Pedestrian Groups Matter: Unraveling their Impact on Pedestrian Crossings when Interacting with an Automated Vehicle*

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***Abstract*—Since future mobility will change into mixed traffic, the communication approach of automated vehicles should consider multiple human receivers. This virtual reality study investigates the external communication of an automated vehicle in interactions with multiple pedestrians. Involving 42 participants, the study explores the impact of a simulated pedestrian group at the roadside, a seldom-explored aspect in current research on human-vehicle interactions. Results reveal a significant influence of the additional pedestrian group on participants' behaviors and perceptions, emphasizing the need for nuanced communication strategies in automated vehicle design. This paper contributes to understanding social factors in automated vehicle interactions, providing valuable insights for future research and the development of human-centric automated vehicle communication systems.**

I. Introduction

With the growing prominence of automation in road traffic, the integration of automated vehicles (AVs) introduces a dynamic mix of vulnerable road users, conventionally operated vehicles, and AVs [1]. This convergence necessitates interactions among these traffic entities [2]. Current research primarily focuses on road users' safety, traffic efficiency, and alleviating responsibilities from human drivers. In scenarios where AVs and at least one human road user share the same space, the need for clear communication between them is evident [3, 4].

For a vehicle approaching a pedestrian poised to cross the road, communication occurs through two channels: implicit and explicit. Implicit communication, facilitated by dynamic human-machine interfaces (dHMIs), encompasses cues of vehicle movement that all road users can interpret, such as acceleration, speed, braking distance relative to the pedestrian, and trajectory [5]. On the other hand, explicit communication involves additional signals beyond basic vehicle movements, indicating a human driver's or AV's awareness or intent [5]. Examples in conventional traffic include hand gestures, eye contact, head nodding, or external human-machine interfaces (eHMIs) like turn signals [1, 6].

For AVs, eHMIs may replace traditional human gestures projecting from or installed on the vehicle surface [6]. These interfaces enable AVs to convey information about their status or intentions to other road users, potentially enhancing traffic efficiency and perceived pedestrian safety [7–9]. Numerous eHMI concepts have been explored in the literature, showing promise in reducing pedestrian decision time and fostering comfort, trust, and acceptance toward AVs, e.g. [10–12].

This paper concentrates on the communication dynamics between AVs and multiple pedestrians. While past research often focuses on one-to-one scenarios, such as an AV communicating with a single pedestrian at the roadside [7, 13], this study delves into more realistic scenarios involving multiple pedestrians or pedestrian groups [14]. Previous studies indicated that the behavior of one pedestrian influences others, with the initiation of crossing often following the lead of fellow pedestrians [14, 15]. Despite the evident impact of pedestrian groups on crossing behavior, there is a lack of literature exploring the interaction between AVs and pedestrian groups [16, 17].

In the literature, the specific influence of a pedestrian group on the crossing behavior of an individual in front of an AV remains underexplored [18]. Addressing this gap, studies by [17], [19], and [20] have contributed valuable insights. Results of the virtual reality (VR) study by [17], involving twelve participants, suggested that the presence of a pedestrian group could influence individuals, although no statistically significant impact on behavior was observed. Conversely, [19] found that the mere presence of additional people did not alter the participants' behavior. However, simulated pedestrians' active crossing impacted decision-making and crossing duration. Notably, this study was limited to an LED-based eHMI concept and involved 18 participants exposed to additional factors such as timer based communication [19]. Reference [20] observed that the road crossing of a simulated group in front of a moving AV resulted in participants' quicker initiation of crossing and increased perceptions of safety, albeit with exposure to additional factors such as smartphone distraction.

This paper seeks to bridge this research gap by systematically examining the behavior of pedestrian groups interacting with AVs, ensuring a robust sample size and eliminating extraneous factors. To achieve this, a comprehensive communication concept derived from existing literature is the foundation for this investigation.

II. Objectives

To address the described research gap, the following research questions are formulated:

- To what extent is the derived communication concept suitable for facilitating interactions between pedestrians and AVs?
- How do participants' behavior and perceptions of AV communication differ between single scenarios and those involving a simulated pedestrian group?

*This research was funded by the German Federal Ministry of Education and Research (BMBF) within the project Wies´n Shuttle (FKZ 03ZU1105AA) in the MCube cluster.

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III. METHOD

A. Sample

In this study, 42 participants initially took part. However, three participants encountered language communication issues, and seven faced technical difficulties, resulting in 32 valid datasets for addressing the research questions. The participants' mean (*M*) age was 32.52 years, with a standard deviation (*SD*) of 11.58 years and an age range from 22 to 60 years. Gender distribution was balanced, with 50% of the participants being female. Eleven participants reported using visual aids while driving; two had red-green visual impairment. All participants, except one, held a valid driver's license. The average time since obtaining a driver's license was 15 years, indicating a diverse range of driving experiences within the group, as evidenced by the *SD* of 11.49 years and a range from one to 43 years. The recruitment and execution of the study occurred at the Technical University of Munich's campus in Garching, with participants receiving €10 as compensation for their involvement.

