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Effects of a light-based communication approach as an external HMI for Automated Vehicles — a Wizard-of-Oz Study

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ABSTRACT: *Communication between automated vehicles (AVs) and vulnerable road users (VRUs) is highly relevant in coordinating traffic maneuvers and therefore ensuring road safety. Especially in shared spaces such as parking areas, communication is highly important. As automated driving changes the driver's role, communication between different traffic participants will also change. External human-machine interfaces (eHMIs) may enhance safety and effective communication between VRUs and AVs by providing relevant information to other traffic participants if informal communication is insufficient. Hence, a variety of information (e.g., about AVs' driving mode or future maneuvers) is recommended to be communicated to VRUs. Therefore, we investigated the effects of three different light signals, presented by a light bar placed on the test vehicle's roof, as a form of an eHMI: automation mode, starting mode and crossing mode. Moreover, two different driving conditions (i.e., a manual and a simulated automated driving condition) were implemented to investigate the effects between these conditions. Either the driver was visible in the manual condition or the vehicle appeared driverless as a seat suit covered the driver in the simulated automated condition (Wizard-of-Oz design). A total of N = 173 random pedestrians passing by were interviewed and behavioral data were collected from over 1500 pedestrians. Results indicate that participants felt significantly safer during the interaction with the vehicle when a driver was visible. Although VRUs evaluated the general approach of applying light signals as eHMIs for AVs as useful, they assessed the presented light signals as only partially trustworthy and rather unintuitive. Moreover, many participants were unsure of whether the light signals were directed towards them, thus the directedness of light signals should be considered when implementing a light-based eHMI in AVs. Further, moving light signals attracted more attention (i.e., increased pedestrians' head movements towards the vehicle) than a steady or no light signal did. Interestingly, no difference existed between the investigated steady light signal and the baseline condition (i.e., no light signal) regarding head movements towards the vehicle. The results underline the importance of implementing an appropriate eHMI design in AVs.*

KEYWORDS: *Wizard-of-Oz; automated vehicles; external HMI; light-based communication; vulnerable road users*

1. INTRODUCTION

Vehicle features have become increasingly automated in recent years, resulting in various classifications of different levels of automation (SAE, 2018). Therefore, a long transition period including mixed traffic of different levels of automation (i.e., manual, partially and fully automated vehicles) is expected (Litman, 2019). One crucial aspect in terms of road safety is the assurance of clear and intuitive communication between vulnerable road users (VRUs) and vehicles (Rasouli, Kotseruba, & Tsotsos, 2018) with a variety of levels of automation, even if the driver is absent to ensure road safety (Ackermann, Beggiato, Schubert, & Krems, 2019).

1.1. The role of communication in manual driving

In manual driving scenarios, the interaction between VRUs and drivers occurs as a dynamic bidirectional process where traffic participants have to act and react to each other's maneuvers (Hölzel, 2008) to negotiate priority and coordinate prospective movements (Schieben et al., 2019; Witzlack, Beggiato, & Krems, 2016). In SAE Levels 4 and 5 the driving task is executed by the system (SAE, 2018) while the driver might be engaged in other tasks than driving (Jamson, Merat, Carsten, & Lai, 2013). Consequently, the interaction between vehicles and other traffic participants (e.g., VRUs) will change across these varying levels of automation (Schieben et al., 2019). To design a safe and comfortable interaction, and therefore support VRUs' trust and acceptance of automated vehicles (AVs), communication needs to be designed appropriately (Merat, Louw, Madigan, Wilbrink, & Schieben, 2018). In manual driving settings, formal (for Germany road traffic regulations (StVO; Straßenverkehrsordnung, 2018)) and informal communication allows the interaction between the different traffic participants (Hölzel, 2008). Formal communication is described by laws (e.g., StVO; Straßenverkehrsordnung, 2018), whereas informal communication includes trajectory, eye contact or gestures (Hölzel, 2008). Informal communication is particularly relevant in shared spaces (e.g., parking areas), where different traffic participants (i.e., vehicles and VRUs) need to interact and communicate to ensure traffic flow and road safety (Hamilton-Baillie, 2008). Since the traffic regulation by law is ambiguous in parking areas, there is a high variety of possible maneuvers, thus resulting traffic situations might be ambiguous (Witzlack et al., 2016). Informal communication (e.g., eye contact; Šucha, Dostal, & Risser, 2017) could help to coordinate interpersonal movements and right of way in ambiguous traffic situations (Hamilton-Baillie, 2008). Eye contact presents an important form of communication by creating a social relationship between different interaction partners (Rasouli & Tsotsos, 2018). Currently in manual driving scenarios, eye contact signals awareness of the mutual presence between drivers and surrounding traffic participants and thereby coordinates their actions (Rasouli et al., 2018). Previous research has highlighted the importance of eye contact between VRUs and drivers during the interaction in manual driving: For example, Šucha et al. (2017) found that 84% of pedestrians made eye contact with the driver while crossing a road. Moreover, this eye contact increased cooperation between the different traffic participants, resulting in increased traffic safety (Guéguen, Meineri, & Eyssartier, 2015). In AV scenarios, where the driver is potentially distracted or absent, this source of information will not be available to establish communication between the different traffic participants. Hence, the mutual coordination of movements between the different traffic participants is inhibited (Rasouli & Tsotsos, 2018).

