Investigating the Influence of External Car Displays on Pedestrians' Crossing Behavior in Virtual Reality

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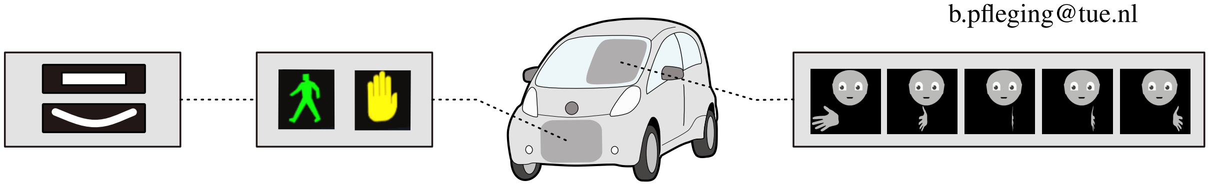

Figure 1: Positions and concepts of evaluated external car displays (ECDs) for pedestrian crossing guidance.

ABSTRACT

Focusing on pedestrian safety in the era of automated vehicles, we investigate the interaction between pedestrians and automated cars. In particular, we investigate the influence of external car displays (ECDs) on pedestrians' crossing behavior, and the time needed to make a crossing decision. We present a study in a high-immersion VR environment comparing three alternative car-situated visualizations: a smiling grille, a traffic light style indicator, and a gesturing robotic driver. Crossing at non-designated crossing points on a straight road and at a junction, where vehicles turn towards the pedestrian, are explored. We report that ECDs significantly reduce pedestrians' decision time, and argue that ECDs support comfort, trust and acceptance in automated vehicles. We believe ECDs might become a valuable addition for future vehicles.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Virtual reality*.

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KEYWORDS

External car displays; Autonomous vehicles; Pedestrian-autonomous vehicle interaction; Traffic safety; Virtual reality

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1 INTRODUCTION

Automated vehicles (AVs) are expected to become a part of traffic in the near future [25]. While pedestrians are particularly vulnerable in traffic, accounting for 21% of all road casualties in Europe[1], the advent of AVs is predicted to reduce the overall frequency and severity of accidents caused by human error. At the same time, the challenge arises how to support interaction of AVs with other cars, pedestrians, and cyclists. It has been argued that AVs call for an entirely new way of thinking in user interface design [19], with the level of automation affecting acceptability and user experience [33].

Traditional vehicles' means for communication (e.g. turn signals, horn, lights) are occupied by established applications and legal regulations. For example, using a horn to signals an AV's intention is unlikely to be understood as instructions for crossing decisions by pedestrians. Also, signals from a

[1]https://ec.europa.eu/transport/road_safety/users/pedestrians_en, accessed: Jan 2019

human driver, e.g. gestures, are not available. Hence, there is a need to investigate novel means for communication. We investigate external car displays (ECDs) as one such means, with the goal of increasing trust and acceptance of AVs.

Prior research indicates that pedestrians benefit from information regarding awareness and intent of AVs [26]. This is particularly true in situations where it is difficult to infer a vehicle's intention from other cues (e.g., speed). Such situations have not yet been closely investigated. To close this gap, we focus on two scenarios where it is difficult for pedestrians to identify whether an AV is about to stop or not. In scenario one (Figure 2, straight), the car approaches from the back of the pedestrian. In scenario two, the car is approaching from a junction (Figure 3, turn). We explored ways in which the AV's intent could be communicated through the use of ECDs.

Using a simulated virtual reality (VR) environment, we investigated pedestrian crossing decisions with AVs equipped with ECDs showing: (1) a smiling display, (2) a visualisation based on traffic lights, (3) a robot driver shown in the windshield, and (4) a base condition (inactive external display), as shown in Figure 1. We address the following research questions regarding one-way AV to pedestrian interaction: (1) How do ECDs influence pedestrians' crossing decisions? (2) How do different graphical design concepts perform? (3) How do ECDs influence pedestrians' confidence in their decisions?

Our results show that in 98% of all cases (N=255) participants made the correct crossing decision. In line with prior work, the main reason to wait or to start crossing seems to be based on the vehicle's motion rather than any vehicle mounted external display. However, an external display can significantly lower the decision time, with the traffic light style display performing best in this respect.

Contribution Statement: We contribute a study including two relevant scenarios that have not been previously addressed: first, a vehicle performs a turn into the pedestrian's street and second, an AV approaches from behind a pedestrian. We compare three visualizations of how an AV can externally communicate its intent to pedestrians in-situ (in VR). Through qualitative and quantitative data, we derive findings for researchers and practitioners designing external human-machine interfaces (HMIs) for automated vehicles.

2 RELATED WORK

Our work draws from several strands of prior research: communication between (automated) vehicles and pedestrians and the use of VR for simulating pedestrian contexts.

