Investigating the Effects of External Communication and Automation Behavior on Manual Drivers at Intersections

MARK COLLEY, Institute of Media Informatics, Ulm University, Germany
TIM FABIAN, Institute of Media Informatics, Ulm University, Germany
ENRICO RUKZIO, Institute of Media Informatics, Ulm University, Germany

Automated vehicles are expected to substitute or even improve driver-driver communication, for example, via LED strips or displays. Numerous situations exist where ambiguities have to be resolved via gestures or implicit communication (i.e., movement). An already demanding situation is the unsignalized four-way intersection. Additionally, Vehicle-To-Everything technology enables automated vehicles to perform maneuvers impossible before such as blocking an intersection to safely let an emergency vehicle pass. Therefore, we report the results of a within-subject Virtual Reality study (N=17) evaluating these two scenarios. Results show that external communication increased perceived safety and reduced mental workload, and also that the novel behavior confused participants. Our work helps better to integrate external communication in settings with manual drivers.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**.

Additional Key Words and Phrases: Automated vehicles; self-driving vehicles; external communication; Virtual Reality.

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1 INTRODUCTION

Automated vehicles (AVs) are expected to greatly alter traffic both for vulnerable road users (VRUs) such as pedestrians [11, 21] as well as manual drivers [43, 44]. Current literature expects the necessity of AVs to communicate their intent due to a potentially missing human driver, which itself could unsettle drivers and VRUs. While numerous works investigated the crossing process of VRUs (e.g., the impact of vehicle shape [17], modality [12], or scenario [10]), the potential encounters of AVs with manually driven vehicles ("manual drivers") have been less investigated. In these encounters, there exists the possibility for uncertainty, for example, when the road is partially blocked [34, 43]. The problem of the unclear right of way is also present in unsignalized uncontrolled four-way intersections (called "Deadlock Intersection"). Compared to partially blocked streets, there are even more vehicles (both autonomous and manually driven) present. This is even challenging with today's methods of communication: in 2019 in the USA, there were 36 096 traffic fatalities at unsignalized intersection[1]. While these include both priority-controlled and right-hand

[1]https://safety.fhwa.dot.gov/intersection/about/; Accessed: 24.01.2022

Authors' addresses: Mark Colley, mark.colley@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany; Tim Fabian, tim.fabian@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany; Enrico Rukzio, enrico.rukzio@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany.

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priority intersections, De Ceunynck et al. [16] showed that the number of right-of-way violations is significantly higher at right-hand priority intersections (i.e., at uncontrolled intersections). This indicates that there are more challenges with this type of intersection which is why we investigated the uncontrolled deadlock intersection in this work. Besides these naturally emerging uncertain scenarios, currently, emergency vehicle crashes have been recognized as a severe challenge due to the high impact of both the crash itself and the non-arriving help [28]. With future Vehicle-to-Vehicle (V2V) or Vehicle-to-Everything (V2X) technology [3, 40], novel prevention concepts seem feasible due to using AVs as early warning systems. The AVs could then use this information to block risky intersections (scenario called "Approaching Emergency Vehicle").

Therefore, we investigated the "Deadlock Intersection" and the "Approaching Emergency Vehicle" scenario in a within-subjects virtual reality (VR) study with N=17 participants. We found those novel behaviors made feasible via V2X [40] communication led to confusion and even six accidents. In the "Deadlock Intersection", external communication (also called *external Human-Machine Interface* or *eHMI*) was seen as helpful and improved passing times.

Contribution Statement: This work provides insights into two scenarios regarding the external communication of AVs towards manual drivers. The scenarios investigate the effects of communication and behavior at a deadlock crossing as well as the case of an approaching emergency vehicle into an intersection. The results of a VR study with N=17 participants showed that eHMIs are useful and reduce mental workload. Additionally, novel behaviors confuse manual drivers despite external communication. Our work helps in introducing AVs safely into general traffic.

2 RELATED WORK

This work is based on research in the field of external communication of AVs toward manual drivers. However, we also provide general insights from studies on external communication of AVs towards pedestrians as these can guide the design also for other road users.

2.1 External Communication Towards Vulnerable Road Users

According to Holländer, Colley et al. [27], vulnerable road users are not protected by an outside shield and can be grouped, for example, by age or abilities. To substitute a possibly missing human driver, external communication is evaluated for crossing scenarios. The designed concepts were grouped based on modality, message type, and communication location [11] and also situation characteristics such as acoustic noise have to be considered.