1.2. The prospective transformation of communication in automated driving

One important issue in automated driving is the effect of a distracted or absent driver, which might be the case for AV scenarios, on different aspects of vehicle to pedestrian communication (e.g., Lundgren et al., 2017; Rodríguez Palmeiro et al., 2018; Rothenbücher, Li, Sirkin, Mok, & Ju, 2016). Previous studies underlined the importance of informal communication between VRUs and drivers (e.g., eye contact in manual driving scenarios; see Šucha et al., 2017). Drivers' distraction or absence could be shown to influence participants' evaluation of the interaction with the vehicle. Participants felt safer when they made eye contact with the driver, whereas feeling of safety decreased when the driver was inattentive (Lundgren et al., 2017). Moreover, VRUs' uncertainty about the vehicle's behavior increased when the driver was absent (Deb, Hudson, Carruth, & Frey, 2018). In contrast, Fuest, Michalowski, Traris, Bellem, and Bengler (2018) reported that ratings of perceived criticality did not differ depending on whether the driver was visible. However, Nuñez Velasco, Rodriguez, Farah, and Hagenzieker (2016) found that VRUs perceived higher levels of safety during AV interactions in shared spaces compared to manual vehicle interactions. In sum, inconsistent results exist across previous studies regarding VRUs' feeling of safety in terms of making eye contact with the driver in AVs (Fuest et al., 2018; Lundgren et al., 2017). Furthermore, the drivers' distraction or absence has shown to influence VRUs' behavioral aspects. Previous studies have revealed that VRUs' road crossing decisions are not only influenced by vehicles' speed and distance, but also by the perceived level of driver distraction (Rodríguez Palmeiro et al., 2018). Participants' willingness to cross the street decreased when the driver was noticeably engaged in secondary tasks compared to when eye contact to the driver could be established (Lundgren et al., 2017). Due to drivers' distraction or absence, the communication between vehicles and VRUs requires transformation in AVs, where eye contact needs to be replaced

(Schieben et al., 2019). Informal communication could provide a variety of information about the vehicles' current state (e.g., by trajectory; Beggiato, Witzlack, Springer, & Krems, 2018). In addition, explicit communication could supplement implicit messages (Ackermann et al., 2019) and therefore ensure an accurate interpretation of the AVs' maneuvers (Schieben et al., 2019).

External human-machine interfaces (eHMIs) offer one opportunity for AVs to communicate with other traffic participants and thereby enhance traffic flow, road safety (Schieben et al., 2019) and feeling of safety of surrounding traffic participants (Böckle, Brenden, Klingegård, Habibovic, & Bout, 2017; de Clercq, Dietrich, Núñez Velasco, de Winter, & Happee, 2019). For instance, eHMIs might communicate with other traffic participants by providing a variety of information about the vehicles' states and future maneuvers (Schieben et al., 2019) as well as compensate for the lack of eye contact between the driver and other traffic participants (Lundgren et al., 2017). To encourage acceptance and trust of eHMIs, a report by the International Organization for Standardization (ISO) on external communication in AVs recommends having consistent signals among different manufacturers (International Organization for Standardization, 2018). Previous studies emphasize the demand for communication between VRUs and AVs (where the driver is potentially absent; SAE, 2018) to enhance VRUs' feeling of safety (Schieben et al., 2019). VRUs' need for communication is reflected in their feeling of safety ratings (de Clercq et al., 2019) as well as in their observable behavior (Rothenbücher et al., 2016). In general, participants preferred eHMIs as a form of communication compared to having no eHMI present in AVs (de Clercq et al., 2019). Previous studies have found a positive effect of eHMI application on emotional ratings (Lagström & Lundgren, 2015). Particularly, VRUs' feeling of safety significantly increased when interacting with a vehicle containing an eHMI, in contrast to when no eHMI was presented (Böckle et al., 2017; de Clercq et al., 2019). The application of eHMIs could help to increase the amount of safe street crossing by participants in front of a vehicle (Lagström & Lundgren, 2015). In addition, VRUs perceived comfort increased significantly during the interaction, when an eHMI was applied, in contrast to when no eHMI was used (Böckle et al., 2017). Other studies have investigated the effects of eHMIs on VRUs behavior (e.g., Chang, Toda, Sakamoto, & Igarashi, 2017; Rothenbücher et al., 2016). For example, Chang et al. (2017) found significantly decreased reaction times for crossing decisions in the eHMI condition compared to a baseline condition without any communication between the vehicle and VRUs. Further, VRUs reduced their walking speed and searched for vehicles' implicit movement cues due to the uncertainty during the interaction when no driver was visible inside the vehicle (Rothenbücher et al., 2016). Therefore, eHMIs have the potential to communicate AVs' intentions and future maneuvers to VRUs (Lagström & Lundgren, 2015).

1.3. Designing interactions in automated driving

Various studies have investigated eHMI signals' specific content. Specifically, various presented information were evaluated to be differently relevant (Ackermann et al., 2019; Merat et al., 2018; Zhang, Vinkhuyzen, & Cefkin, 2018). Information regarding AVs' intention was considered more important than information about whether the vehicle detected the VRU (Mahadevan, Somanath, & Sharlin, 2018). An exploratory study by Merat et al. (2018) showed that VRUs rated messages about AVs' starting, stopping and turning maneuvers as significantly more important than information regarding the vehicles' speed. Therefore, it was recommended to present messages about the vehicles' current state and future maneuvers to VRUs. In particular, AVs should provide information about a) the activation of the automated driving system, b) approaching maneuvers and c) yielding maneuvers (SAE as cited in Wilbrink et al., 2018). In a study by Zhang et al. (2018) VRUs interpreted the presented light signals as information about the vehicles' future states and maneuvers. Therefore, the authors suggested designing light signals in form of vehicles' state information rather than VRUs' advice-based information. In contrast, Ackermann et al. (2019) found that advice-based eHMI messages were rated as more comfortable than information about the vehicles' current state did. However, AVs' explicit general advice to VRUs could potentially be problematic regarding liability and traffic safety (Schieben et al., 2019). Schieben et al. (2019) collected VRU demands regarding an appropriate interaction configuration between AVs and other traffic participants. Based on the previous literature, four information categories were identified, including information about a) the vehicles' driving mode, b) the vehicles' next maneuvers, c) the perception of the environment, and d) the capabilities for AV and VRU cooperation. Information about AVs' behavior could enhance understanding and anticipation of their maneuvers (Schieben et al., 2019). Participants rated communication with the AVs as significantly more important in shared spaces with no road markings as opposed to when road markings existed. Furthermore, information about the AVs' stopping behavior were rated as the most important in shared spaces, suggesting that providing information in these particular situations is more likely to enhance traffic safety (Merat et al., 2018).