B. Experimental Environment

A VR experiment was conducted to investigate variations in pedestrian crossing behavior between solo and group scenarios. Utilizing VR allowed participants to engage with scenarios realistically but safely while enabling researchers to collect comprehensive data. VR studies, noted for their effectiveness in studying eHMIs [11, 17], have been validated for full-motion task research [21]. The virtual environment (see Fig. 1) was crafted using the game engine Unity. The virtual vehicle model, a VW T7 Bus from HUM3D, and the Population System Asset from aGlobex were integrated to represent the pedestrian group realistically.

VR goggles were utilized to immerse participants in the simulation. The Varjo Aero goggles were chosen for their advanced display technology, simulating human vision by rendering a high-resolution central area ("fovea") combined with a larger peripheral area, providing a natural VR experience with a 115° viewing angle. The goggles boasted a resolution of 2880 x 2720 pixels per eye, a refresh rate of 90 Hz, and real-time gaze capture through two pupil cameras, tracking gaze at a frequency of up to 200 Hz. [22]

C. Scenarios

The standardized test procedure for eHMIs by [3] limited the number of pedestrian crossing scenarios to minimize potential familiarization effects. The foundational scenario (see Fig. 2) was consistent across all conditions: Participants interacted with an AV while positioned on a roadside in an urban setting, with the task of safely crossing the road. The road comprised two lanes, each 3.50 m wide, mimicking dimensions found in certain German inner-city roads with a high frequency of bus-traffic encounters [23]. Sidewalks flanked both sides, accompanied by houses and parks, creating a typical cityscape (see Fig. 1). The participants' starting position was marked on the sidewalk using a manhole cover 0.50 m from the roadway. The AV approached from the left at a 30 km/h speed and initiated communication at 29.40 m—i.e. 3.53 s—from the participants.

Figure 1. View of the participants in the virtual environment with the pedestrian group on their left and an oncoming AV.

Communication modes involved the AV claiming the right of way (*AVfirst*) or granting pedestrians the right of way (*PEDfirst*). While the AV approached, participants experienced two conditions: either alone (*solo*) at the roadside or in the presence of a pedestrian group (*cG*). Combining these independent variables resulted in four distinct scenarios (see TABLE I). Each participant encountered all scenarios twice, presented in a randomized order.

D. Communication Concept of the Automated Vehicle

The communication strategy employed by the AV acknowledged multiple receivers—the individual participant and the pedestrian group. The communication concept must establish trust and efficacy among diverse road users in this evolving traffic scenario.

The primary objective is to convey the AV's intent and status clearly, fostering efficient and safe interactions, especially in the presence of a pedestrian group. The proposed concept integrates both implicit cues and explicit signals, recognizing their significance in effective communication [24, 25]. Implicit communication is crucial in designing effective communication strategies for AVs [6].

Before the AV initiated communication with pedestrians (t_{start}) and after completely passing them (t_{passed}), the vehicle communicated its automated state, differentiating itself from manual vehicles. The explicit communication component involved a 360° LED strip as an eHMI [8]. Fig. 2 illustrates a fully illuminated LED strip encircling the AV's windscreen and roof. The research identified cyan as a suitable color for marking automated vehicles, chosen for its neutral significance in road traffic and positive associations of safety and trust among pedestrians [7, 8, 26]. The RGB code for the LED strip was set to (0, 201, 255).

During the communication phase (from t_{start} to t_{passed}), the AV signaled pedestrian awareness through the LED strip [27]. In scenarios with a pedestrian group, separate areas were illuminated for the participants and the group [28]. To clarify the right of way, the AV initiated communication with

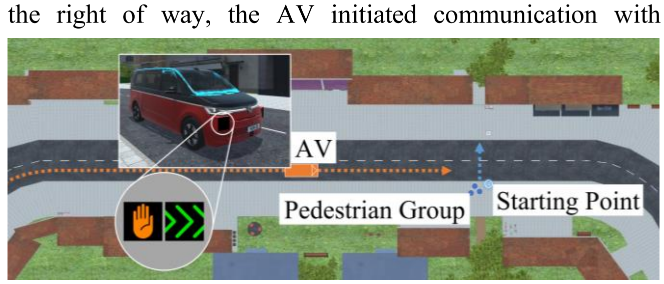

Figure 2. Bird´s eye view of the virtual environment with the AV approaching from the left and the pedestrian group present next to the participants' starting point. The AV is depicted communicating its automated state. The displays are able to signal *AVfirst* with an orange stop hand or *PEDfirst* with animated green arrows.

TABLE I. SCENARIOS.

