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Interaction between pedestrians and autonomous vehicles: Protocol analysis and preliminary results

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Abstract

This research focuses on pedestrian crossing behavior when interacting with autonomous vehicles equipped with visual external Human Machine Interfaces (eHMIs). This study introduces an experimental procedure implemented in a CAVE-type pedestrian simulator in an approach that avoids the technical and ethical issues in doing such experiments in a real-world setting. Two preliminary experiments were conducted: the first included both autonomous and conventional vehicles on the road, and the second included only autonomous vehicles with visual eHMIs. Initial results show that the visual features incorporated in the autonomous vehicle helped participants decide to cross the road more quickly.

Keywords: autonomous vehicles; pedestrian behaviour; vehicle-pedestrian interaction; virtual environment; pedestrian crossing; road safety.

1. Introduction

A major challenge that autonomous vehicles (AVs) face today is driving in urban environments. For that to be possible, AVs require, among other things, the ability to interact and coordinate with other road users. Such interactions are essential between conventional vehicles (CVs) and pedestrians (Rasouli and Tsotsos, 2020). A pedestrian crossing the road will observe the behavior of the approaching vehicle and its driver, trying to anticipate if the vehicle is about to yield before it attempts to cross.

External Human-Machine Interfaces (eHMIs) that inform pedestrians of the intention of the vehicle will need to be implemented to improve safety and efficiency for all road users and increase trust and acceptance of AVs (Habibovic et al., 2018).

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This research focuses on pedestrian crossing behavior while interacting with AVs equipped with eHMIs. A study was conducted in a CAVE-type (Cave Automatic Virtual Environment) pedestrian simulator. The study considers that an AV refers to a highly automated vehicle with or without a human in the driver's seat (the driver may have the option to control the vehicle), which corresponds to SAE level 4 (SAE, 2021).

The participants are asked to take the role of a pedestrian who must cross the road in front of an approaching autonomous or conventional vehicle. The appearance and communication capabilities of the AVs are randomized during two experimental blocks.

The aim of the first experiment (with AVs and CVs on the road) is to determine if the behavior of the pedestrian changes for each type of vehicle, considering that the participant was able to distinguish the AV from the CV. The personal characteristics of each participant are also considered.

The second experiment aims to determine if the visual messages displayed by the AV improve the pedestrian's ability to perceive the vehicle's intention (yielding or not yielding). The visual messages are deployed at different distances from the crosswalk to evaluate the best moment for the vehicle to initiate its communication of intent to the pedestrian. Messages issued too far from the crosswalk can transmit a wrong message to other pedestrians, and too close may lose their effectiveness (Razmi Rad et al., 2020).

2. Method

2.1. Participants

A total of 20 participants (ten female and ten male) participated in the experiments. The volunteers were between the age of 18 and 39 years old. The participants were informed they would participate in a virtual experiment with AVs. There was economic compensation, and their participation was voluntary.

2.2. Experimental setup

In the first experiment, both autonomous and conventional vehicles are present in the simulation. AVs are equipped with visual communication features to inform pedestrians if the vehicle is in manual or autonomous mode. In the second experiment, only AVs are present in the simulation. They are always in autonomous mode and have visual communication features to inform pedestrians that the vehicle is yielding or not yielding. The vehicle used the green color to indicate it would stop and the red color to indicate it would not stop. Both visual messages conveying the vehicle's intention were triggered at different distances from the crosswalk.

Two questionnaires were prepared to be filled by the participants, one before and the other after the experiments (Razmi Rad et al., 2020). The first was used to collect basic information about the participant's characteristics, such as age, gender, education level, and familiarity with autonomous driving. The second one was used to assess several variables during the experiments namely if the participants could distinguish the AV from the conventional human-driven vehicle in the simulated environment and to collect their opinion about the visual messages used in the display of the AV. Fig. 1 shows an outline of the procedure.