To sum it up, informal communication, particularly eye contact should be highlighted to coordinate actions in ambiguous traffic situations (Šucha et al., 2017) and therefore ensure road safety (Rasouli et al., 2018). In automated driving, communication using eye contact will be limited, since the driver is potentially distracted (SAE, 2018). Hence, an appropriate alternative regarding this source of information needs to be investigated to support road safety (Merat et al., 2018) especially if implicit communication is insufficient (Ackermann et al., 2019). Moreover, ISO's recommendations should be also considered in research. Therefore, the current study considers both: a) the findings of previous studies (e.g., Lagström & Lundgren, 2015; Rothenbücher et al., 2016) and b) ISO recommended guidelines (International Organization for Standardization, 2018). Upon previous results the current study examined three different light signals including different information categories and a baseline condition without any light signal in a shared space setting as an important interaction scenario (Hensch, Neumann, Beggiato, Halama, & Krems, 2020). Aspects of feeling of safety, trust, acceptance, comprehensibility and usefulness, as well as the behavioral indicator of head movements towards the vehicle, were compared across two driving conditions.

1.4. Research questions and aim of the study

The aim of the current study was to assess the effects of three different light signals and a baseline condition (without any light signal) as a form of AV's explicit communication. The different light signals intended to communicate different messages to the surrounding traffic participants (a) information about vehicles' state; b) information about vehicles' future maneuvers; and c) advice-based information to surrounding traffic participants; according to Ackermann et al., 2019; Schieben et al., 2019). Therefore, a light bar, which represented an eHMI, was implemented on the test vehicle's roof (see also Rodríguez Palmeiro et al., 2018). During the study, uninformed pedestrians passing by were interviewed randomly in a parking area. Additionally, two different driving conditions were compared: a manual driving condition (i.e., driver present) and a simulated automated driving condition (i.e., driver hidden by a seat suit) using a Wizard-of-Oz approach. Since uninformed pedestrians were interviewed, each participant evaluated one condition, resulting in a 4 (three different light signals, baseline condition) x 2 (driving conditions) between-subjects design.

Beside questionnaire and interview data, behavioral data from video recordings were examined. The collected questionnaire and interview data examined comprehensibility, trust and perceived usefulness of the light signals that represented an eHMI for AVs. Moreover, the perceived safety during the interaction with the vehicle was assessed. These data were supplemented by behavioral data from video recordings, which documented the duration of head movements towards the test vehicle.

Therefore, the subsequent constructs and respective research questions were analyzed:

(Q1) *Comprehensibility:* How do participants interpret the meanings of the different light signals? Do any differences exist for assessed comprehensibility between the different light signals and driving conditions?

(Q2) *Trust:* Do any differences exist for participants' trust ratings amongst the presented light signals and driving conditions?

(Q3) *Feeling of Safety*: Do any differences exist for participants' feeling of safety between the presented light signals and driving conditions? What reasons do participants state for their ratings?

(Q4) *Usefulness of the presented light signals:* Do any differences exist for participants' perceived usefulness ratings between the presented light signals and driving conditions?

(Q5) *General usefulness of light signals:* Do any differences exist for participants' perceived *general* usefulness ratings between the presented light signals and driving conditions? What reasons do participants mention for their assessment?

(Q6) *Alternative design suggestions:* What are participants' suggestions regarding alternative eHMI designs?

(Q7) *Head movements towards the vehicle:* Do any differences exist for pedestrians' head movements towards the vehicle between the investigated light signals or driving conditions?

2. METHOD

2.1. Setting

The current study was conducted within three days in June 2018, from 10am to 3pm each day. The parking area on the Chemnitz University of Technology campus (Germany) represented a shared space as it connects the cafeteria with the rest of the campus. Hence, there was a high appearance of VRUs present in between lectures, necessitating a high amount of communication between the different traffic participants.

2.2. Procedure

Various drives across the different conditions (i.e., assessed light signals and driving conditions) were conducted in a randomized order on the university's parking area. To prevent biases during the data collection (e.g., due to weather conditions), all conditions were constantly conducted across the investigation period. Moreover, the investigated light signals and driving conditions occurred in a random order. There were two researchers inside the vehicle; one as the driver and the other to communicate with additional researchers in the parking area via mobile phone. In addition, four to six interviewers were present throughout the study to interview pedestrians passing by randomly. Pedestrians were interviewed immediately after the vehicle was visible to them.

2.3. Participants

A total of N = 173 uninformed pedestrians passing by were randomly interviewed by investigators. Since the study's participants were selected randomly they were not invited or informed about the study's purpose. In sum, the sample consisted of 66% men and 34% women with a mean age of M = 29 years (SD = 10.6). Before the interview, participants' informed consent was obtained and anonymity was guaranteed. No financial compensation was given for study participation, which took about 5 minutes.

Behavioral data was collected from N = 1526 pedestrians during the study. After exclusion due to a lack of visibility of the participants' head movement towards the vehicle n = 1018 pedestrians (68.9% men, 31.1% women) with an estimated mean age of $M \approx 29$ years ($SD \approx 9.1$) were available. Since differences in head movements towards the vehicle should be analyzed, participants never or always looking towards the vehicle were excluded. This resulted in a final sample of $n = 389$ pedestrians (68.4% men, 31.6% women) with an estimated mean age of $M \approx 29$ years ($SD \approx 9.9$).

2.4. Design

To investigate the effects of an eHMI in AVs, a Wizard-of-Oz approach was employed in a field study (Hensch et al., 2020). This approach was adopted since previous studies have demonstrated to successfully simulate an AV by making participants believe the vehicle was automated and the driver was missing (Rothenbücher et al., 2016).

The present study examined: 1) three different light signals representing an eHMI (automation mode, starting mode, crossing mode), as well as a baseline condition without any light signal; and 2) two different driving conditions (simulated automated driving condition vs. manual driving condition) on uninformed pedestrians randomly passing by.