Communication between Vehicles and Pedestrians

When crossing a street at an unsigned location, in 90% of cases pedestrians gaze at the approaching cars prior to crossing [30]. The decision to cross is predominantly made based on implicit communication, i.e. approaching vehicle's speed and distance [12, 23, 30, 31], which holds for situations with external information displays on the car [7, 12]. Šucha [37] highlights the importance of eye contact as a factor impacting crossing decision, which Lagstrom and Lundgren define as "the pedestrian's perception of being noticed by the driver." [20]. However, eye-contact and explicit communication is less important for decisions than vehicle motion [12].

Context also plays a role in crossing behaviour. Currano et al. [8] highlight the effect of location: pedestrians in a large city are more likely to cross in front of oncoming vehicles than in a smaller city. The impact of other pedestrians has also been studied [14, 27]. Merlino et al. investigated how pedestrians and drivers coordinate and communicate [27].

Automated Car to Pedestrian Communication

Recent work on pedestrian–AV communication also focused on using external displays [7, 15, 23, 26, 32, 41]. Other channels, such as "eyes" on a car [5], LED stripes [11], projection [4], mobile devices or physical attachments like a waving hand [26] have also been investigated. Whilst generally research has rejected the use of text, a text display was one of the preferred formats reported by Deb et al. [9] and Chang et al. [4]. Most external displays on vehicles are semantically inspired from crosswalk signals, i.e. using symbols of a walking person and red and green colours [15, 23]. Such indications are prone to misinterpretations, since colors could be interpreted as either instruction for a pedestrian or intention of an AV [41]. Further aspects include the need to help pedestrians, in particular children, to identify whether a vehicle is (highly) automated or manual [6]. The idea of *socially acceptable* AV behaviour has also been raised, noting that often human motorists and pedestrians break traffic rules [39].

Using VR in Pedestrian Simulations

Utilising VR to simulate pedestrian experiences with AVs has become a common approach. Initial work tested participants' ability to estimate vehicle speed and distance at an empty crossing [13]. To avoid the need to wear an HMD, Cavallo et al. used a rear projected cave "tunnel" [3]. Teague labs explored a VR HMD simulation of a multi-lane crossing and three alternative displays [34]. The concepts include the notion of an AV signalling both awareness of pedestrians and its movement intention, highlighting the instruction vs. intention conflict mentioned above [41]. A potential complication caused by a passenger of an AV sitting in the "driving seat" has been studied using a VR simulation by Hudson et al. [18].

Summary

Prior work found external displays to be of limited benefit for the majority of pedestrian crossing decisions, in particular in situations where real drivers are involved. Yet, we believe external car displays could be of value in cases of real-time negotiation between AVs and pedestrians. Such cases occur if an AV is moving at low speed and implicit motion cues do not provide sufficient data to make a safe decision.

3 RESEARCH APPROACH

The gaps identified in prior research led us to investigate two aspects: We look at *scenarios* in which pedestrians can see the car either shortly before crossing a road or in which it is difficult to interpret the car's movements. In such situations, pedestrians cannot necessarily rely on guessing a vehicle's behavior to take a decision. Hence, we created two scenarios for such cases. First, a situation in which people walk on a sidewalk before turning to cross the road. At this moment they recognize a car which is approaching from their rear. Second, a car that turns right before the crossing situation. Hence, pedestrians do not know if the car is slowing because of the turn or because it will yield the right of way.

For the *visualisation concepts*, we chose designs from different origins: a design presented from industry, one that was discussed in scientific work, and a novel approach contrasting the others. The following subsections describe our investigated scenarios and visualizations in detail.

Scenarios

In our first scenario, a vehicle approaches a pedestrian from behind, who then turns 90 degree to cross the road (Figure 2). In scenario two, a vehicle approaches frontally from behind a curve (Figure 3). An automated vehicle approaches in each scenario from position A and follows the trajectory indicated with a blue arrow. Participants start walking at point B and are supposed to cross in front of the vehicle (pink arrow).

Display Concepts

We designed three different visualization concepts to instruct pedestrians and to communicate a vehicle's intent (Figure 4).

Smiling Car. Semco[2] and the research institute RISE Viktoria[3] developed a front-display mounted at the grille of an AV, which evokes the impression of a human smile. The display represents a mouth while the car lights represent the eyes. A single line is presented in black and white, providing high contrast while still being unobtrusive. In its neutral state the display shows this horizontal bar indicating that the vehicle is in motion and does not intend to stop. If the system intends to let pedestrians cross, the horizontal bar is animated to a smile. We adapted the animation[4] for our simulation, see Figure 4.

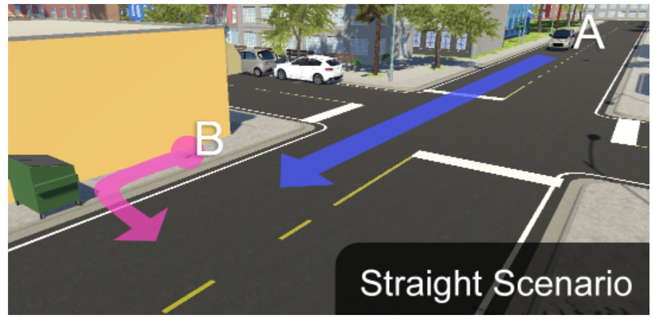

Figure 2: Vehicle approaching the pedestrian from behind.