In addition, participants were required to answer a simulation sickness questionnaire (SSQ) before they started the experiments and after their completion of the two experiments to confirm that motion sickness symptoms did not interfere with the results (Deb et al., 2017).

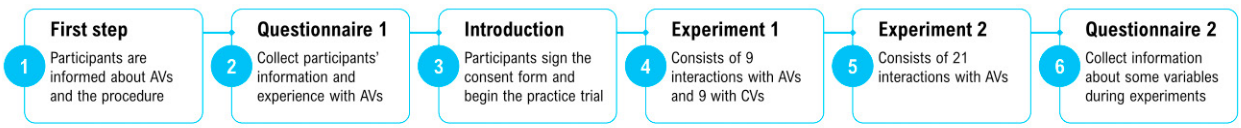

Fig. 1. Outline of the experimental method.

2.3. Simulation environment

The virtual environment is implemented in a CAVE-type pedestrian simulator installed at the Centre for Computer Graphics (CCG) at the University of Minho (see Fig. 2). A flat white screen forms the simulator with 9×3 meters, where three projectors display a stereoscopic image. A motion capture system is used to keep track of the participant's head position in the room and adjust the viewpoint of the projected image to make it coherent with the real-world location of the participant. The projectors generate a stereoscopic high-resolution image that provides them with depth cues when seen through the 3D glasses used by the participants. No ground projection is provided. The simulation is managed at a control station behind the screen, not visible to the participants.

The simulator is installed in a black room, i.e., the only available light originates from the three image projectors, the luminosity of the image projected on the flat screen, the infrared lights from the motion capture cameras, and the emergency exit light above the room's entrance. A VICON motion tracking system acquires the participant's position, and reflective markers placed on the headphones are tracked through infrared cameras positioned around the room. This type of simulation has proven successful in modeling pedestrian crossing situations for vehicles and pedestrians (Cavallo et al., 2019; Soares et al., 2020, 2021).

2.4. Virtual scenarios

Two virtual scenarios are used in the experiments. Both are copies of two real-world locations in the cities of Guimarães and Braga in Portugal. Each scenario was previously modeled in the scope of previous research projects developed at the University of Minho (Soares, 2022).

The information collected from the real-world locations allowed modeling each virtual scenario with the detail to provide the participants with a more immersive experience. For instance, the scenarios include parking meters, traffic signs, lampposts, and bus stops. They contain different vehicles parked in parking spaces to mitigate the sensation of an empty street, as illustrated in Fig. 3.

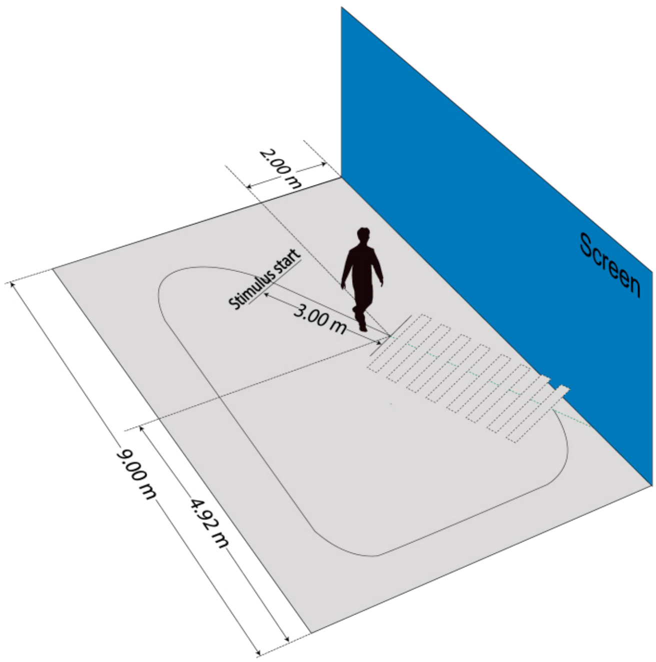

Fig. 2. Schematic view of the CAVE-type pedestrian simulator (Soares, 2022).