2.5. Apparatus and material

The study's test vehicle was a Ford Tourneo Connect. Since eHMIs in AVs were assessed, a manual driving condition (including a visible driver) was compared to a simulated automated driving condition that included a seat suit to let the vehicle appear driverless (similar to Röthenbücher et al., 2016). Moreover, a similar suit was placed over the front passenger seat to keep the appearance of both seats consistent (Figure 1a). Three different light-based communication messages were investigated as an eHMI (Figure 1b):

a) Automation mode: steady light, intended to indicate that the vehicle was operating autonomously (information about vehicles' driving mode according to Schieben et al. (2019));
b) Starting mode: flashing light, intended to indicate that the vehicle was approaching (information about vehicles' state and future maneuvers according to Schieben et al. (2019)); and

c) Crossing mode: sweeping light, intended to indicate that a pedestrian could cross in front of the vehicle (advice-based information about vehicles' future maneuvers according to Ackermann et al. (2019)).

A light bar presented the light signals to pedestrians passing by. It was placed on the test vehicles' roof to ensure sufficient visibility of the light signals. The eHMI presented the messages at the vehicle's front side. The light bar included 12 horizontally spaced LEDs with a luminous flux of two lumen respectively. As recommended by Wilbrink et al. (2018), the light signals were presented in a cyan color (Figure 1c). Spectrum analysis revealed a dominate wavelength of 488.86nm. The driver of the vehicle selected the respective light signal via a touch pad in the center console.

Furthermore, a baseline condition (without any light signal) was investigated. To examine pedestrians' behavior (i.e., head movements towards the vehicle), four dashcams were installed in a 360° angle inside the test vehicle. Therefore, one Black Vue DR650S-2CH (Blackvue, 2018) front camera (1920x1080 pixels, 30 fps) was installed in the windscreen and the rear window respectively. Moreover, one Black Vue DR650S-2CH rear camera (1280x720 pixels, 30 fps) was placed in the right and left side window of the test vehicle respectively.

2.6. Questionnaires and behavioral data

The interview included 7-point Likert scale ratings (from [1] "*I completely disagree*" to [7] "*I completely agree*"), judgments and open-ended questions. During the first part of the interview, the assumed meaning and the intuitiveness of the respective *presented* light signal was investigated. For this reason, participants were uniformed about the study's context and the intended meaning of the *presented* light signals. This part of the interview was supplemented by data regarding participants' perception of the respective light signal, directedness of the light signals, feeling of safety during the interaction with the vehicle as well as participants' assumption of the test vehicle's automation and drivers' visibility. For the second part of the interview, participants were informed about the study's context and meaning of the *presented* light signals. Participants' feedback was collected regarding the comprehensibility of the respective light signal, trust in the light signal, and its perceived usefulness of the presented light signals and light signals in AVs in general. Trust towards the respective light signal was assessed across three items from the trust in automation scale (Jian, Bisantz, & Drury, 2000; items adapted). The item values were aggregated into an overall satisfactory score that was used for further analysis (Cronbach's α = .68; Hair, Black, Babin, & Anderson, 2014). Further details are given in Table 1.

The recorded interview data of the judgements and open-ended questions were transcribed verbatim and then screened. A coding system relating to the thematic analysis (Braun & Clarke, 2006) was developed and reviewed. Finally, the transcribed data were coded according to the developed coding system. Two independent raters coded 25% of participants' answers, showing a substantial interrater reliability (Cohen's Kappa κ = .75; Landis & Koch, 1977). Behavioral data considering the duration of pedestrians' head movements towards the vehicle were investigated by video data. Therefore, video data were screened and an an-

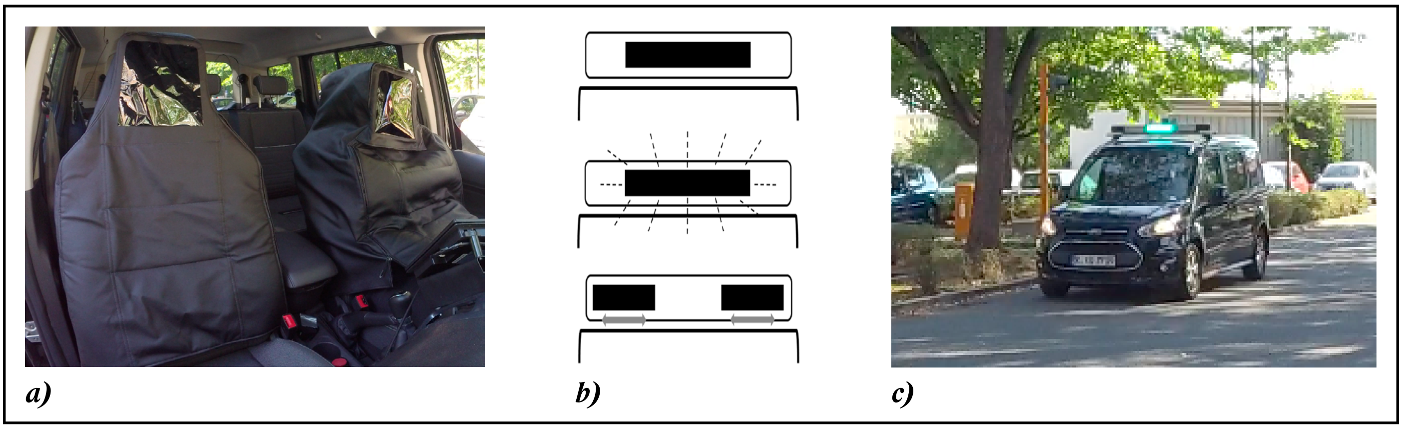

Figure 1. The seat suit covering the driver to simulate the automated driving condition (a), schematic visualization of the presented light signals (top: automation mode; middle: starting mode; bottom: crossing mode) (b), light bar on the vehicle's roof presenting the investigated automation mode (c).

notation scheme was developed that contained four categories. The first category included pedestrians' head movements towards the vehicle, assuming the attention was directed to the vehicle or light bar. The second category focused on head movements other than towards the vehicle, assuming the attention not on the vehicle or light bar (Anderson, 2014). Annotation category three and four included obscured (e.g., by other pedestrians) or barely visible head movements (e.g., due to the distance between cameras and pedestrians). The video data were annotated frame by frame. The respective category's onset was specified by either the first frame pedestrians' head was allocated towards the vehicle or the first frame of head movements towards other than the vehicle. Behavioral data were annotated by the software ELAN (2004). Afterwards, the duration of pedestrians' head movements towards the vehicle was qualified by the total duration the pedestrians were visible in the video data.