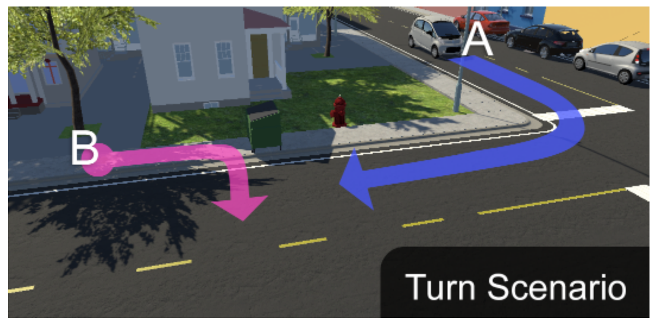

Figure 3: Scenario with vehicle turning around a corner.

Traffic Light. Fridman et al. [15] compared 30 external vehicle-to-pedestrian display concepts in a preliminary online study (N = 200). Their comparison was carried out with pictures and animations showing the front of a vehicle including an external car display. The best performing results were achieved by utilising text ("walk" in green color and "don't walk" in red), and a "green man / yellow hand" traffic light like design. We decided to implement the second concept, since it works independently of red-green color blindness and language or reading skills. A raised yellow hand signals pedestrians to wait, whereas a walking green man symbol indicates that it is safe to cross (Figure 4). These visual cues were displayed at the grille, similar to the smiling car concept. However, unlike Fridman et. al [15], we decided against a flashing animation of the symbols, since we did not want to introduce another independent variable (flashing visual cues).

Robot. Scientific work confirms that anthropomorphic features, e.g., represented by robots driving AVs in science fiction movies, increase trust in AVs [21, 40]. Additionally, mimicry of familiar objects by design can improve intuitiveness and ease of use [24, 29]. We use the windshield as a surface to display a humanoid robot placed at a familiar position, the drivers seat. Thus, in contrast to the other concepts, an implementation of the robot requires a windshield display. The animated robot only interacts with pedestrians if the vehicle intends to stop: the virtual driver waves its hand from left to right indicating that it is safe to cross (Figure 1, right). If the vehicle does not come to a halt, a static image of the robots face is presented (Figure 4, bottom left).

[2]https://semcon.com/ accessed: Jan 2019
[3]https://www.viktoria.se/, accessed: Jan 2019
[4]https://youtu.be/INqWGr4dfnU, accessed: Jan 2019

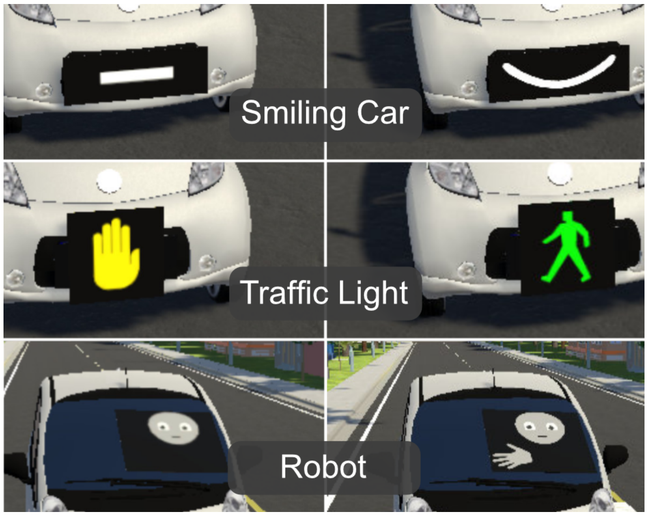

Figure 4: Screenshots of investigated display concepts.

In our base condition, the vehicle appears with a plain, inactive ECD that does not display any instructions.

4 USER STUDY

We selected to investigate the aforementioned scenarios and concepts in virtual reality. The main reasons being the practicality under laboratory conditions and that there is no danger for participants. The study was conducted in accordance with the latest version of the Helsinki Declaration and the study procedure complied with university ethics regulations.

The implemented VR environment includes an urban intersection with an approaching vehicle and no further moving entities. The size and appearance of a vehicle could influence crossing decisions [10]. Hence, we selected a friendly looking vehicle inspired by a Citroën C-Zero[5], advertised as *"electric car designed for urban driving"*.

Study Design

The study was designed as a within-subjects, repeated measures experiment with 2 *(scenarios)* × 2 *(AV stops or drives)* × 4 *(display concepts)* conditions. These 16 different crossing situations were assigned randomly among participants using Latin Square randomisation. Each of the 16 combinations of independent variables was collected 32 times. To that end, 32 participants completed 512 study cases in the VR simulation. Each of the four display concepts occurred 128 times, of which 64 happened within the straight scenario and 64 cases in the turn scenario. In 32 cases the AV would come to a halt to let the pedestrian cross.