	AV claiming right of way	AV granting right of way
Participants alone	*AVfirst_solo_1* *AVfirst_solo_2*	*PEDfirst_solo_1* *PEDfirst_solo_2*
Pedestrian group present [a]	*AVfirst_cG_1* *AVfirst_cG_2*	*PEDfirst_cG_1* *PEDfirst_cG_2*

a. The pedestrian group was crossing the street conform to the AV's communication. The abbreviation *cG* therefore stands for the presence of a conform acting pedestrian group.

pedestrians at t_{start}, utilizing dHMI and eHMI at 29.40 m from the participants. Alongside the LED strip, the eHMI featured two external displays directed at pedestrians [29], displaying symbols for AV intent rather than text [30–32].

In *AVfirst* scenarios, the display showed an orange [30] stop hand, signaling the AV's intention to halt [10, 11, 33] (see Fig. 2). For *PEDfirst* scenarios, animated green [30] arrows were displayed, indicating the AV's intent to yield [11, 34] (see Fig. 2).

The dHMI in *AVfirst* scenarios conveyed the AV's intent by maintaining a constant speed of 30 km/h [25, 30, 32, 35]. Additionally, a lateral offset of 0.50 m towards the middle of the road was implemented [25, 32, 36], with a maximum lateral acceleration of 0.40g [37].

As part of the dHMI in *PEDfirst* scenarios, the AV signaled a safe crossing through a lateral offset 0.50 m from the road edge [25, 32, 36]. The speed profile featured a two-step deceleration [24, 25, 36]. The initial step involved deceleration to 15 km/h, lasting 2.08 s, signaling the AV's intention to yield. The deceleration rate was set to -2.00 m/s², considering the comfort limit of vehicle occupants during deceleration [38]. Subsequently, the AV maintained a constant speed for a duration of 2.17 s. This timing aimed to align with the theoretical decision and crossing time of pedestrians on the AV's lane. Theoretical calculations assumed a pedestrian decision time of one second and a crossing time from the starting position to the middle lane of 3.25 s with a walking speed of 1.23 m/s [25, 39]. If pedestrians crossed within this time, the AV could accelerate back to 30 km/h without further deceleration. If not, the AV would need to decelerate further. To ensure safety, the AV's stopping point was set 3.00 m in front of the participants [25, 32]. Considering the safety distance and the distance required for the two-step deceleration, the AV initiated communication at 29.40 m from the participants.

E. Pedestrian Group

In *cG* scenarios, the presence of the pedestrian group was essential for addressing the research question concerning the potential influence of the pedestrian group on participants' crossing behavior. Throughout the study, the behavior of the pedestrian group consistently aligned with the instructions communicated by the AV (*PEDfirst* or *AVfirst*), ensuring no conflicts between AV communication and the pedestrian group's actions. The pedestrian group thus qualified as an additional interaction partner for the AV, given its strategic position and intention to cross.

The pedestrian group initiated their road crossing 1.00 s after t_{start} in *PEDfirst_cG* scenarios or 1.00 s after t_{passed} in *AVfirst_cG* scenarios. This behavior should reflect the theoretical behavior of pedestrians who immediately process the AV's communication and make the correct decision to cross (see D). Positioned 0.80 m to the left of the participant, with 0.80 m to the curb, this arrangement offered participants a clear view of the approaching AV and its communication. Simultaneously, the distance maintained a sense of connection, ensuring participants felt that the AV's communication was directed towards both the participants and the pedestrian group. Comprising three pedestrians [19, 20]—two male and one female person (see Fig. 1)—the group presented a cohesive visual unit through their spatial arrangement and synchronized movements.

F. Experimental Procedure

The research employed a within-subject design with repeated measurements, encompassing eight road crossings per participant, featuring a rotation among four distinct scenarios (see TABLE I.). Fig. 3 illustrates the procedural steps of the study.

Upon welcoming participants, the study began by signing consent forms and a demographic survey. Participants then donned the VR glasses and, post-eye-tracking calibration, immersed themselves in the virtual space. Following this, the experimenter guided participants through the virtual space, elucidating the specific sequence of movements from the starting point to the endpoint. Two initial test scenarios featuring a vehicle approaching from the left served to familiarize participants to VR dynamics, offer a sense of movement and address any procedural queries. Participants executed road crossings in both scenarios, followed by a survey with the experimenter. The main study commenced once participants were acquainted and had no further comments. The experimenter explained the test instructions: an AV would approach from the left, initiating communication, and participants were encouraged to cross the road after t_{start} when they deemed it safe. Measurements and scenario execution commenced, with the experimenter starting each crossing. After each road crossing, an intermediate survey was presented, capturing participants' immediate experiences, which were verbally communicated to the experimenter for recording. Participants remained within the VR environment between scenarios, avoiding interruptions. After completing all eight crossing scenarios, participants were asked to complete a final interview. This interview delved into participants' perceptions of the communication concept and the pedestrian group through a semi-structured format. To conclude, participants received their expense allowance and were bid farewell.