Several modalities such as displays [23], LED strips [5, 23, 36], windshield displays [6], projections [1] auditory or tactile cues [38] and combinations [38] or enhanced infrastructure [9, 48] were proposed.

The focus on eHMI research shifts towards scalability [14], accessibility [13], or social aspect questions [45] and challenges with passenger actions such as pedestrian mode confusion [7, 15]. For example, Dey et al. [19] evaluated an eHMI with distance-dependent information (i.e., indicating when the AV will come to a halt), improving pedestrians' comprehension of the AV's intention. While *text* was reported to be least ambiguous [4, 18], this is not universally comprehensible, for example, for children or foreigners and can lead to problems in a highly dynamic scenario such as for the communication with manual drivers.

Previous work on communication with vulnerable road users guided our work for communication with manual drivers. Intention-based visual messages seem most appropriate on the AV itself. Auditory and tactile communication is less appropriate because of the absorption by the vehicle. Our work also addresses scalability aspects in the "Deadlock Intersection" scenario, therefore, addressing a major research question in this area [14].

2.2 External Communication Towards Manual Drivers

Rettenmaier et al. [43] considered the communication between an AV and a manual driver in a bottleneck scenario. In their work, two parked cars block the road so that both the MV and the AV have to use the lane of the oncoming traffic to drive past the parked vehicle. This leads to an unregulated scenario in which both vehicles must yield the right-of-way to the oncoming vehicle. Therefore, communication is necessary. The communication is realized via displays on the AV's radiator grill or projections on the road. The displays showed German road signs, which are typically used to regulate traffic at bottlenecks. The study showed that the displays produced better results than the projections (in terms of visibility), especially at greater distances [43]. The driver's view is primarily directed at the oncoming AV, therefore, the display is recognized earlier. In addition, the projections are transparent and, thus, not as noticeable as the displays.
Rettenmaier et al. [42] altered indications shown on the display to communicate the AV's intention to the manual driver in a bottleneck scenario. The result of this study was the most appropriate design for the communication visualization in the form of a red or green colored arrow which we also used.
Finally, Klaus et al. [31] discussed different types of communication. They distinguish between four eHMIs ("marking a vehicle as an automated vehicle", "light strips", "display," which shows texts or symbols, and "projection"). They consider the latter two eHMIs to be more useful for communication with other road users, as displays and projections can show a large amount of information (textual or pictorial). Therefore, we used both in our communication concepts. In the work of Avsar et al. [2], an intersection scenario was considered in which an AV had the right of way but still yielded it to a manual driver. The AV communicated this via a "360° LED light-band" [2]. They found that perceived safety and confidence in the AV were improved by the eHMIs, and handling was rated as easier. This further solidifies the idea that eHMIs benefit traffic and communication with MV.
Schlackl et al. [47] used the entire visible car body as eHMI in their work. The chosen scenario was the zipper procedure at a road extension (here a construction site). The eHMI was divided into three parts. The first part was the hood, the second the rear, and the third part was the driver's side of the AV. On each of these parts, a part of the communication took place. The side recorded the position of the perceived vehicle driving next to the AV in the form of a dot. This was to replace the missing eye contact. On the vehicle's rear, the traffic situation was shown in the form of a pictogram. On the front of the AV, there were triangles pointing and moving in the direction in which the subjects were supposed to turn in. The use of the pictograms and the triangles turned out to be "much better than the ordinary headlight flasher" [47, p. 82].

While these works indicate positive influences in terms of communication with other MVs, the scenarios investigated were limited in the number of vehicles and variation of traffic participants. We close this gap with our two scenarios.

3 EXPERIMENT

To evaluate the effects of eHMIs and the behavior of other AVs, we designed and conducted a within-subject study with N=17 participants. This study was guided by the research questions (RQs):

RQ1: What impact does the variable "AV" behavior (of an approaching emergency vehicle; i.e., block risky intersections) have on manual drivers in terms of (1) behavior, (2) mental workload, (3) trust, (4) perceived safety, and (5) communication quality?
RQ2: What impact do the variables "eHMI", "number of AVs", and "behavior" have on manual drivers in

terms of (1) behavior, (2) mental workload, (3) trust, (4) perceived safety, and (5) communication quality?