[5]https://www.citroen.co.uk/new-cars-and-vans/citroen-range/citroen-c-zero accessed: Jan 2019

Table 1: Implemented events within the VR-simulation

Event	Description
Is able to see	Triggered if vehicle is potentially visible (spawned in VR-world) and not occluded by any object.
Has seen	Triggered if the vehicle's center is within the field of view (gaze frustrum).
On road	Triggered if participants step on the road.
Collided	Triggered if a collision between the bounding boxes of the vehicle and the pedestrian occurred.

Task

The task of the participants was to stand at the starting point (Location B in Figure 2 and Figure 3) on the sidewalk, and then to cross a street (Figure 2 and Figure 3, pink arrow). To that end, a green dumpster blocking the sidewalk guided pedestrians on the road. If they were close enough to the container, an automated car at position A appeared with a distance of 39 m to the participants. The vehicle was driving straight ahead at a constant speed of 30 km/h (Figures 2 and 3, blue arrow). In case of the turn scenario, it slowed down to about 15 km/h prior to the curve. As a motivation for pedestrians to walk on the street, a banknote was placed in the middle of the road. Participants were able to pick up the bill if they decided to step on the road. They were instructed, as in real life, that there is traffic to which they need to pay attention to.

Measures

The scope of this study includes user behavior, confidence and attitudes when crossing in front of an AV with ECD.

User Behavior. We evaluated user behavior via implemented events (Table 1) of the simulation and questionnaires. Each event consists of a timestamp, type of display (yellow hand / green man; smile; robot or inactive), vehicle behavior (stopping or driving) current speed of the vehicle (km/h), position of the vehicle (x,y,z coordinates), and the distance of the pedestrian to the vehicle (m).

Similarly to previous studies in the context of vehicle-to-pedestrian communication, we included measures regarding decision time and error rate [5, 7]. Since we focused on user behavior and did not want to disturb immersion we could exclusively observe decision times if pedestrians walked on the street. If they decided to wait it was impossible for us to detect when a decision was made. In a pre-study (N = 4) we employed an acoustic cue (*beep sound*) as a call for participants to take a decision. However, we removed it because test subjects criticized that the sound felt unnatural and destroyed immersion in the VR world. We calculated decision time (in seconds) by subtracting the event timestamps of pedestrians stepping onto the road with the timestamp when they first noticed the vehicle. Thus, we defined the time span from noticing a vehicle to taking the first step on the street in front of it as decision time. We also tracked the decision of the pedestrians (waiting or walking). Furthermore, we counted errors (wrong decisions). A wrong decision was considered either if participants stepped onto the road although the vehicle indicated they are not supposed to do so, or if pedestrians waited even if they could have walked onto the street.

Pedestrians Confidence in Crossing Decision. Based on prior work about strategies for measuring confidence in the context of decision making [2, 16, 22, 28, 35, 36], we decided to collect self-reported confidence with a 5-point Likert scale ranging from *strongly disagree* to *strongly agree*.

Attitudes Towards AVs and ECDs. Participants were asked to indicate if they considered *the attached car display*, *the speed and movement of the vehicle* or *something else* when crossing the road by using a questionnaire after the study. It was allowed to tick multiple options. Additionally, we confronted participants with the questions presented in Figure 7. Furthermore, we asked in an open question if participants thought external car displays are necessary and if they would invest extra money in ECDs when purchasing an AV.

Display Concepts. We investigated *visibility*, *understandability*, *aesthetics*, and *personal preferences* regarding each concept. Ratings were given on 5-point Likert scales from *poor* to *great*. To present a subjective ranking of the display types, we calculated an overall score based on the aforementioned criteria by summing up collected median values.

Participants

A total of 32 people (20 female, 12 male) within the age range from 18 to 45 years and a mean age of 25.53 years (SD: 6.26, Median: 24) participated in the study. Participants were recruited via university email lists, social media posts, and personal invitations. For seven (21.9%) this study was their first VR experience. The other 25 persons (78.1%) stated that they had tried VR headsets before. None of them used VR on a regular basis. All participants had normal or corrected to normal vision. It was not allowed to wear glasses due to possible changes in the field of view when an HMD is fitted. We compensated participants with 10 Euro e-shop vouchers.

Apparatus

The experiment took place in a laboratory room (8.6 m × 3.6 m). The physical movement area for the participants was about 3 m × 3 m. The physical room walls were substituted by physical objects in the virtual environment, e.g., a yellow wall as shown in Figure 2. Therefore the physical environment was unrecognised by the users when in VR. The VR system consists of an HTC Vive (first generation) and the respective lighthouse tracking system. The simulation was run on a Windows 10, VR-ready computer which comprised an Nvidia GTX 1980Ti, IntelCore i7- 6700 k, and 16 GB of RAM. The simulation was made with Unity 2018.2.0f2. Participants wore Bose QC25 noise cancelling headphones.

