frontiers | Frontiers in Computer Science

ORIGINAL RESEARCH
published: 14 June 2022
doi: 10.3389/fcomp.2022.863072

Go Ahead, Please!—Evaluation of External Human—Machine Interfaces in a Real-World Crossing Scenario

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In the future, automated vehicles (AVs) without a human driver will potentially have to manage communication with vulnerable road users, such as pedestrians, in everyday traffic interaction situations. The aim of this work is to investigate pedestrian reactions to external communication concepts in a controlled, but real-world crossing scenario. The focus is to investigate which properties of external human–machine interfaces (eHMIs) promote the comprehensibility of vehicle intention (yielding for the pedestrian) and therefore lead to faster and, at the same time, safer crossing decisions of pedestrians. For this purpose, three different eHMI concepts (*intention-based light-band*, *perception-based light-band*, and the *combination of light-band and signal lamp*) were examined and compared to a baseline (no eHMI). In a Wizard-of-Oz experiment, participants ($n = 30$) encountered a test vehicle equipped with the eHMIs in a real-world crossing scenario. The crossing initiation time in seconds and the participant's intention recognition were measured. Furthermore, the influence of the eHMIs on acceptance and perceived safety was evaluated. It was shown that the presence of the *intention-based light-band*, and the *combination of light-band and signal lamp* led to an earlier crossing decision compared to baseline with no eHMI. In summary, the results indicate that the *intention-based light-band* has a positive effect on the comprehensibility of the vehicle's intention. All concepts were evaluated positively regarding acceptance and perceived safety, and did not differ significantly from each other.

Keywords: external human-machine interfaces, automated driving, human-computer interaction, real-world study, Wizard-of-Oz, vulnerable road user

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Human-Media Interaction, a section of the journal Frontiers in Computer Science

Received: *26 January 2022*
Accepted: *09 May 2022*
Published: *14 June 2022*

Citation:
Loew A, Graefe J, Heil L, Guthardt A, Boos A, Dietrich A and Bengler K (2022) Go Ahead, Please!—Evaluation of External Human—Machine Interfaces in a Real-World Crossing Scenario. Front. Comput. Sci. 4:863072. doi: 10.3389/fcomp.2022.863072

INTRODUCTION AND BACKGROUND

Automated driving is currently a ubiquitous and much discussed topic. Automated vehicles (AVs) have the potential to fundamentally change traffic systems by making traffic safer, more efficient, and more comfortable (Fagnant and Kockelman, 2015). With the introduction of AVs, the interaction and communication between pedestrians and AVs in road traffic and their importance have come to the forefront (Rothenbucher et al., 2016; Rasouli et al., 2017; Othersen et al., 2018). This applies in particular as AVs are entering urban environments where vehicle–pedestrians interactions are common. Nowadays, human drivers use a variety of signals to communicate with other road users. In principle, there is a distinction between formal and informal communication in road traffic (Sucha, 2014; Färber, 2015; Lagström and Lundgren, 2015; Rasouli et al., 2017).

Formal communication is also referred to as explicit or standard communication and is regulated by road traffic regulations. It includes visual signals of vehicles, such as indicators, brake lights, hazard warning lights, or blue flashlights of emergency vehicles, as well as acoustic signals, such as horns or sirens (Färber, 2015; Fuest et al., 2018). In contrast, there is informal or implicit communication, which is not represented by any regulated signals. Examples include eye contact, gestures, facial expressions, the reduction of speed, etc. (Färber, 2015; Lagström and Lundgren, 2015; Beggiato et al., 2018). The latter type of communication is especially important in situations where formal rules do not apply (Sucha, 2014; Färber, 2015). This can be necessary to ensure that the driver sees the pedestrian or is aware of his/her intention to cross the road (Song et al., 2018). AVs eliminate the interaction with a driver as a source of information for pedestrians, creating a potential communication deficit. However, communication with other road users, especially vulnerable ones, should always be ensured (Pillai, 2017; Rasouli et al., 2017). This leads to the fact that AVs should have alternative communication strategies that can replace the driver's communication signals to establish comfortable and safe interactions between pedestrians and AVs (Schneemann and Gohl, 2016; Othersen et al., 2018; Ackermann et al., 2019a), as well as to ensure the trust and acceptance of AVs (Weber et al., 2019b).