Fig. 3. Virtual scenarios: (a) city of Guimarães and (b) city of Braga.

2.5. Experimental procedure

Participants are received in the simulator room and presented with the situation of crossing the road using the nearby crosswalk. Then, the experimental task is explained to them. When the simulation starts, participants are presented with a virtual crossing environment. They are located on the virtual sidewalk, facing the road, with a zebra crossing in front of them. Participants are informed that they will be interacting with both conventional vehicles passing by and autonomous vehicles with eHMIs.

Participants are asked to cross the road to reach the other side as soon as possible when they feel it is safe rather than always waiting for the vehicle to pass. When they begin walking, a vehicle is shown moving towards the zebra. The moving vehicles (AVs or CVs) used in the simulation are models of actual cars. A Kia Ceed SW model is used for the conventional vehicle with a human driver (driver not visible), and a Renault Zoe ZE is used for the autonomous vehicle. The interior of the vehicles is blocked from outside view by design. This way participants are not influenced by the human avatar in the driver's seat on both vehicles. This can be considered a limitation of this study since it does not allow participants to use eye contact or look for hand gestures.

In total, each participant crossed the street 54 times in the first experiment (18 trials repeated three times) and 63 times in the second experiment (21 trials repeated three times). The order of the trials was randomized, and participants would rest for as long as necessary between experiments.

Before the first questionnaire was presented, participants were informed about the AV they would be interacting with. A brief explanation about the technology, including how the eHMIs work, was presented to each one. They confirmed the ability to participate in the experiments and were asked to act as much as possible as they would normally do in real life. Each participant read and signed an informed consent form to allow the usage of their data for research. Then, they answer the first survey and the SSQ and start the practice trial.

After the practice trial takes place, participants are asked if they feel any immediate discomfort and if they are ready to start the experiments. Each session takes around one hour, including the time to complete both experiments, the practice trial, the questionnaires, and the breaks between experiments.

2.5.1. Visual communication features (eHMIs)

The eHMI included in the AV model is placed on the front of the vehicle, above the license plate and bumper, concealing a portion of the car grille. The eHMI display includes different visual messages, such as the vehicle's intent and the vehicle's operational characteristics. The visual messages are derived from the literature (displayed in Fig. 4). The displays were created specifically to be used in this study, and the colors used to convey the messages were chosen based on the literature (Habibovic et al., 2018; Mahadevan et al., 2018; Razmi Rad et al., 2020).

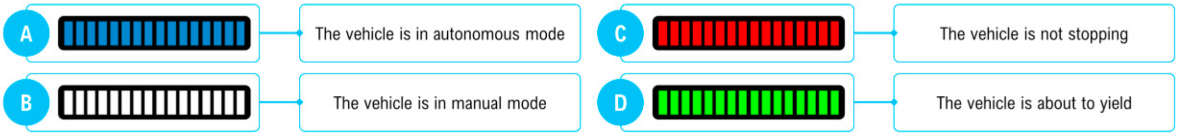

Fig. 4. Visual communication features of the AV.

2.5.2. Speed patterns

The vehicles approach the crosswalk at three speeds (40, 30, and 20 km/h). To study different time-to-passage (TTP) values, the initial distance of the vehicle when the simulation starts needs to compensate for the fact that participants must walk three meters from the stimulus start until they reach the crosswalk. Three values of TTP were considered (2 s, 3 s, and 4 s). For each TTP value there is a corresponding speed profile: (i) 40 km/h for TTP2, (ii) 30 km/h for TTP3, and (iii) 20 km/h for TTP4. TTP is also referred to as time-to-arrival (TTA) in some studies (Soares et al., 2021).

An average walking speed of 1.2 m/s was initially considered. However, this value was proven in the experiments to be overestimated.