3.1 Materials

To answer the two RQs and as briefly explained in the introduction, we designed two scenarios.

3.1.1 Virtual Reality Simulator. We modeled the scenarios in Unity version 2020.3.10f1 [50]. All scenarios take place in a city, thus, velocity was limited to 50 km/h. The Thrustmaster T150 Pro steering wheel with pedals and HTC VIVE Pro were used. The VIVE Hand Tracking SDK [29] in version 1.0.0 was used for tracking the hands. Hand-tracking was solely used to visualize the hands, thus, improving immersion. We used the Simple Traffic System asset [49] to generate the required traffic on the roads in the simulation.

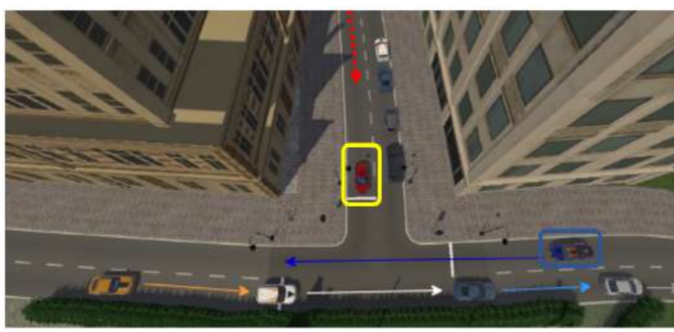

Fig. 1. Overview of the Approaching Emergency Vehicle scenario. The red car is an AV (highlighted with yellow borders) and the blue car is driven by the participant. The yellow, white, light blue, and gray cars on the lower lane are manually driven vehicles. The arrows indicate the driving direction. The emergency vehicles approached from the lane of the AV (i.e., from the top; red dotted arrow).

3.1.2 Scenario — Approaching Emergency Vehicle. In this scenario, there is a three-way intersection with traffic lights. For the participant, the traffic light is green, for the AV, it is red. The view into the side street is blocked partially from sight for the participant. Vehicles are parked on the right-hand side of the street (viewed from the intersection), which represents a typical scenario in a city. A fire truck with flashing lights is approaching from this street and turns right. The German StVO §35 StVO allows the fire truck to pass the red light. Besides, the German §38 StVO obliges the AV to make space for the fire truck and, if necessary, also to pass the red light [35]. In this case, the AV has to make space for the emergency vehicle because of the parking cars. We assume that the AV receives the required information about the fire truck's route via V2X technology [3, 40].

Here, we compared two conditions: either the AV makes space by driving onto the curb or it blocks the intersection. Blocking the intersection could lead to improved safety both for the manual driver as well as for the emergency vehicle as the physical barrier prohibits driving onto the intersection. In both cases, external communication is employed. The AV signals the approaching fire truck with a short text "Nearing fire truck" (translated from German) on the front display and an animation on both side displays. Li et al. [33] showed that for an intersection with manual drivers, the side was the most understandable. Therefore, the combination with the front display attached to the bumper grille should be even more visible. The view of the participant is shown in Figure 2. The orange arrows on the side displays are animated to move smoothly from the back to the front to indicate the arrival of the fire truck, which is shown at the end of the display. In case of

Fig. 2. Player view AV drives to side (top; emphasized with a yellow arrow) and blocks crossing (bottom).

entering the intersection, the AV additionally projects two red lines on the road (see the red arrow in Figure 2) to show other drivers where the AV is headed to.

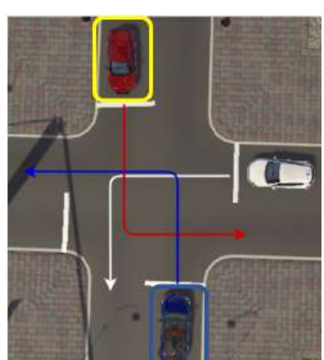

Fig. 3. The Deadlock Intersection. The (highlighted) blue car is driven by the participant. The red car represents the AV (highlighted with yellow) and the white car represents an AV or a manually driven vehicle. All three vehicles turn left as indicated by the arrows.

