Investigating the Effects of Feedback Communication of Autonomous Vehicles

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ABSTRACT

Autonomous vehicles (AVs) are expected to communicate to vulnerable road users as a substitution of, for example, driver-pedestrian communication, leading to increased safety and acceptance. This communication is currently one-directional, i.e., from the AV to the pedestrian. However, today's communication between drivers and pedestrians in crossing scenarios is bidirectional. Pedestrians gesture "thank you" or wave drivers through in case they do not want to cross. Human drivers often acknowledge this, for example, with a nod. We present an experiment in Virtual Reality (*N*=20), in which the effect of such acknowledgment of the AVs via its external communication is investigated for the two described scenarios and concerning pedestrian presence. Results show that such feedback is perceived as highly necessary, depends on the scenario, and improves the perceived intelligence of the AV, confirming a Halo-Effect.

CCS CONCEPTS

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

KEYWORDS

External communication; interaction design; feedback.

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1 INTRODUCTION

In the future, autonomous vehicles (AVs) will most likely become ever more prevalent. While there are still technical challenges [66, 69], the technology is on the verge of becoming available at least for several operational driving domains, such as highways. Already, companies such as Waymo [64] allow paid rides in cities in the USA.

Currently, problematic situations in which traffic is not clearly ruled or deviant behavior such as jaywalking occurs, implicit and explicit communication between a human driver and the pedestrian is used. This involves slowing down early, gesturing, honks, and eye-contact [54].

However, in AVs, the human user could be engaged in numerous non-driving related tasks such as eating, sleeping, or playing games [52]. A human driver could even be missing. Therefore, external Human Machine Interfaces (eHMIs) are evaluated as a substitution for the communication of the driver. Most work until now focuses on command- and intention-based communication [11]. However, interpersonal communication includes non-pragmatic aspects (e.g., affective messages) [11]. As technical situational sensing approaches, i.e., detecting pedestrian intention, is not perfect, situations could emerge in which the AV falsely assumes that pedestrians want to cross. Thus, the question arises of how bidirectional communication should be designed for AV—pedestrian communication in such and in general crossing scenarios [49]. Such communication from pedestrian to AV could take place via gestures (as today [54]).

In personal assistants, mimicking human behavior is already employed to make the technology more acceptable and, ultimately, increase usage. Technology can only be effective if accepted. A positive attitude towards other people and objects can increase the willingness to accept advice or commands/instructions from these [57]. Therefore, in this work, we evaluate whether feedback for gesture-based communication towards an AV improves the perception of AVs and the communication comfort provided by the eHMI. To be able to evaluate the most relevant aspects of communication, we conducted a structured literature survey regarding the evaluated components of the communication: the communication (e.g., the AV) or the communication itself, and the variables measuring the component (e.g., trust).

As communication is dependent on the situation it is used in [11] and humans tend to behave differently in the mere presence of others [27], we also evaluated how the presence of other pedestrians affects such communication. For this, we simulated two scenarios in which gesture usage is common and plausible: (1) Standing at the curb of a street where a vehicle comes to a halt as a crossing intention is assumed. Here, the pedestrian waves the vehicle through when the pedestrian does not want to cross, henceforth called Stand scenario. (2) Standing at a street and wanting to cross. If the vehicle/driver lets the pedestrian pass at an unsignalized crossing, pedestrians might thank the vehicle/driver via a gesture. Henceforth, this is called the Cross scenario. In these scenarios, the AV could thank the pedestrian or acknowledge that it has perceived the "thank you" of the pedestrian (henceforth called feedback communication). This could lead to increased communication comfort.

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Therefore, in our experiment in Virtual Reality (VR; *N*=20), we focus on the research question:
What impact do the independent variables feedback communication of the AV, presence of (other) pedestrians, and scenario have on a pedestrian in terms of (1) mental workload, (2) perceived safety, (3) trust, (4) communication comfort, the (5) AV's perceived intelligence, and (6) the perceived intention of developers?

Contribution Statement: This work contributes to the body of knowledge on the design of efficient and pleasant eHMIs. We focus on an, in the field of eHMIs, underrepresented aspect of communication: feedback. First, we present the results of a structured literature survey regarding the focus of the research and the dependent variables. In the subsequently reported experiment, we showed that participants interacting with an AV clearly want to receive feedback and that this feedback, in turn, triggers a Halo-Effect, a well-known cognitive bias positively influencing non-related characteristics assessments based on one specific good characteristic, making the participants believe in higher intelligence of the AV.

2 RELATED WORK

This work builds on previous research on (interpersonal) communication and the work on eHMIs.

2.1 Interpersonal Communication

Interpersonal communication is a widely studied field since 1949 [61]. In interactional models, the position as sender or receiver of messages [59] is switched, e.g., in the Sender-Message-Channel-Receiver (SMCR) Model of Communication [7]. Further factors can be included [5], for example, social or cultural context. DeVito's interactive model [15] incorporates the factors context, feedback, and noise. As Richardson [55] put it: listening and feedback are essential for successful communication. Interpersonal communication was already used as a basis for the AV—pedestrian communication design In the field of eHMIs, Colley and Rukzio built their design space on this model and included these factors (e.g., affective communication) [11]. As feedback is essential for successful interpersonal communication, we investigated the effect of such communication in AV — pedestrian communication.

