The Effects of External Human-Machine Interfaces of Automated Vehicles on the Crossing Behaviour of Pedestrians.

Master thesis
by
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The Effects of External Human-Machine Interfaces of Automated Vehicles on the Crossing Behaviour of Pedestrians

Thesis report

by

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Abstract

Automated vehicles (AVs) are being developed by several companies and research groups worldwide. The implicit communication (e.g., eye contact) of the vehicle or driver seems to play an important role in the expected behaviour of vehicles. It is possible that vulnerable road users (VRUs) are less able to estimate the intention of vehicles (e.g., deceleration, braking behaviour and stopping distance) when this type of communication changes or disappears when AVs are introduced. An external human-machine interface (eHMI) (i.e., a display showing when it is safe to cross) can be introduced to overcome the lack of implicit communication between driver and pedestrian. The goal of this study was to examine the effects of eHMIs of AVs on the crossing behaviour of VRUs.

A virtual reality (VR) simulation was set up, where the participant was standing on the pavement on a two-lane two-way road in a European setting. The yielding behaviour (yielding, non yielding), the type of vehicle (small, medium, large), the type of eHMI and the timing of an eHMI were varied in a within-subject design ($N = 28$). Four types of eHMIs were implemented, which all consisted of a screen in the front of the vehicle; with the four eHMIs being 1) the Frontal braking lights, 2) a Knightrider animation, 3) a Smiley and 4) a Text showing 'WALK' was shown when it was safe to cross.When it was not safe to cross, the Frontal braking lights were turned off, the Knightrider animation was not shown, the Smiley was neutral and the Text showed 'DON'T WALK'.

Results showed that the presence of an eHMI made participants significantly feel safer when trying to cross. This was measured by measuring the total time that participants indicated they felt safe to cross using a remote control on which participants could press a button. The total time ratio that participants pressed the button when vehicles were yielding was 0.655, 0.743, 0.747, 0.751, and 0.765 for the baseline, Frontal braking lights, Knightrider, Smiley, and Text, respectively. Thus, participants felt safer to cross when an eHMI was present compared to when no eHMI was present. Secondly, the vehicle size was found to play a role in the total time that participants felt safe to cross. Specifically, the total time ratio was 0.746 for a Smart fortwo, 0.732 for a BMW z4, and 0.725 for a Ford f150 in the yielding cases. The total time ratio was 0.206 for a Smart fortwo, 0.190 for a BMW z4, and 0.156 for a Ford f150 in the non-yielding cases. Furthermore, the distance at which an eHMI changes state (e.g., 'WALK'/'DON'T WALK') was found to play a role in the total time that participants felt safe to cross. The total time ratio was 0.796 for 50 m, 0.761 for 35 m, 0.698 for 20 m and 0.655 for the baseline. Participants reported in a post-experiment questionnaire that the Text eHMI was least ambiguous.

Future research can focus on which aspects improve AV-VRU interaction, so that eHMIs can be optimised. Now merely screens in front of the vehicle were tested; other techniques (e.g., projected pedestrian crossings) could yield different results. Differences between research methods can be examined as well, as this study showed differences in revealed behaviour in the simulation and conscious stated preferences of people in the questionnaires.

CONTENTS

List of Figures

LIST OF TABLES

The Effects of External Human-Machine Interfaces of Automated Vehicles on the Crossing Behaviour of Pedestrians

G.K. de Clercq Dipl.-Ing. A. Dietrich J.P. Núñez Velasco, MSc.
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***Abstract*—Automated vehicles (AVs) are being developed by several companies and research groups worldwide. The implicit communication (e.g., eye contact) of the vehicle or driver seems to play an important role in the expected behaviour of vehicles. It is possible that vulnerable road users (VRUs) are less able to estimate the intention of vehicles (e.g., deceleration, braking behaviour and stopping distance) when this type of communication changes or disappears when AVs are introduced. An external human-machine interface (eHMI) (i.e., a display showing when it is safe to cross) can be introduced to overcome the lack of implicit communication between driver and pedestrian. The goal of this study was to examine the effects of eHMIs of AVs on the crossing behaviour of VRUs.**

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Future research can focus on which aspects improve AV-VRU interaction, so that eHMIs can be optimised. Now merely screens in front of the vehicle were tested; other techniques (e.g., projected pedestrian crossings) could yield different results. Differences between research methods can be examined as well, as this study showed differences in revealed behaviour in the simulation and conscious stated preferences of people in the questionnaires.

***Index Terms*—automated vehicle, autonomous vehicle, AV, AV-VRU interaction, behavioural adaptation, communication interface, crossing behaviour, crossing strategy, eHMI, gap, human-machine interaction, pedestrian, pedestrian crossing behaviour, pedestrian-vehicle interaction, safety margin, self-driving vehicle, virtual reality, VR**

I. Introduction

Automated vehicles (AVs) are currently being developed by several companies and research groups, such as BMW, Tesla, TNO, TU Delft and TU München (Tesla, 2017; DAVI, 2017; *The future of the smart car*, 2017). The interaction between drivers and vulnerable road users (VRUs), consisting of pedestrians and cyclists, will be replaced by the interaction between AVs and VRUs, especially when dealing with highly automated driving modes where the system monitors the environment (level 3 and up, according to the SAE definitions (International, 2016)). The need for researching and developing AVs is acknowledged by numerous companies and organisations because it is expected that automated driving can reduce the number of traffic accidents (Vissers, van der Kint, van Schagen, & Hagenzieker, 2016; Tillema et al., 2015). One of the challenges is to recognise the intent of VRUs, such that safe interaction can be ensured. According to the European Commission (Commission, 2015), 22% of all road deaths are pedestrians, with 69% of these accidents happening in urban areas. This means pedestrian deaths can effectively be decreased by increasing safety in urban areas.

What seems to play an important role in the expected behaviour of vehicles is the implicit communication (e.g., eye contact) of the vehicle or driver (Malmsten Lundgren et al., 2016; Núñez Velasco, Farah, Arem, & Hagenzieker, 2017). Implicit communication can be an indicator for deceleration and braking behaviour. It is possible that vulnerable road users (VRUs) are less able to estimate the intention of vehicles (e.g., deceleration, braking behaviour and stopping distance) when this type of communication changes or disappears when AVs are introduced. Therefore, an external human-machine interface (eHMI) can be introduced to overcome the lack of implicit communication between driver and pedestrian.

Research shows that traffic will consist of conventional vehicles and AVs in the near future with an expected adoption rate between 24.8% and 87.2% of AVs in 2045 in the USA, depending on the public acceptance (Bansal & Kockelman, 2017). It is not known yet whether AVs need to communicate driving intention towards VRUs. First, research should find out whether it is necessary for pedestrians to make clear with what type of vehicle pedestrians are dealing with in the forthcoming years and what the vehicles' intention is when pedestrians try to cross, to prevent confusion in pedestrians.

A. *Effect of vehicle size on gap acceptance*

A number of studies show that implicit communication plays a significant role in vehicle-pedestrian interaction. For instance, vehicle size plays a role in adopted safety margins. Kadali and Vedagiri (2016) observed that the type of vehicle influences the behaviour of the pedestrian. They used 5890 safety margins of pedestrians extracted from videos of intersections. The mean safety margin was 3.50 seconds for a truck, 3.04 seconds for a car, 2.69 seconds for an auto rickshaw and 2.06 seconds for a two-wheeler when vehicles were not yielding for pedestrians.

Terry, Charlton, and Perrone (2008) showed a similar trend. By defining the Tau ratio as the current headway rate divided by the current relative velocity, which in essence is the time-to-collision (TTC), Terry et al. showed that larger vehicles had higher Tau values at the time that the participant started to yield, with 7.27 seconds for trucks, 6.45 seconds for vans and 5.83 seconds for cars.

B. *Research on communication of AVs on gap acceptance*

Besides vehicle size, implicit communication with the driver is shown to play a role in vehicle-pedestrian interaction. Núñez Velasco, Rodrigues, Farah, and Hagenzieker (2016) concluded from interviews and an online survey that the majority finds eye contact important for extracting intentions from the driver. This means that pedestrians have certain expectations of the driving behaviour of the approaching vehicle when pedestrians make contact with the driver. When AVs are introduced, this can result in different expectations when pedestrians try to cross.

A study by Beggiato, Witzlack, and Krems (2016) studied the effect of velocity on the gap acceptance and TTC estimates of differently aged people. It was found that the gap acceptance and accepted TTC are different depending on the velocity. They pointed out that using videos to test gap acceptance and TTC can be influencing results, due to a limited field of view, and ambient sounds among other things.

Regarding AV-pedestrian interaction, differences in the attention of the perceived driver changed the comfort level of the pedestrian (Malmsten Lundgren et al., 2016). During these simulated experiments it turned out that the pedestrians felt less secure when the driver seemed inattentive and therefore would be less likely to cross. In 13 out of 13 cases the pedestrian would cross in the field experiment when there was eye-contact. This amount was reduced to 5 out of 13 cases when there was no driver in the driving seat.

Furthermore, Rodriguez Palmeiro et al. (2017) tested the effect of AVs on pedestrians' crossing decisions in a real-life Wizard of Oz experiment with 24 participants. Participants were led to believe they interacted with self-driving vehicles, whereas a human driver remained in control of the vehicle. The critical gap and self-reported levels of stress did not differ significantly between vehicles which indicated that it was a self-driving vehicle or traditional vehicles. A questionnaire after the experiment indicated that most participants noticed the differences in the appearance of the vehicles and they acted differently upon these differences. They recommended examining the effects of dynamic eHMIs (e.g., artificial lights or gestures) for future research.

Not only the type of vehicle was shown to play a role in vehicle-pedestrian interaction, but also the way of communicating intention changes vehicle-pedestrian interaction.

In a study of Clamann (2015) two concepts of eHMIs were presented to 50 participants in a real-life environment. The results indicate that implementing these eHMIs did not have significant effects on the decision time of crossing compared to having no eHMI and between the two tested eHMIs. They state that it is likely that participants already had some sort of crossing strategy which relies on gap distance and that this strategy possible remained dominant over the effect of the newly presented eHMIs.

A questionnaire-based study of Merat, Madigan, Louw, Dziennus, and Schieben (2015) showed that in three cities in Europe (La Rochelle in France, Lausanne in Switzerland and Trikala in Greece) the preferred way of communicating was different, but they want to be informed about the driving intention of AVs. The preferred way of communicating is by using auditory signals for all modalities in La Rochelle, except for turning where visual lights are preferred. In Lausanne, visual lights and text are preferred for all modalities, except for whether the AV is going to move where an auditory signal was preferred. In Trikala, Greece, the preferred way of communicating for turning and stopping was with visual lights or text. Other modalities showed no clear preference in Trikala. The preferred way of communicating is different in each city and that means that there is not one way of communicating yet that can be used everywhere, so future standard solutions should be tested in different locations.

Fridman et al. (2017) asked 200 participants for 30 eHMIs through an online survey system (Amazon Mechanic Turk) if they feel safe to cross by using screen shots of each eHMI. This study concluded that using Amazon Mechanic Turk is a cost-effective and fast way to test design elements or minor variations of eHMIs. It was found that, from the tested eHMI designs, a walking human and a text saying 'WALK' is the least ambiguous when it is safe to cross and a red hand with a palm facing the pedestrian and a text saying 'DON'T WALK' is the least ambiguous when it is not safe to cross.

Lagström, Lundgren, and Lagström (2015) tested an eHMI on an AV using real-life experiments. The eHMI consisted of a LED-strip on the front-side, which could show if the vehicle was decelerating or not. It was found that pedestrians feel safer when they know if the vehicle is automated or not, so they are able to adjust their communication strategy accordingly. After a short training, the pedestrians were able to understand the communication of the AV and were confident in their understanding of the communication system. The design of the LED-strip increased crossing ratios from 13% to 38% when asked if the participants would cross when the vehicle did not fully stop yet but was yielding. This study found that the pedestrians reported that this interface could replace and even exceed the interaction with drivers because they were able to see the LED-strip from a sufficient distance.

These studies show that AVs and eHMIs affect vehicle-pedestrian interaction and that eHMIs can be used to increase perceived safety of pedestrians.

C. Research on effects of AVs on VRU using VR

Effects of AVs can be studied using VR set-ups to increase fidelity and decrease confounding variables. For example, one study of Feldstein, Dietrich, Milinkovic, and Bengler (2016) showed in a motion capture VR-experiment that the accepted gap size during the pilot study was 3.3 (SD = 0.62) seconds with 12 participants aged between 20 and 30 years old, which is in line with other studies done on gap acceptance. Fidelity levels are sufficient during VR-experiments when using the presence questionnaire and the norms defined by UQO Cyber Psychology Lab (Witmer, Jerome, & Singer, 2005).

Chang (2017) did a study using VR where an eHMI concept called 'Eyes on a Car' was tested. The use of 'Eyes on a Car' decreased the average time for decision making from 2.319 (SD = 0.850) seconds to 2.032 (SD = 0.877). The results show that the decision-making time decreased significantly ($t(14) = 2.971$, $p<0.05$).

Furthermore, Human et al. (2017) scrutinised the differences between real and virtual environments by asking 60 participants how they experienced the real-life city centre of Chemnitz, Germany and a Cave Automatic Virtual Environment (CAVE) simulating the same city centre. Presence factors and usability correlated in the CAVE, but not in the real-life environment. Presence and user experience were partly correlated in both environments. Stimulation and novelty were higher in the real-life environment. It was concluded that their results indicate that VR can be used for user experience studies, when a high presence is achieved, noting there are still enough possibilities to improve VR experiences.