Procedure

The experimenter welcomed the participants and explained the purpose of the study, the procedure, and the tasks. We collected data in case an individual agreed to participate. We did not explain the display concepts, as we wanted to see if participants understand them without training. Also, we asked the participants to sign a consent form about the given information and the anonymous usage of collected data.

The interpupilar distance of each participant was measured using a digital optical device and transferred to the settings of the HTC Vive. A test moderator introduced participants to the VR system, the HMD and the VR experience. Participants were then asked to walk between several locations in the street scenario of the experiment to become accustomed to the VR world. Furthermore, they were introduced to the walking path including the spots in the environment indicating the starting and target points of both scenarios, as well as the lanes and directions vehicles would move. Aiming to avodi unnatural behavior, we ensured participants that there was no danger to hit a physical object. All instructions by the test moderator were transmitted via a microphone to the participant's headphones to minimize disturbance of the presence experience in VR. Finally, we ran the experiment. After each course we collected subjective confidence ratings. Once all 16 runs were finished, participants completed the post-study questionnaire, spending in total about 45 minutes in our lab.

Limitations

The risk of death at each road crossing is rather small (1 in 300 million)[6], and thus it is difficult for any study to claim it fully addresses the potential danger. We acknowledge that our participant sample size and demographic distribution may limit generalizability of our findings (prior work identified location-based differences in road crossing behaviour [8]).

We acknowledge that VR does not represent the complexity of the real world. However, 97% of our test subjects agreed that their actions within the simulation represented, more or less, how they would act in the real world. 9/32 participants commented that they would be more careful in the real world, e.g. wait longer / only walk if the vehicle stops. For future work, extending the simulation to include multiple vehicles, other pedestrians and distractions [14, 27] would increase the validity of the findings. Despite its limitations, we consider

[6]https://blogs.dnvgl.com/oilgas/safety/what-is-the-risk-of-crossing-the-road/ accessed: Jan 2019

	Decision Time			Decision Time (Straight Scenario)			Decision Time (Turn Scenario)		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	6.03	4.57 – 7.50	**<0.001**	6.75	4.91 – 8.59	**<0.001**	5.93	4.28 – 7.58	**<0.001**
Display Type (Smiling Car)	-1.28	-1.78 – -0.79	**<0.001**	-1.56	-2.33 – -0.78	**<0.001**	-1.01	-1.62 – -0.41	**0.001**
Display Type (Robot Driver)	-0.94	-1.44 – -0.45	**<0.001**	-1.19	-1.97 – -0.41	**0.003**	-0.68	-1.29 – -0.08	**0.027**
Display Type (Green Man / Yellow Hand)	-1.85	-2.34 – -1.35	**<0.001**	-2.37	-3.14 – -1.60	**<0.001**	-1.32	-1.92 – -0.72	**<0.001**
Scenario (Straight)	0.65	0.30 – 1.00	**<0.001**						
Observations	255			127			128		
R^2 / Omega-squared	0.412 / 0.403			0.447 / 0.428			0.494 / 0.464		

Figure 5: Results of ANOVA for decision time on independent variables, p values correspond to the base condition (inactive display).

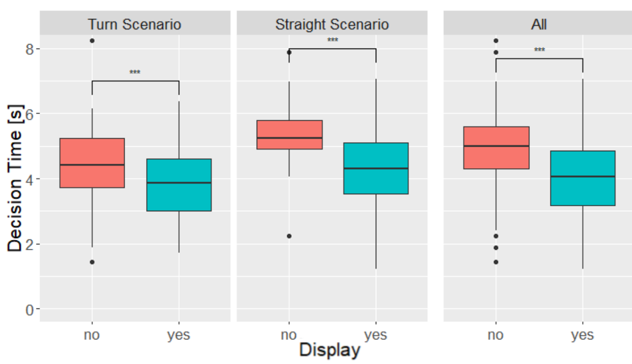

Figure 6: Decision time related to external car displays turned on (yes) or turned off (no) in each scenario and both combined.

findings from VR environments such as ours form a safe and useful first step in evaluating pedestrian-to-AV interaction.

The concept adopted from Fridman et al. [15] uses bright colors which are well perceivable from a distance and can be preattentively processed [38]. Therefore, this approach might outperform the other concepts. However, we deliberately decided to compare existing ECD concepts. Investigating the effect of displayed colors is not within the scope of this work.

5 RESULTS

We report results regarding decision times, user behavior, confidence, attitudes and feedback on the display concepts. We refer to the 'green man/yellow hand' concept as 'GMYH'.