2.2 External Communication of AVs

For the substitution of driver-pedestrian communication, several modalities such as displays [23], LED strips [23, 42], movement patterns [72], projections [2] auditory or tactile cues [44] and combinations [44] or enhancement of the infrastructure [62] were proposed. The first works showed the usefulness of such communication in simple scenarios of one vehicle approaching one pedestrian. For example, Löcken et al. [41] compared six eHMI concepts. The *Smart Road* (based on work by Umbrellium [45]) was rated best. Also, there are still ongoing discussions about the need for external communication of AVs [48]. Nonetheless, Dey et al. [19] showed the support eHMIs can give in communicating the intent of AVs. Still, when communicated intent and driving behavior contradicted each other, participants relied more on the behavior than on the eHMI [19]. Currently, work on eHMIs tend towards unresolved questions such as overtrust [33] or scalability [14]. For example, Dey et al. [17] evaluated an eHMI additionally showing distance-dependent information indicating when the AV will stop. This improved pedestrians' comprehension of the AV's intention and increased willingness to cross. Additional work is undergone with accessibility in mind. For example, Colley et al. [12] included people with vision impairments in the design process. They found that additional auditory communication is necessary and can lead to improved communication quality also with seeing pedestrians.

While most work until now has focused on pragmatic communication, research has often included and now starts to focus more on hedonic (i.e., pleasurable, non-goal-oriented) communication (see [37, 58]). Some hedonic aspects of this communication were already addressed: politeness and respect [38] and traffic prosociality [58]. Sadeghian et al. raise the question "how 'mindful' and 'prosocial' automated vehicles (AV) behave and communicate" [58, p. 205]. Sadeghian et al. [58] evaluated the prosociality of the previously suggested on-road light projections. They found that such communication is trusted and perceived as clear, adequate, and effective. This is in line with previous work [3, 10, 12, 17, 41, 44]. They showed that communication is situation- and role-dependent. Being in the role of the pedestrian, communication was received worse than from the driver. Additionally, in scenarios where pedestrians are more vulnerable (e.g., unsigned crossings), communication was perceived better. Lanzer et al. [38] compared a Chinese with a German sample regarding different communication strategies concerning politeness for AVs. They employed these strategies in two scenarios: at a crosswalk and while the pedestrian was blocking the way on the street. The polite strategy lead to higher acceptance in both samples but only the Chinese sample complied more often to the polite request. In both studies (and in the broader research field on eHMIs), communication is still one-directional, i.e., from the AV to the pedestrian. Therefore, we present a study on bidirectional communication [38, 58].

2.3 Analysis of the Communication Evaluation in eHMI Research

As we wanted to measure the effects of feedback communication, we first determined currently employed measurements for eHMIs and AVs in general. Therefore, we queried the proceedings of the five most cited Human-Computer Interaction venues, according to Google scholar [26]. Due to their focus on (future) mobility, we also retrieved publications from the *Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutoUI)* [4] and the *International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI)* [46]. We considered publications from the last ten years (01/2010 - 10/2020). The first and second authors carried out the literature search and categorization. Our exclusion criteria were: (1) eHMIs on AVs must be the main focus of the work, (2) the publication must contain some form of user study regarding eHMIs, and (3) either system (i.e., the AV) or communication must be evaluated. The search query for each conference or venue in the respective digital library was: `"query": AllField:("external communication" OR "eHMI" OR "eHMIs") "filter": Conference Collections: [Conference / Venue]`. First, the title and the abstract were screened to determine the research focus of the paper. Then, the full text was analyzed. Both authors evaluated all publications. Disagreements among the authors were resolved via discussion. We found and screened 45 publications and excluded 30 of them. 18 of the 30 exclusions were based on the focus not being on AVs and eHMIs and 12 were excluded as they did not present a user study evaluating AV or communication (e.g., [11]). The remaining 15 papers were analyzed regarding the evaluated measurements on the communication and the AV. Our literature search led to the following results:

We found that either only the communication (8 times) or communication and the AV (6 times) were investigated. For the AV, measurements were included that are only partly related to the system. For example, trustworthiness (e.g., in [13]) is a characteristic of a system but trust (e.g., in [10, 13, 21, 33, 35, 41]) is not. Trust is a relationship [30], which is dependent on potentially a variety of characteristics including situation [34] or personal disposition [36]. As measured by Lanzer et al. [37], compliance and acceptance also describe a relationship towards the AV. Communication was evaluated using numerous aspects. There seems to be no consensus on appropriate measurements. However, pragmatic (including efficiency, clarity, etc.) and hedonic (including aesthetics, novelty, pleasantness, etc.) aspects of communication were often measured. This analysis showed that mostly only the evaluation is examined. Therefore, we also focused on these aspects in our subsequent experiment.

3 METHOD

To evaluate the feedback communication effects, we designed and conducted a within-subject study (*N*=20).

3.1 Study Design

Typical scenarios for communication involving gestures include waving a driver to go on as one does not want to cross the street and crossing and saying thank you for letting one cross [39]. This led us to the factor *scenario*. As the behavior is dependent on the mere presence of other people (see "Mere Presence Theory" [28, 70]) and participants were included in the bi-directional communication, which might be perceived as unusual or even wrong, we added the factor *presence of (other) pedestrians*. In the case of other pedestrians being present, they were implemented as a group of people standing at the opposite curb (see Figure 2 (3)).