VR was used in an experiment to find effects of an eHMI on shared automated vehicles (SAVs) (Brenden & Habibovic, 2017). 34 participants encountered SAVs with and without an eHMI. The participants were asked to indicate their level of perceived safety and comfort. 29 participants indicated that they felt safe to cross when the eHMI was switched on and 13 participants felt safe to cross when the eHMI was switched off. The results showed that the level of perceived safety was higher when participants interacted with a SAV with an eHMI.

D. Research needs

As reviewed above, a number of studies has been conducted to find eHMIs which communicate driving behaviour effectively. There is no consensus yet on if and which eHMIs can be implemented in AVs and what the other design parameters (e.g., colour, size, timing) are. It is expected that if AVs have an interface that communicates their intentions to pedestrians clearly and intuitively, AV-VRU interaction will be safe, unambiguous and time efficient.

(Online) questionnaires, VR studies and real-life experiments have been conducted up till now. A clear comparison between the research methods is not made yet. Questionnaires are faster and cheaper than real-life experiments, but it is not known how the results from these methods compare. Furthermore, using VR has the benefit that all parameters can be controlled in a more effective way compared to real-life experiments and questionnaires. However, the fidelity of VR is lower compared to real-life experiments by definition.

E. Theoretical behaviour of pedestrians

First, the behaviour or the appearance of vehicles can influence the perceived safety of pedestrians. The hypothesised percentage of people feeling safe to cross for certain distances is visualised in Figure 1. The theory consists of two curves. The grey curve on the left-hand side shifts when, for instance, vehicle size or velocity changes. The curve is hypothesised to move to the left when the vehicle size increases, due to a distance that pedestrians need to feel safe due to visual looming effects. The blue curve on the right-hand side shifts to the left when people start to feel safe to cross at larger distances, due to a perceived improved communication (e.g., clear eye-contact, the use of an eHMI, a larger distance when the state of an eHMI changes or earlier deceleration of the vehicle). The dotted curve is an example of a change in perceived safety when this perceived communication is improved. If AV-VRU interaction is improved, then it can be expected that the dotted curve is steeper compared to the original curve, meaning that different people show more consistent behaviour.

What is important to note is that communication can also be interpreted wrongly (e.g., it is safe to cross, whereas the vehicle is not yielding) and cause unsafe situations. In these cases, the curves of Figure 1 do not change because this theoretical behaviour merely describes the perceived communication of vehicles towards pedestrians, not the actual (implicit) communication.

Subsequently, the perceived safety of pedestrians can influence the crossing behaviour of pedestrians. Figure 1 shows the hypothesised perceived safety of all participants. When looking at one participant, similar information looks like a binary profile over the distance. If people perceive that the situation is safe, they may decide to cross the road. Example profiles of intention to cross the road are shown in Figure 2. The binary profiles in this figure consist of the times that a participant feels safe to cross (e.g., are pressing the button on the remote), which summed form the total time a participant feels safe to cross. If the total time that participants feel safe to cross is higher, then the AV-VRU interaction is perceived as safer.

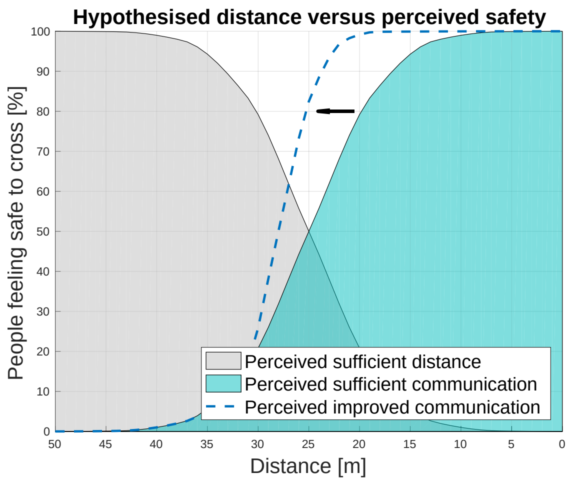


Fig. 1: Hypothesised distance versus perceived safety. The different areas represent the hypothesised reason why people feel safe to cross. An overlap takes place in the middle, where people can feel safe due to a perceived sufficient distance between the vehicle and themselves and due to the perceived communication of the vehicle or driver indicating the pedestrian can cross safely. A higher minimum value at a certain distance means that pedestrians feel safer to cross, with the highest curve at 0% meaning that no one feels safe to cross (e.g., in this figure at 0 m, when the vehicle is not yielding) and with the highest curve at 100% meaning that everyone feels safe to cross (e.g., in this figure at 50 m). The area of perceived sufficient communication is not valid when a vehicle is not yielding, in this case only the area of perceived sufficient distance is present. Perceived sufficient communication means that it is clear for the pedestrian what the intention of the vehicle is (e.g., clear eye-contact, the use of an eHMI, a larger distance when the state of an eHMI changes or deceleration of the vehicle).

F. Goal of research

It has been determined that the focus of this research lies on finding the effects of eHMIs of AVs on pedestrians, therefore the main research question of this master thesis is composed as:

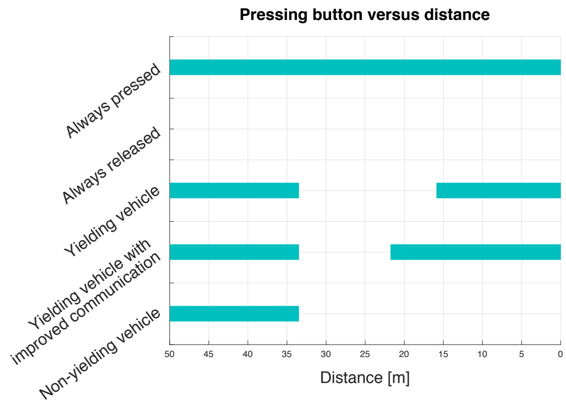


Fig. 2: Pressing profiles versus distance. Coloured regions are the distances in which participants hypothetically feel safe to cross (e.g., are pressing the button on the remote). The sum of these regions represent the total time that people feel safe to cross. The last button press is defined as the left-hand side of the region on the (most) right-hand side.

What are the effects of external human-machine interfaces (eHMIs) of automated vehicles on the crossing behaviour of pedestrians?

In order to answer the main research question, the following hypotheses are composed.

H1 *The total time that people feel safe to cross is higher when interacting with automated vehicles which communicate deceleration through an eHMI compared to automated vehicles without an eHMI.*

H2 *The total time that people feel safe to cross increases with decreasing vehicle size.*

H3 *The total time that people feel safe to cross is independent of the vehicle size when an eHMI is used.*

II. Methods

A. Experimental design

A within-subject experiment was designed to study the crossing behaviour of pedestrians when faced with eHMIs. This experimental design was implemented in a VR-environment using Oculus Rift and Unity.

Independent variables: Four independent variables were used (see Table I). All distances relate to the distance between the vehicle and the VRU. The participant was standing on a pavement at a two-lane two-way road in a European setting with traffic coming only from the left side on a clear and sunny afternoon as shown in Figure 4. Three types of vehicles were implemented (see Figure 3). These vehicles came around a corner at approximately 90 m on the left side from the participants' perspective

TABLE I: Independent variables

Type of vehicle	Smart fortwo, BMW z4, Ford f150
Yielding behaviour	Yielding at 35 m, No yielding
Type of eHMI	Baseline, Frontal braking lights, Knightrider, Smiley, Text
Timing of eHMI	50 m, 35 m, 20 m

Fig. 3: Vehicles in the simulation. From left to right: Smart fortwo, BMW z4, Ford f150

Fig. 4: View of participant wearing VR glasses showing a BMW z4 approximately 35 m away.

and drove past the participant to disappear by turning left on a corner at the right-hand side approximately 30 m away from the participant (see Figure 5). When the vehicle yields, braking is always initiated at 35 m with a deceleration rate of 3.5 m/s^2 and is coming to a stand-still at 7.6 m.

The velocity/distance profiles for yielding and non-yielding vehicles is shown in Figure 6b. The time-to-collision (TTC) is visualised in Figure 6c. The relationship between time and distance depends on the yielding behaviour of the vehicle. TTC goes to infinity when a vehicle yields, therefore there are multiple points which have the same value (see Figure 6c). The relation between time and distance is different depending on the yielding behaviour of the vehicle (see Figure 6a), so distance was used for visualising the pressing behaviour. However, time was used to discuss and analyse the behaviour of pedestrians and vehicles.

The eHMIs all consist of a screen/LED's implemented in front of the vehicle as shown in Figure 7. Background noise and driving sounds were implemented. The driving sounds were the same for each vehicle to reduce the influence of confounding variables. The frequency and the volume of the driving sound depend on distance and velocity. The Frontal braking lights were developed by the first author. The Knightrider was developed by Dipl.-Ing. A. Dietrich. An animation was shown when the Knightrider is in its yielding state. A bar going from left to right (from the pedestrians' perspective) indicates that it is safe to cross. The Smiley was inspired by the concept of Semcon (Semcon, 2017). The Text eHMI was based on the results of the questionnaire of Fridman et al. (2017). The eHMIs were designed in such a way that the colour, the number of states, the timing of the animations are the same and the sizes and positions are similar. This was to reduce the amount of confounding variables.

Kinematics of vehicles: 45 waves of vehicles were programmed to include all independent variables in one experiment. These waves consisted of a yielding, a non-yielding vehicle and some 'filler' vehicles as shown in Figure 8. Non-yielding vehicles and 'filler' vehicles do not show different yielding behaviour, so the participant cannot just focus on the yielding and non-yielding vehicles. The 'filler' vehicles showed the same eHMI or baseline as the other non-yielding vehicles in the same wave. The temporal gap between 'filler' vehicles was randomised between 1.5 and 3.5 seconds. The gap between waves of vehicles varied between 2.0 seconds and 8.0 seconds. Temporal gaps before a measured yielding or non-yielding vehicle were exactly 4.0 seconds between the front of the measured vehicle and the rear of the preceding vehicle, which should be sufficient for most people (Kadali & Vedagiri, 2016; Feldstein et al., 2016). This was confirmed in the pilot study where people pressed the button during these 4.0 seconds when a vehicle was not yielding.

For randomising conditions to account for fatigue, learning effects and stress, 30 Latin squares with N = 5 were used for varying the order of the appearances of the eHMI and 300 Latin squares with N = 9 were used for varying the order of the type of vehicle and the timing of the eHMI (see Appendix I). This means that all participants were exposed to one eHMI with each timing of the eHMI and each vehicle for 9 waves. These waves consisted of a yielding, a non-yielding vehicle and some 'filler' vehicles as shown in Figure 8. After these 9 waves, the participant was asked to take a break. Another eHMI was shown for 9 waves after the break and this continued for 5 blocks (4 eHMI and baseline) with 4 breaks. Latin squares with N = 5 are fully balanced, meaning that the sums of rows were the same and the sums of the columns were the same. Latin squares with N = 9 were almost balanced; out of the 300 sequences, the last three sequences were not fully balanced. All participants encountered 360 vehicles of which 45 were yielding, 45 were non-yielding and the rest were filler vehicles which did not yield.

Additionally, only people aged between 18 and 30 years and from right-hand side driving countries were accepted to participate in this experiment, due to previous research showing different crossing behaviour depending on pedestrian characteristics (Dommes, Cavallo, Dubuisson, Tournier, & Vienne, 2014; Dommes & Cavallo, 2011; Holland & Hill, 2009, 2007).

Task: A handheld remote was used to measure when the participant feels safe to cross. The participant was instructed to press the button when they feel safe to cross. The task of this experiment was continuous. The task was described as follows:

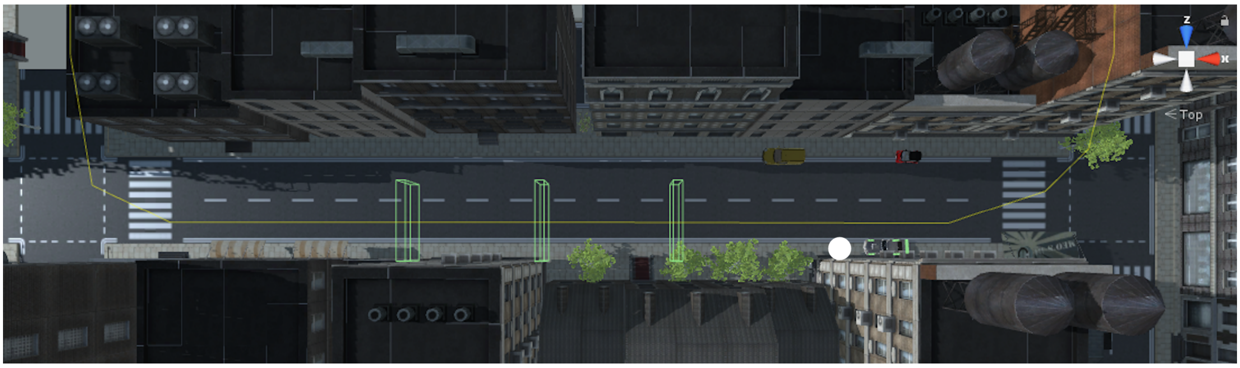


Fig. 5: Route of vehicles in simulation in Unity. Yellow line is the planned route which vehicles will follow in a smooth manner. The white circle represents the location of the participant and the three green boxes are the locations where the eHMI switches state at 50, 35 and 20 m respectively. The yielding vehicles start decelerating at 35 m.