3.1.3 Scenario — Deadlock Intersection. This scenario is a crossing of four intersecting roads (see Figure 3). The intersection neither has signs nor traffic lights. Therefore, according to the German StVO §8 Section 1 (right before left), the car coming from the right (from the participant's point of view) has the right to go first. Thus, the blue car has to wait for the white car, and the white car has to wait for the red car. Also, the German §9 section 3 StVO has to be applied. This means that a vehicle (e.g., the blue car in Figure 3) must yield right of way to an oncoming vehicle (the red car) if it wants to turn left. The result is that each vehicle has to wait for another vehicle. Thus, a deadlock occurs. The participant drives the blue car in Figure 3. The red car is an AV, and the white car is either a simulated manually operated vehicle or a second AV. We assume that the AVs communicate and decide that the red AV will go first or give way to the blue car (the participant). If there is only one AV (the red one), the decision is also up to the AV.

Fig. 4. Animation for AV yielding right of way.

Fig. 5. Animation for AV insisting on driving first.

In this scenario, we evaluated eight conditions, representing a $2 \times 2 \times 2$ within-subjects design. The parameter we tested were *AV behavior* (the red AV yields or insists on driving first), *external communication* (present or not), and *number of AVs* (one or two, the second meaning that the white vehicle is modeled as an AV). Depending on the condition, the AV signals its decision with the display and an animated projection in front of the car (see Figure 4 and Figure 5). The red bar widens to the width of the AV, while the green arrows gradually appear on the road. The arrows at the display are animated, with the red arrow becoming slower as it progresses towards the bottom, indicating a slowing down of the AV. The green arrow moves smoothly from top to bottom to illustrate the AV driving without becoming slower. The external communication is based on the work by Rettenmaier et al. [42].

3.2 Measurements

3.2.1 Objective measurements: Depending on the scenario, different variables were logged.

Emergency Vehicle. In this scenario, the minimum distance to the AV and whether there was a collision was logged. The minimum distance to the fire truck and whether it was obstructed by the participant was also recorded (distance <2m). However, it was also recorded whether the participant drove through the intersection before the fire truck and also passed it (both were recorded individually). In addition, the minimum distance to the sidewalk before the intersection was logged. This should indicate whether the participant is also trying to make way for the fire truck.

Deadlock Intersection. The distance to the oncoming AV and whether there was an accident were logged. In addition, the time of entry and exit of the participant into the intersection and the resulting duration were logged.

3.2.2 Subjective Measurements. The subjective measurements were equal for both scenarios. Participants rated their perceived safety using four 7-point semantic differentials from -3 (anxious/agitated/unsafe/timid) to +3 (relaxed/calm/safe/confident) as proposed by Faas et al. [20]. We also employed the mental workload subscale of the raw NASA-TLX [25] on a 20-point scale ("How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?"; 1=Very Low to 20=Very High). Additionally, we used the subscales *Predictability/Understandability* (*Understanding* from here) and *Trust* of the *Trust in Automation* questionnaire by Körber [32]. Understanding is measured using agreement on four statements ("The system state was always clear to me.", "I was able to understand why things happened."; two inverse: "The system reacts unpredictably.", "It's difficult to identify what the system will do next.") using 5-point Likert scales (1=Strongly disagree to 5=Strongly agree). Trust is measured via agreement on equal 5-point Likert scales on two statements ("I trust the system." and "I can rely on the system."). We also asked whether the participants perceived a projection (boolean), whether this supported the information on the display(s) (five point Likert scale) and whether the eHMIs themselves were helpful or not (five point Likert scale). To assess the communication of the AV, we used the short version of the User Experience Questionnaire (UEQ-S) by Martin et al. [39], which measures pragmatic and hedonic quality. In addition, communication was assessed using the self-defined aspects unfriendly/friendly, impolite/polite, ambiguous/unambiguous, unnatural/natural, machine-like/human-like (as suggested by Powers and Kiesler [41]) and insufficient/adequate according to Sadeghian et al. [45]. After all ten conditions, participants had to complete a final questionnaire to provide an overall rating of the proposed systems. After evaluating the AV's communication and the necessity and usefulness of each communication, participants could provide positive and negative open-ended feedback.

3.3 Procedure

Each participant started with signing a declaration of consent. Every participant was required to have a driver's license. Following this, each participant received a short introduction to the study.