The study, therefore, was designed as a $2 \times 2 \times 2$ within-subjects, repeated measures experiment. The independent factors were *scenario* (**stand**: waving vehicle through or **cross** with saying "thank you"), *presence of pedestrians* (yes/no), and *feedback* (yes/no). The factor *feedback* corresponds to the AV responding to the gesture of the participant. With *feedback*, the AV will present "Thank you" in the Stand and "You're Welcome" in the Cross scenario. Therefore, the study resulted in 8 conditions (4 per scenario). Additionally, a baseline for both scenarios was administered. In the baseline, a human driver gesticulates that the participant can cross and then gesticulates, depending on the scenario, "thank you" or "you're welcome"; without pedestrians present. Therefore, we were able to compare the feedback communication of a human driver with the AV's feedback. Our hypotheses (H) were:

H_1: The presence of pedestrians will reduce the comfort of communication.

H_2: Feedback communication of an AV will, compared to the person's, lead to less comfort.

H_3: With feedback communication of the AV, trust in the communication and the AV will increase.

H_4: With feedback communication, the perceived intelligence of the AV will be rated higher (showing a Halo-Effect).

H_5: Feedback will be rated higher in the Stand scenario.

3.2 Materials

We implemented a VR study in Unity [65]. In the simulation, vehicles are approaching and driving past the participant. The simulation provided typical city background noise. An HTC Vive Pro was used. An unsigned crossing was chosen as previous work showed that communication was perceived better in such situations, potentially due to the increased vulnerability compared to scenarios with traffic lights [58]. Gestures of the participants were detected using a Microsoft Kinect (worked 133 / 200 times). In the case of detection failure, the experimenter was able to trigger the detection in a Wizard-of-Oz style (67 times, the gesture was often performed indistinctly). Gesture recognition via a Kinect was implemented with the goal of increasing execution objectivity (reduced dependence on investigator). After two vehicles from the left and one from the right drove past, the fourth AV stopped to let the participant pass. The AV signalized its intention to stop 30m before reaching the pedestrian. Due to space constraints, we added a gain factor of 1.7 in the straightforward and sideways (not height) axis. An overview and two participants are shown in Figure 1.

The eHMI concept is based on previous work by Dey et al. [20] who showed that gaze moves from the street to the windshield during the vehicle's approach. Dey et al. [17], therefore, also included an eHMI in the windshield. Such windshield displays already are feasible [50]. We employed intention-based messages (i.e., "stopping"), as these are recommended by the ISO 23049:2018 [1]. (Spoken) Text was found to be the least ambiguous [9, 12, 24].

3.3 Measurements

The system logged the position of the participant with 10 Hz. Additionally, we logged the duration to cross in relation to when the AV came to a halt in the Cross scenario. An additional objective measurement was the timing of the gesture (time and distance to vehicle).

After each condition, participants filled out a questionnaire asking them to rate subjective mental load using the mental load subscale of the raw NASA-TLX [29] on a 20-point scale and perceived safety using four 7-point semantic differentials from -3 (anxious/agitated/unsafe/timid) to +3 (relaxed/calm/safe/confident) [21]. Regarding the communication quality, the short version of the User Experience Questionnaire (UEQ-S) [60] with the subscales pragmatic and hedonic quality was used. Additionally, participants were asked on 7-point Likert scales how much they trusted the communication and, using seven-point semantic differentials, several aspects of the communication: unfriendly/friendly, impolite/polite, ambiguous/unambiguous, unnatural/natural, machine-like/human-like (see [53]), inadequate/adequate (see [58]). Regarding the AV, we

Component Examined	**Publications** + [References]	Examined Aspects + [References]	
		System	Communication
System	**1:** [37]	Trust [37], Compliance [37], Acceptance [37]	X
Communication	**8:** [3, 16, 17, 31, 40, 47, 48, 67]	X	Intuitiveness [16], Pleasantness [3], Comfort [3], Perceived Safety [3], Clarity [40], Attractiveness [17], Acceptance [67], Perspicuity [17], Efficiency [17], Dependability [17], Stimulation [17], Novelty [17], Interaction Quality [47, 48], Intent [47, 48], Understandability [31], Visibility [31], Aesthetics [31]
Communication & System	**6:** [10, 13, 21, 33, 35, 41]	Trust [10, 13, 21, 35, 41], Trustworthiness [13], Acceptance [21, 41], Reliability [13], Confidence [33]	Comprehensiveness [10, 13], Unambiguity [10, 13], Pragmatic & Hedonic Quality [21, 41], Trust [33], Clarity [35], Visibility [35], Perceived Safety [41]

Table 1: Publications analyzed by component and research aspect. Most work focused on communication per se, but some works included factors relevant to the system (i.e., the AV).