Decision Times

In cases where the car did not stop, nobody tried to cross the road. Hence, 256 of 512 recorded cases were taken into account. We excluded the data of participants that did not cross, leading to a sample size of N = 127 in the straight scenario and N = 255 for both scenarios. Figure 6 shows boxplots with decision times. For overall decision times we measured a minimum of 1.21 s and a maximum value of 14.99 s. To examine correlations within our data set we built Linear Mixed Effects Models (LMEs). First, we checked our data for normally distributed residuals with homogeneous variance and normally distributed random effects, as required for LMEs [17]. As independence among observations was not fulfilled for our data, we conducted repeated-measures Analyses of Variance (ANOVAs) on our LMEs. The calculated estimates, confidence intervals (CI) and p-values are provided in Figure 5. All display concepts showed significantly ($\alpha < 5\%$) lower decision times in comparison to the base condition in both scenarios. Figure 8 presents a pairwise comparison of the ECD concepts. The estimated mean decision time, excluding the base condition, decreases least when a robot 'driver' display is mounted (-0.94) and most for the GMYH concept (-1.85). Pairwise comparisons of the ECD concepts revealed that there is a significant decrease in decision times when using the GMYH approach compared to the gesturing robot.

User Behavior

During the study there were no collisions between a participant and a virtual car. Only in 1 out of 512 cases, a participant decided not to cross the road, even though the car was static and displayed the gesturing robot. Hence, there were 99.8% correct crossing decisions and we had an error rate of 0.2%. In 54 out of 255 cases (21.2%) in which the vehicle intended to stop, people stepped onto the road while it was still driving (Mean speed: 10.43 km/h; SD: 9.37). Consequently, in 78.8% of cases pedestrians waited until the car did not move anymore. The results of a corresponding linear mixed effects model revealed that participants crossed the road at significantly higher AV speeds (p .015) if there was an active external car display compared to the base condition. The GMYH indication encouraged pedestrians to cross the road before the car came to a halt in 42.2%. Respectively, 23.4% of participants walked when a smile was shown, 10.9% when the robot was presented, and 7.8% with an inactive ECD.

Distances between the AV and pedestrians are in line with the observed speed. The distance was measured in meters, beginning from the center of the vehicle to the position of the eyes (VR headset). We observed that pedestrians went on the street in front of a driving AV with a mean distance of 6.98 m (SD: 3.09 m; Median: 5.97 m; Min: 4.89 m; Max: 18.89 m).

We asked participants to choose the main reason that influenced their decision to cross. Obeying solely the display was selected by 9.4%, 12.5% relied on vehicle speed, and 78% stated "both". In addition, two participants mentioned the car's distance as another important factor.

In response to the open question: "how do you usually decide in everyday traffic if it is safe to cross a road?" most participants answered: *"when the driver gives a sign" (eye contact or gesture)* (16/32). The second most stated answer was: *"by means of distance" (gap estimation)* (14/32). Additionally named were: *"the vehicle's speed"*, *"if the car slows down or stops"*, and *"if there is no vehicle visible"* (all 6/32).

Pedestrians' Confidence in Crossing Decision

Regardless of the presence of an ECD, 60% of participants were confident in their crossing decision (confidence rating 4 (*agree*) or 5 (*strongly agree*). About 20% of individuals submitted a medium value of three (*neutral*)). Other participants were not very confident in their crossing decisions.

We calculated linear mixed effects models with a random individual effect to identify if the ECD concept influences participants' self-reported confidence. We included "car stopped" binary values and "has seen" timestamps as additional independent variables. We examined if there is a difference if the AV stops or not and if an earlier recognition of the vehicle influences participants confidence. Results from the LMEs indicated that neither the usage of an ECD in general nor any concept in particular had a significant influence on confidence. No significant correlation between confidence and the other independent variables was discovered. However, comparing both scenarios, the straight one showed slightly higher confidence scores, presumably because breaking can be more easily mapped to the intention of the car to stop.

Attitudes Towards AVs and ECDs

Most participants agreed that an ECD affects their crossing decision. 80% stated to at least agree that an external car display increases their perception of safety and found ECDs useful in general (Figure 7). The participants reported neutrally regarding the effect of ECDs on trust towards AVs.

We asked if ECDs are considered unnecessary. Participants stated the opposite (87.5%). Two even stressed that external vehicle displays are *"absolutely necessary"* (P1 and P27). Stated reasons are manifold, e.g., *"communication on both sides (car and pedestrian) is natural, convenient and important. Such communication could be supported by ECDs,*

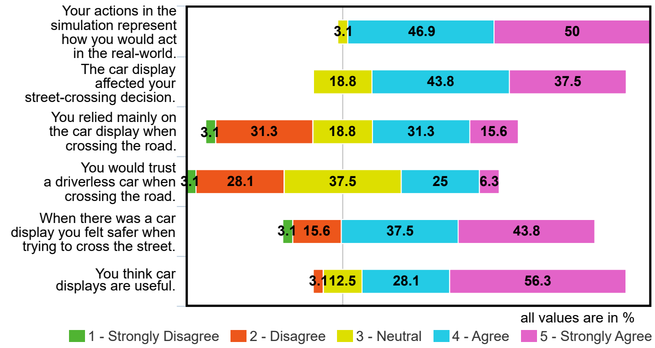

Figure 7: Likert scale questions and responses (N = 32).

especially if there is no driver present" (P12). If there is no driver present *"ECDs could serve as a replacement for car-to-pedestrian communication"* (P14), as they help to avoid uncertainty and confusion. One participant stated that *"without the display(s) the car seems unpredictable"* (P26). Participants said that these types of displays not only increase road safety but also the acceptance for automated vehicles as *"they can greatly take away the public's fear"* (P7) and make *"it much easier to trust the car if a display is attached"* (P27 and P31). One subject mentioned that computers make nearly no mistakes and therefore ECDs would be more accurate.