> You will drive through a city in a virtual reality (VR) environment in a self-controlled vehicle. You encounter automated and manually controlled vehicles. Automated vehicles can be recognized by their displays on the radiator grille and, if necessary, on the sides. There are intersections with traffic lights and intersections without traffic lights or signs. According to StVO § 8 "Right before left" and §9 "When turning, the oncoming traffic has the right of way". If at any time you are not comfortable, you can cancel the study without giving reasons and without any disadvantages. In this case, simply take off the VR glasses and inform the head of the study.
> (Translated from German)

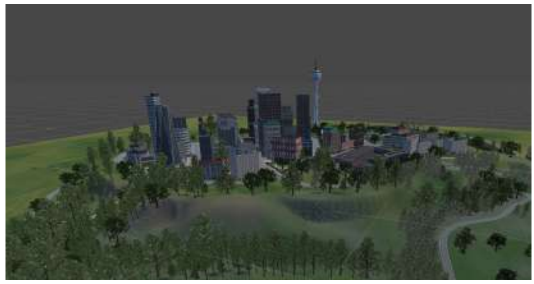

Fig. 6. The generated city in Unity. The individual scenarios all take place in this city or with a short journey to the city. The road in front of the city (lower right corner) leads once around the whole city with a few approaches to the city.

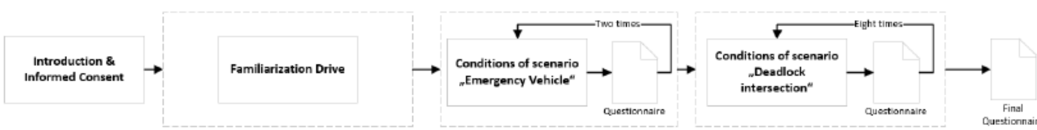

Fig. 7. The study procedure.

Afterward, each participant was able to familiarize themselves with the steering wheel and the VR environment (see Figure 7). For the familiarization, participants were able to drive around the scene (see Figure 6) for approximately 10 minutes. Following this, the participants first encountered the scenario *Emergency Vehicle* with the two conditions counterbalanced. The introduction to this scenario read:

> In this scenario, you will come to an intersection with traffic lights. Your goal is to cross the intersection to reach the visualized destination safely.
> (Translated from German)

Afterward, the eight conditions of the scenario *Deadlock Intersection* were encountered counterbalanced. The introduction to this scenario read:

> You arrive at an unsigned intersection with no traffic lights. You want to turn left at this intersection. An automated vehicle will come toward you. From the right, either an automated or a manually driven vehicle will reach the intersection.
> (Translated from German)

We introduced the different concepts to the participants and encouraged them to ask questions. After each condition, participants filled out a questionnaire. At the end of the study, participants completed a final questionnaire in which they were able to provide open feedback. The study took approximately 60 min. Participants were compensated with 10€. The study was conducted in German. The hygiene concept for studies regarding COVID-19 (ventilation, disinfection, wearing masks) involving human subjects of our university was applied.

4 RESULTS

In the following, we report the results per scenario.

4.1 Data Analysis

We independently analyzed each of the two scenarios, "Deadlock Intersection" (eight conditions representing the 2 x 2 x 2 design) and "Approaching Emergency Vehicle" (two conditions). Before every statistical test, we checked the required assumptions (e.g., normality distribution). For non-parametric data, we used the non-parametric ANOVA (NPAV) as implemented by Lüpsen [37]. We used Bonferroni correction for post-hoc tests. R in version 4.2.0 and RStudio in version 2022.02.0 was employed. All packages were up to date in May 2022.

4.2 Participants

We determined the required sample size via an a-priori power analysis using G*Power in version 3.1.9.7 [22]. To achieve a power of .8 with an alpha level of .05, 16 participants should result in an anticipated medium to high effect size (0.25 [24]) in a within-factors repeated measures ANOVA with eight measurements.

Fig. 8. Study apparatus with a participant.

N=19 participants with a mean age of *M*=23.63 years (*SD*=2.54, between 20 and 30 years) commenced the study, of which 17 completed it. Every participant held a valid driver's license. Most participants (12) drove between 7000 and 24999 km in the past year. Four drove less than 7000 km, two between 25000 and 32999 km, and one participant even over 33000 km. Four of the participants use a vehicle daily, two at least on weekdays, twelve one to four times a week, and one participant only one to three times a month. On 5-point Likert scales (*1 = Strongly Disagree — 5 = Strongly Agree*), participants showed interest in AVs (*M*=4.05, *SD*=1.05), believed AVs to ease their lives (*M*=3.79, *SD*=1.00), and were unsure whether AVs become reality by 2031 (*M*=3.44, *SD*=0.82).