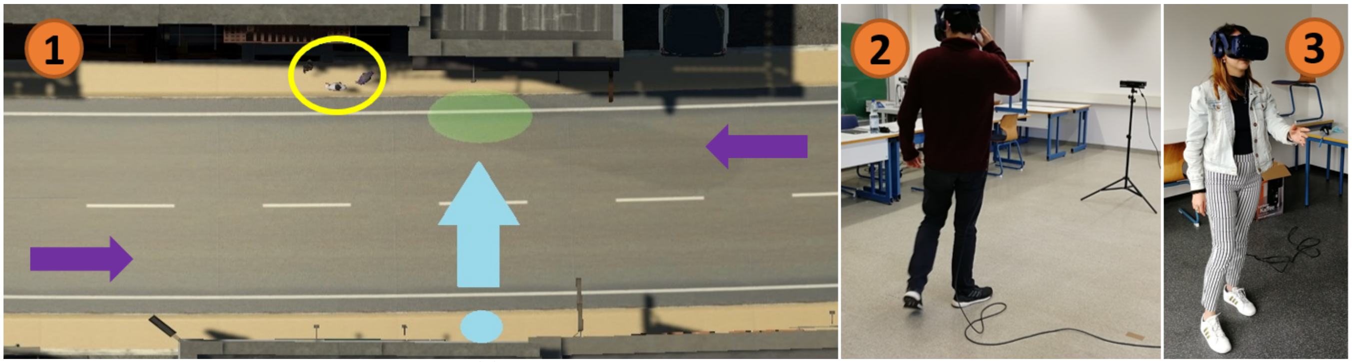


Figure 1: Scene overview and participants. (1) shows the overview over the scene: the lila arrows show the direction of the approaching vehicles. The yellow circle shows the position of the other pedestrians. The blue circle and arrow shows the participant's position and direction. (2) shows a Kinect and a participant gesturing "Thank you". (3) shows a participant waving the vehicle through.

Figure 2: VR simulation. (1) shows the baseline with the human driver, (2) shows the German "Stopping" (in line with the recommendation of the ISO 23049:2018 technical report [1]), (3) shows "Thank you" together with other pedestrians present on the other roadside, and (4) shows "You're Welcome". The green waypoint is shown in (2) and (4) on the right.

measured trust on a 7-point Likert scale and perceived intelligence using Warner and Sugerman's intellectual evaluation scale [68], a proposed measurement for robots [6]. Also, we measured the *Intention of Developers* subscale of the Trust in Automation subscale by Körber [36]. This subscale uses two 5-point Likert scale items ("The developers are trustworthy." and "The developers take my well-being seriously.")

Finally, participants were asked about their assessment of the communication regarding necessity, reasonability, and comfort on individual 7-point Likert scales. Participants were also asked for open feedback and to assess the frequency of occurrence for the scenarios. Additionally, participants were asked to rank their preference between *no communication*, *communication with*, and *communication without feedback*.

3.4 Procedure

After providing informed consent and receiving an overview of the study, participants filled out a demographic questionnaire. Afterwards, participants were able to adjust the VR headset. Then, participants were randomly assigned to the conditions via a Latin Square. Participants were, for one scenario, instructed to wave the vehicle to go on and in the other to reach their goal (a position indicated by a green waypoint; see Figure 2) on the other side of the road as soon as they feel safe to cross and to thank the vehicle for letting them pass. The scenario Stand was introduced as: "You want to stop on your side of the road. However, if a car stops to let you cross the street, your task is to wave the car through." The scenario Cross: "You want to cross the street at the crosswalk. Your destination is the green marked zone on the other side of the road. To get there, you wait until a car stops and lets you cross the street. In addition, your task is to thank the stopping car by gesture." Participant experienced every condition one time. After every condition, participants filled out the questionnaires described in Section 3.3. Subsequently, participants were informed about the study objectives and were compensated with 8€. Each session lasted approximately 50 min. 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

We used Friedman's ANOVAs (due to non-parametric data) to compare the ten conditions. We investigated main and interaction effects (IEs: two-way and three-way) of *scenario* × *pedestrian presence* × *feedback*. For the non-parametric data [63], we used the factorial non-parametric analysis of variance (NPAV) provided by Lüpsen [43] and included a random intercept for participants for each dependent variable because of the hierarchical nature of the data (measurements nested within participants). For post-hoc tests, Bonferroni correction was used. The figures show the described effect in bold lines. Effect sizes were calculated using Rosenthals's formula [56]. We used Version 4.0.5 of R with all packages up-to-date as of May 2021. RStudio Version 1.4.1103 was used.

4.1 Participants

Prior to the experiment, we computed the required sample size via an a-priori power analysis using G*Power [22]. To achieve a power of .95, with an alpha level of .05, 20 participants should result in medium effect size (0.25 [25]) in a within-factors repeated measures ANOVA.

Participants were recruited via mailing lists, social media, and notice boards. The sample consisted of N=20 (10 female, 10 male) participants with an average age of M=25.60 (SD=8.31). Participants reported medium interest in AVs (M=3.85, SD=1.18), medium belief that AVs will ease their lives (M=3.65, SD=.99), and were unsure about whether AVs would become reality by 2030 (M=3.65, SD=1.04). Participants showed medium propensity to trust [36] before (M=2.97, SD=.68) and after the experiment (M=3.07, SD=.72). A Wilcoxon Signed Rank test showed no significant difference between the two measurements.

4.2 Trust, Perceived Safety, and Cognitive Load

Friedmans's ANOVAs found no significant mental workload differences, perceived safety, or trust towards the communication and the AV. Regarding trust, the NPAV showed a significant effect of *feedback* on trust towards the communication ($F(1,19) = 7.07$, p=.015, r=-0.19, Z=-2.43) and on trust towards the AV ($F(1,19) = 4.51$, p=.047, r=-0.16, Z=-1.99). In both cases, trust was significantly higher with feedback communication. The NPAV found no significant effects on mental workload but a significant effect of *feedback* on perceived safety ($F(1,19) = 5.64$, p=.028, r=-0.17, Z=-2.19). Perceived safety was higher with feedback communication (M=2.60, SD=.55) than without (M=2.32, SD=.91).