Each time you feel safe to cross, please do the following:

1) *Press the button on the remote.*
2) *Keep pressing the button as long as you feel safe.*
3) *When you do not feel safe to cross anymore, release the button.*

The instruction was given in the informed form of consent (see Appendix B). The task was practised in a practise session of approximately 2 minutes (script can be found in Appendix K) and was explained once more in the questionnaire before the experiment (see Appendix C).

B. Materials and equipment

A desktop with Windows 10 Enterprise and Unity version 5.5.0f3 Personal 64bit was used to conduct the research. An Oculus Rift with a constellation tracking camera and a remote were used for providing the VR-environment (see an example in Figure 9). The specifications of the hardware are listed in tables II till IV.

A software framework in Unity was provided by Dipl-Ing. André Dietrich. This framework was further developed to create this experiment. Two relevant scripts for the ability to reproduce this experiment can be found in Appendices J and K. The first script (Appendix J) logged the position and orientation of the vehicles and Oculus Rift and the state of the remote. The second script (Appendix K) initiated all the vehicles with the use of a randomisation script, which randomised all vehicles within and in between participants. Furthermore, the first author imported several buildings, assets and vehicles to build up the scene. All used assets (except for the Smart fortwo model) can be found in the Unity Asset Store. All used assets are listed in Appendix F.

Procedure: A form of consent (see Appendix B) was signed before starting the experiment. A general questionnaire containing several demographic questions and a BSSS (*Brief Sensation Seeking Scale*, 2017) was given before the experiment on a laptop using Google Forms (see Appendix C). Using VR-glasses can cause nausea, headaches or other discomforts and use longer than one hour is not advised (Karner, 2017). The participant was asked to indicate the well-being using a MISC questionnaire (Emmerik, De Vries, & Bos, 2011) during the breaks of the experiment (see Appendix E) to make sure the experiment was done in a safe and responsible manner. After the experiment, another questionnaire was given, see Appendix D. For measuring the understanding and preferences of the interfaces the participant was asked to answer if they felt safe to cross with screenshots of each interface in each state. This is the same question as another study which asked 200 participants for 30 eHMIs through Amazon Mechanic Turk (Fridman et al., 2017). The presence questionnaire of Witmer et al. (Witmer et al., 2005) was used to measure the fidelity of the VR-experience. Also, a NASA-TLX (*NASA-TLX*, 2017) was given after finishing the experiment. The protocol of the experimenter can be conducted in Appendix A.

TABLE II: Specifications of Oculus Rift

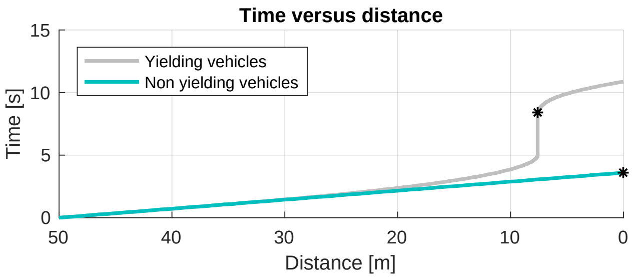
Screen	OLED, 5.6 inch, 2160 x 1200
Field of view	110 °
Refresh rate	90 Hz
Connections	HDMI, USB 2.0/3.0
Tracking area	150 x 330 cm (5 x 11 feet)
Sensors	Accelerometer, gyroscope, magnetometer, constellation tracking camera Built-in audio and microphone

TABLE III: Specifications of desktop for simulations

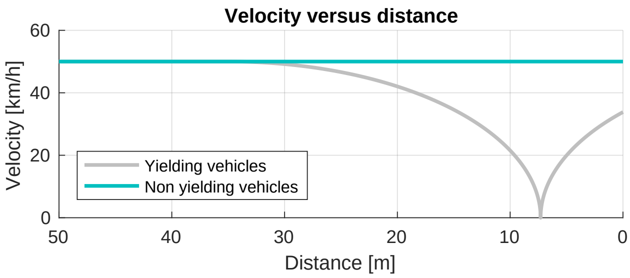
Processor	Intel(R) Xeon(R) CPU E5-1620 v4 @ 3.50 GHz 3.49 GHz
RAM	16.0 GB
Operating system	Windows 10 Enterprise
Graphics	NVIDIA Quadro M5000
System type	64-Bit operating system, x64-based processor

TABLE IV: Specifications of laptop for questionnaires

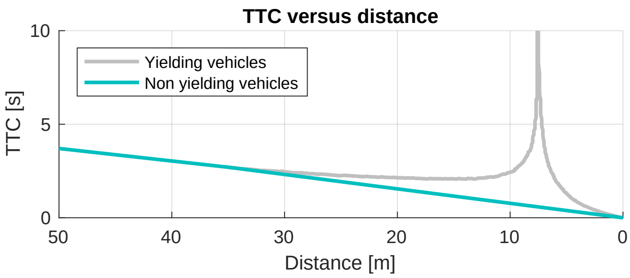
Processor	2,7 GHz Intel Core i5
RAM	8 GB 1867 MHz DDR3
Operating system	macOS Sierra 10.12.6
Graphics	Intel Iris Graphics 6100 1536 MB
System type	64-Bit operating system, x64-based processor



(a) Time versus distance for yielding and non-yielding vehicles. The asterisks indicate the cut off times for the analysis for the yielding and non-yielding vehicles.



(b) Velocity versus distance for yielding and non-yielding vehicles. Initial velocity is 50 km/h for all vehicles. Yielding vehicles are decelerating with 3.5 m/s.



(c) TTC versus distance for yielding and non-yielding vehicles. At 7.6 m the TTC increases to infinity for yielding vehicles.

Fig. 6: Cohesion of distance, TTC, time and velocity.

C. Approach, post-processing and statistical analysis

A pre-study with two experts was conducted. Subsequently, a pilot study with three participants was done. The results can be found in Appendix H. The contrasts and the sizes of the eHMIs were verified during the pilot study. Red vehicles and a light blue colour for the eHMI with the designed sizes showed to be distinguishable from a distance smaller than 50 m.

The metric is the total time that pedestrians felt safe to cross. This metric includes behaviour over the distance between −50 and −7.6 m for yielding vehicles and −50 and 0 m for non-yielding vehicles and is calculated by using the following formula: $ratio = time\ pressed\ /\ total\ time$. This represents the pressing behaviour of pedestrians because it takes into account when a pedestrian releases the button and presses it at a later time again. Time is used to calculate the ratios of the total time pressed. Distance is used to visualise the results because it is more intuitive when comparing for instance the timing of the eHMI at distances 50, 35 and 20 m.

The log files of each participant were post-processed using Matlab. The Matlab scripts can be found in Appendix L. All data was filtered based on the distance between the participant and the vehicle.

Fig. 7: Implemented eHMIs. From top to bottom: Baseline, Frontal braking lights, Knightrider (animation of bar moving from left to right from the perspective of the pedestrian in yielding state), Smiley, Text. The left column represents state while not yielding, the right column represents state while yielding.

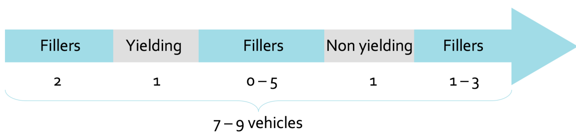


Fig. 8: One wave of vehicles. Vehicles are approaching the participant from the left side. The yielding and non-yielding vehicle show different eHMIs in one block of 9 waves. The timing of the eHMI varies for the yielding vehicle and the type of vehicle varies for all the vehicles. The type of vehicle of the yielding and non-yielding vehicles is not necessarily the same in one wave, accounting for people trying to predict which vehicles will yield. All distances between vehicles are randomised, except for the distances between the measured vehicles (only the grey vehicles (e.g., yielding and non-yielding vehicles)). The distance between these vehicles is 4.0 seconds between the front of the measured vehicle and the rear of the preceding vehicle.

III. Results

The experiment was conducted at TU München and 28 participants took part in the final study. The participants were 24,57 (SD = 2,63) years old on average, were from five countries (Germany, Switzerland, Italy, China,

Fig. 9: Participant wearing the Oculus Rift during an experiment.

Spain), all living in Germany and 25 % was female and 75 % was male. Two out of 28 participants had colour blindness. Nine people wore glasses and two people wore contact lenses in the experiment. Both colour blindness and sight did not show any large correlations with respect to the total time that the participants felt safe to cross per participant, with low negative correlations of 0.105 and 0.094 respectively.

A. Task performance

All participants completed the experiment. The total time feeling safe (the button was pressed) is used for analysis. The total time feeling safe ($ratio = time\ pressed\ /\ total\ time$) was calculated by cutting off the state of the button at -50 and -7.6 m for the yielding vehicles and at -50 and 0 m for the non-yielding vehicles and dividing it by the total time within the cut off distances. All participants showed decisive pressing behaviour (i.e. no releasing and pressing the button very quickly). The ratios of total time pressed for yielding and non-yielding vehicles are included in Appendix G for a visualised overview of the differences between conditions and the baseline.

Non-yielding: Some participants did not press during the non-yielding case, which is likely due to an insufficient gap for crossing. Approximately half of the participants accepted gaps of smaller than 4 seconds in the non-yielding conditions (see Figure 10). The hypothesised curve of 'sufficient distance' in Figure 1 can be seen when looking at the distributions in Figure 10. There was a statistical difference when looking at vehicle type using the Friedman test (see Table V). Post hoc analysis with Friedman's 2-way ANOVA by ranks pairwise comparisons showed that the Ford is significantly different from the Smart (see Table VII). Other combinations showed no significant difference. This means that people pressed the button for a shorter total time when they encountered a Ford instead of a Smart.

There was no statistical difference when looking at the type of eHMI (including baseline) (see Table V).

Yielding: All participants pressed the button in each case when the vehicle stopped, which is to be expected (see Figure 11). Comparing the distributions in Figure 11 with the hypothesised curves of 'perceived sufficient distance' and 'perceived sufficient communication' in Figure 1 can be seen. The hypothesised shifts are visible in Figure 11 as well. Statistical analysis is used to find which independent variables played a role in shifting these curves.

There was no statistical difference when looking at vehicle type including the baseline only using the Friedman test (see Table V). There was a statistical difference when looking at vehicle type including eHMI using the Friedman test (see Table V). Post hoc analysis with Friedman's 2-way ANOVA by ranks pairwise comparisons showed that the Ford is significantly different from the Smart (see Table VII). The other combinations showed no significant differences. This means that people pressed the button for a shorter total time when they encountered a Ford instead of a Smart. These differences are the same compared to the non-yielding case.

A statistical difference was found when looking at the type of eHMI (including baseline) (see Table V). The post hoc analysis with Friedman's 2-way ANOVA by ranks pairwise comparisons is shown in Table VI. Participants pressed the button significantly longer when they encountered an eHMI instead of no eHMI.

A statistical difference was found when looking at the timing of eHMI (including baseline) (see Table V). The post hoc analysis with Friedman's 2-way ANOVA by ranks pairwise comparisons is shown in Table VIII. No significant difference between 35 m - 50 m and baseline - 20 m was found. This means that people press the button for a longer time when the eHMI is changing state from a longer distance and that 20 m and the baseline show similar pressing behaviour.

Comparing the distributions of total time pressed when vehicles are yielding of each eHMI between different vehicles. Differences were analysed using Friedman's test (see Table IX). The eHMI defines the total time participants feel safe to cross for when looking at both vehicle type and eHMI. This indicates that the eHMI is more 'dominant' in determining the pressing behaviour than the vehicle size.