On the other hand, participants shared the opinion that AVs do not necessarily have to be equipped with an ECD (4/32). P3 mentioned: *"I would always wait until the car stops"*. One participant mentioned that it is rather unfamiliar and uncomfortable to receive instructions from a kind of "robot" in daily life. Two participants reported that they prefer to ignore the additional cue with no further reason. Surprisingly, only one subject considered that car displays are not necessary because her decisions were made solely on the vehicle's behaviour.

More than half of the participants (56.3%) would pay extra money for an ECD on an AV. Whilst 21.9% were uncertain and 12.5% would not purchase it. Potential buyers claimed that car displays should be a standard in every AV (2/32). Reservations for a purchase decision were based on the precondition that an ECD provides understandable signals, has a well-developed technology or a reasonable price (3/32).

Display Concepts

To find out which display concept was the most convincing one, we invited participants to rate *understandability*, *visibility*, *aesthetics* and *personal preference* regarding all concepts.

The GMYH concept scored highest (mean=5) in all categories, except *aesthetics*. Inactive ECDs received the lowest mean rating for *understandability* and *visibility*. Furthermore, presenting no concept (*base condition*) scored significantly lower than each of the other concepts in all conditions.

For every criteria, GMYH scored significantly higher results than the robot car and an inactive display. For example,

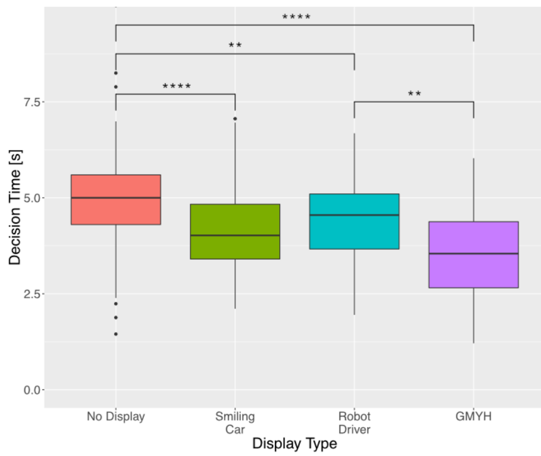

Figure 8: Decision times regarding display concepts. Stars indicate the degree of significance for pairwise comparisons.

participants rated *understandability* of the GMYH approach with a mean value of 4.50 (SD: 0.76; median: 5.00) against 2.97 (SD: 1.03; median: 3.00) for the smiling car; a mean of 2.63 (SD: 1.1; median: 2.5) for the robot "driver" and 1.69 (SD: 1.03; median: 1.0) for an inactive display.

To reveal significant differences ($\alpha = 1\%$) between the concepts we first applied Friedman tests. We found a significant difference, e.g., in *understandability* among the four display conditions ($\chi^2(3) = 59.54$, $p < 0.001$). A post-hoc analysis through Wilcoxon signed-rank tests with Bonferroni correction indicated significant differences between the base condition and the smiling car (W=187.5, $p < 0.001$), the waving robot (W=260, $p < 0.01$), and the GMYH (W=39.5, $p < 0.001$) conditions. Between the smiling car and the GMYH (W=134.5, $p < 0.001$) concept, and lastly between the GMYH and the robot (W=926.5, $p < 0.001$).

Similar relations were found for the other categories (*visibility*, *aesthetics* and *personal preference*). Participants rated *aesthetics* for GMYH and the smiling car almost the same.

6 DISCUSSION

In this section we summarize and discuss our findings.

Influence of ECDs on Crossing Decisions

When an ECD was present, participants waited for the vehicle to completely stop before crossing the road in 80% of the test cases and in nearly 100% of the cases with no display. According to our results, for 78% of pedestrians, the combination of vehicle speed and the indications of the external display are the main reason for making a crossing decision. Pedestrians would probably still take the right decision, even without a display. However, the presence of an ECD decreases decision time significantly. In particular, we found that participants started to walk 1.85 seconds earlier when the car communicated that it is safe to cross using a green man symbol displayed on the front of the vehicle. Pedestrians react up to 25% *(turn scenario)* and 35% *(straight scenario)* faster with an external display, compared to an inactive ECD. Thus, even if the vehicle is difficult to see, ECDs are valuable.

