood what the vehicle was planning to do and to rate how well they were able to predict what the vehicle did after each trial on a scale from 1 (‘very unclear’) to 7 (‘very clear’). The MIsery SCore (MISC) [18] scale was used to evaluate motion sickness. If a score of 4 or higher on the MISC scale was reached, the experiment would be terminated.

After completing the experiment, the participants were asked to fill in a post-experiment questionnaire to get inside on how natural and realistic the simulator felt and the utility of the eHMI. The questionnaire for during and after the experiment can be found in Appendix E and Appendix F and Appendix G respectively.

H. Safety Metrics

Five safety metrics were defined: amount of collisions, pedestrian’s direction of movement relative to the movement of the vehicle, minimum distance between vehicle and pedestrian, pedestrian’s feeling of safety and understanding of the behaviour of the vehicle.

I. Exclusion of a trial from the results

A trial was excluded from the results if the eHMI was displayed in the wrong direction (ie., left eHMI being enabled when the right eHMI should have been displayed and vice versa). For Environment 1 this was the case for n = 23 trials, and for Environment 2, n = 3 trials were excluded. Two trials when the eHMI was off were excluded because a driving mistake (participant drove into a tree or truck before seeing and reaching the pedestrian) found place early on. These exclusions apply for all analyses unless stated otherwise.

IV. RESULTS

Fig. 12 shows position of the pedestrian to elapsed time. The stars show the point where the eHMI was turned on if this was the case. The colored line segments display the pedestrians' movements around the point of minimum distance between vehicle and pedestrian.

A. *Collision between pedestrian and vehicle*

In Environment 1, the driver passed the pedestrian behind for 72% of the trials. In Environment 2, 65% of the drivers passed the pedestrian in front. Seventeen collisions found place, with the opportunity of collision in 212 scenarios, 93 with eHMI and 119 without eHMI. The amount of the eHMI being on and off in collisions was 7 and 10, respectively. All collisions, apart from one, were in the second environment. A collision occurred in 7.5% and 8.4% of all the trials with the eHMI on and off, respectively, $\chi^2(1, N = 212) = 0.057$, $p = 0.811$.

B. *Seeing and complying with the eHMI*

During the experiment, questions were asked to the pedestrian-participants about whether they saw the eHMI and whether they acted accordingly. When the eHMI was present, 67% (n = 37) and 82% (n = 57) of the pedestrian-participants mentioned that they had seen the eHMI in Environments 1 and 2, respectively. 75% (n = 24) and 81% (n = 47) of the participants who reported that they had seen the eHMI claimed that they complied to the eHMI instruction in Environments 1 and 2, respectively.

C. *Minimum distance between vehicle and pedestrian*

The minimum distance between vehicle and pedestrian for the non-yielding scenario's is depicted in Fig. 11. No significant difference was found for the minimum distance in Environment 1 with eHMI on ($M = 2.82$, $SD = 1.12$) and off ($M = 2.85$, $SD = 1.19$), t (37) = 0.43, $p = 0.671$. In Environment 2. also no significant difference was found with eHMI on ($M = 4.07$, $SD = 2.48$) and off ($M = 4.10$, $SD = 3.04$), t (54) = 0.28, $p = 0.780$.

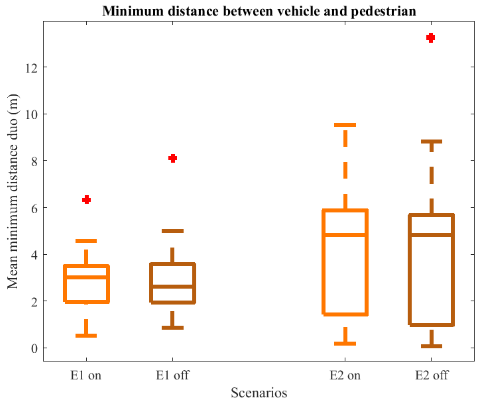

Fig. 11. Mean distances in the different environments with the eHMI turned on and off. Abbreviations: E1 = Environment 1, E2 = Environment 2, on = eHMI turned on, off = eHMI turned off.