4.3 Scenario "Approaching Emergency Vehicle"

4.3.1 Mental Workload, Trust, Perceived Safety. A student's t-test ($t(16)$=-3.03, p=0.008) showed that mental workload was significantly lower with the AV driving to the side (*M*=6.82, *SD*=3.57) than with it driving into the intersection (*M*=9.76, *SD*=5.72). A student's t-test ($t(16)$=3.36, p=0.004) showed that Understanding was significantly higher with the AV driving to the side (*M*=3.10, *SD*=0.63) than with it driving into the intersection (*M*=2.66, *SD*=0.83). A Wilcoxon signed-rank test showed no significant differences for Trust (p=0.17). A student's t-test ($t(16)$=2.91, p=0.01) showed that perceived safety was significantly higher with the AV driving to the side (*M*=1.40, *SD*=1.05) than with it driving into the intersection (*M*=0.16, *SD*=1.55).

4.3.2 Communication Quality. Student's t-tests found no significant differences neither for the pragmatic (p=0.95) nor the hedonic quality (p=0.13) of the communication.

Wilcoxon signed-rank tests and Student's t-tests also found no significant differences for Friendliness (p=0.89), Politeness (p=0.77), Human-Likeness (p=0.60), Unambiguousnes (p=0.18), Naturalness (p=0.44), or Appropriateness (p=0.75).

4.3.3 Crashes & Obstructing The Fire Truck. There were six accidents when the AV blocked the intersection and no accidents when the AV pulled over.

A Wilcoxon signed-rank test found a significant difference for the distance to the fire trucks (V = 111.00, p=0.004). The distance was significantly higher when the AV blocked the intersection (*M*=18.33, *SD*=13.88) than when it drove to the side (*M*=3.36, *SD*=2.12).

4.4 Scenario "Deadlock Intersection"

4.4.1 Mental Workload, Trust, Perceived Safety. The NPAV found a significant main effect of *behavior* on mental workload ($F(1, 16) = 12.23$, p=0.003). The behavior passing led to lower mental workload (*M*=7.68, *SD*=4.68) than yielding (*M*=9.49, *SD*=4.93), The NPAV found a significant main effect of *eHMI* on mental workload ($F(1, 16) = 6.02$, p=0.026). Communication led to lower mental workload (*M*=7.71, *SD*=4.38; no communication: *M*=9.46, *SD*=5.21).

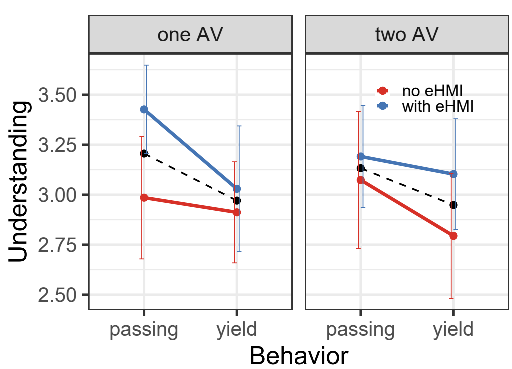

Fig. 9. Three-way interaction effect on Understanding on 5-point Likert scales. The dashed line represents the combined values of with and no eHMI. The solid lines represent the significant interaction effect.

The NPAV found a significant main effect of *eHMI* on Understanding ($F(1, 16) = 8.50$, p=0.01). The NPAV found a significant three-way interaction effect of *number of AVs* × *behavior* × *eHMI* on Understanding ($F(1, 16) = 5.12$, p=0.038; see Figure 9). Understanding was higher with an eHMI. It declined strongly with the behavior yielding, more so with one AV for the conditions with an eHMI and more so without an eHMI in the *two AV* condition.

The NPAV found no significant effects on Trust.

The NPAV found a significant main effect of *behavior* on perceived safety ($F(1, 16) = 8.46$, p=0.01). Perceived safety was higher with the behavior passing (*M*=1.71, *SD*=1.34) than with the behavior yielding (*M*=0.90, *SD*=1.83). The NPAV found a significant main effect of *eHMI* on perceived safety ($F(1, 16) = 6.69$, p=0.02). Perceived safety was higher with (*M*=1.55, *SD*=1.48) than without an eHMI (*M*=1.06, *SD*=1.78).

4.4.2 Communication Quality. The UEQ-S by Martin et al. [39] measures pragmatic and hedonic quality of the communication.