For the vehicles, three different speed patterns were used: (i) vehicle drives at a constant speed and does not stop at the crosswalk, (ii) vehicle drives at a constant speed, slows down before reaching the crosswalk but fails to stop (CVs only) and (iii) vehicle drives at a constant speed, starts to slow down before reaching the crosswalk and comes to a full stop approximately five meters before the crosswalk (close to the stop line). In these cases, the maximum deceleration occurs for TTP2 (3.6 m/s^2) and the lowest for TTP4 (0.9 m/s^2). Some authors consider a deceleration rate of 2.4 m/s^2 a "gentle braking" (Dey et al., 2021), and others found it as the deceleration rate for average and common braking (and 5.17 m/s^2 for hard braking) (Deligianni et al., 2017).

2.5.3. Experiment 1 (AVs and CVs in the simulation)

In this experiment, participants were informed that they would interact with conventional and autonomous vehicles and that vehicles could or could not stop at the crosswalk. Also, they were informed that AVs would have one of the following eHMIs: (i) vehicle is in autonomous mode (message A), and (ii) vehicle is in manual mode (message B).

It must be noted that participants were informed of the meaning of the messages, but they were not aware the AV always stops when in autonomous mode, i.e., situation (i). Participants responded to 54 interactions (18 trials repeated three times) in random order for this experiment, presented in Fig. 5.

This experiment aims to determine if the participants can distinguish the AV from the CV in the environment and, if their behavior changes for each type of vehicle.

2.5.4. Experiment 2 (only AVs in the simulation)

In this experiment, all vehicles were autonomous. Participants were informed that they would be interacting with AVs equipped with eHMIs. The behavior of the vehicle and eHMI would be one of the following: (i) the vehicle is always in autonomous mode (message A) and does not change, (ii) vehicle is in autonomous mode displaying message A and changes to message C before arriving at the crosswalk, and (iii) vehicle is in autonomous mode (message A) and changes to message D before arriving at the crosswalk.

The visual messages are deployed at different distances from the crosswalk. The vehicle starts the trial indicating it is in autonomous mode (message A). It triggers the display with messages C or D at three distances (25, 30, and 35 meters) from the crosswalk. The display is always activated before the vehicle starts to decelerate.

For this experiment, participants responded to 63 interactions (21 trials repeated three times) in random order, presented in Fig. 6.

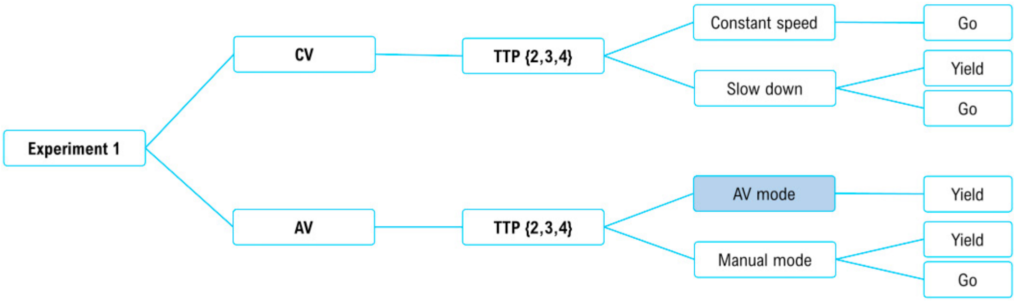

Fig. 5. Outline of experiment 1 (AVs and CVs in the simulation).