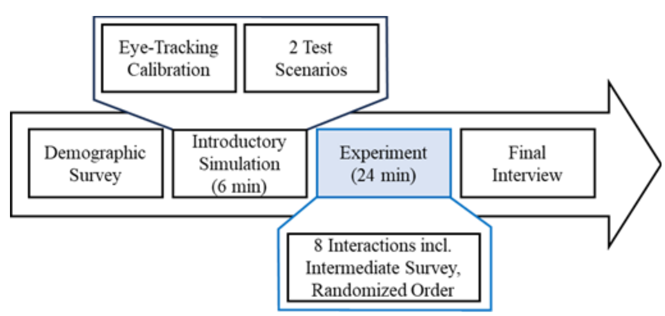

Figure 3. Experimental procedure. Adapted from [30].

G. Dependent Variables

Various dependent variables were considered as objective measures, encompassing the velocity of participants, crossing initiation time (CIT), crossing time (CT), and eye-tracking data. The participants' velocity was determined by calculating the derivative of their position within the VR environment [25, 32]. Analyzing velocity over time allowed for the identification of distinct behavior patterns.

CIT, representing participants' time to initiate (t_{init}) crossing after t_{start}, was calculated as CIT = t_{init} - t_{start} [25, 32]. Recognizing a forward movement of 0.50 m into the road as participants started to cross, CIT served as an indicator of how promptly pedestrians responded to communication from the AV. A low CIT reflected an unequivocal, easily understandable, and trustworthy communication concept, leading to swift responses and efficient traffic flow. Conversely, a prolonged CIT suggested an unclear or untrustworthy communication concept, inducing hesitation in pedestrians [25, 32].

Similarly, CT, denoting the time participants required to traverse the AV's lane (covering a distance of 3.50 m, i.e. $t_{crossed}$), was calculated as CT = $t_{crossed}$ - t_{init} [25, 32].

Eye-tracking data were systematically recorded for gaze analysis during the decision phase (from t_{start} to t_{init}). Areas of interest (AOIs) such as Target Area, AV, Pedestrian Group, and Other were defined. Given the dynamic nature of the AV and Pedestrian Group during scenarios, an overlapping of AOIs was considered. Visualization of these AOIs in Fig. 4 involved cuboid colliders adapted to object dimensions, moving in real-time with the objects.

Subjective measures play a crucial role in documenting phenomena that are not directly measurable through physical parameters. This study utilized qualitative interviews to gather subjective insights and quantitative assessments through questionnaires featuring Likert scales, quantifying personal perceptions and evaluations.

Following each scenario, participants were asked to assess their trust in the AV using the Trust in Automation (TiA) scale developed by [40]. Based on three questions on a 7-point Likert scale, it represents a trust scale tailored for the automotive context.

Additionally, after each scenario, participants were queried about their decision-making basis for crossing the road and their perceived components of the AV's communication.

Figure 4. AOIs for the gaze analysis (green: Target Area; orange: AV; blue: Pedestrian Group). The AV is depicted communicating *AVfirst*.

Both before and after the experiment, participants' general attitude toward the development of automated driving and their general trust in AVs were evaluated using a 5-point Likert scale.

Finally, the survey included an evaluation of the usefulness and satisfaction with the AV's communication concept using the van der Laan acceptance questionnaire (on a scale from -2 to 2) [41], an assessment of the overall impression of the communication concept, and a determination of the percentage of participants subjectively influenced by the presence of the pedestrian group.

H. Statistical Analysis

The initial data processing involved using MS Excel and MATLAB, while R [42] was employed for subsequent statistical analyses. The chosen significance level for all tests was set at $\alpha = 0.05$.

Linear mixed models [43] using the lme4 package [44] were employed to analyze CIT, CT, and TiA statistically. In these models, participants were included as a random effect to accommodate random individual variability. The fitting of models was executed using the Restricted Maximum Likelihood (REML) estimation method. The tests were conducted to explore the influence of factors, including the trial number (1 or 2), the presence of the pedestrian group, and AV communication type (*AVfirst* & *PEDfirst*). For CIT, separate statistical tests were performed for *AVfirst* and *PEDfirst* scenarios. Due to the divergent nature of the scenarios (*AVfirst* required the AV to pass participants before crossing, while *PEDfirst* allowed participants to cross since t_{start}), a direct comparison of CIT was deemed inappropriate.

To examine differences in participants' general attitude and trust before and after the experiment, a Wilcoxon signed-rank test was performed for each metric due to the non-normal distribution of the data.