Our participants described ECDs as *"absolutely necessary"*(P1 and P27) or a *"replacement for car-to-pedestrian communication"*(P25) if no driver is present. Our results show that ECDs influence pedestrians' decision-making process. Additionally, 56.3% of our participants would even increase their investment in an AV, if it was equipped with an ECD.

Prior work has generally claimed that explicit communication is less important than vehicle motion [12, 23, 30, 31]. However, we argue that investigating cars' traditional turn indicator lights would yield similar statements. The blinking yellow turn lights on vehicles also indicate intention and although (typically) the car's behavior follows, the indicators enable other road users to adapt in advance. We believe that external communication of an AV's intentions towards pedestrians in specific situations could achieve similar results.

Pedestrians not only benefit by receiving additional information to support decision making. They also benefit from being able to cross safely sooner. Communicating intentions increases trust and can *"help to clear confusion"* (P8). Avoiding any confusion or misunderstandings is critical in the domain of AVs, since they will become an integral part of future traffic [1, 25] and even people who do not "drive" such vehicles need to learn how to interact with them as pedestrians.

Performance of Graphical ECD Design Concepts

By comparing a concept presented in prior research ("green man / yellow hand" (GMYH)), an industry concept ("smiling car") and a novel approach ("waving robot"), we learned that the "green man / yellow hand" representation performed best in the objective perception of the participants and the qualitative data. Our finding that GMYH is preferred, aligns with the findings of prior work, which evaluate it using different methods [15, 23]. In addition, the GMYH display reduced pedestrian decision time significantly compared to our proposed robot "driver" representation.

ECD's Influence on Pedestrians' Decision Confidence

Regardless of an indication through a display being available, participants reported to be confident in their crossing decision 60% of the time and unsure in 20% of all cases. Consequently, the installation of displays shows no significant impact on reported confidence. Similarly, no differences were found between the straight and turn scenarios, even though the display was visible for slightly longer in the turn case.

7 LESSONS LEARNED

Most participants preferred the GMYH concept and mentioned its familiarity as the main reason. The same reasons were noted in Fridman et al.'s study [15] in which participants were exposed to pictures of the GMYH concept. We validated prior findings in our study and additionally show that this concept performed best in quantitative measures.

Lessons learned include that the colors used on ECDs should provide high contrast and consider the background of the display. Additionally, the speed of animated elements, such as the movement of or (waving) robot hand, should be rather slow. Note that our gesture animation was perhaps too simple and fast to be clearly identified. The ECD should actively indicate two states: "walk" and "do not walk". As we developed the robot concept following the metaphor of a human driver signalling, we did not implement a specific "do not walk" gesture, but presented just the robot's face. The success of the GMYH concept suggests that adding a negative gesture may improve the perception of the concept, e.g., an open hand inspired by the yellow hand of the GMYH approach.

As vehicle motion is already the main cue for pedestrians, ECDs should focus on enhancing this intent communication, rather than aiming to explicitly instruct pedestrians. Vehicle intent communication is also superior in scenarios including multiple vehicles, non-AVs and multiple pedestrians, where multiple instructional ECDs risk presenting conflicting or mis-targeted instructions. Our participants' suggestions for AV-pedestrian communication included adding sounds (either acoustic cues or speech), changing the color of the entire vehicle, or adjusting the color of the headlights (red and green).

8 FUTURE WORK

Future work should investigate further modalities to inform pedestrians about intentions of an AV and go beyond displays only. Including acoustic cues, headlights and mobile devices might be a promising approach. Furthermore, the position for displaying intentions, the effect of colors, transmission of urgency and flashing information should be evaluated in context of car-to-pedestrian communication. Our work did not reveal obvious drawbacks of the VR based study approach. Hence, future work could also employ this methodology, for example, in scenarios including multiple vehicles and pedestrians, investigating two-way interaction or adjusting the surface of the road to become a "smart street" where indications about crossing and stopping are shown on the ground.

9 CONCLUSION

To explore the effectiveness of external car displays (ECDs) in communicating between automated vehicles (AVs) and pedestrians, we evaluated three ECD concepts in a Virtual Reality (VR) based user study. We compared 1) a symbol based concept consisting of a green man / a raised open yellow hand from prior research work, 2) an animation giving the impression of a smiling car demonstrated by the automotive industry, and 3) a novel concept showing a robot in the vehicle windshield, performing a hand gesture inspired by human drivers. To understand the strengths and weaknesses of these concepts we implemented a VR simulation including two road-crossing scenarios: an AV approaching from behind a pedestrian and a scenario where the AV approaches from around a corner. Such cases have not been previously investigated, but are common in everyday life. From our study, 32 participants generated a dataset containing 512 road crossings.

We conclude that ECDs have the potential to raise trust and acceptance of fully automated vehicles. The availability of an external display is an effective approach to increase trust in automated vehicles, with 81% of our participants reporting feeling safer if an external display communicated the cars intentions. Additionally, an ECD significantly reduced the crossing decision time of pedestrians.

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