4.3 Quality of Communication

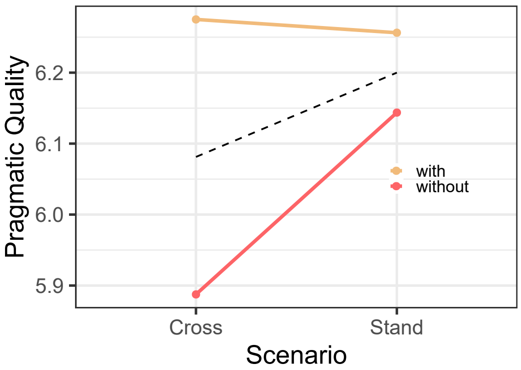


Figure 3: IE of *scenario* × *feedback* on pragmatic quality.

A Friedman's ANOVA showed no significant effect on pragmatic quality. It did, however, show a significant effect on hedonic quality (χ^2 (9)=57.2, p<.001). Post-hoc tests showed that the baseline communication (human driver) of the scenario Cross was rated significantly worse in terms of hedonic quality compared to the same scenario with the AV *communicating with feedback* and no pedestrians present. Post-hoc tests also showed that the baseline communication (human driver) of the scenario Stand was rated significantly worse compared to all other communication in this scenario except in the no pedestrians and no feedback condition.

The NPAV showed a significant IE of *scenario* × *feedback* on the pragmatic quality of the communication ($F(1,19) = 5.07$, p=.036; see Figure 3). Pragmatic quality was rated higher with feedback than without. However, the difference was less in the Stand scenario.

The NPAV also showed a significant effect of *feedback* on hedonic quality ($F(1,19) = 18.37$, p<.001, r=-0.28, Z=-3.54). Hedonic quality was significantly higher with feedback (M=4.45, SD=1.49) than without (M=4.09, SD=1.41). The NPAV also showed a non-significant IE of *pedestrians* × *scenario* ($F(1,19) = 4.11$, p=.057; see Figure 4). With pedestrians, hedonic quality was rated lower in the Cross scenario, but higher in the Stand scenario.

Figure 4: Non-significant IE of *pedestrians* × *scenario* on hedonic quality of the communication.

Regarding the single items assessing the communication, results of the Friedman's ANOVAs are shown in Table 2, and results of the NPAV concerning feedback are shown in Table 3. Presenting feedback lead to participants rating all items significantly better except Naturalness.

Variable	Friedman's ANOVA	χ^2 (9)=	Post-hoc (Bonf.)
Appropriateness	p=.03*	18.1	-
Human-likeliness	p<.001***	59.4	1,2,4, 6, 7 < 5; 1, 2, 6,7 < 10;
Naturalness	p=.04*	17.3	-
Friendliness	p<.001***	34.2	2 < 8
Clarity	p=.006**	22.9	-
Politeness	p<.001*	39.3	1, 2, 6, 7 < 8; 7 < 9

Table 2: Results of Friedman's ANOVAs regarding single items. The post-hoc results resemble the conditions (1=Cross, *without* ped., *without* feedback; 2=Cross, no ped., *with* feedback; 3=Cross, *with* ped., *with* feedback; 4=Cross, *with* ped., *with* feedback; 5=Cross, no ped., *with* feedback - Baseline; 6=Stand, *without* ped., *without* feedback; 7=Stand, no ped., *with* feedback; 8=Stand, *with* ped., *with* feedback; 9=Stand, *with* ped., *with* feedback; 10=Stand, no ped., *with* feedback - Baseline).

Variable	F-value	p-value	Effect size	with	without
Appropriateness	F=11.18	p=.003**	r=-0.23	M=6.01, SD=1.06	M=5.48, SD=1.22
Human-likeliness	F=14.91	p=.001**	r=-0.26	M=3.81, SD=1.47	M=2.95, SD=1.02
Naturalness	F=3.55	p=.07	r=-0.14	M=5.06, SD=1.44	M=4.69, SD=1.40
Friendliness	F=29.18	p<.001***	r=-0.33	M=5.79, SD=1.08	M=4.63, SD=1.31
Clarity	F=6.94	p=.016*	r=-0.19	M=6.25, SD=1.01	M=5.78, SD=1.40
Politeness	F=4.21	p<.001***	r=-0.35	M=5.61, SD=1.22	M=4.38, SD=1.30

Table 3: Single item communication measurements (mean, standard deviation, all *F(1,19)*) with and without feedback.

The NPAV found a significant IE of *scenario* × *pedestrians* ($F(1, 19) = 4.65$, p=.04; see Figure 5a) on communication clarity. In the Cross scenario, clarity was rated lower without pedestrians than with. In the Stand scenario, however, clarity was rated higher without pedestrians.

The NPAV also found a significant effect of *pedestrians* ($F(1, 19) = 5.38$, p=.03, r=-0.17, Z=-2.15) and a significant IE of *feedback* × *scenario* ($F(1, 19) = 6.59$, p=.02, see Figure 5b) on communication politeness. Politeness was rated lower in the Stand scenario without feedback, but higher with feedback, compared to the Cross scenario. Without pedestrians (M=5.14, SD=1.31), communication was rated significantly more polite than with pedestrians (M=4.85, SD=1.48).