D. *Moving away from the vehicle*

Fig. 12 shows the position of the pedestrian on the crosswalk against elapsed time. The movement of the pedestrian has been divided into three categories: pedestrian moved away from the vehicle, pedestrian moved towards the vehicle and pedestrian stopped, this can be seen in Table I and Table II. Within each category the chi-squared test was conducted between the scenario with and without eHMI. All chi-squared tests in Table I and Table II were conducted with DF = 1. The movement of the vehicle has been divided into driving in front and driving behind the pedestrian.

TABLE I. MOVEMENT PEDESTRIAN ENVIRONMENT 1

	eHMI on (n = 20) Vehicle drove behind pedestrian	eHMI off (n = 47) Vehicle drove behind pedestrian	χ2	p
Moving away from vehicle	95%	96%	0,03	0,855
Moving towards vehicle	5%	0%	2,35	0,125
Pedestrian stopped	0%	4%	0,81	0,368
	eHMI on (n = 16) Vehicle drove in front of pedestrian	**eHMI off (n = 13) Vehicle drove in front of pedestrian**		
Moving away from vehicle	25%	8%	1,39	0,238
Moving towards vehicle	56%	69%	0,50	0,481
Pedestrian stopped	19%	23%	0,07	0,795

TABLE II. MOVEMENT PEDESTRIAN ENVIRONMENT 2

	eHMI on (n = 16) Vehicle drove behind pedestrian	eHMI off (n = 12) Vehicle drove behind pedestrian	χ2	p
Moved away from vehicle	63%	83%	1,30	0,254
Moved towards vehicle	6%	8%	0,04	0,839
Pedestrian stopped	31%	8%	0,84	0,148
	eHMI on (n = 35) Vehicle drove in front of pedestrian	**eHMI off (n = 36) Vehicle drove in front of pedestrian**		
Moved away from vehicle	34%	11%	5,34	0,021
Moved towards vehicle	20%	61%	12,18	0,001
Pedestrian stopped	46%	28%	0,52	0,473

No significant differences were found in environment 1. In environment 2, no significant differences were found when the vehicle drove behind the pedestrian. Significant differences were found in environment 2 when the vehicle drove in front of the pedestrian and the pedestrian moved away from and towards the vehicle. When the vehicle drove in front of the pedestrian and the pedestrian stopped, no significant difference was found.