3. RESULTS

3.1. Manipulation check

In general, most participants (89%) noticed the light signals presented by the light bar on the top of the test

Table 1. Overview of the Wizard-of-Oz Study.

Construct	Statement/ Question	Information to participants	ANOVA		
			Main effects		Interactions (Light signals x Drivers' visibility) *p*
			Light signals *p*	Drivers' visibility *p*	
Perception of light signals	Did you notice the light signal on the vehicle's roof?	uninformed	-	-	-
Directedness of light signals	Did you believe that the light signal was addressed to you?	uninformed	-	-	-
Vehicles' automation	Did you see any driver inside the vehicle?	uninformed	-	-	-
	Did you think that the vehicle operated autonomously?	uninformed	-	-	-
Feeling of safety	I felt safe when interacting with the vehicle.*	uninformed	.193	.046	.335
	Could you please explain the extent of agreement?	uninformed	-	-	-
Comprehensibility	What do you think was indicated by the light signal?	uninformed	-	-	-
	The light signal is comprehensible.*	informed	.991	.991	.099
Trust (Jian et al., 2000)	The system is deceptive.*	informed	-	-	-
	The system provides security.*	informed	-	-	-
	I can trust the system.*	informed	-	-	-
	Aggregated overall trust score		.964	.724	.428
Usefulness (*presented* light signals)	The presented light signal is useful.*	informed	.101	.875	.232
Usefulness (*general* use of light signals)	A light signal that indicates [meaning of the respective light signal] is generally useful.*	informed	.471	.157	.774
	Could you please explain the extent of agreement?	informed	-	-	-
Alternative design suggestions	Do you have alternative design suggestions for an eHMI indicating [meaning of the respective light signal]?	informed	-	-	-

*A 7-point Likert scale from [1] "I completely disagree" to [7] "I completely agree" was used.

vehicle. However, most VRUs (86%) did not believe that the light signal was addressed to themselves. The majority of participants (79%) did not see any driver inside the vehicle during the simulated automated driving condition. However, in the manual driving condition, when the driver should have been visible, only a slight majority (52%) reported seeing a driver. This could have been due to windshield glare. Most VRUs (59%) in the simulated automated driving condition believed the vehicle drove autonomously, whereas over two thirds of participants (69%) did not assume the vehicle drove autonomously in the manual driving condition.

3.2. Comprehensibility (Q1)

When asked about the intended meaning of the presented light signals, participants assumed diverse interpretations. Table 2 presents the extracted response categories referred by at least 5% of participants in the interviews as well as example quotes regarding the suspected meaning of the presented light signals (translated from German into English). Participants most often indicated uncertainty about the presented light signals' meanings (38%). About one-fourth of interviewed VRUs (22%) hypothesized that the light signals represented a warning/caution message to other road users. Some participants associated the presented light signals with a police (16%) or emergency vehicle in general (8%). Findings from qualitative data regarding comprehensibility of the light signals are supported by questionnaire ratings, suggesting that the investigated light signals were perceived as rather unintuitive (M = 3.16, SD = 1.67). A two-way ANOVA (including the factors light signal and driving condition) revealed no statistical difference between the investigated *light signals* ($F(2,116) = 0.01$, $p = .991$, $\eta_p^2 = .00$) or *driving conditions* ($F(1,116) = 0.00$, $p = .991$, $\eta_p^2 = .00$) across comprehensibility ratings. Further, no interaction effect was found ($F(1,116) = 2.36$, $p = .099$, $\eta_p^2 = .04$).

3.3. Trust (Q2)

Overall, participants felt that the investigated light signals were only partially trustworthy (M = 4.01, SD = 1.35). A two-way ANOVA revealed no statistical difference for *light signals* ($F(2,117) = 0.04$, $p = .964$, $\eta_p^2 = .00$) or for *driving condition* ($F(1,117) = 0.13$, $p = .724$, $\eta_p^2 = .00$) across trust ratings. Further, there was no interaction effect ($F(1,117) = 0.85$, $p = .428$, $\eta_p^2 = .01$).

3.4. Feeling of safety (Q3)

Generally, ratings regarding feeling of safety indicated that participants felt rather safe during the interaction with the vehicle (M = 5.17, SD = 1.64). Although a two-way ANOVA revealed no main effect for *light signals* ($F(3,161) = 1.59$, $p = .193$, $\eta_p^2 = .03$), it did show a main effect for *driving condition* across participants' feeling of safety rating ($F(1,161) = 4.03$, $p = .046$, $\eta_p^2 = .02$). A pairwise post-hoc comparison (Bonferroni-corrected) revealed a significant effect for starting mode ($t_{starting}(44.69) = 2.47$, $p = .017$, $d = -0.68$). Specifically, VRUs felt significantly safer during the manual driving condition compared to the simulated automated driving condition. There

Table 2. Extracted response categories and example quotes regarding the assumed meaning of the light signals.

Category	Frequency (quantity)	Example quotes (participant number)
No idea	52	"I have no idea." (P24)
Warning/ caution	30	"Usually it [the light signal] is some kind of warning signal." (P228)
Attention	12	"[The light signal] attracts attention." (P280)
Police	22	"I thought: police." (P05)
Emergency vehicle (not specified)	11	"[...] this blue caution light is associated with the fire department, police [vehicles], and ambulance vehicles." (P87)
Automated/ driverless vehicle	10	"[The light signal means] it's autonomous driving [...] there is no driver inside [the vehicle]." (P17)
Object/ obstacle detection	8	"[...] looking for obstacles, maybe." (P327)

Note. N = 137; extracted response categories referred to by at least 5% of participants; analysis of answers across all conditions. Information in square brackets were added by the authors to enhance comprehensibility.

was no significant interaction between light signal and driving condition (F(2,161) = 1.10, p = .335, η_p^2 = .01).