4.4 Autonomous Vehicle's Perceived Intelligence and Intention of Developers

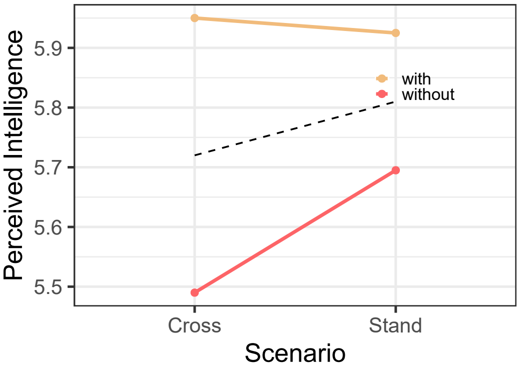


Figure 6: IE of *feedback* × *scenario* on perceived intelligence.

A Friedman's ANOVA showed a significant difference in perceived intelligence (χ^2 (9)=26.0, p=.002). Post-hoc tests showed that the AV was rated more intelligent (M=6.09, SD=.80) in the Cross scenario with pedestrians and with feedback compared to the Cross scenario without pedestrians and without feedback (M=5.38, SD=.95).

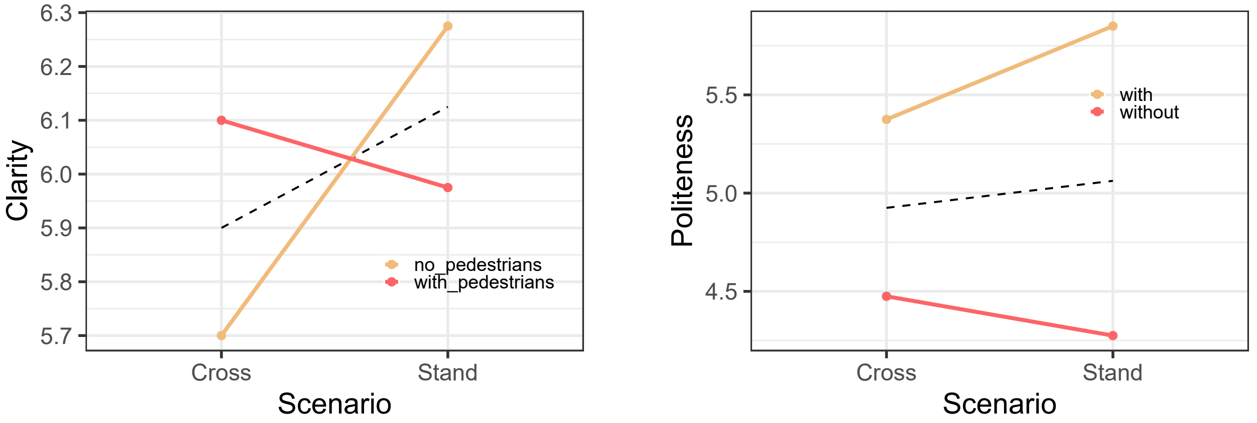
The NPAV showed a significant effect of *feedback* on the perceived intelligence of the AV ($F(1, 19) = 17.99$, p<.001). It also showed a significant IE of *feedback* × *scenario* on the perceived intelligence of the AV ($F(1, 19) = 5.72$, p=.027; see Figure 6). Perceived intelligence was higher in both scenarios with feedback communication. However, perceived intelligence was higher in the scenario Cross without feedback communication and was slightly lower in the scenarios with feedback communication.

A Friedman's ANOVA showed a significant difference in the assessment of the intention of developers [36] (χ^2 (9)=35.3, p<.001). Post-hoc tests, however, showed no significant differences.

The NPAV showed a significant effect of *feedback* on the assessment of the intention of developers [36] ($F(1, 19) = 10.44$, p=.004, r=-0.23, Z=-2.85) and of *scenario* ($F(1, 19) = 6.45$, p=.02, r=-0.18, Z=-2.33). The intention of the developers was perceived significantly higher with feedback communication (M=4.02, SD=.74) than without (M=3.81, SD=.72). The intention was rated significantly higher for the scenario Stand (M=3.96, SD=.73) than for the scenario Cross (M=3.86, SD=.74).

4.5 Gesture Timings and Crossing Duration

We measured the timings of the gestures and the distance between the participant and the approaching vehicle at the timing of the gesture. 5 data points had to be excluded due to technical difficulties in the logging process. The distance between the participant at the curb and the AV when standing was 5.13m. The NPAV showed a significant effect of *scenario* ($F(1, 19) = 199.15$, p<.001) for the distance between AV and participant. In the Cross scenario, the distance (M=4.58, SD=.33) was significantly lower than in the Stand scenario (M=5.19, SD=.47). Therefore, we also investigated the data per scenario but found no significant differences. We also determined how many participants waved the vehicle through before



(a) IE of *scenario* × *pedestrians* on communication clarity. **(b) IE of *feedback* × *scenario* on communication politeness.**

Figure 5: IEs on communication clarity and politeness.

the AV came to a halt (i.e., how many times was the distance below 5.13m). 37 / 80 data points were over the threshold of 5.13m, therefore, approximately half of the participants waved before the vehicle came to a stop.