IV. Results

Fig. 5 presents the velocity curves with the corresponding CIT for all interactions. In two instances (3.89 s & 4.08 s) out of 125 *AVfirst* interactions, the CIT was lower than 4.10 s when the AV passed the participants. Both occurrences involved the same participant who stepped onto the road as the AV approached, maintaining a distance of over one meter due to the lateral offset of the AV. Therefore, it is affirmed that, in *AVfirst* scenarios, participants crossed after the AV had passed. In *PEDfirst* scenarios, two behavior patterns emerged: the participants either crossed shortly after t_{start} or waited until the AV came to a standstill (6.34 s). More participants crossed directly after t_{start} both in the second trial compared to the first and when the pedestrian group was present compared to *PEDfirst_solo*.

In TABLE II, the CIT for all interactions is provided. For *AVfirst* scenarios, the mean CIT for the second interaction is lower than for the first, with participants crossing sooner when no pedestrian group is present, according to descriptive data. The linear mixed model confirmed a significantly shorter CIT in *AVfirst* scenarios for the second compared to the first interaction with a small effect ($\beta = -0.35$; $SE = 0.16$; $t = -2.19$; $p = 0.031$), indicating a 0.35 s earlier crossing in the second trial. The presence of the pedestrian group did not have a significant effect (β = -0.20; *SE* = 0.16; *t* = -1.27; *p* = 0.208). For *PEDfirst* scenarios, the mean CIT for the second interaction is also lower than for the first, and participants crossed sooner when the pedestrian group was present, as per the descriptive data. The linear mixed model confirmed a significantly shorter CIT in *PEDfirst* scenarios for the second compared to the first interaction with a small effect (β = -0.62; *SE* = 0.26; *t* = -2.34; *p* = 0.021), indicating a 0.62 s earlier crossing in the second trial. The presence of the pedestrian group had a significant effect with a medium effect (β = 0.85; *SE* = 0.26; *t* = 3.21; *p* = 0.002), indicating participants crossed 0.85 s sooner with the pedestrian group present.

The CT for all interactions is listed in TABLE II. The linear mixed model confirmed a significantly shorter CT for the second compared to the first interaction with a medium effect (β = -0.09; *SE* = 0.03; *t* = -2.63; *p* = 0.009), with participants crossing 0.09 s faster in the second trial. The presence of the pedestrian group also had a significant effect with a medium effect (β = 0.10; *SE* = 0.03; *t* = 3.05; *p* = 0.003), indicating participants crossed 0.10 s faster with the pedestrian group present. The factor communication mode (β = 0.02; *SE* = 0.03; *t* = 0.51; *p* = 0.610) did not result in significant differences in CT. The mean CT over all scenarios was 3.11 s (*SD* = 4.42 s), and the mean velocity of the participants in the middle of the road at $t_{crossed}$ was 1.26 m/s (*SD* = 0.14 m/s).

In Fig. 6, the results of the gaze analysis are presented by the percentage of AOIs looked at during the decision phase of the participants over time. In all scenarios, the percentage of AOI AV was the most looked-at target, with at least 66% combined (meaning the AOI alone, in addition to the AOI overlapping another AOI). In *AVfirst_cG* scenarios, participants focused on the AOI Pedestrian Group with only 4% combined, while in *PEDfirst_cG* scenarios, the same AOI had a more considerable impact with a combined 27%. In *PEDfirst_solo* scenarios, the AV was mainly focused on, while in *PEDfirst_cG* scenarios, the Pedestrian Group was looked at by all participants as it crossed the road between the participants and the AV. The AOIs Target Area and Other had a more considerable impact in *AVfirst* scenarios than in *PEDfirst* scenarios. In *AVfirst* scenarios, when the AV passed the participants at 30 m/h, the participants' gaze was directed more to undefined AOIs and the Target Area. Shortly before t_{passed}, the AOIs AV and Target Area overlapped due to the AV passing the participants and Target Area. In both *PEDfirst* scenarios, the two behavior patterns shown in Fig. 5 can be observed by the number of participants initiating their crossing and, therefore, ending the decision phase.

In TABLE II, the TiA for all interactions is provided. For both *AVfirst* and *PEDfirst* scenarios, the mean TiA for the second interaction was higher than for the first. The linear mixed model confirmed a significantly higher TiA over all scenarios for the second compared to the first interaction with a large effect (β = 0.33; *SE* = 0.09; *t* = 3.68; *p* < 0.001), indicating participants had higher trust in the second trial. The factors presence of the pedestrian group (β = -0.03; *SE* = 0.09; *t* = -0.34; *p* = 0.735) and communication mode (β = 0.15; *SE* = 0.09; *t* = 1.66; *p* = 0.099) did not result in significant differences in TiA.