In addition, participants provided further explanations for their feeling of safety ratings during the interview. Over half of interviewed VRUs (56%) reported feeling safe during the interaction. In detail, participants described not perceiving hazards (25%) as the most common reason for feeling safe. However, several participants mentioned the slow speed of the vehicle (19%) and the distance of the vehicle (10%) as affecting their safety rating during the interaction. Interestingly, some participants reported not perceiving any interaction with the vehicle at all (17%), resulting in higher perceived safety ratings. Some VRUs felt that the light signals were an announcement of the vehicle's presence (9%), which increased feeling of safety during the interaction. Furthermore, other aspects of driving behavior (e.g., trajectory, flexible adaptation of maneuvers) were mentioned to improve safety during the interaction (9%). In contrast, some participants (21%) felt rather unsafe during the interaction. These participants referred to their inexperience with this scenario (15%) and confusion regarding the light signal (7%) as reasons for lowering their safety ratings. Besides, the absence of a driver noticeable negatively influenced feeling of safety (9%). Another 10% of interviewed VRUs were undecided about the scenario's safety.

3.5. Usefulness of the presented light signals (Q4)

Overall, participants were rather undecided regarding the usefulness of the *presented* light signals (M = 4.01, SD = 1.92). A two-way ANOVA did not reveal a statistical effect for *light signal* (F(2,116) = 2.33, p = .101, η_p^2 = .04) or *driving condition* (F(1,116) = 0.03, p = .875, η_p^2 = .00) across the perceived usefulness of the *presented* light signals. Moreover, no interaction effect was found (F(2,116) = 1.48, p = .232, η_p^2 = .03).

3.6. General usefulness of light signals (Q5)

Light signals as a form of an eHMI in AVs were *generally* assessed as beneficial by the participants (M = 5.80, SD = 1.74). No statistical effect could be found for *light signals* (F(2,130) = 0.76, p = .471, η_p^2 = .01). Interestingly, there was also no statistical differences for *driving conditions* (F(1,130) = 2.03, p = .157, η_p^2 = .02) regarding the perceived general usefulness of the light signals, indicating that light signal use in AVs is independent of whether the driver is visible. Moreover, no interaction existed (F(2,130) = 0.26, p = .774, η_p^2 = .00). Additionally, interviewed VRUs provided further explanations for their *general* usefulness ratings of the specific light signal. Table 3 provides the extracted response categories (referred to by at least 5% of participants) and translated example quotes from the interview. Over half of participants (57%) indicated that light signals could be generally useful as a form of communication in AVs. In more detail, several VRUs highlighted that light signals could provide information about AVs' current states and future maneuvers (39%). Moreover, light signals were assessed as beneficial in communicating with other traffic participants (31%). In contrast, several participants felt that the general application of light signals was not useful (17%), particularly due to light signals' incomprehensibility (18%). Some participants were undecided about whether light signals in AVs were useful (14%). In addition, several participants believed that light signals as an eHMI were only useful in the context of mixed traffic that included manual and automated vehicles (7%).

3.7. Alternative design suggestions (Q6)

Concerning alternative designs, participants most often suggested that light signals should be used as a modality for eHMIs (25%). However, several VRUs recommended a different color than the investigated cyan in general (17%). Depending on the signals' meaning, participants suggested using green (7%), yellow/ orange (6%) or red (6%) as an appropriate color for a light signal in AVs. Furthermore, some interviewed VRUs proposed using text messages (10%) or icons (7%) in the design of the eHMI. Participants indicated that the eHMI should also be visible by following traffic (5%). However, several VRUs stated that the current light signal set-up was sufficient and did not need improvement (12%). In contrast, some participants felt that eHMIs were rather unnecessary in context of AVs (9%).

3.8. Head movements towards the vehicle (Q7)

The analyzed video data were log-transformed to correct for the violated homogeneity of variance. A two-way ANOVA showed significant differences between the investigated *light signals* regarding VRUs' head movement towards the vehicle (F(3,381) = 9.17,

$p < .001$, $\eta_p^2 = .07$). Pairwise comparisons (Bonferroni-corrected) revealed that head movements towards the vehicle lasted significantly longer during the starting and crossing mode compared to the baseline condition without any light signal ($p = .001$ respectively). Moreover, these head movements towards the vehicle lasted significantly longer during the starting ($p = .002$) and crossing mode ($p = .004$) compared to the automation mode. No significant difference existed between the automation mode and the baseline condition or between the crossing and starting mode ($p > .999$ respectively, Figure 2). Further, no statistical differences could be found for the *driving conditions* ($F(1,381) = 2.71$, $p = .101$, $\eta_p^2 = .01$). There was also no significant interaction effect ($F(3,381) = 0.592$, $p = .621$, $\eta_p^2 = .01$).

Table 3. Extracted response categories and example quotes regarding the general usefulness of light signals in AVs.

Category	Sub-category	Frequency (quantity)	Example quotes (participant number)
General usefulness (agree)	Information about AVs' states and maneuvers	54	"For this reason, I think it is better one knows that it [the vehicle] is automated." (P218)
	Communication with other traffic participants	43	"It would be useful [to know] that the vehicle is automated, for drivers, for other drivers [in surrounding vehicles] and for pedestrians." (P124)
	AV interaction/ feeling of safety	25	"It [the light signal] can create trust." (P133)
	Traffic safety	25	"Well, I like it for [the reason of] safety." (P285)
	Behavioral adaptation	24	"[…] maybe that one looks again, looks additionally […]." (P23)
	Replacing driver as communication partner	18	"A driver makes eye contact with me as a pedestrian. This [the eye contact] is difficult for an automated system." (P184)
	Communication of signals' meanings/ consensus	12	"Publicity, if everybody knows that it [the light signal] indicates an automated vehicle then everybody knows it. Just as I know [for example] the fire truck with horn and signal."(P69)
General usefulness (disagree)	Lack of knowledge about light signals' meanings	25	"It [the light signal] didn't help me, because I didn't know what it meant." (P33)
	Mistrust/ reliability	8	"[…] technology could fail." (P15)
	Information presented by implicit communication	8	"Generally, a normal [manual] vehicle has no approaching signal besides the […] sound of the engine." (P183)

Note. $N = 138$; extracted response categories referred to by at least 5% of participants; analysis of answers across all conditions. Information in squares bracket were added by the authors to enhance comprehensibility.