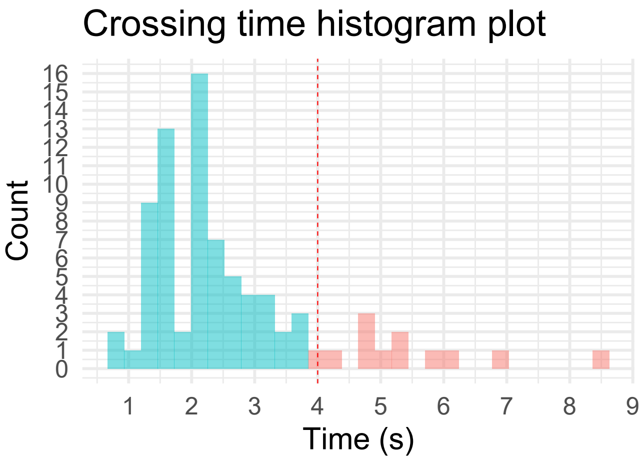


Figure 7: Crossing time histogram with the threshold of 4s needed to cross the street. Blue shows values below the threshold.

Crossing duration refers to the timing the participant reached the other side in relation to a halt in the Cross scenario. Negative values would indicate that participants reached the waypoint before the AV came to a halt. Values ranged from 0.90s and 8.60s (*M*=2.61, *SD*=1.36). The NPAV found no significant effects. For the 5.37m to the waypoint, we needed ≈ 4s (see Figure 7; ≈ 1.4 m/s is the preferred walking speed for normal-weight people [8]). 68 / 80 data points were below this threshold, showing that most participants started to cross before the AV came to a halt.

4.6 Scenario Prevalence, Preference, Model Association, Necessity, Appropriateness, and Open Feedback

On 7-point Likert scales, participants reported a medium prevalence of the waving through of vehicles (*M*=3.15, *SD*=1.04) and a high prevalence of thanking drivers for letting them cross (*M*=4.80, *SD*=.95).

After all conditions, participants ranked the options *no communication*, *communication without feedback*, and *communication with feedback*. A Friedman's ANOVA showed a significant difference in the mean rankings for the participants (χ^2 (2)=38.1, p<.001). Post-hoc tests showed that all differences were significant. The *communication with feedback* received rankings indicating the highest preference, i.e., the lowest mean (*M*=1.05, *SD*=.22). This was followed by *communication without feedback* (*M*=1.95, *SD*=.22) and *no communication* (*M*=3.00, *SD*=.00).

We also asked participants about brand association to determine potential biases (as appearance influences willingness to cross [18]). All participants were reminded of a sportive vehicle, i.e., Tesla (4), Porsche (4), Audi (3), Maserati (2), Mercedes (2), Mazda (2), Ferrari (1), Aston Martin (1), no brand (1). However, we could not derive any bias from related work regarding this appearance.

The mean value for the item rating the intention communication as necessary (*M*=6.82, *SD*=.53) and appropriate (*M*=6.59, *SD*=.62) was very high. Feedback communication was rated as necessary (*M*=4.47, *SD*=.1.59) and highly appropriate (*M*=6.06, *SD*=.90).

Ten participants highlighted the feedback as positive (e.g., "when the car says thank you, makes you happy", "I liked it when the car showed a reaction to my actions which made it appear more natural to me"). At the same time, participants clearly stated that once encountered, not having feedback made them feel uncomfortable (e.g., "I felt like something was missing and wrong if the car did not react to my gestures after I experienced it otherwise"). Three participants mentioned auditory feedback as an improvement proposal. Quotes were given in German and were translated.

5 EVALUATION OF HYPOTHESES

H_1: The presence of pedestrians will reduce the comfort of communication. Comfort was operationalized using the UEQ-S [60] and six single items. The significant effect of pedestrian presence on perceived politeness shows that some aspects of comfort seem to be influenced by pedestrian presence. However, we also believed appropriateness to be affected negatively by the presence of pedestrians. Therefore, we only partially accept the hypothesis.

H_2: Feedback communication of an AV will, compared to the person's, lead to less comfort. Friedman's ANOVAs showed that, as expected, human-likeness was rated significantly higher compared to most conditions with AV communication. However, the other assessments with regard to comfort were not affected. Regarding hedonic quality, the Friedman's ANOVA and post-hoc tests revealed that the human driver's communication was even rated worse for the scenario Cross. Therefore, we reject this hypothesis.

H_3: With feedback communication of the AV, trust in the communication and the AV will increase. A significant main effect of feedback communication was shown for trust towards the communication and the AV itself (see Section 4.2). Therefore, we accept this hypothesis.

H_4: With feedback communication, the perceived intelligence of the AV will be rated higher (showing a Halo-Effect). A significant main effect of feedback communication was shown for perceived intelligence (see Section 4.4). Therefore, we accept this hypothesis.

H_5: Feedback will be rated higher in the Stand scenario. We found significant main effects of the scenario for the intention of developers and unambiguity. We also found IEs including scenario. From these, we derive that *feedback* is only rated better in the Stand *scenario* for some aspects such as politeness (e.g., see Figure 5b). It also seems to be related to other factors such as *pedestrians' presence* (e.g., see Figure 5a). Therefore, we partially accept this hypothesis.

6 DISCUSSION

As suggested in the literature [11, 49], our results show the necessity to enable bidirectional eHMIs. It seems reasonable to assume that pedestrians will either oversee the autonomous nature [48] or will want to receive feedback from AVs. While we told participants to gesture towards the AV, we believe this happens naturally in future traffic. Our results show that participants believe such feedback communication to be necessary and highly appropriate.