The participants' general attitude toward the development of automated driving was assessed using a 5-point Likert scale. Before the experiment, the median rating was 4.00, and after the experiment, it remained at 4.00. The Wilcoxon signed-rank test (*z* = -1.68, *p* = 0.066, *r* = -0.30) indicated that the difference was not statistically significant, suggesting that the participants' attitude did not change significantly. In contrast, the participants' general trust in AVs showed a notable shift. Before the experiment, the median trust rating was 3.00; after the experiment, it increased to 3.50. The Wilcoxon signed-rank test revealed a significant difference (*z* = -1.89, *p* = 0.041, *r* = -0.33) with a small effect, indicating that the participants' trust in AVs significantly improved following the experimental scenarios.

Over all 249 interactions, participants were asked about the perceived components of AV communication. The display was perceived in almost every interaction with 97%, while the

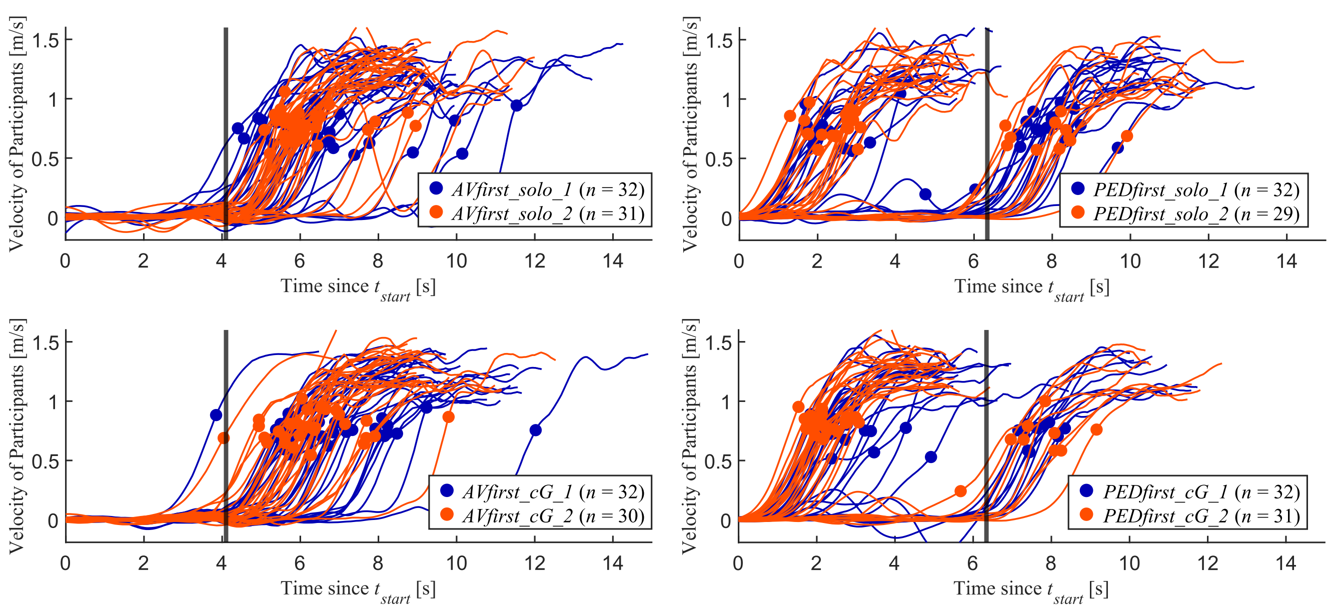

Figure 5. Velocity profiles of the participants from t_{start} to $t_{crossed}$. Blue lines represent the first interactions, while orange lines depict the second interactions. In *AVfirst* scenarios, black vertical lines at 4.10 s indicate t_{passed}, and in *PEDfirst* scenarios, lines at 6.34 s mark the point at which the AV came to a halt. Filled dots denote the CIT for each interaction.

TABLE II. MEAN AND STANDART DEVIATION OF CIT, CT, AND TIA.

			CIT		CT		TiA	
			1. trial	2. trial	1. trial	2. trial	1. trial	2. trial
AVfirst	***solo***	***M***	**6.41 s**	**6.19 s**	**3.15 s**	**3.13 s**	**3.77**	**3.95**
		SD	1.67 s	0.94 s	0.40 s	0.52 s	1.22	1.36
		n	32	31	32	31	32	31
	cG	***M***	**6.77 s**	**6.30 s**	**3.10 s**	**2.99 s**	**3.84**	**4.14**
		SD	1.52 s	1.12 s	0.32 s	0.28 s	1.22	1.39
		n	32	30	32	30	32	30
PEDfirst	***solo***	***M***	**5.20 s**	**4.50 s**	**3.24 s**	**3.11 s**	**3.90**	**4.36**
		SD	2.86 s	2.86 s	0.62 s	0.35 s	1.45	1.47
		n	32	29	32	29	32	29
	cG	***M***	**4.18 s**	**3.78 s**	**3.10 s**	**3.04 s**	**3.93**	**4.24**
		SD	2.47 s	2.58 s	0.37 s	0.36 s	1.45	1.50
		n	32	31	32	31	32	31