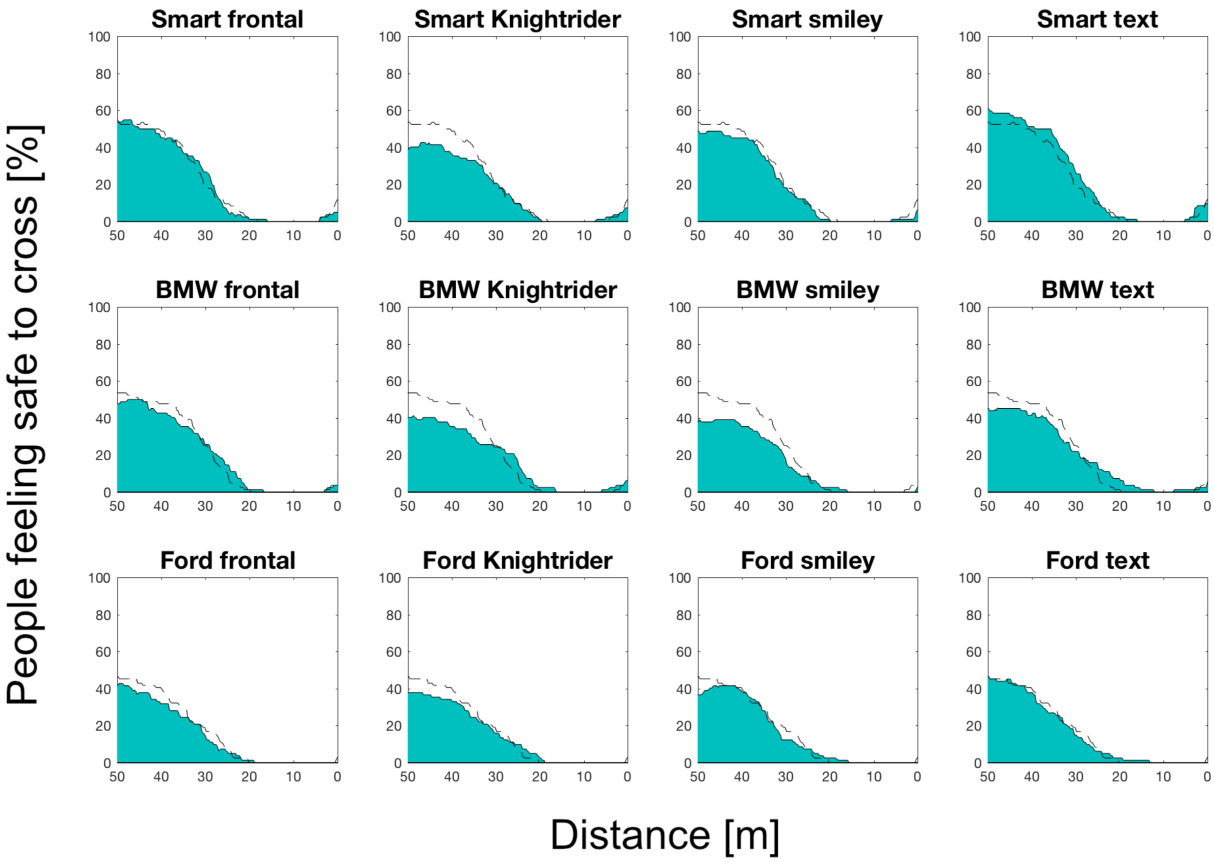


Fig. 10: Proportion of participants feeling safe over distance for non-yielding vehicles. The dotted line represents the baseline. All figures have people feeling safe to cross [%] on the y-axis and distance [m] on the x-axis.

TABLE V: Overview of Friedman's tests with *df*, χ^2 being the test statistic, *p-value* and the mean ranks of each group within the tested variable.

Tested variable		*df*	χ^2	*p-value*	*mean ranks*				
					Smart	*BMW*	*Ford*		
Vehicle	Non-yielding	2	9.750	**0.008***	2.33	2.11	1.56		
	Yielding	2	9.500	**0.009***	2.46	1.86	1.68		
	Yielding (baseline)	2	3.071	0.215	2.21	2.04	1.75		
					Baseline	*Frontal*	*Knightrider*	*Smiley*	*Text*
eHMI	Non-yielding	4	5.144	0.273	3.07	3.00	2.67	2.78	3.48
	Yielding	4	30.200	$<$ **0.001***	1.57	3.21	3.21	3.32	3.68
					Baseline	*20 m*	*35 m*	*50 m*	
Timing eHMI	Yielding	3	54.214	**0.001***	1.39	1.89	3.07	3.64	

The mean ranks can range between the number of categories within one independent variable (e.g., when looking at type of vehicle the mean ranks can range between 1 (for the smallest total time ratios) and 3 (for the largest total time ratios)). Friedman test was done for the yielding and non-yielding cases over type of vehicle, type of eHMI and timing of eHMI. The critical *p-value* was 0.05. Frontal stands for the Frontal braking lights. Asterisks indicate significant p-values.

TABLE VI: Post hoc analysis of type of eHMI when vehicles are yielding using total time that participants felt safe to cross.

Pair		*Mean (SD)*	*Mean (SD)*	*test statistic*	*p-value*
Baseline	– Frontal	0.655 (0.150)	0.743 (0.174)	1.643	**0.001***
Baseline	– Knightrider	0.655 (0.150)	0.747 (0.177)	1.643	**0.001***
Baseline	– Smiley	0.655 (0.150)	0.751 (0.156)	1.750	$<$ **0.001***
Baseline	– Text	0.655 (0.150)	0.765 (0.156)	2.107	$<$ **0.001***
Frontal	– Knightrider	0.743 (0.174)	0.747 (0.177)	0.000	1.000
Frontal	– Smiley	0.743 (0.174)	0.751 (0.156)	0.107	1.000
Frontal	– Text	0.743 (0.174)	0.765 (0.156)	0.464	1.000
Knightrider	– Smiley	0.747 (0.177)	0.751 (0.156)	0.107	1.000
Knightrider	– Text	0.747 (0.177)	0.765 (0.156)	0.464	1.000
Smiley	– Text	0.751 (0.156)	0.765 (0.156)	0.357	1.000

The *p-value* is the significance with a Bonferroni correction (*p-values* were multiplied by the number of hypotheses of 10). The critical *p-value* was 0.05. The mean ranks can be found in Table V. Frontal stands for Frontal braking lights. Asterisks indicate significant p-values.

TABLE VII: Post hoc analysis of type of vehicle using total time that participants felt safe to cross.

		Non-yielding				***Yielding***			
Pair		*Mean (SD)*	*Mean (SD)*	*test statistic*	*p-value*	*Mean (SD)*	*Mean (SD)*	*test statistic*	*p*
Ford	– BMW	0.156 (0.200)	0.190 (0.223)	0.556	0.124	0.725 (0.167)	0.732 (0.166)	0.179	1.000
Ford	– Smart	0.156 (0.200)	0.205 (0.215)	0.778	**0.013***	0.725 (0.167)	0.746 (0.167)	0.786	**0.010***
BMW	– Smart	0.190 (0.223)	0.205 (0.215)	0.222	1.000	0.732 (0.166)	0.746 (0.167)	0.607	0.069

The *p-value* is the significance with a Bonferroni correction (*p-values* were multiplied by the number of hypotheses of 3). The critical *p-value* was 0.05. The mean ranks can be found in Table V. Frontal stands for Frontal braking lights. Asterisks indicate significant p-values.

TABLE VIII: Post hoc analysis of timing of eHMI on yielding vehicles using total time that participants felt safe to cross.

Pair		*Mean (SD)*	*Mean (SD)*	*test statistic*	*p-value*
Baseline	– 20 m	0.655 (0.150)	0.698 (0.135)	0.500	0.884
Baseline	– 35 m	0.655 (0.150)	0.761 (0.168)	1.679	$<$ **0.001***
Baseline	– 50 m	0.655 (0.150)	0.796 (0.178)	2.250	$<$ **0.001***
20 m	– 35 m	0.698 (0.135)	0.761 (0.168)	1.179	**0.004***
20 m	– 50 m	0.698 (0.135)	0.796 (0.178)	1.750	$<$ **0.001***
35 m	– 50 m	0.761 (0.168)	0.796 (0.178)	0.571	0.586

The *p-value* is the significance with a Bonferroni correction (*p-values* were multiplied by the number of hypotheses of 6). The critical *p-value* was 0.05. The means and standard deviations are shown behind the condition after the comma and in brackets respectively. The mean ranks can be found in Table V. Asterisks indicate significant p-values.

TABLE IX: Effects of vehicles on eHMI distributions using total time that participants felt safe to cross.

eHMI	*df*	χ^2	*p-value*	*Smart*	*BMW*	*Ford*
Frontal braking lights	2	4.071	0.131	2.25	1.71	2.04
Knightrider	2	5.856	0.054	2.27	2.09	1.64
Smiley	2	2.000	0.368	2.07	2.14	1.79
Text	2	2.288	0.318	2.12	2.11	1.77

Friedman's test was used with the mean ranks of each vehicle with each eHMI and with *df* the degrees of freedom, χ^2 being the test statistic and *p-value* the significance. The critical *p-value* was 0.05. The mean ranks can range between 1 (for the smallest total time ratios) and 3 (for the largest total time ratios).

TABLE X: Paired-sample t-tests of the total time participants pressed the button for each bin, before and after state change.

Pair		*Mean (SD)*	*Mean (SD)*	*df*	*t-value*	*p-value*
Baseline: 50 – 7.6 m	– eHMI: 50 – 7.6 m	0.655 (0.150)	0.796 (0.178)	27	-8.576	$<$ **0.001***
Baseline: 50 – 35 m	– eHMI: 50 – 35 m	0.484 (0.457)	0.472 (0.473)	27	0.335	0.740
Baseline: 35 – 7.6 m	– eHMI: 35 – 7.6 m	0.681 (0.141)	0.804 (0.165)	27	-7.119	$<$ **0.001***
Baseline: 50 – 20 m	– eHMI: 50 – 20 m	0.309 (0.317)	0.297 (0.323)	27	0.588	0.562
Baseline: 20 – 7.6 m	– eHMI: 20 – 7.6 m	0.792 (0.148)	0.856 (0.136)	27	-4.607	$<$ **0.001***

Means, standard deviations, t-value and p-value of paired-sample t-tests of the total time participants pressed the button for each bin, before and after state change. Asterisks indicate significant p-values. The critical *p-value* was 0.05.

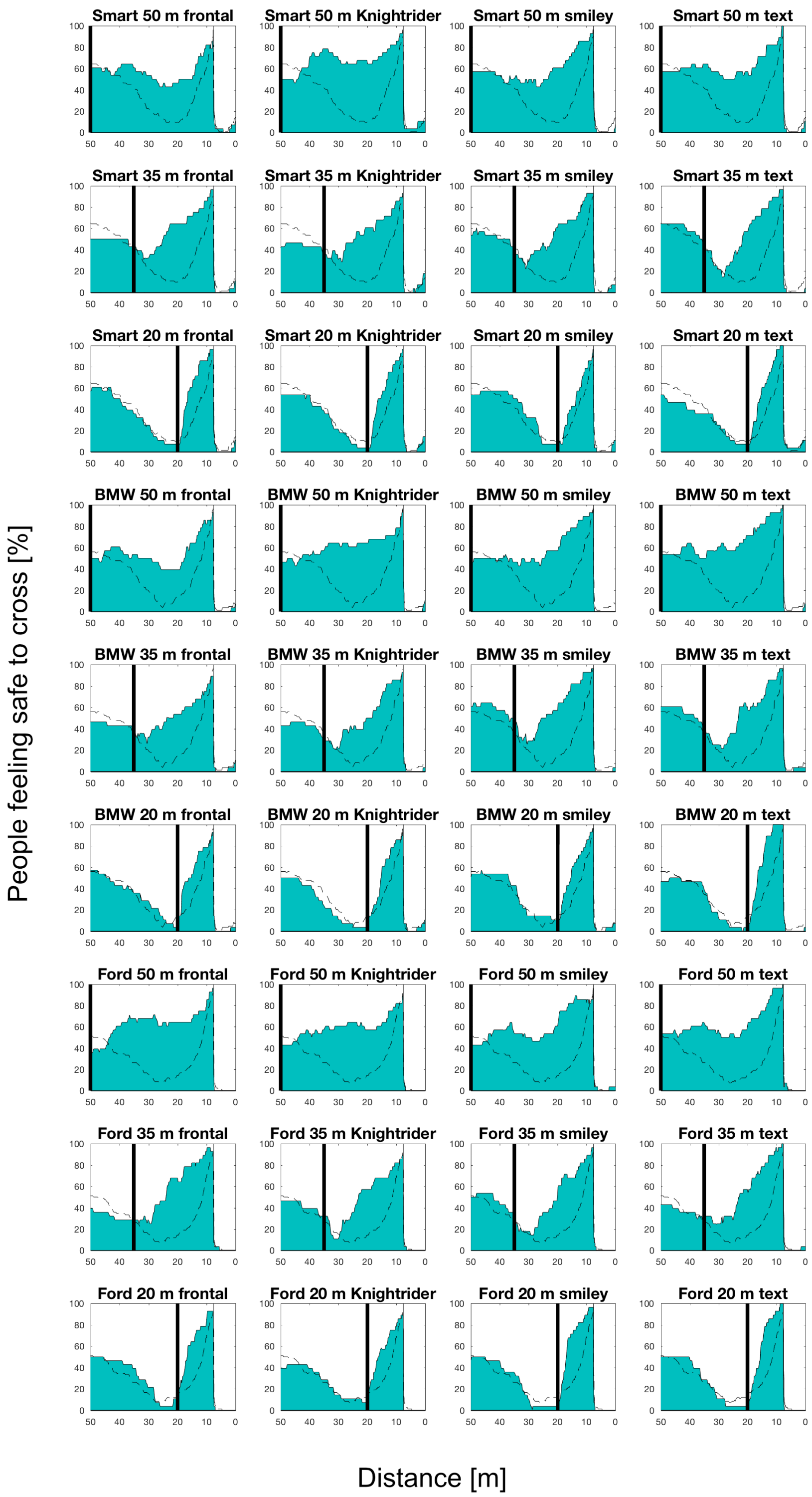


Fig. 11: Proportion of participants feeling safe over distance for yielding vehicles. A black vertical line indicates the distance where the eHMI is changing states. The dotted line represents the baseline. All figures have people feeling safe to cross [%] on the y-axis and distance [m] on the x-axis.

B. *Effect of pressing behaviour before and after state switch of eHMI*

The baseline and eHMI data were divided into bins. In the case of the 50 m, the data was not split. The data was split into two bins when the eHMI switched state at 35 and 20 m. The bins were tested for normality and they were all normally distributed. Table X shows the means, standard deviations and p-value of paired-sample t-tests of each bin. Using paired-sample t-tests, it was found that the distributions are different after the eHMIs changed state, but the t-tests failed to reject the null hypotheses before the eHMIs changed state.