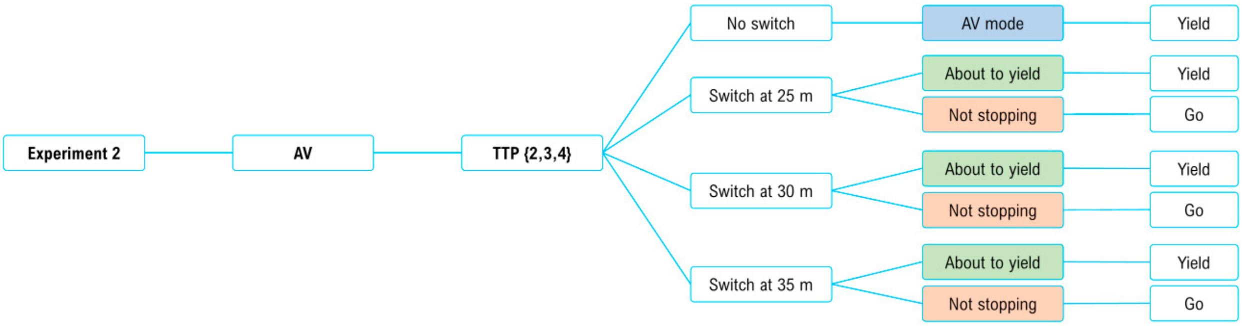

Fig. 6. Outline of experiment 2 (only AVs in the simulation).

This experiment aims to determine if the messages displayed in the AV improve the participant's ability to perceive the vehicle's intention (e.g., yielding and not yielding), and if the participants cross the road regardless of the AV signaling them with message C (not yielding), thus, resulting in a "virtual" accident.

3. Results and discussion

In the first experiment, the participants walked at an average speed of 0.49 m/s (SD = 0.1), 0.53 m/s (SD = 0.2) and 0.66 m/s (SD = 0.25) for TTP2, TTP3 and TTP4, respectively. In the second experiment, the participants walked at an average speed of 0.59 m/s (SD = 0.16), 0.63 m/s (SD = 0.22) and 0.69 m/s (SD = 0.27) for TTP2, TTP3 and TTP4, respectively. Participants walked faster during the first two meters and slowed their pace around one meter before the start of the crosswalk.

Considering that the average speed of the participants was overestimated, the observed TTP values were slightly different from the initial TTP values projected for the experiments. In the first experiment, the average TTP was 1.5 s (SD = 0.1), 2.35 s (SD = 0.46) and 3.34 s (SD = 0.5) for TTP2, TTP3 and TTP4, respectively. In the second experiment, the average TTP was 1.27 s (SD = 0.66), 2.5 s (SD = 0.4) and 3.51 s (SD = 0.4) for TTP2, TTP3 and TTP4, respectively.

A total of 1070 interactions were validated in the first experiment and a total of 1247 in the second one. There were ten accidents out of 534 interactions (vehicle not stopping) during the first experiment and a total of eight accidents out of 532 interactions (vehicle not stopping) during the second experiment. Participants had eight crashes for TTP2, eight crashes for TTP3, and only two crashes for TTP4 (this last case occurred only in the first experiment).

3.1. Experiment 1 (AVs and CVs in the simulation)

In this experiment, for both types of vehicles (scenarios where vehicles did not stop), with an increase in TTP, the participants' crossing percentage before the vehicle arrived at the crosswalk increased significantly (note: a crossing was considered valid if the participant was able to cross before the vehicle passed). The observed crossing percentage was 0% for TTP2, 18.7% for TTP3 (23.6% for AV and 16.4% for CV) and 59% for TTP4 (55.2% for AV and 60.8% for CV). The results show that the crossing percentage is very similar for both types of vehicles.

In this experiment (scenarios where vehicles are yielding), with an increase in TTP, the crossing percentage before the vehicles fully stop at the crosswalk increased significantly: 48.9% for TTP2, 82.7% for TTP3, and 93.9% for TTP4. By type of vehicle: (i) for TTP2: 54.2% for AV (60.3% for AV mode and 48.3% for manual mode) and 38.3% for CV, (ii) for TTP3: 85% for AV (83.3% for AV mode and 86.7% for manual mode) and 78% for CV, and (iii) for TTP4: 95% for AV (98.3% for AV mode and 91.7% for manual mode) and 91.5% for CV. In all cases, the percentage of crossings before the vehicle fully stopped was higher when the vehicle was autonomous. In most cases (i.e., TTP2 and TTP4), for AV only, it was higher when the AV was signaling it was in autonomous mode.