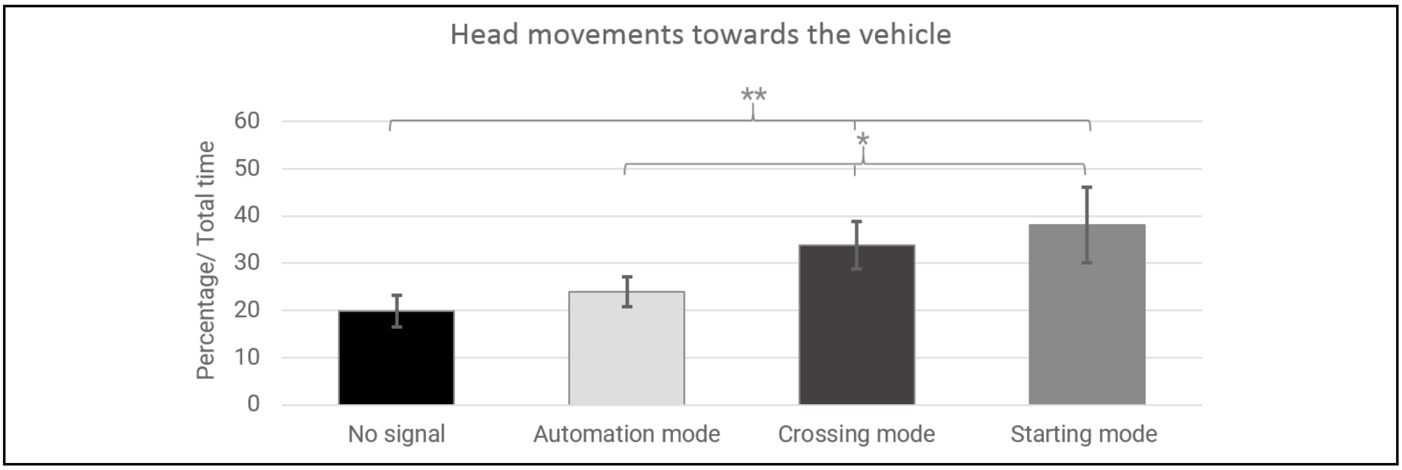

Figure 2. The qualified percentage of pedestrians' head movements towards the vehicle by total time.
Note. ***Error bars indicate 95% confidence intervals. * indicates a significant difference of*** $p < .01$***. ** indicates a significant difference of*** $p < .001$***.***

4. DISCUSSION

4.1. Findings

The current study investigated three different light signals (i.e., automation mode, starting mode, and crossing mode) serving as an eHMI compared across a manual and a simulated automated driving condition. Results demonstrated a successful manipulation of the drivers' visibility by employing the seat suit during the simulated automated driving condition, confirming findings by Rothenbücher et al. (2016) (for Wizard-of-Oz studies in general see Dahlbäck, Jönsson, & Ahrenberg, 1993). However, during the manual driving condition, only half of participants noticed a driver inside the vehicle. This may have been due to windshield glare, a phenomenon also observed in other studies that reported only a small amount of eye contact between pedestrians and the driver of a vehicle due to windshield glare (Schneemann & Gohl, 2016). The current study assessed participants' general perception of a driver inside the vehicle, which is less specific than eye contact. Nevertheless, the number of participants indicated perceiving a driver in the manual driving condition remained relatively small. Moreover, the findings revealed that the applied AV manipulation was partially successful. Only half of participants were convinced that the vehicle was operated autonomously during the simulated automated driving condition in the current study. This is quite lower compared to Rothenbücher et al. (2016), where 87% of participants assumed the vehicle driving autonomously. However, this discrepancy might be explained by the different study locations and the resulting statutory regulations: AVs would more likely be expected on the streets in Silicon Valley, CA (Rothenbücher et al., 2016) than in Chemnitz, Germany (current study). Since this study incorporated a field setting, specific parameters (e.g., distance between the VRU and vehicle) might have varied between different participants. In addition, influencing issues such as prior knowledge and experience with AVs likely differed between participants. However, these parameters might also vary under real-world conditions. The study's aim was to investigate VRUs' unbiased evaluation and reaction to light signals as eHMIs in AVs in a field setting and therefore enhance external validity of the results.

Furthermore, the study examined the (Q1) comprehensibility of the applied light signals, (Q2) trust in the respective light signal and (Q3) participants' feeling of safety. In terms of comprehensibility of the light signals' meanings the quantitative and interview data matched considerably. Questionnaire data consistently revealed a rather low level of comprehensibility of the presented light signals. Interview data displayed a wide range of assumed meanings given by participants, though those interpretations predominantly did not match the intended meaning. Overall, the evaluated eHMI light signals were not considered intuitive (as also mentioned in Schieben et al., 2019). The results are also supported by previous findings from Ackermann et al. (2019) showing that participants misinterpreted the investigated light signals since the light bar represents an ambiguous eHMI. In the current study, some participants suggested using text messages as an alternative design approach for eHMIs, which is also similar to Ackermann et al. (2019). However, incorporating text messages as an eHMI in AVs may potentially require a large display for presentation and VRUs' reading and language skills should be considered when implementing text messages as eHMIs in AVs (Schieben et al., 2019).