C. *Learning behaviour*

Participants encountered 9 yielding vehicles with the same eHMI in one of the five blocks during the experiment. The ratios of total time pressed is shown in Figures 12 till 14. The total time pressed does not seem to go down when people encounter yielding vehicles more often. The tested eHMI and the presence of an eHMI do not show different learning behaviour. Only during the first encounter of a yielding vehicle participants seem to press the button slightly longer compared to later encounters.

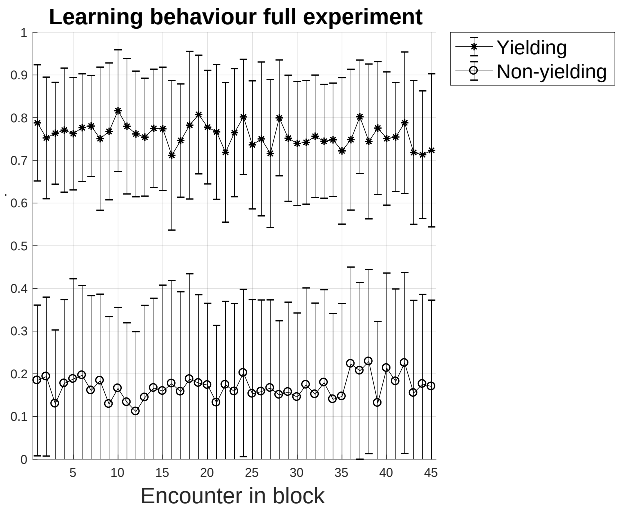


Fig. 12: Learning behaviour over the full experiment. The stars are the means of the total time pressed for each encounter in a block. Error bars represent standard deviations of the total time pressed.

D. *Questionnaires*

Before the experiment, a BSSS questionnaire was answered. The median total time that participants felt safe to cross per participant was correlated with the BSSS scores (see Table XI). Only low correlations were found, with the highest positive correlation (corr. = 0.287) for people who like wild parties.

After conducting the experiments participants were asked to fill in a questionnaire asking them to order the eHMIs on their preferences (see Figure 15). The baseline is chosen last by more than 80% of the participants.

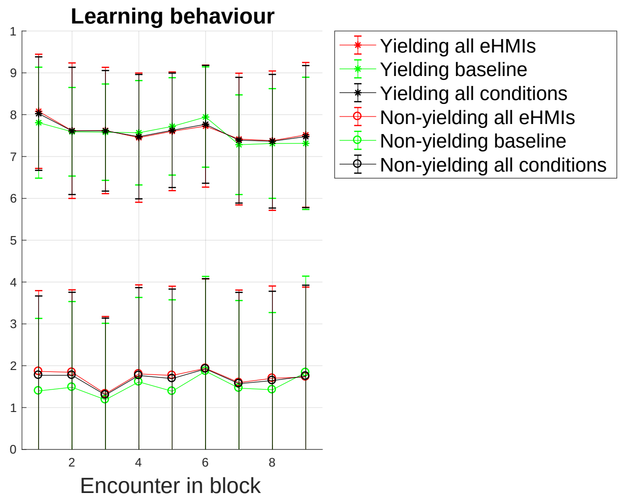


Fig. 13: Learning behaviour during one block with and without eHMI. The stars are the means of the total time pressed for each encounter in a block. Error bars represent standard deviations of the total time pressed.

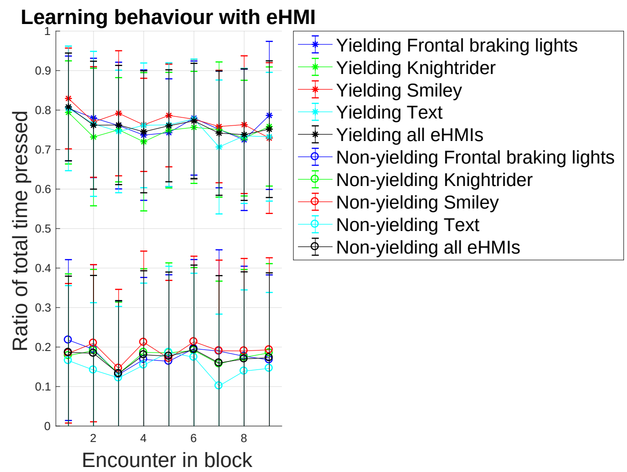


Fig. 14: Learning behaviour during one block for each eHMI. The stars are the means of the total time pressed for each encounter in a block. Error bars represent standard deviations of the total time pressed.

Furthermore, the participants were asked if they feel safe to cross when screenshots of the eHMIs in their yielding and non-yielding state are shown (see Figure 16). The Text is the least ambiguous and the baseline is most ambiguous.

The 19-item presence questionnaire with 3 items about sound was used to measure fidelity. The results are shown in Figure 17, where a comparison with Feldstein et al. (2016) is made. Total scores and standard deviations are very similar for both experiments; 94 (SD = 10) for this study and 93 (SD = 11) for the study of Feldstein et al. (2016).

The participant was asked to indicate how they felt before, during and after the experiment (see Figure 18). Results indicate that the discomfort increased very little over the course of the experiment. All participant finished the experiment.

The workload was subjectively measured using a six item NASA-TLX after carrying out the experiment (*NASA-*

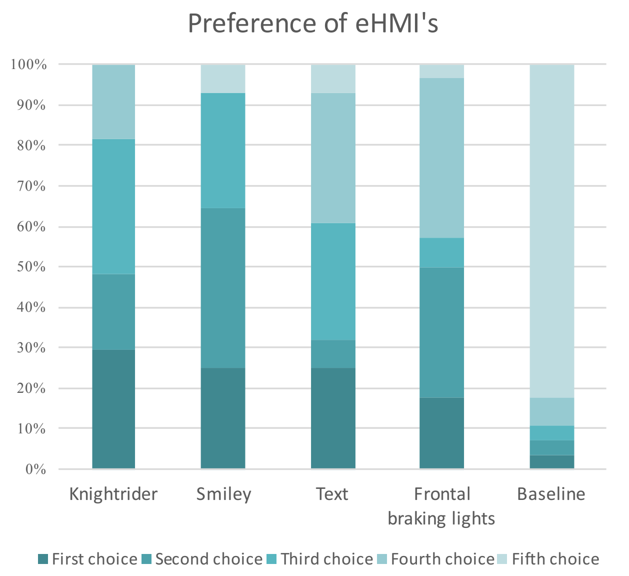


Fig. 15: Preferences of eHMIs. Sorted based on times chosen for number 1 from top to bottom: Knightrider, Smiley, Text and Frontal braking lights, baseline.

TLX, 2017). The overall workload was scored with 39.07 (SD = 17.60) out of 126 (see Table XII). These scores indicate that the workload of this experiment is not too high.

IV. Discussion

The effects of eHMI of AVs on the crossing behaviour were tested using a VR simulation. This simulation was set up using Unity and the Oculus Rift. Four independent variables were tested (see Table I).

TABLE XI: Correlation values of BSSS versus median total time that participants felt safe to cross

Question	*Correlation*
I would like to explore strange places.	0.090
I get restless when I spend too much time at home.	0.018
I like to do frightening things.	0.003
I like wild parties.	0.287
I would like to take off on a trip with no pre-planned routes or timetables.	-0.172
I prefer friends who are excitingly unpredictable.	-0.018
I would like to try bungee jumping.	0.225
I would love to have new and exciting experiences, even if they are illegal.	0.205
BSSS score 0.141	

TABLE XII: NASA-TLX scores. Each item has a maximum score of 21 and the maximum score of the total is 126.

Item	*Mean*	*SD*
Mental demand	8.91	3.85
Physical demand	4.73	3.77
Temporal demand	7.98	3.72
Performance	6.20	3.79
Effort	6.66	3.76
Frustration	4.59	3.66
Total	39.07	17.60

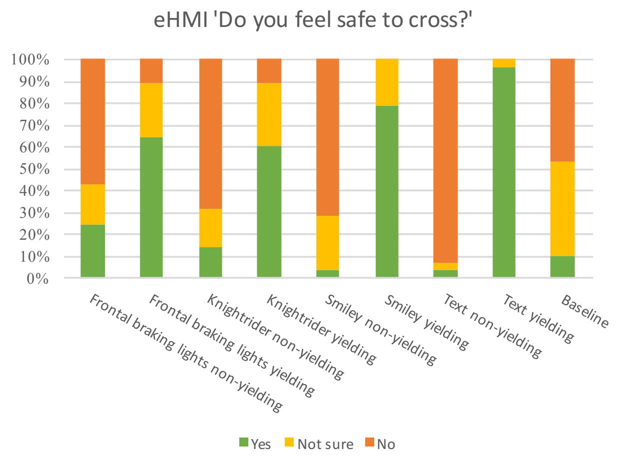


Fig. 16: Clarity of eHMIs by showing a screen shot of the eHMI in each state and by asking *'Do you feel safe to cross?'*, which is the same as in (Fridman et al., 2017). Sorted from least ambiguous to most ambiguous: Text, Smiley, Knightrider, Frontal braking lights, baseline.

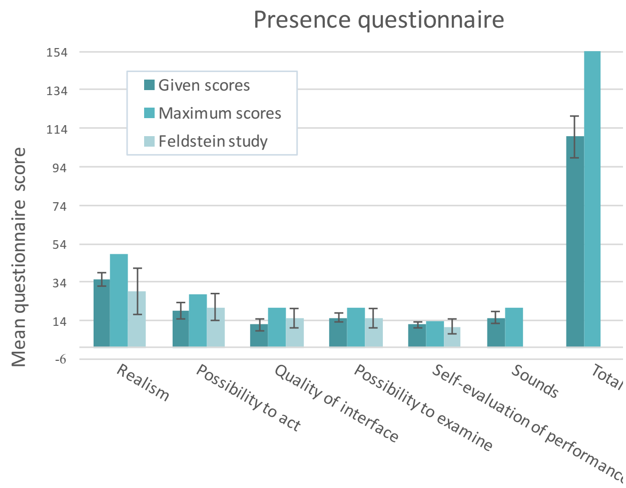


Fig. 17: Presence questionnaire with error bars indicating SD. Total score with sounds is 110 (SD = 11) out of 154. Total score without sounds is 94 (SD = 10) out of 133. Total score of (Feldstein et al., 2016) is 93 (SD = 11) out of 133.

A. Main findings

Yielding behaviour: There are clear differences in total time ratios between yielding and non-yielding vehicles (see Figures 10 and 11). This is to be expected since in the case of non-yielding vehicles it is not safe to cross when the vehicle is closer. The non-yielding vehicles show that participants do not behave differently when confronted with a vehicle with an eHMI that does not switch state. However, in the yielding cases, the pressing behaviour differs significantly between the baseline and the eHMIs. This can also be seen in Table VI, where the differences between baseline and eHMIs are significant in the yielding cases and not significant in the non-yielding cases.

Type of vehicle: The total time that participants felt safe to cross was significantly smaller for the Ford compared to the Smart in both the yielding and non-yielding cases.

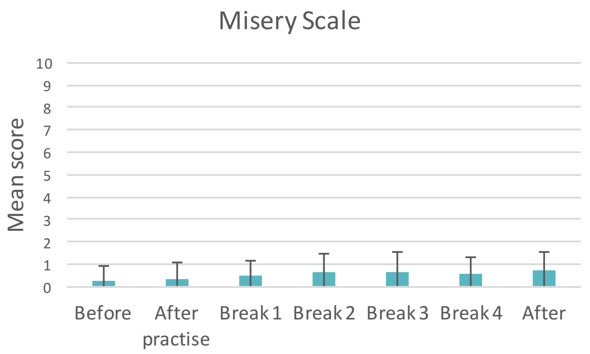


Fig. 18: Misery Scale with error bars indicating SD. From left to right: before practising, during each break and after the experiment. 0 = No problems, 1 = Slight discomfort but no specific symptoms, 2 to 5 = Vague / Some / Medium / Severe dizziness, warm, headache, stomach awareness, sweating, etc., 6 to 9 = Some / Medium / Severe / Retching nausea, 10 = Vomiting.

The total time that participants felt safe to cross was not significantly different when comparing the other pairs. However, the effect size is quite small when looking at the means of each vehicle in Table VII. It can be concluded that the difference between the Ford and Smart is larger than the differences between the other vehicles and that larger vehicles cause the total time that participants feel safe to decrease.

Type of eHMI: When looking at the eHMI in yielding vehicles, different eHMI did not show any significant differences. Only the baseline was different from each eHMI distribution. The effect size is considerable when looking at the means of the baseline and the eHMIs in Table VI. This indicates that the use of an eHMI does change the total time that participants felt safe to cross of pedestrians, but that it is more important to at least convey the message when considering the tested eHMIs.

However, in the case of the non-yielding vehicles there was no statistical difference between eHMIs and baseline. Indicating that when vehicles are not yielding the participants did not change their crossing behaviour (i.e., pressing behaviour).

When looking at interaction effects of eHMI and vehicle, it can be seen that for all eHMIs the type of vehicle is less important than the use of an eHMI in the total time that participants felt safe to cross. Comparing this with the overall different distributions when comparing the type of vehicle gives insight in the dominance of an eHMI over the vehicle appearance. When looking at the mean ranks of the vehicles in Table IX, it can be seen that all vehicles still show different ranks. Therefore, vehicle size remains present when using an eHMI although not statistically significant. It could be possible that this information was lost because the means were taken to calculate the total time ratios per participant.