3.2. Experiment 2 (only AVs in the simulation)

Like the first experiment, with an increase in TTP, the participants' crossing percentage before the vehicle passes increased significantly in the second one (scenarios where vehicles are not stopping). The observed crossing percentage was 0% for TTP2, 15.9% for TTP3, and 31.6% for TTP4. During this experiment, in these scenarios, AVs signaled their intention with a visual message meaning not stopping (i.e., "red light"). This improved the participants' ability to understand the vehicle's intention significantly, i.e., more participants waited for the vehicle to pass before crossing compared to the first experiment. This finding was consistent with other research (Razmi Rad et al., 2020). In TTP2, participants only have approximately 2 s to cross before the vehicle pass. Therefore, all the participants who tried to pass in this case were involved in a "virtual" accident.

With an increase in TTP, the percentage of crossings before the vehicle fully stopped (scenarios where vehicles are yielding) increased significantly (mostly from TTP2 to TTP3): 82% for TT2 (51.7% for AV mode and 92.2% for "green light"), 96.2% for TTP3 (91.5% for AV mode and 97.8% for "green light") and 99.6% for TTP4 (98.3% for AV mode and 100% for "green light"). The most substantial difference occurs for TTP2, where the percentage of crossings before the vehicle stopped was significantly higher when the vehicle was signaling with the "green light".

In this experiment, in scenarios where the vehicle was stopping, the average time that participants took from the start of the trial (stimulus start) to start crossing was lower in the cases where the vehicle was signaling it was yielding with the "green light": (i) for TTP2, it took participants 4.7 s (SD = 1.1) to start crossing with "green light" and 5.9 s (SD = 1.1) with the vehicle signaling AV mode, (ii) for TTP3, 4.4 s (SD = 1.4) with "green light" and 6.1 s (SD = 1.8) with AV mode, and (iii) for TTP4, 4.1 s (SD = 1.7) with "green light" and 5.4 s (SD = 2.3) with AV mode. When participants know that the vehicle is about to yield, they decide to cross more quickly.

4. Study limitations

The use of the simulator allowed manipulating the variables of interest. However, it presents some questions regarding realism and the ability to induce a form of risk perception. The sense of danger of approaching AVs might have, for instance, influenced participants' trust in AVs and, eventually, their interaction with such technology (e.g., crossing behavior in front of AVs).

It must be noted that during the experiments, the human avatar (driver) is not visible to the participants. Therefore, participants could not use "informal" communication methods, such as eye contact or looking for a waving hand. According to some studies, these methods could be effective in pedestrians' behavior when crossing the road in real-world scenarios (Habibovic et al., 2018; Sucha et al., 2017).

Other elements may have influenced the decision and behavior of the participants, such as the absence of other pedestrians in the virtual environment. Another limitation that must be noted is that there were no audio cues during the experiments. This will be revised in future experiments.

5. Conclusions and future work

This study investigated the influence of pedestrians' characteristics in crossing the road when interacting with both autonomous and conventional vehicles in a virtual environment. Preliminary results indicate that some participants failed to distinguish the CV from the AV, focusing mainly on crossing the road regardless of whether the vehicle was conventional or autonomous. However, when looking at the scenarios where the vehicle was yielding to participants, the percentage of crossings before the vehicle stopped was higher with AVs.

In the second experiment, some results show that the visual features in the AV helped participants decide to cross the road more quickly. Further analysis will be conducted to evaluate if the distance at which the message was presented to the pedestrians influences their crossing behavior.

The experiments include different visual communication features for autonomous vehicles (eHMIs). One of the main purposes of the experiments at this stage is to evaluate pedestrians' crossing behavior in response to the visual eHMIs implemented in the AVs. Future experiments will be conducted with a wider sample of participants, using different eHMIs proposals, and considering different risky situations.

A different approach will be conducted to understand why some of the crashes happened when there was enough time for the participants to cross the road safely (mainly in TTP3 and TTP4 scenarios).

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