The NPAV found a significant main effect of *eHMI* on pragmatic quality ($F(1,16) = 8.41$, p=0.01). Pragmatic quality was higher with (M=4.86, SD=1.35) than without an eHMI (M=4.10, SD=1.51).

The NPAV found a significant main effect of *eHMI* on hedonic quality ($F(1,16) = 16.15$, p<0.001). Hedonic quality was higher with (M=4.61, SD=1.20) than without an eHMI (M=3.52, SD=1.17).

The NPAV found a significant main effect of *eHMI* on Friendliness ($F(1,16) = 5.16$, p=0.04). Friendliness was higher with (M=4.34, SD=1.10) than without an eHMI (M=3.74, SD=1.15).

The NPAV found a significant main effect of *eHMI* on Politeness ($F(1,16) = 6.10$, p=0.03). Politeness, interestingly, was lower with (M=3.63, SD=1.01) than without an eHMI (M=4.16, SD=1.10).

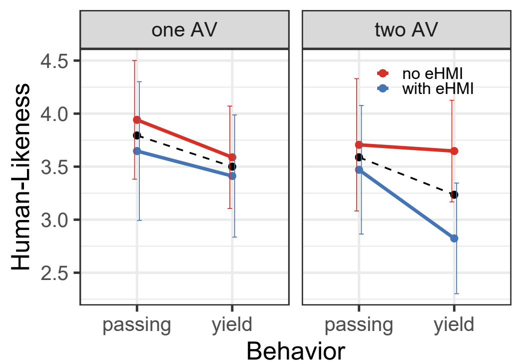

Fig. 10. Three-way interaction effect on Human-Likeness on a 7-point semantic differential (1 = machine-like to 7 human-like). The dashed line represents the combined values of with and no eHMI. The solid lines represent the significant interaction effect.

The NPAV found a significant main effect of *eHMI* on Human-Likeness ($F(1,16) = 5.73$, p=0.03). The NPAV found a significant three-way interaction effect of *number of AVs* × *behavior* × *eHMI* on Human-Likeness ($F(1,16) = 5.44$, p=0.03; see Figure 10). Human-Likeness was higher without the eHMI and declined for the yielding behavior. It declined stronger with an eHMI in the two AV conditions than in the one AV conditions. Overall, the eHMI was found to be less human-like.

The NPAV found no significant effects on Unambiguousness, Naturalness, and Appropriateness.

4.4.3 Crashes, Intersection Crossing Duration, and Distance to Automated Vehicle. There were three accidents, all of which occurred when there was no communication and the AV was driving. Two of these accidents occurred with only one AV, and one accident occurred with two AVs in the scene.

The NPAV found a significant main effect of *eHMI* on duration ($F(1,16) = 5.24$, p=0.04). With an eHMI, duration was significantly shorter (M=7.93, SD=6.75) than without (M=10.62, SD=18.20). The NPAV found a significant main effect of *behavior* on duration ($F(1,16) = 31.07$, p<0.001). Duration was significantly longer when the AV first passed (M=12.48, SD=18.75) compared to yielding (M=6.07, SD=2.83).

The NPAV found a significant main effect of *eHMI* on minimum distance to AV ($F(1,16) = 5.77$, p=0.03). The distance was significantly higher with (M=2.45, SD=0.87) than without an eHMI (M=2.17, SD=1.10). The NPAV found a significant main effect of *behavior* on minimum distance to AV ($F(1,16) = 23.67$, p<0.001). The distance was significantly higher when the AV first passed (M=2.73, SD=0.52) compared to yielding (M=1.90, SD=1.18).

4.5 Open Feedback

In general, participants emphasized the communication as being useful and helpful (e.g., "I found it better when the vehicles had some display/projection, and communicated, than just doing nothing or driving without displaying anything"). The combination of display and projection was mentioned five times as being positive. Nonetheless, there were several improvement proposals. Participants were confused by the combination of having the AV signal that it wants to turn left and still signal that it will yield (in the scenario "Deadlock Intersection"). Additionally, participants mentioned the unclear viewpoint for the arrows in the scenario "Deadlock Intersection" (e.g., "The green and red displays are not clear, as I don't know if the red (= standing) refers to me or to the vehicle across the street"). This confusion was also present in the scenario "Approaching Emergency Vehicle". Here, five participants mentioned that the moving arrows from the back to the front did not help them understand that an emergency vehicle is approaching but that they were unsure whether this meant that the AV will continue to drive on.