Timing of eHMI: Changing the state of an eHMI showed to yield significantly different distributions of the total times that participants felt safe to cross, with people feeling safer when the state of an eHMI switched earlier. The difference between 35 m and 50 m did not show significant results. This can indicate that the participants decide to cross based on an eHMI in a later stadium and not so much before the vehicle starts to yield (which was at 35 m). There was also no difference between the baseline and 20 m. This can indicate that the state switch happened too late for people to respond differently compared to the baseline without an eHMI. The effect size is considerable when looking at the means of the timing of eHMI in Table VIII.

Pressing behaviour before and after state switch of eHMI: Pressing behaviour before the state switch did not show significant differences. Pressing behaviour after the state switch were all significantly different. So the pressing behaviour only changes when vehicles start to behave differently compared to the baseline, which is to be expected.

Learning behaviour: Latin squares were used to normalise for crossover effects. Figures 12 to 14 show no clear trends. However, the slightly higher total time ratios at encounter 1 raises questions. It is unknown how this increase was caused and there is no clear explanation for this. A possible explanation is that participants learned how the vehicle was behaving, so they started pressing the button shorter. Another explanation could be that these differences are caused merely by noise.

B. Usability of VR

Fidelity: The fidelity is 110 (SD = 10) out of 154, and this score seems quite good. Fidelity is concluded to be sufficient for this type of experiments, because it compares well with a previous study (Feldstein et al., 2016) (see Figure 17).

There are, however, points were the VR experiment can be improved and could have influenced the results. Four participants denounced that the resolution was too low for them, saying this was especially the case when looking further away. This could possibly explain that the timing of the eHMI did not show significant differences when changing the state of the eHMIs at 35 and 50 m.

No avatar was implemented in the simulation environment (e.g., there are no feet and legs shown when the participant looked down). This could have driven down the scores in the presence questionnaire.

This experiment used a remote control to measure whether people feel safe to cross. Actually crossing the street could help increase fidelity, as was done in the study of Human et al. (2017) where a Cave Automatic Virtual Environment (CAVE) was set up. The downside is that this costs more time and resources (e.g., physical walking space). This means that fewer conditions can be tested or the experiment takes longer.

Safety: All participants finished the experiment and the MISC did not reveal any large discomforts. Therefore, it can be concluded that VR can be used safely when participants take breaks approximately every five minutes. However, caution remains advised since (long-term) effects of VR on the comfort and safety of people (i.e., possible decrease in vision or strained eyes) are still under-scrutinised.

C. Comparing research methods

Questionnaires after the VR experiment show different results when participants rank the eHMIs and if they find the eHMI clear. For instance, Text is the least ambiguous when asking participants if they feel safe to cross, but is number 3 when asked to rank the tested eHMIs.

When the eHMIs are implemented in VR, no clear differences between eHMIs were observed. There were differences between eHMIs when using the questionnaires. These discrepancies mean that the results of one research method do not necessarily translate well to other research methods. These differences can be caused by differences in revealed behaviour in the simulation and conscious stated preferences of people in the questionnaires.

It can be expected that this holds true for the real world as well, so eHMIs should always be tested in a real-life scenario before it is implemented in vehicles on public roads.

V. Conclusions

This study tried to find the effects of eHMI of AVs on the crossing behaviour of pedestrians. A VR experiment was set up to test the influence on crossing behaviour of the yielding behaviour of a vehicle, the type of vehicle, the type of eHMI and the timing of eHMI. Three hypotheses were composed to describe these effects. Below, the three hypotheses are answered.

***H1** The total time that people feel safe to cross is higher when interacting with automated vehicles which communicate deceleration through an eHMI compared to automated vehicles without an eHMI:* The total time ratio that participants pressed the button when vehicles were yielding was 0.655, 0.743, 0.747, 0.751, and 0.765 for the baseline, Frontal braking lights, Knightrider, Smiley, and Text, respectively. Significant differences were found when comparing the total time that participants pressed the button on the remote for the baseline and the use of en eHMI, in each scenario where a vehicle was yielding, the results were significant. Therefore, H1 is confirmed.

***H2** The total time that people feel safe to cross increases with decreasing vehicle size:* Results show that vehicle size does play a role. The total time ratio was 0.746 for a Smart fortwo, 0.732 for a BMW z4, and 0.725 for a Ford f150 in the yielding cases. The total time ratio was 0.206 for a Smart fortwo, 0.190 for a BMW z4, and 0.156 for a Ford f150 in the non-yielding cases. The Ford and the Smart showed significant differences in both the yielding and non-yielding cases where the Ford showed shorter total times compared to the Smart. Therefore, H2 is confirmed.

***H3** The total time that people feel safe to cross is independent of the vehicle size when an eHMI is used:* For all eHMIs, the distributions were statistically the same when an eHMI is used when comparing different vehicles. The mean ranks of the vehicles are still different, showing that the total time that people feel safe to cross is not fully independent of the vehicle size when an eHMI is used. It could be possible that vehicles still play a role, because the means were taken to calculate the total time ratios per participant. Therefore, H3 is not confirmed nor rejected.

It is concluded that the use of an eHMI influences the crossing behaviour of pedestrians. The results of the VR experiment show that the use of an eHMI increases the total time that pedestrians feel safe to cross. The differences between eHMI seem to be much smaller than the difference between the baseline and an eHMI. The results of the questionnaires indicate that pedestrians prefer the use of an eHMI over the lack of an eHMI and that pedestrians find eHMIs less ambiguous compared to the lack of an eHMI.

VI. Recommendations

eHMIs perform differently in different situations and some eHMIs seem to be more dominant than the type of vehicle. Future research can focus on which aspects improve AV-VRU interaction so that eHMIs can be optimised. Also, this experiment did not include false positives (e.g., how does the crossing behaviour of participants change when the eHMI does not work as explained/expected). Now merely screens in the front of the vehicle were tested, projected pedestrian crossings or other techniques may yield different results and more research is needed.

This experiment used an environment with a two-lane two-way street in a European setting with clear weather. Other conditions may ask for other eHMIs or different behaviour of the vehicle and its eHMI.

Three research methods of testing the eHMIs were used, the VR experiment (1) and a questionnaire asking the participant about the clarity (2) and the preferences of the eHMIs by ranking them (3). The methods yield different results, so results cannot easily be extrapolated to other methods or real-life. Research can focus on the exact differences between research methods.

When looking at using VR specifically, the resolution was indicated as an aspect that could have influenced the results. Minimum sizes of eHMI can be researched in both real-life and VR to prevent readability issues. VR with higher resolutions is expected to increase fidelity and clarity of eHMIs for larger distances (> 35 m).

Participants encountered AVs for one of the first times in their lives in this experiment. No clear short-term learning effects were observed. Long-term learning effects are not taken into account in this study. It could be possible that the effect of eHMIs changes when the general public knows more about how eHMIs function.

VII. Acknowledgements

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APPENDIX

A.

Steps for conducting the experiment

Steps for conducting the experiment

Before presence participant

- Assign participant number to participant.
- Open up the two questionnaires on Google Forms (on laptop).
- Open up the excel called: Overview_files_participants.xlsx (on laptop).
- Print and lay down form of consent and NASA-TLX on table.
- Fill in participant number on Unity on the SpawnFountain.
- Check volume of VR-glasses: set it to 20/100.
- Activate practise session in script Instantiator.cs (Practice).

During presence participant

- Let participant read and sign form of consent.
- Let participant fill in the questionnaire called: Questions before experiment (on laptop).
- Let participant do the practise session with VR-glasses and remote.
- Check if log-file is written.
- Activate actual experiment in script Instantiator.cs (Block_test_with_breaks).
- Check if right participant number is filled in in SpawnFountain.
- Answer possible questions of participant.
- Let participant do the actual experiment.
- Make sure that the participant takes off the VR-glasses during the two 2-minute breaks.
- Let participant fill in the questionnaire called: Questions after experiment (on laptop).
- Let participant fill in the NASA-TLX.
- During questionnaire:
    - Check if log-file is written.
- Answer questions participant.
- Give participant a snack or drink.

After presence participant

- Check log-files, two questionnaires, form of consent and NASA-TLX.
- Write down participant number, name of the log-files for the practise session and the final experiment in the excel file called: Overview_files_participants.xlsx (on laptop)
- Make scans or pictures of form of consent and NASA-TLX.
- Save and back-up all data on my laptop and on OneDrive in the folder DATA_PARTICIPANTS.

B.

Form of consent

Informed form of consent

Researchers

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Andre Dietrich andre.dietrich@tum.de

Location of the experiment

Lehrstuhl für Ergonomie, Office 0328
Technische Universität München
Boltzmannstraße 15
D - 85747 Garching

Introduction

You are invited to join a research study to look at crossing behaviour of pedestrians in several traffic situations. The decision to join, or not to join, is up to you. In this study, we are comparing crossing behaviour of pedestrians for half an hour. Before agreeing to participate in this study, it is important that the participant fully read and understood this informed form of consent.

General procedure

You will be asked to wear VR-glasses and to hold a remote with a button. In this experiment you will see a stream of vehicles approaching you. Some vehicles will yield to let you cross; others will continue driving.

First, you will answer a few questions about yourself. Then you will familiarise yourself with the VR-glasses and the remote by completing a practice session of 2 minutes. After completion of the practice session you can ask questions about the task or clarify anything that is unclear.

After the practice session, you will do the actual experiment. This will take approximately 30 minutes.

When this is finished, I will ask you to answer a few questions about the experiments you just did. This last part will take approximately 5 minutes.

The investigators may stop the study or take you out of the study at any time they judge it is in your best interest.

Task instructions

Each time you feel safe to cross, please do the following:

1) Press the button on the remote.
2) Keep pressing the button as long as you feel safe.
3) When you do not feel safe to cross anymore, release the button.

DO NOT actually cross. If for some reason you lost your orientation, look at the pavement and you will see a well, this well is your point of reference.

Risks

During this study, you will be asked to wear Virtual Reality glasses (VR-glasses) and hold a remote on which you are required to press (and hold) a button multiple times. There are no known risks to wearing VR-glasses for the duration of this experiment. However, there is a small chance the participant may experience nausea or a headache. VR-glasses have a higher chance of causing dizziness or headaches if they are worn for multiple hours at a time. However, this is likely **not** the case during this experiment. If you feel any dizziness or headaches, please inform the experimenter and we can stop the experiment.

Benefits to taking part in the study

The research is expected to give insights in crossing behaviour of pedestrians. The outcomes will be used to design safer vehicles. Therefore, it is possible that this study helps to improve road safety. There will most likely be no direct benefits for the participants.

Confidentiality

To keep information about you confidential and protect it from unauthorized disclosure, it will be pseudo-anonymised and stored on an encrypted computer that is only accessible to Koen de Clercq (me). The data that will be used for the analysis of the study will be anonymised. The published work will not in any way give an indication of your personal performance. Throughout the study you will be identified by a participant number only.

Incentives

For completing this study, you will receive a snack or drink as a thank you.

Your rights as a research participant

Participation in this study is voluntary. You have the right not to participate at all or to leave the study at any time.

Contacts for questions or problems

Contact Koen de Clercq or André Dietrich if you have questions about the study afterwards.

Consent of participant

I have fully read this form and I understand the task and possible implications of this experiment.

Name of participant:	Signature of participant:	Date:

C.

Questionnaire before experiment

Questions before experiment

*Required

1. **What is your participant number? (The experimenter knows this number and will fill in this question for you.)** *

Questions before experiment

Thank you for participating in this study! Before we start, you are asked to answer a few questions about yourself. This will take just a few minutes.

2. **Nationality** *

3. **Current country of residence** *

4. **Age (in years)** *

5. **Gender** *
   Mark only one oval.
   - Female
   - Male
   - Prefer not to say
   - Other: ____________

6. **Are you in possession of a drivers' license?** *
   Mark only one oval.
   - Yes
   - No

7. **How often did you drive a vehicle in the last 12 months on average?** *
   Mark only one oval.
   - Every day
   - 4 to 6 days a week
   - 1 to 3 days a week
   - Once a month to once a week
   - Less than once a month
   - Never
   - I prefer not to respond

8. **How many kilometres did you drive in the last 12 months?** *
Mark only one oval.

- 0
- 1-5.000
- 5.001-10.000
- 10.001-15.000
- 15.001-20.000
- 20.001-25.000
- 25.001-35.000
- 35.001-50.000
- 50.001-100.000
- More than 100.000
- I prefer not to respond.

9. **Are you colour blind?** *
Mark only one oval.

- Yes
- No

10. **Do you wear glasses at the moment?** *
Mark only one oval.

- Yes
- I wear contact lenses
- No

11. **Do you have computer gaming experience?** *
Mark only one oval.

- Yes, I play several times a week.
- Yes, I play approximately once a month.
- Yes, but rarely / not anymore.
- No, I have never played computer games.

12. **Have you worn Virtual Reality-glasses before?** *
Mark only one oval.

- Yes, multiple times
- Yes, once
- No

13. **I would like to explore strange places.** *
Mark only one oval.