LED strip was only perceived 30% of the time. Concerning the dHMI, the speed of the AV was perceived at 40% as a communication component, and the lateral offset at 46% of the interactions. Due to all participants crossing the road after the AV in *AVfirst* scenarios and to answer the research question regarding the influence of the pedestrian group, the basis for the decision to cross the road is only evaluated in *PEDfirst_cG* scenarios. Out of 63 *PEDfirst_cG* interactions, participants stated in 67% of the interactions that the display was, among others, the basis for their crossing. They mentioned in 10% the LED strip, in 38% the speed of the AV, in 29% the lateral offset, and in 30% the stopping of the AV. The pedestrian group was mentioned in 24% of the interactions.

After the experiment, 38% of the 32 participants stated that the pedestrian group subjectively influenced them. The overall impression of the communication concept was rated positively by 75%, neutrally by 16%, and negatively by 9%. After the experiment, the perceived usefulness of the AV's communication concept tested by the van der Laan acceptance score [41] was $M = 1.11$ ($SD = 0.94$; $n = 31$). Conversely, satisfaction was rated with a mean of $M = 0.84$ ($SD = 0.93$; $n = 32$).

V. DISCUSSION

A. Suitability of the Derived Communication Concept for Pedestrian-AV Interactions

The communication concept developed for this study, aimed at facilitating interactions between pedestrians and AVs, demonstrated its effectiveness in ensuring safety. All participants successfully interpreted the AV's signals in *AVfirst* scenarios, resulting in consistent and safe crossings after the AV had passed. Comparing these findings to similar studies on eHMI communication, a communication concept that ensures safety in all interactions appears feasible [25, 32]. The positive outcomes may be attributed to a clear communication strategy incorporating various modalities [25] initiating signals simultaneously. Additionally, the positioning of the display [29] likely played a pivotal role.

Three-quarters of the participants rated the communication concept as positive, garnering medium scores for usefulness and satisfaction compared to the study of [27]. While the display emerged as the most noticeable and crucial communication modality, the LED strip's supplementary role seemed less impactful. The speed of the AV was also less conspicuous, possibly because participants did not perceive it as a distinct communication modality, although literature suggests its significant influence [35, 36]. The participants' general attitude toward automated driving and their trust in AVs before the experiment matched the sample in [25], whereby other characteristics of the participants could have influenced those answers. The experiment contributed to a descriptive improvement in participants' general attitude and a statistically significant increase in their trust.

Unlike prior studies, distinct behavior patterns emerged for *PEDfirst* scenarios [32]. Participants exhibited two primary crossing patterns: those crossing shortly after t_{start} demonstrated an early understanding of AV signals. Here, the simultaneous signaling of different communication modalities [25] and display placement [29] likely influenced participants' behavior similarly to *AVfirst* scenarios. In the second trial,