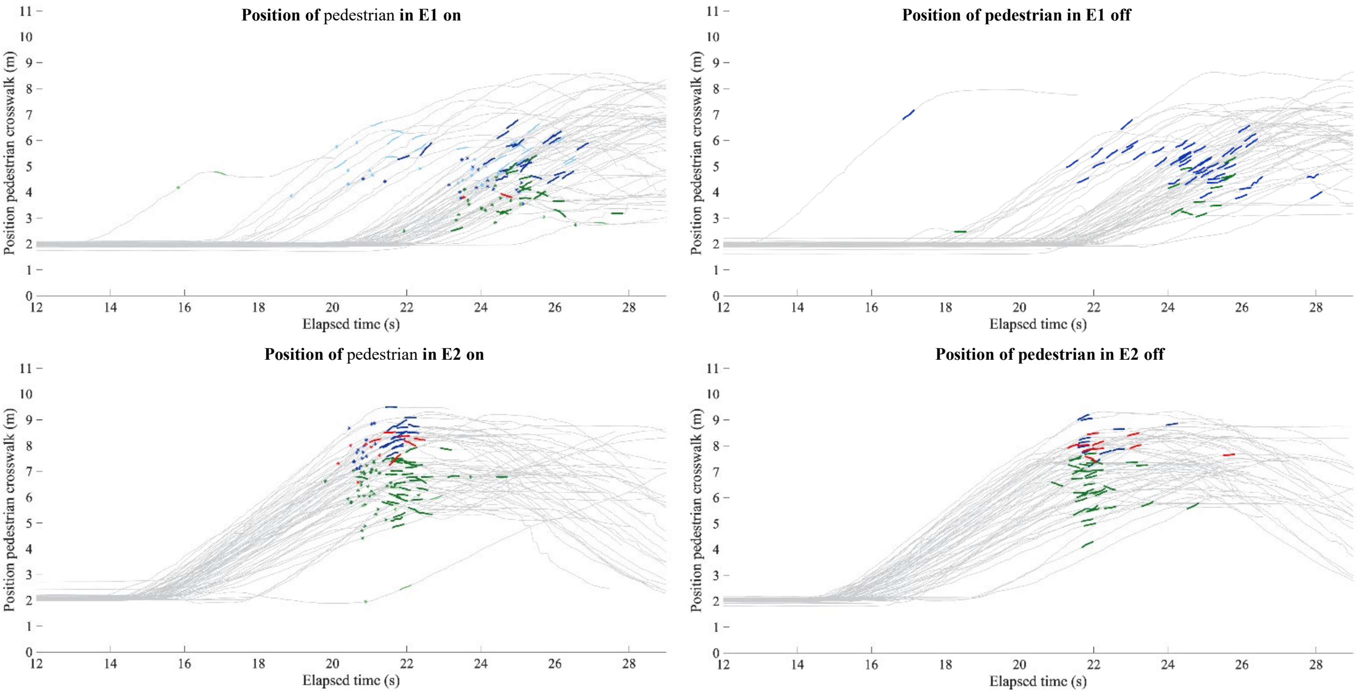

Fig. 12. Position of the pedestrian to elapsed time. The stars show the point where the eHMI was turned on if this was the case. The coloured line pieces display the pedestrians' movements around the point of minimum distance between vehicle and pedestrian. For the first three figures, 60 grey lines are depicted (3 sessions * 20 participants). For the bottom right figure, 58 grey lines are depicted (3 sessions * 20 participants – 2). Two datasets are excluded from E2 off because there was a driving mistake early on. This figure legend includes environment 1 (E1), environment 2 (E2), eHMI on (on) and eHMI off (off).

- Dark green = the vehicle is in front of the pedestrian with an eHMI (E1 on: n = 16, E1 off: n = 13, E2 on: n = 35, E2 off: n = 36).
- Light green = the vehicle is in front of the pedestrian with the wrong eHMI (E1: n = 4, E2: n = 3).
- Dark blue = the vehicle is behind the pedestrian with an eHMI (E1 on: n = 21, E1 off: n = 47, E2 on: n = 16, E2 off: n = 12).
- Light blue = the vehicle is behind the pedestrian with the wrong eHMI (E1: n = 19, E2: n = 0).
- Red = trajectory of collision of the vehicle and pedestrian (E1 on: n = 1, E1 off: n = 0, E2 on: n = 6, E2 off: n = 10).

E. Self-reported measures

a) During the experiment

The mean subjective feeling of safety in the two different environments is shown in Fig. 13. No significant differences were found for the safety rating in Environment 1 with eHMI on (M = 3.78, SD = 1.93) and off (M = 4.05, SD = 1.91), $t(36)$ = 0.29, p = 0.773. For Environment 2 with eHMI on (M = 4.39 SD = 1.63) and off (M = 4.08, SD = 1.44), also no significant difference was found, $t(56)$ = 0.97, p = 0.334.