	1	2	3	4	5	
Strongly disagree						Strongly agree

14. **I get restless when I spend too much time at home.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

15. **I like to do frightening things.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

16. **I like wild parties.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

17. **I would like to take off on a trip with no pre-planned routes or timetables.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

18. **I prefer friends who are excitingly unpredictable.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

19. **I would like to try bungee jumping.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

20. **I would love to have new and exciting experiences, even if they are illegal.** *

Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Task instruction

Each time you feel safe to cross, please do the following:

1) Press the button on the remote.
2) Keep pressing the button as long as you feel safe.

3) When you do not feel safe to cross anymore, release the button.

DO NOT actually cross. If for some reason you lost your orientation, look at the pavement and you will see a well, this well is your point of reference.

21. **I have read the task and have asked for clarification if anything was unclear.** *

Mark only one oval.

( ) Yes

Thank you! You are now ready to start the experiment.

D.

Questionnaire after experiment

Questions after experiment

*Required

1. **What is your participant number? (The experimenter knows this number and will fill in this question for you.) ***

Questions after experiment

Now that you have done the experiment, you are asked to answer a few questions about the interfaces you have just encountered during the experiment. This questionnaire finishes with some questions about your experience with VR and the workload of this experiment. It will take approximately 5 minutes to finish this questionnaire. This questionnaire will help us to improve future experiments and to increase insight in traffic safety. Thank you in advance!

This experiment tests the effects of communication interfaces in the front of self-driving vehicles (also known as automated or autonomous vehicles). Self-driving vehicles are vehicles that do not need a human driver to control its speed, orientation or location. A computer inside the vehicle controls the vehicles' behaviour.

The following sections will consist of questions about the communication interfaces you have just encountered during the experiment. Try to answer the questions with how you felt about these communication interfaces DURING the simulation (while wearing the VR-glasses).

2. **Do you feel safe to cross? ***

Mark only one oval.

- Yes
- Not sure
- No

3. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

4. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

5. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

6. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

7. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

8. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

9. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

10. **Do you feel safe to cross?** *

Mark only one oval.

- Yes
- Not sure
- No

11. **Which interface would you prefer the most?** *

Smiley

Frontal brake lights

Text

Knightrider

None

Mark only one oval per row.

	First choice (most preferred)	Second choice	Third choice	Fourth choice	Fifth choice (least preferred)
Smiley					
Frontal brake lights					
Text					
Knightrider					
None					

Presence questionnaire

On this last page you are asked to rate your experience in 22 questions. We want to find out how immersive your experience was.

12. **How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not proficient								Very proficient

13. **How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all								Completely

14. **How closely were you able to examine objects?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very closely

15. **How much did the auditory aspects of the environment involve you?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

16. **How quickly did you adjust to the virtual environment experience?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Less than one minute

17. **How natural was the mechanism which controlled movement through the environment?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Extremely artificial	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely natural

18. **How well could you localise sounds?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

19. **Were you able to anticipate what would happen next in response to the actions that you performed?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

20. **How responsive was the environment to actions that you initiated (or performed)?** *

Mark only one oval.

	1	2	3	4	5	6	7	
Not responsive	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely responsive

21. **How involved were you in the virtual environment experience? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Not involved	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely engrossed

22. **How natural did your interactions with the environment seem? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Extremely artificial	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely natural

23. **How compelling was your sense of objects moving through space? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very compelling

24. **How much did the visual aspects of the environment involve you? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

25. **How much delay did you experience between your actions and expected outcomes? ***
Mark only one oval.

	1	2	3	4	5	6	7	
No delays	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Long delays

26. **How much did your experiences in the virtual environment seem consistent with your real world experiences? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Not consistent	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Very consistent

27. **How completely were you able to actively survey or search the environment using vision? ***
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Completely

28. **How well could you identify sounds?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	( )	( )	( )	( )	( )	( )	( )	Completely

29. **How much did the control devices interfere with the performance of assigned tasks or with other activities?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	( )	( )	( )	( )	( )	( )	( )	Interfered greatly

30. **How well could you examine objects from multiple viewpoints?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	( )	( )	( )	( )	( )	( )	( )	Extensively

31. **How compelling was your sense of moving around inside the virtual environment?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not compelling	( )	( )	( )	( )	( )	( )	( )	Very compelling

32. **How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	( )	( )	( )	( )	( )	( )	( )	Prevented task performance

33. **How much were you able to control events?** *
Mark only one oval.

	1	2	3	4	5	6	7	
Not at all	( )	( )	( )	( )	( )	( )	( )	Completely

34. **Do you have any comments or notes about the experiment? If not, you can leave this question empty.**

Disclaimer

35. **You have just participated in an experiment about communication interfaces in self-driving vehicles. These self-driving vehicles are not fully developed yet and cannot be found on the road currently. We are not responsible for changes in your behaviour in the real world. Always participate in traffic with your complete attention and in a safe responsible manner.** *

Mark only one oval.

( ) Yes, I understand that TUM and the experimenters are not responsible for my behaviour in real world traffic.

You are finished! Thank you for participating in this study.

E.

Misery Scale

MISC

1) Make use of the MIsery SCale (MISC), a formal subjective rating scale (scale 0-10) for evaluating the progression of motion sickness:

Symptom		Score
No problems		0
Slight discomfort but no specific symptoms		1
Dizziness, warm, headache, stomach awareness, sweating, etc.	Vague	2
	Some	3
	Medium	4
	Severe	5
Nausea	Some	6
	Medium	7
	Severe	8
	Retching	9
Vomiting		10

2. Include a thorough briefing of what motion sickness feels like in the briefing for the experiment. For instance, it should be clear for participants that the moment they start feeling oddly warm and start getting sweaty palms, th2. y are in the danger zone (4-5 on the scale). After that point, the real sickness feeling in most cases follows very soon. If at all possible, this should be avoided (see later point) and I think the participants should be explicitly briefed on this.

3. Use the MISC to track the development of sickness during experiments and plan breaks to avoid real sickness. Then we ask participants to score their sickness feeling after every completed test run, for instance. In case of very rapid moving up the scale, or participants indicating a score of 4 or higher, we take a break (without emergency shutdown) to let the sickness feeling fade before continuing.

In case people still get truly sick and nauseous in an experiment, there is a potential risk in letting them get in their car/on their motorcycle too quickly after the experiment. If you do not let the feeling of sickness really fade, it could come back very quickly when driving home, in real traffic. Like the "druppel" that let the "emmer" overflow. So, if participants in our experiments reach 6-7 on the MISC, we ask them to stay after the experiment (possibly an hour or two) before we let them get on their way.

F.

Used assets in Unity

Used assets in Unity

Other possible assets were already in the framework provided by Dipl.-Ing. A. Dietrich. For the use of other assets I refer to his framework.

Table 1: Assets

Asset name	Version	Creator
Oculus Integration	1.15	Oculus
Simple modular street Kit	1.0	Jacek Jankowski
Realistic Tree 10	1.0	Rakshi Games
Small Town America - Streets - FREE	1.0	MultiFlagStudios
Cars Free - Muscle Car Pack	1.0	Super Icon LTD
Mini Cargo Truck	1.0	Marcobian Games
Street Bench	1.0	Rakshi Games
waste bin	5.3.5	Lowpoly_Master
Smart fortwo	1.0	Filippo Citati

G.

Results of all conditions, of the differences between participants and of the proportion over time

This appendix contains a selection of the results for readability. More results can be found in the folder available through this url: `https://1drv.ms/f/s!ArqK9OFohM-gh7IhtHxR9UYMxYKY1Q` .

The results included in this report:

1) Ratios of total times for each condition
2) Differences between participants
3) Proportion pressed for all conditions over time

The results included in the online folder, besides the results included in this report:

1) Misery Scale
2) NASA-TLX
3) Questionnaire before the experiment
4) Questionnaire after the experiment
5) Position and orientation of participants
6) Raw data of selected conditions
7) Calculated ratios based on raw data

1) Ratios of total times for each condition:

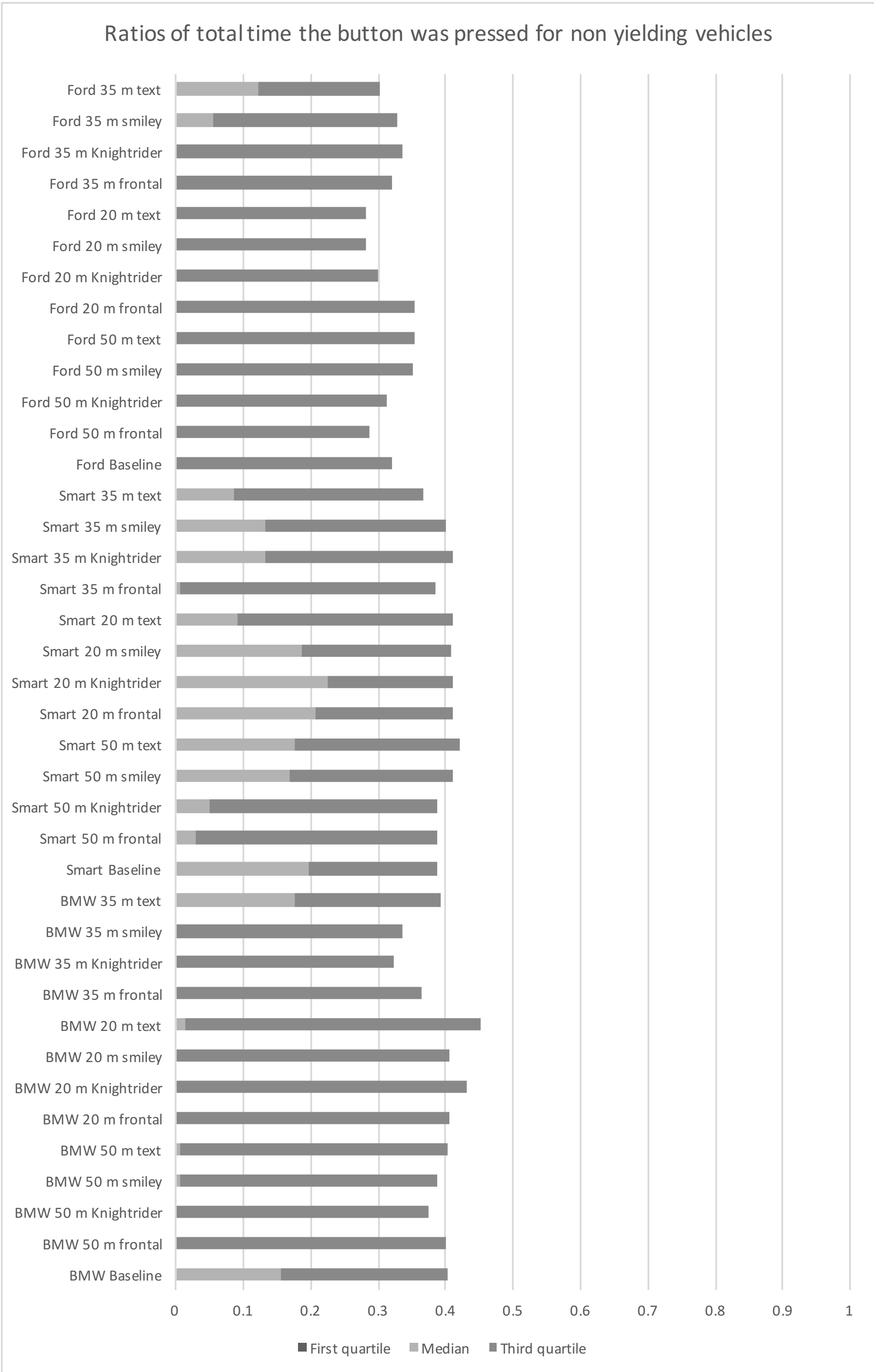

Fig. 19: Ratios of total time the button was pressed for non-yielding vehicles in all conditions.