Moreover, the interviewed VRUs perceived the light signals as only partially trustworthy. Participants' feeling of safety enhanced during the manual driving condition where a driver was present compared to the simulated automated driving condition where the driver was apparently missing, which was also found in previous studies (Lagström & Lundgren, 2015; Rothenbücher et al., 2016). Only half of participants noticed a driver in the manual driving condition whereas in the simulated automated driving condition the majority believed there was no driver present. This expectation might influence VRUs' attention. No difference in safety ratings across the investigated light signals could be found, which might be confounded by the low comprehensibility and trust ratings of the investigated light signals. Moreover, the primary reasons reported for rating safety as low during the interaction with the vehicle were a) the missing experience during the interaction with AVs and eHMIs as well as b) the perceived distrust towards the light signals. Since previous research indicated a positive effect of comprehensibility (e.g., for icon usage; Isherwood, McDougall, and Curry (2007)) and experience on trust, that could be increased by further experience during the interaction with eHMIs and AVs (as shown with AVs in general e.g., by Penmetsa, Adanu, Wood, Wang, and Jones (2019)). Although most participants generally noticed the respective light signal, they did not assume that it was directed to themselves. The results underline the influence of light signals' directedness with regard to feeling of safety and an intuitive design. Hence, eHMIs' directedness should be considered as an important factor when implemented in AVs (Willrodt, Strothmann, & Wallaschek, 2017). Thus, the results underline the importance of a) comprehensibility (Isherwood et al., 2007) and b) experience with light signals as eHMIs, both of which could increase perceived trust and safety during the interaction with AVs (Penmetsa et al., 2019). Therefore, it is suggested that information about light signals' meanings should be provided beforehand to other traffic participants. Moreover, a consensus regarding applied eHMIs might be necessary across different manufacturers (International Organization for Standardization, 2018). Qualitative data could also show that over half of VRUs felt safe during the interaction with the vehicle given the vehicle's slow speed and the large distance to the vehicle. The reported parameters describe implicit communication characteristics that should also be considered in AVs (Beggiato et al., 2018).

Furthermore, participants evaluated (Q4) the usefulness of the *presented* light signals and (Q5) the *general* usefulness of light signals as eHMIs in AVs. Participants' evaluation regarding both types of usefulness did not differ significantly between the investigated light signals. Interestingly, ratings also did not differ between the investigated driving conditions. However, it should be considered that only half of participants noticed a driver present in the manual driving condition, whereas merely a slight majority believed the vehicle operated autonomously during the simulated automated driving condition. Participants indecision about the usefulness of the presented light signals might be also confounded by the light signals' comprehensibility. Based on the quantitative and qualitative data, participants believed that light signals in general were useful as an eHMI for AVs, which corresponds with Clamann, Aubert, and Cummings (2016). However, in the study by Clamann et al. (2016) the investigated eHMIs were marginally used by participants, nevertheless most participants perceived the applied eHMIs as useful.

For the behavioral data (Q7), significant differences in head movement durations towards the vehicle were observed amongst the investigated light signals. The two animated signals (i.e., starting mode and crossing mode) particularly led to longer durations of head movements towards the vehicle compared to the non-animated light signal (i.e., automated mode). This effect could be explained by an increased salience due to the signals' movement, which could have led to longer durations of head movements towards the vehicle. Surprisingly, no statistical difference was found between the automation mode and the baseline condition despite using a light signal in general. Furthermore, there was also no statistical difference between the two driving conditions regarding head movements towards the vehicle. The latter matches participants' ratings regarding whether the driver was visible that might be affected by windshield glare (which is similar to the results for eye contact from Schneemann and Gohl, 2016). The current study did not examine eHMI's effect on participants' road crossing behavior. Moreover, precise implicit communication parameters (e.g., vehicles' trajectory) regarding a potentially necessary transition from informal to formal communication need to be further investigated when applying eHMIs in AVs (Beggiato et al., 2018). It should also be considered that eHMIs potentially increase complexity of traffic situations (Ackermann et al., 2019), particularly if they are used by several traffic participants (Schieben et al., 2019). Therefore, Ackermann et al. (2019) suggested the application of eHMIs as an addition in AVs if informal communication is insufficient to ensure road safety. However, participants believed that the general use of light signals as eHMIs was beneficial, despite that the investigated light signals rather decreased feeling of safety due to incomprehensibility. Regarding alternative design applications (Q6), light signals were the most favored communication approach in eHMI application (as also shown by Mahadevan et al., 2018) and thereby were preferred over acoustic signals as the modality for eHMIs (also shown by Merat et al., 2018). When referring to a specific communication content, VRUs particularly focused on information about AVs' current and future states and maneuvers. The results are in line with previous findings regarding the design of AVs' capability to communicate with VRUs (Schieben et al., 2019).

4.2. Implications

Results of the present study showed that participants evaluated the *general* use of light signals in AVs as beneficial for providing information about the AVs' states and maneuvers and therefore maintain road safety. However, the *presented* light signals were assessed as unintuitive if there was no prior knowledge about their specific meaning. Hence, it seems recommendable to introduce AVs' means of communication to the public before it is implemented in transport. Information about AVs in general and experience in the interaction with AVs should be provided to improve trust in AVs (Penmetsa et al., 2019) and the perceived comfort during the interaction with AVs (Böckle et al., 2017). Prior information could enhance the development of an eligible mental model concerning AVs means of communication. Therefore, the resulting expectations regarding AVs' interaction behavior might be more appropriate. Moreover, the respective light signals should be attributed to a specific meaning in analogy to the direction indicator. The three investigated light signals presenting an eHMI for AVs would refer to:

a) Automation mode: indicates that the vehicles is operating autonomously (steady light signal);
b) Starting mode: indicates that the vehicle is approaching (flashing light signal);
c) Crossing mode: indicates that a pedestrian could cross in front of the vehicle (sweeping light signal).

Moreover, the applied signals should be considered as cultural independent (Schieben et al., 2019) and could be standardized among manufacturers (International Organization for Standardization, 2018). Further studies should also consider different eHMI design aspects regarding, for example, the directedness of communication signals (Willrodt et al., 2017) or its visibility from behind the vehicle. Moreover, it should be considered that vehicles' speed and trajectory could be used as specific parameters of informal communication in AVs (Beggiato et al., 2018) to avoid an informational overload in complex situations (Schieben et al., 2019). In general, eHMIs could potentially support the communication between AVs and surrounding traffic participants in ambiguous traffic situations when informal communications' resources are exhausted (e.g., in deadlock situations; Ackermann et al., 2019).

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