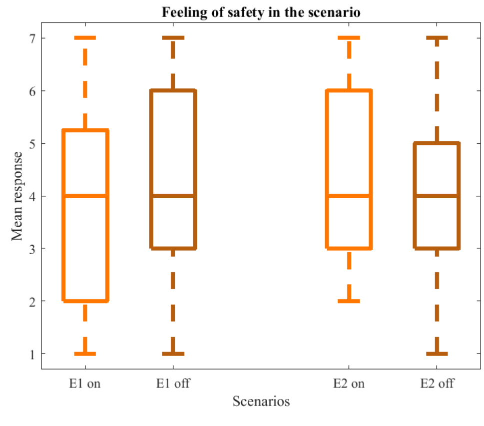

Fig. 13. Mean feeling of safety in the two environments with the eHMI turned on and off, between1 = 'very unsafe' and 7 = 'very safe'. Abbreviations: E1 = Environment 1, E2 = Environment 2, on = eHMI turned on, off = eHMI turned off.

The mean subjective understanding of the behaviour of the vehicle in the two environments is shown in Fig. 14. A significant difference was found for the prediction of the vehicle behaviour in Environment 1 with eHMI on (M = 3.73, SD = 2.38) and off (M = 3.02, SD = 2.01), $t(35)$ = 2.09, p = 0.044. Also for Environment 2 a significant difference was found between eHMI on (M = 4.12, SD = 2.16) and off (M = 3.17, SD = 1.83), $t(56)$ = 2.95, p = 0.005.

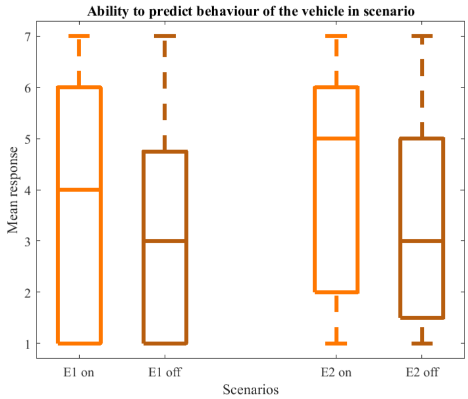

Fig. 14. Prediction of understanding of the behaviour of the vehicle out of the questionnaire in the two environments with the eHMI turned on and off, between 1 = 'very unclear' and 7 = 'very clear'. Abbreviations: E1 = Environment 1, E2 = Environment 2, on = eHMI turned on, off = eHMI turned off.

b) Post-experimental

In the post-experiment questionnaire, participants rated the realism of the experiment relatively low (M = 4.03, SD = 1.33). There was no significant difference between the pedestrians (M = 3.90, SD = 1.52) and drivers (M = 4.15, SD = 1.14), $t(19)$ = 1.24, p = 0.605. The usefulness of the eHMI scored an average of M = 4.60 (SD = 1.27) by the pedestrians.

The participants were given the opportunity to leave a comment in the last section of the post-questionnaire. Nineteen out of the 40 participants provided an answer. Six people mentioned that they had fun doing the experiment. Five people commented that they had some kind of recognition of the repeating two environments and all scenarios with quotes like 'On a certain point I recognized all the situations, whereby it became very predictable.' and 'You notice when the pedestrian will show up (because it's at the same point every time)'. Some driver participants suggested to make the green rectangle of the pedestrian not visible for the driver, because this made it obvious where the pedestrian was walking. thirteen participants asked to add in sound to make it more realistic. 'The wall in the room makes you not want to walk all the way' suggests a kind of fear when walking around in the experiment with the Oculus Rift on blocking vision in real life.

V. Discussion

A. Safety metrics

a) Collisions

The first safety metric is the amount of collisions. It seems, that the amount of collisions does not decrease if an eHMI is present. However, as the result is not significant, this statement cannot be proofed.

b) Pedestrian's direction of movement relative to the movement of the vehicle

When assessing the pedestrian's direction of movement relative to the movement of the vehicle, the scenarios with and without eHMI will be compared separately for the cases in which the vehicle drove behind versus in front of the pedestrian. The reason for this separation is the unequal number of exclusions of the wrong eHMIs: In environment 1, when the vehicle drove behind the pedestrian, the wrong eHMI turned on 19 times.