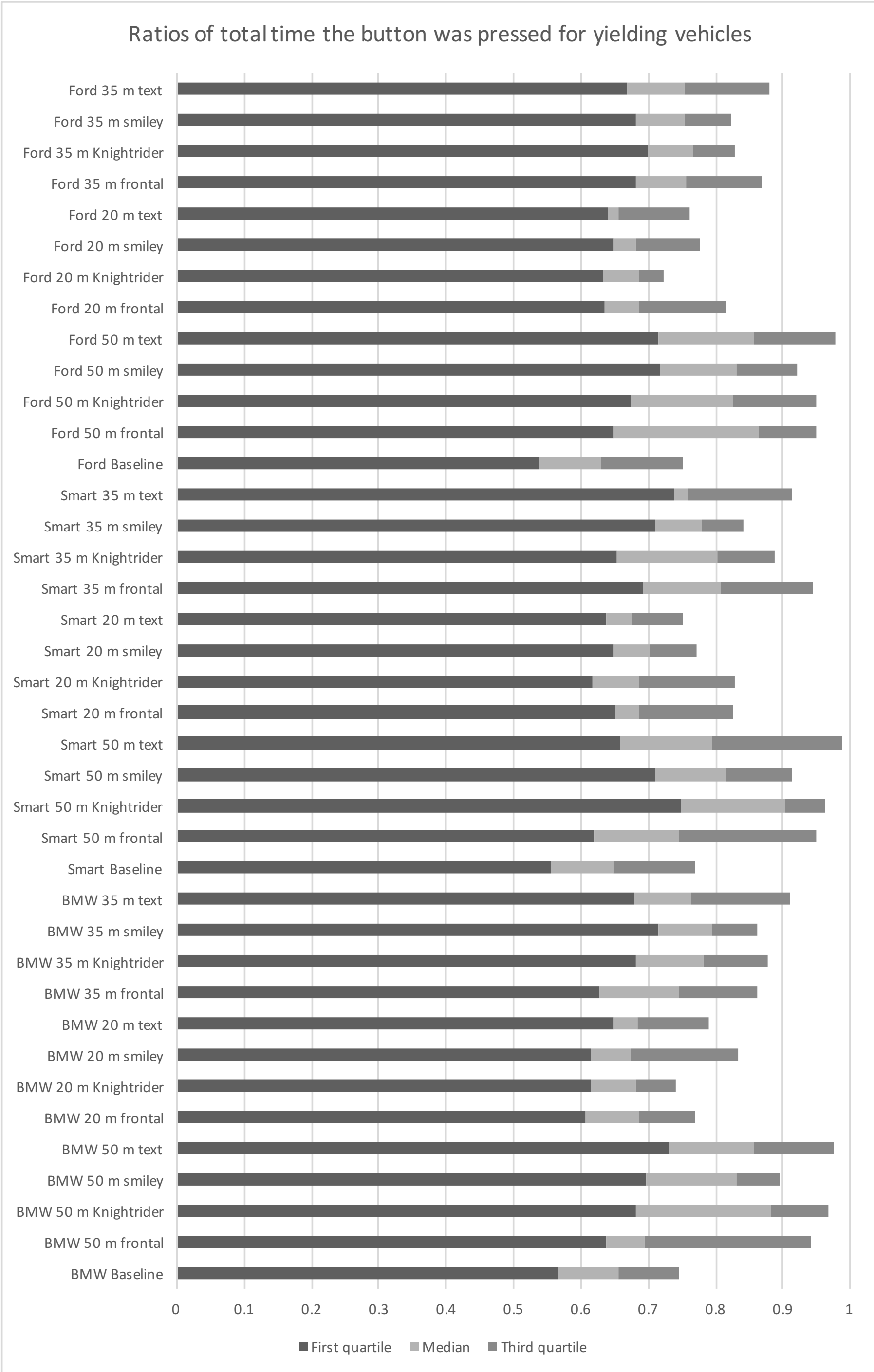

Fig. 20: Ratios of total time the button was pressed for yielding vehicles in all conditions.

2) Differences between participants: Figures 21 and 22 show clear differences between participants. The largest differences are observed in the non-yielding cases due to differences in gap acceptances. It can be observed that all participants pressed the button when vehicles came to a standstill when looking at the yielding cases. Therefore, no participants were excluded from the analysis. When comparing both figures, one can see that the left sides (distances between 50 and 35 m) show similar percentages, possibly indicating that participants start to behave differently when the vehicle comes closer.

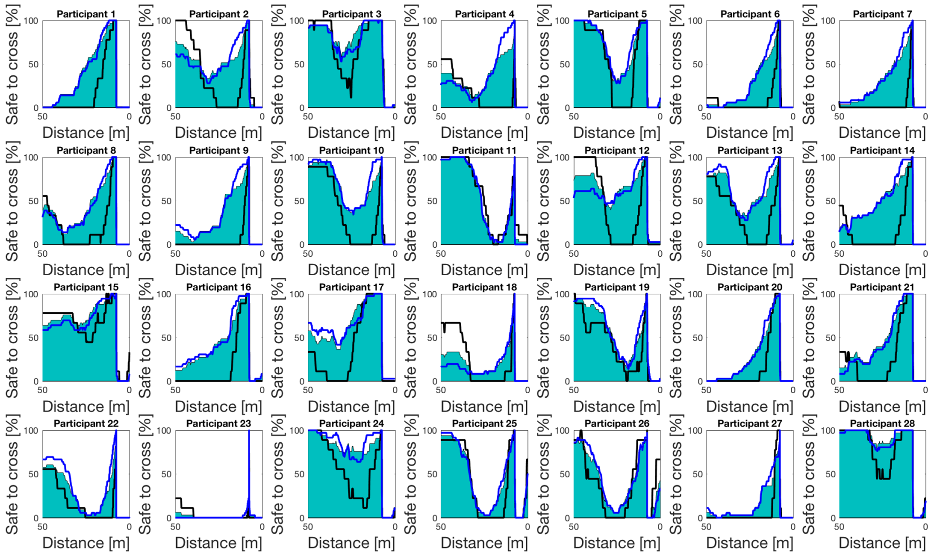

Fig. 21: Pressing profiles for each participant when vehicles are yielding. The percentage of the cases that the participant feels safe to cross is shown on the y-axis. The distance [m] is shown on the x-axis. The black line represents all the conditions without an eHMI and the blue line represents all the conditions with an eHMI with timing 35 and 50 m. The turquoise area represents all the cases of feeling safe to cross per participant.

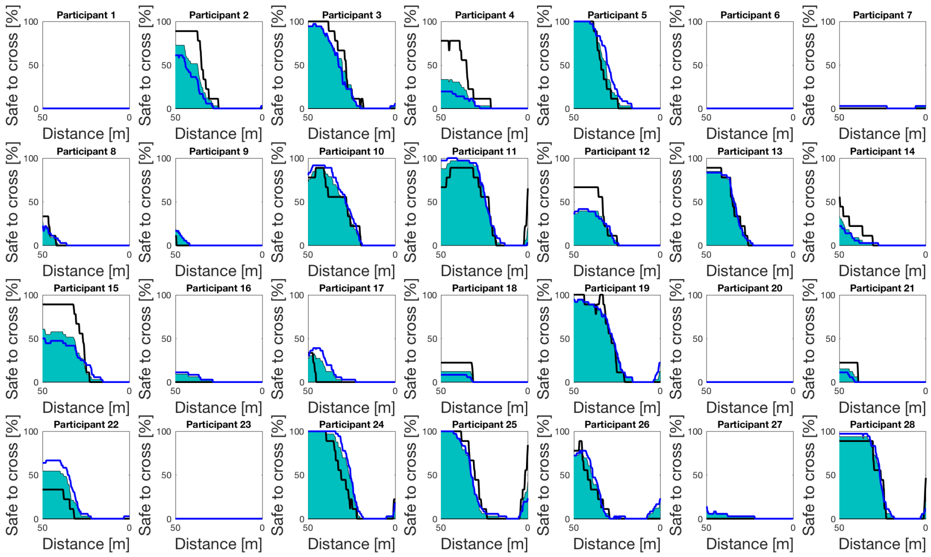

Fig. 22: Pressing profiles for each participant when vehicles with an eHMI are not yielding. The percentage of the cases that the participant feels safe to cross is shown on the y-axis. The distance [m] is shown on the x-axis. The black line represents all the conditions without an eHMI and the blue line represents all the conditions with an eHMI with timing 35 and 50 m. The turquoise area represents all the cases of feeling safe to cross per participant.

3) Proportion pressed for all conditions over time:

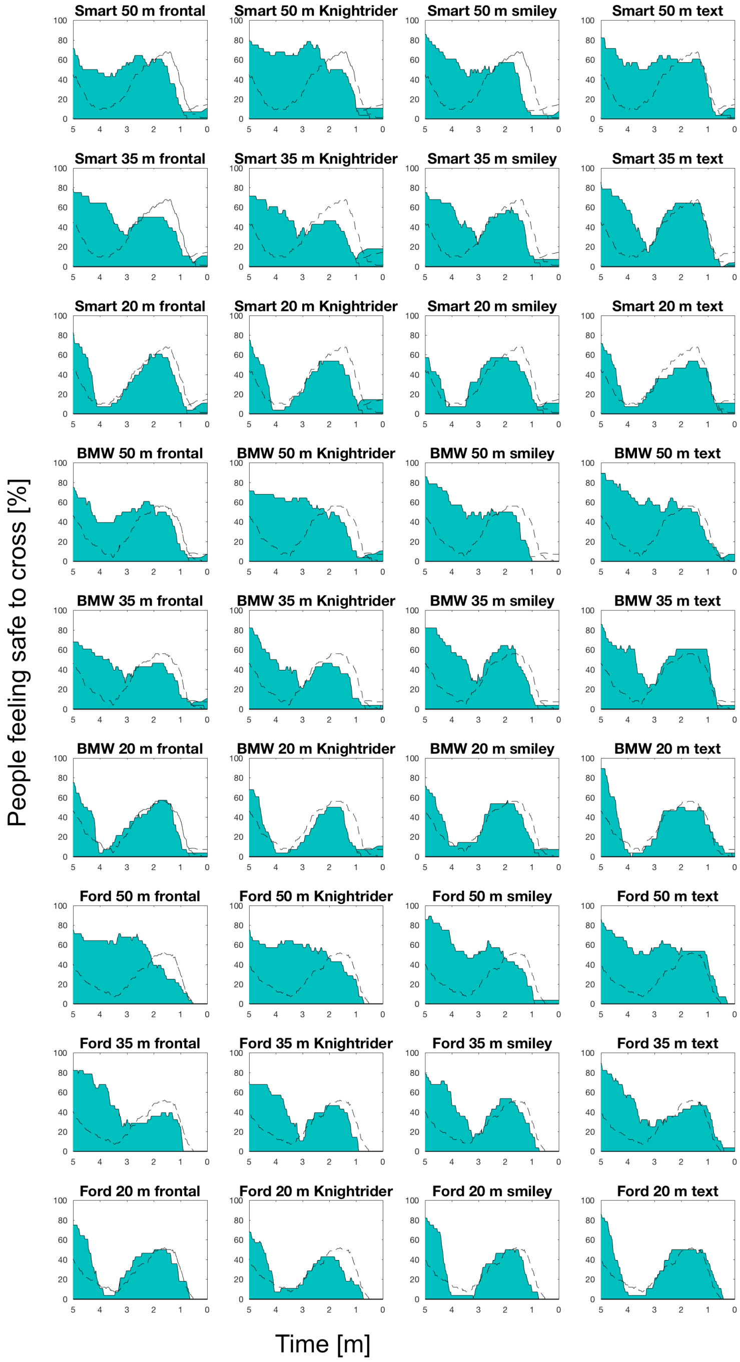

Fig. 23: Proportion of participants feeling safe over time for yielding vehicles. This is a different representation than shown in Figure 11. The x-axis shows the time instead of the distance. The relation between distance and time can be seen in Figure 6a. Participants do not feel safe at t = 0 s, because in this case a previous vehicle was still in front of them.

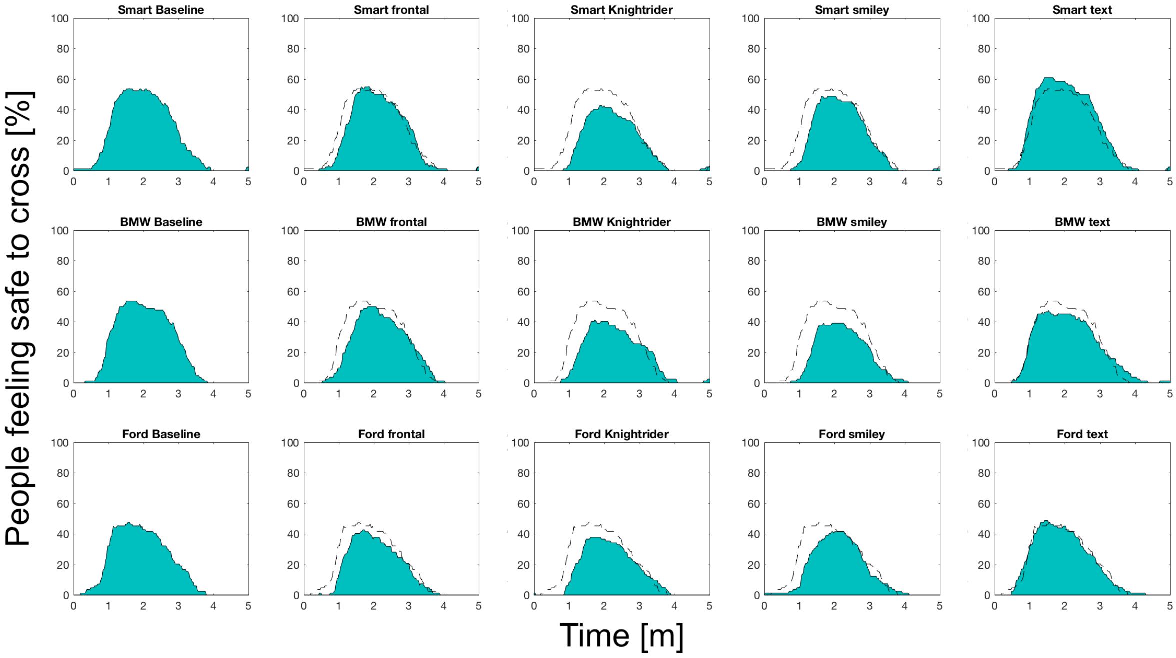

Fig. 24: Proportion of participants feeling safe over time for non-yielding vehicles. This is a different representation than shown in Figure 10. The x-axis shows the time instead of the distance. The relation between distance and time can be seen in Figure 6a. Participants do not feel safe at t = 0 s, because in this case a previous vehicle was still in front of them.

For reproducibility purposes all the appendices and source codes can be found in the provided zip-file available through this url: `https://1drv.ms/f/s!ArqK9OFohM-gh7IhtHxR9UYMxYKY1Q` . The following appendices are only available through the mentioned url.

H. Results pilot study

I. Randomiser

J. LogWriter

K. Instantiator

L. Matlab scripts