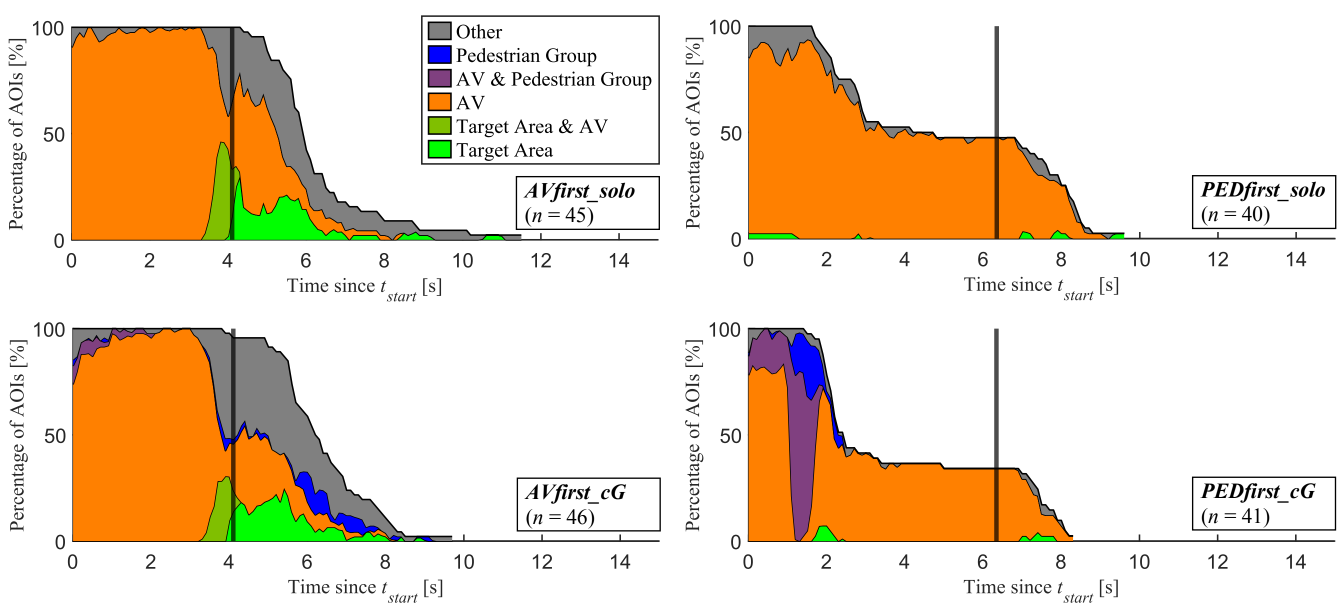

Figure 6. Percentage of AOIs observed by the participants from t_{start} to t_{init}. In *AVfirst* scenarios, black vertical lines at 4.10 s indicate t_{passed}, and in *PEDfirst* scenarios, lines at 6.34 s mark the point at which the AV came to a halt.

participants were more inclined to cross promptly after t_{start}, preceding waiting for the AV to come to a halt.

Objective measures, such as CIT and CT, corroborated the findings, indicating significantly faster pedestrian decisions and crossings in the second trial, suggesting a notable learning effect. This trend aligns with the subjective measure of trust, as indicated by the TiA scale, showcasing significantly higher trust in the second trial. These results suggest a rapid learning and comprehension of the communication concept by the participants.

B. Impact of the Simulated Pedestrian Group on Participants' Behavior and AV Communication Perception

Introducing a simulated pedestrian group significantly influenced participants' behavior in *PEDfirst* scenarios, manifesting in a notable effect on CIT and CT—contrary to the results of [17]. Reference [19] and [20]'s findings corroborate the observed impact of a pedestrian group, aligning with the outcomes presented here. In scenarios featuring a pedestrian group at the roadside, participants exhibited a propensity to initiate crossings shortly after t_{start}, preceding the previous pattern of waiting for the AV to come to a halt. Contrary to the gaze analysis in *AVfirst* scenarios, where the pedestrian group garnered limited attention during the decision-making process, it can be argued that participants perceptually registered their presence and actions peripherally. Consequently, this measure may not fully capture the nuanced influence of AOIs. In *PEDfirst* scenarios, the pedestrian group attracted considerably more attention, primarily because they traversed the road between the participants and the AV. When participants crossed simultaneously with the pedestrian group, their gaze focus substantially overlapped with the AV's.

Concerning the subjective trust measure using the TiA scale, no discernible differences emerged in the presence of the pedestrian group. At the time of writing, comparable experiments employing this questionnaire in a similar context have yet to be documented in the literature, making direct comparisons unfeasible. Therefore, these results hold promise as a valuable reference for future research on external AV communication. Despite the lack of a statistically significant influence on TiA, 24% of participants cited the pedestrian group as among various factors influencing their crossing decisions in *PEDfirst_cG* scenarios. Moreover, 38% reported a subjective influence of the pedestrian group after the experiment, reinforcing that other pedestrians at the roadside noticeably impact crossing decisions [19, 20].

VI. Conclusion and Future Work

This study lays the groundwork for future investigations into the complex interaction dynamics involving multiple human road users and AVs. The employed communication concept, derived from existing literature, demonstrated safety, with participants consistently understanding signals in *AVfirst* scenarios, affirming its suitability for subsequent in-depth studies. The presence of a simulated pedestrian group significantly influenced crossing behaviors in *PEDfirst* scenarios, underscoring the substantial impact of social factors on participants' decision-making. Objective measures revealed shorter CIT and CT when a pedestrian group was at the roadside intending to cross. However, relying solely on gaze focus might be inadequate due to the influence of peripheral vision and eye-tracking inaccuracies.

While this paper comprehensively addresses multiple human road users as receivers of AV communication, it is essential to acknowledge the limitations of the experimental scenarios. The absence of additional oncoming traffic or pedestrians on the opposite side of the road in this study may limit the generalizability of the findings to more complex real-world situations. Moreover, the simulated pedestrian group consistently adhered to AV communication cues and was always positioned on the same side of the road as the participants. These controlled aspects, while contributing to experimental rigor, may not fully capture the variability and challenges associated with real-world pedestrian behaviors.

Overall, the identified impact of the pedestrian group on participants' behavior and AV perception underscores the necessity of considering this element in future evaluation studies. This study contributes valuable insights to the broader discourse on human-AV interaction, highlighting the need for nuanced communication strategies and social context considerations in AV design.

Acknowledgment

The experiment was approved and accepted by the Ethics Commission of the Technical University of Munich (approval code 2023-86-S-NP). The authors thank Alexander Jacobi for preparatory work, Stephan Haug for statistical advice, and Niklas Grabbe for proofreading the manuscript.

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