No significant differences were found in Environment 1, but the results do suggest that the eHMI made the pedestrians walk backwards away from the vehicle more often when the vehicle passed them in front. In Environment 2, a significant difference was found when the vehicle passed in front, indicating that the eHMI helped the pedestrians to move backwards more often when the vehicle passed them in front.

c) Minimum distance between vehicle and pedestrian

No significant differences between eHMI and without eHMI were found for the minimum distance between vehicle and pedestrian. A possible cause could be that the distance is mainly determined by the path of the vehicle, which was not influenced by the eHMI due to the fact the driver did not know if he or she was driving in a vehicle with an eHMI or without.

d) Subjective feeling of safety and understanding behaviour of the vehicle

The pedestrian's feeling of safety seems to be the same for with and without eHMI. From the responses to the question: "Did you understand what the vehicle was going to do?", it can concluded that the eHMI did give the pedestrians a better subjective understanding of the vehicle's behaviour compared to no eHMI.

By combining the results from the safety metrics, it can be concluded that there is not enough evidence from this experiment that an eHMI has a positive effect on safety. A possible reason for a lack of effect of an eHMI could be that pedestrians do not tend to rely on explicit communication and tend to react based on the motion patterns and behavior of the vehicle instead. [19].

B. Questionnaire

If the eHMI was enabled, pedestrians reported that they saw it in 74.5% of all trials. The remaining percentage not seeing the eHMI could be due to the fact that the Oculus Rift has a field of view (FOV) of 94.3 degrees [20], contrary to a FOV of 135 degrees of humans in real life [21].

C. *Initiating the eHMI*

Activating the eHMI by using box colliders as described in section *III. Experimental F* was not proved to be a reliable method, as it comes with the risk of activating the wrong eHMI if the corner is not taken perfectly by the driver. An example of this can be seen in Fig. 15. The driver avoids a collision by passing the pedestrian from behind. In this particular situation, the vehicle should show an eHMI with arrows to the right (from pedestrian's point of view), so the pedestrian knows that he or she should walk further. However, the vehicle drives through Box 1 first, therefore the wrong eHMI is activated, and shows arrows to the left (from pedestrian's point of view), that would mean that the pedestrian had to walk back to the pavement and into the vehicle.

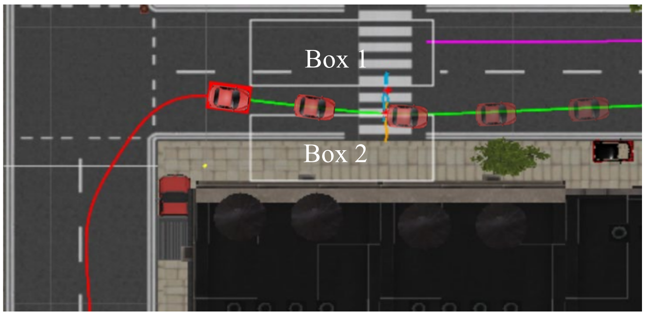

Fig. 15. The box colliders with an example of a driver participant driving through the top box with a little corner. In this way, the wrong eHMI was activated.

During the experiment, the eHMI has been activated 60 times in each environment. In the first environment, the driver went 20 times in front of the pedestrian and 40 times behind. Therefore, the left and right eHMI should have been active 20 and 40 times, respectively. However, 4 out of 20 and 19 out of 40 in front and behind, respectively, the eHMI's have been activated to the wrong side. The biggest amount of wrong eHMIs, when the vehicle was behind the pedestrian in environment 1, was due to the mistake displayed in Fig. 15. Because of the fact two corners needed to be taken in a quick manner, in nineteen cases the driver was not able to be in the middle of the road before the arriving at the box colliders.

In the second environment, the driver went 39 times in front of the pedestrian and 21 times behind. Therefore, the left and right eHMI should have been active 39 and 21 times, respectively. However, 3 out of 39 of the left eHMI's have been activated to the wrong side. The right eHMI was activated correctly in all the trials.