6.1 Comparison Communication of Human Driver vs. Autonomous Vehicle

We hypothesized that the communication of the human driver will lead to higher comfort due to the familiarity with it. However, our results only showed a significantly higher human-likeness. Even contradictory to our hypothesis, hedonic quality was rated significantly lower than the communication of the human driver. Hedonic quality was measured using the UEQ-S [60] with the semantic differentials boring/exiting, not interesting/interesting, conventional/inventive, and usual/leading edge. Therefore, we explain the higher hedonic quality with the questionnaire structure: conventional/inventive, and usual/leading edge are rated with lower scores for the familiar communication of the human driver. This is not necessarily negative but shows the futuristic impression eHMIs elicit. Nevertheless, our data show that eHMI could be perceived as a sufficient substitution (or even enhancement) of current driver—pedestrian interaction.

6.2 Scenario Dependency and Pedestrian Awareness

The scenarios with the gesticulation were rated as medium frequent (Stand: *M*=3.15, *SD*=1.04) to frequent (Cross: *M*=4.80, *SD*=.95). Several measurements indicated a dependency on the scenario (e.g., see Figure 5b and Figure 5a). This also holds for pedestrian presence (e.g., see Figure 5a) even though many participants stated after the experiment that they had not consciously noticed the pedestrians on the opposite side. Clarity was lower in the crossing scenario when pedestrians were present. This lower clarity measurement indicates the scalability issue already mentioned in the literature [14, 41]. However, pedestrian presence had only a direct effect on perceived politeness, therefore, partially invalidating our hypothesis. Thus, this does not seem to be a factor opposing feedback communication. We attribute the higher ratings in the Stand scenario to two factors. Firstly, the communication of the AV is always plainly visible, resulting in a higher exposure time. And secondly, in the Stand scenario, the participant is the recipient of the thanks of the AV, potentially making the participant feel better, an effect shown in interpersonal communication [51].

6.3 Crossing Decision

Several works used a *willingness-to-cross* measurement when examining eHMIs [17, 20, 32]. Compared to this, we measured the actual crossing time in relation to when the AV approached (see Figure 7). We found that 68 / 80 decisions to cross were carried out before the AV came to a halt. As shown in the Figure 7, most decisions were made ≈ 2s before the AV arrived. Dey et al. report for this timing a willingness-to-cross of about 75% [17]. Our data seems to be the first indicator for a threshold necessary in willingness-to-cross to actually turn into the decision to cross.

6.4 Halo-Effect of eHMIs

In the two presented scenarios, in which the pedestrian has to interact with an AV, participants rated feedback communication as highly appropriate, more human-like, friendlier, clearer, and more polite (see Table 3), among others. Additionally, in the conditions including feedback communication, the perceived intelligence was rated significantly higher. Furthermore, the intention of the developers [36] assessed with two items ("The developers are trustworthy" and "The developers take my well-being seriously") was rated significantly higher with feedback communication. Also, trust in the AV was significantly higher. From this, we assume that the Halo-Effect is at work. Previous work focused mainly on measurements that are only partly related to the system. For example, trustworthiness is a characteristic of a system, but trust is not. Trust is a relationship [30], which is dependent on potentially a variety of characteristics including situation [34] or personal disposition [36]. In contrast, we were able to show the Halo-Effect for perceived intelligence and even developers' attributed intention.

6.5 Design Guidelines and Practical Implications

The results show that bidirectional communication is useful and appreciated by the participants. Interpersonal communication today already includes affective messages. Our results indicate that such communication is beneficial for the acceptance of AVs. This allows for manufacturers to distinguish themselves and to potentially create a better traffic climate (see [58]). Therefore, we propose to include mechanisms for bi-directional communication as the sensory information will most likely be available to determine the relevant gestures. This is in contrast to the current ISO 23049:2018 technical report [1] which only encourages intent messages.

6.6 Limitations of the Study (Design)

Our study was limited by the number of participants (*N*=20). Additionally, as we used a VR simulation, external validity is difficult to assess. Participants were asked to gesture towards the AV. Therefore, participants were inclined to expect a reaction. One participant stated that "once I saw the feedback, it was very weird when it was missing". In a real scenario, it is unclear whether a pedestrian would perceive the feedback communication. Thus, it is not clear how participants would feel in real traffic when interacting with an AV via gestures. They could just miss the feedback. Nevertheless, our study shows that if bidirectional communication should be implemented (which was already suggested [11, 49] and which we believe to be important as pedestrians will interact with such novel technology at least in an introductory phase), feedback communication is necessary. Already, there is research into recognizing pedestrian gestures (e.g., [71]) indicating that bidirectional communication will be feasible. We used an intention-based message as recommended by the ISO 23049:2018 technical report [1] for the AV — pedestrian communication, however, this is not the typical communication between a driver and a pedestrian. Therefore, the wave gesture was used by the human, leading to a confounding factor for the comparison between human driver and AV communication. Finally, we employed a within-subject design to minimize random noise. However, as became prevalent in our study, having encountered feedback lead to an altered perception of communication without feedback. Therefore, there was a learning effect which must be considered in future studies.

7 CONCLUSION

In conclusion, in a VR study (*N*=20), we found that if bidirectional communication between AVs and pedestrians is enabled, feedback communication is socially acceptable and preferred. AV—pedestrian communication via eHMIs could benefit from mimicking interpersonal communication. We showed that the communication via eHMIs triggers a Halo-Effect and, therefore, is relevant for the perception, and possibly, the acceptance of AVs. This work helps to safely introduce AVs in realistic scenarios and increase their acceptance.

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