5 DISCUSSION

In this work, we presented a VR study with N=17 participants that was subdivided into two scenarios to investigate the effects of (1) different driving behaviors in the case of an approaching emergency vehicle and (2) the external communication at a deadlock crossing with a varying number of AVs and behaviors.

5.1 Potential and Danger of Behavior in Novel Use Cases Due to V2X Connectivity

In the scenario "Approaching Emergency Vehicle", there were six accidents when the AV blocked the intersection. We envisioned the behavior of the AV when blocking the intersection to actually be safety-increasing as the actual blocking of the intersection was seen as a means to prohibit entering the intersection. Today, most crashes with emergency vehicles occur at intersections [46]. The accompanying external communication was designed to provide the relevant information for the manual driver to understand that an emergency vehicle is approaching. However, Understanding, mental workload, and perceived safety were all rated better with the conventional behavior. Therefore, we conclude that despite enabling a range of novel behaviors that could improve traffic safety in general, this behavior was not intuitively comprehensible and led to dangerous scenarios.

5.2 Necessity and Design of External Communication

As an eHMI was present in both conditions for the scenario "Approaching Emergency Vehicle", the effect of the eHMI can only be deduced by the scenario "Deadlock Intersection". Here, an eHMI significantly improved mental workload, Understanding, and perceived safety. Additionally, pragmatic and hedonic quality were rated higher with an eHMI. The duration in the Deadline Intersection was also lower, which points toward lower ambiguity. Finally, the distance to the AV was also higher with an eHMI, suggesting higher safety for the manual driver. Regarding the design of the external communication, we found that, in the "Deadlock Intersection" scenario, in 73.50% of the cases with an eHMI, the projection was noticed. Consistent with Rettenmaier et al. [43], we, therefore, also found that projections are seen worse than on displays attached to, for example, the radiator grille. Thus, we argue that a projection should only be used as a supplementary modality. More recent work by Li et al. [34] included a Head-Up Display in the ego vehicle allowing to display messages of the AV. We explicitly avoided this condition as it involves the necessity for the ego vehicle to have the technical equipment (i.e., the Head-Up Display and connectivity). Nonetheless, this could be an additional highly visible communication medium to be further explored.

5.3 Practical Implications

Our work provides the first practical implications for the area of novel behavior of AVs due to connectivity as well as the design of explicit and implicit communication at intersections. First, while numerous behaviors seem possible and could be feasible with increased connectivity, their application must be carefully designed. Unknown behavior led to accidents in the scenario "Approaching Emergency Vehicle". Our participants were rather young and, therefore, most likely more adaptable than older drivers (e.g., the elderly). This group is already at more risk of being involved in accidents [30], and, therefore, we assume that unexpected behavior has an even higher impact for this driver group. Additionally, the used moving arrows were not useful as several participants mentioned them to be confusing. Therefore, these most likely should be avoided altogether. In the "Deadlock Intersection" scenario, the yielding behavior led to significantly higher mental workload, less Understanding (see Figure 9), and lower perceived safety. Therefore, the potentially more "social" behavior of yielding actually had a converse effect and had negative consequences for the manual driver. The presence of explicit communication, which was based on work by Rettenmaier et al. [42], proved useful.

5.4 Limitations

A moderate number of participants took part (N=17). As mostly younger participants (on average 23.63 years old) took part, it is unclear whether this work's findings are transferable to other age groups. Also, transferability to a real-world scenario is difficult to assess. While much caution was given to design the scenario realistically and to reduce motion sickness symptoms, two participants had to abort. The collisions also let us believe that participants would have behaved more cautiously in the real world. The scenarios involving driving a vehicle could also benefit from using simulators with higher degrees of freedom (e.g., [8] or [26]).

6 CONCLUSION

Overall, this work presents a subdivided VR study with N=17 participants. The two scenarios were used to evaluate the effect of (1) novel AV behavior enabled via V2X communication and (2) external communication and behavior of AV(s) at a deadlock intersection. The results indicate the novel behavior of AVs, despite external communication, can confuse manual drivers. Nonetheless, eHMIs are helpful. This work investigated relevant factors related to the intersection scenario with both AVs and manually driven vehicles and helps to introduce AVs safely into general traffic.

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