It might be possible to avoid the activation of the wrong eHMI by using the first steering input that occurs after the collision warning appears on the dashboard. The first steering input can be determined with the steering wheel with boundaries set on predetermined degrees. When the rotation of the wheel exceeds the predetermined boundaries, the eHMI will be activated. This method was tested and seemed to work on one computer. However, the input needed to activate the eHMI could not be communicated via the network to the other computer. Therefore, the pedestrian was not able to see the eHMI. For further research it is recommended to solve the network issue to be able to use the steering input to activate the eHMI.

D. *VR immersion*

The feeling of being immersed in VR is an important factor to let the participants of the experiment act like they would in real life. Participants gave the experiment a relative low score in terms of realist feeling. A possible reason for this low score might be that, after each trial, the participant was taken out of Unity back into the Oculus Rift menu, to be placed in the next scenario in Unity. Conducting all the trials consecutively, without taking the participant out of the environment after each trial could improve the immersive feeling.

During this research, participants were limited to walk in a straight line for only six meters due to dimensions of the room. Therefore, it was not always possible for the participants to cross the whole road in the virtual environments. Besides that, the participant had to walk back to the initial position before starting the next trial. By performing the experiment in a larger testing area without obstacles and by using a wireless VR headset, it would become possible to walk around in a virtual world like in a real world and conduct all the trials consecutively by letting the pedestrian walk to the new scenario. This could also contribute to the immersive and realistic feeling of the experiment [22].

E. *Eye tracking*

Another piece of technology that would improve the research would be eye tracking in the pedestrian's VR headset. With eye tracking, it would be possible to measure the timestamp of when the pedestrian sees the eHMI. This information could be used to validate if the reaction is based on the eHMI or solely on the behaviour of the vehicle [19] and if the reaction time will reduce with eHMI. It could also be used to get insight in the time needed to process the eHMI. Besides that, eye tracking could be used to determine the optimal location for the eHMI in a near-collision scenario on the vehicle.

F. *Sound*

Sound was not available in this experiment. Therefore, some of the participants did not notice the vehicle in the first trial, despite the fact that all the participants had been told to look around the whole time while crossing the street. Thirteen of the 20 pedestrians mentioned verbally that they were missing sound in the simulator. From the participant's comments it becomes clear that they had the feeling that the sounds would make the experience more realistic. Therefore, it is advisable to implement sound in the environments for a next research.

VI. CONCLUSION

This paper studied the effect of a directional eHMI in a near-collision scenario with a vehicle. A Unity-based coupled simulator experiment was conducted to test the influence of a yielding vehicle with and without eHMI. In the simulation, two different environments were made, and in each environment, three scenarios were created. The first scenario contained a manual driven vehicle with eHMI, the second scenario contained a manual driven vehicle without eHMI and the third scenario contained a fully autonomous yielding vehicle. The manually driven vehicle had a constant speed and was not able to yield. Four hypotheses were tested.

***H1** More pedestrians move away from the vehicle in near-collision when the vehicle communicates through a directional eHMI compared to a vehicle without an eHMI.* A significant difference was only found when comparing the percentages of collision with and without eHMI within Environment 2 when the vehicle drove past the pedestrian in front.

***H2** The minimum distance between the vehicle and the pedestrian is larger in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*
The minimum distances with and without eHMI in the same environment were not significantly different.

***H3** The feeling of safety is rated higher in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*
No significant differences were found for the safety ratings in Environments 1 and 2.

***H4** The ability to predict the behaviour of a vehicle is rated higher in near-collision when interacting with a vehicle which communicates through a directional eHMI compared to a vehicle without an eHMI.*
Significant differences were found when comparing the ratings with and without eHMI within each environments.

Summarizing, it is concluded that only in the case of environment 2, when the vehicle passed the pedestrian in front, the use of an eHMI positively affected the behaviour of a pedestrian in a near-collision scenario. However, the use of an eHMI increased the subjective understanding of the behaviour of the vehicle.

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