Previous research has intensively addressed this question. One possible approach is to communicate *via* vehicle movement, for example, braking (Risto et al., 2017; Fuest et al., 2018; Ackermann et al., 2019a). However, most proposed solutions involve explicit communication through external human–machine interfaces (eHMIs) (Lagström and Lundgren, 2015; Clamann et al., 2017). The use of eHMIs is recommended by many researchers because they have the potential to improve interactions with pedestrians and facilitate a better understanding of intentions in road traffic (Deb et al., 2017; Merat et al., 2018; Ackermann et al., 2019b). Furthermore, eHMIs can increase the efficiency of the vehicle–pedestrian interaction and the perceived safety of pedestrians (e.g., Matthews et al., 2017; Habibovic et al., 2018; Clercq et al., 2019). Systematic taxonomies of the different HMIs of AVs and their interaction are given by Bengler et al. (2020) and Dey et al. (2020). However, considerable diligence is required to ensure an appropriate eHMI design (Rasouli et al., 2017; Deb et al., 2018).

The international research project interACT, funded under the European Union's Horizon 2020 initiative (interACT Project, n.d.), has addressed this issue by developing a communication concept based on traffic observations and simulation studies with eHMIs for future AVs. This concept was prototypically applied to a BMW i3s and has been evaluated in simulator, virtual reality (VR), and test track studies (Lee et al., 2019; Weber et al., 2019a; Dietrich et al., 2020). These environments account for high controllability of events on one hand, they lack complexity and realism on the other hand (Lee et al., 2019; Faas and Baumann, 2020). To ensure that eHMIs are also useful in real environments in which they are supposed to be used, research should seek ways to conduct studies in environments that are more similar to public road traffic. An evaluation of the eHMI concepts developed by the interACT project in such environments is lacking. Therefore, the present work aims to investigate pedestrian reactions to these eHMI concepts in a real crossing scenario. Before introducing the methodology in detail, Section 2 reviews previous research.

RELATED WORK

Numerous studies have already addressed the question of how communication between AVs and pedestrians might look in the future when there is no longer a human driver. A study by Matthews et al. (2017), for example, examined participants' interactions with a vehicle equipped with an external communication system. The results showed that participants who interacted with a vehicle without the external system were more hesitant to act than when the external communication system was present. The results of questionnaires showed that participants felt higher confidence and felt safer when the external communication system was present than when none was present. Similarly, Mahadevan et al. (2018) examined the utility of interfaces that explicitly communicate AV behavior and intention to pedestrians. Participants were asked to decide whether to cross the street or not. The results suggested that participants preferred to receive explicit information about the vehicle behavior and intention *via* interfaces, rather than just information about vehicle movement. However, a clear and unified design concept of eHMIs is not yet available. To investigate an understanding of the eHMI design, which consisted of a light on top of the windshield, Habibovic et al. (2018) conducted a series of experiments using the Wizard-of-Oz method. This meant that the vehicle control remained obscured from participants during the experiment. They indicated that they felt significantly less safe when they encountered the AV without the interface compared to a conventional vehicle or an AV with the interface. Thus, Habibovic et al. (2018) were able to show that pedestrians felt safer when they received information *via* eHMIs in addition to implicit communication about the vehicle intention. Both Faas and Baumann (2020) and Hensch et al. (2020) used the Wizard-of-Oz technique to investigate different eHMIs. In the study by Faas and Baumann (2020), three different light signals (steady light, flashing light vs. sweeping light) were evaluated. A steady or flashing light was found to be more suitable for a self-driving car to indicate its intention to yield the right-of-way to pedestrians than a sweeping light. They reflected a good to excellent user experience, higher user learning and likability. In the study by Hensch et al. (2020), the eHMI consisted of various light signals and was displayed as a light bar on the roof of the vehicle. A steady light indicated that the vehicle was driving autonomously, flashing lights that the vehicle was approaching, and sweeping lights indicated that the pedestrian in front of the vehicle could cross the street. The study was conducted in a parking garage on the campus of the University of Chemnitz, and random pedestrians passing by the vehicle were surveyed. In contrast to the study by Faas and Baumann (2020), the light signals used were found to be only partially trustworthy and poorly understood. However, the general use of light signals in the context of automated driving is generally perceived as useful (Hensch et al., 2020).

Altogether, previous research showed that eHMIs had the potential to improve perceived safety and were generally perceived as useful. Furthermore, the studies presented revealed that explicit communication through eHMI was preferable to solely implicit communication through vehicle movement. The design of eHMIs seems to play an important role in the perception and understanding of AVs. The results are conflicting whether steady, flashing or sweeping lights are the safest and most intuitive design. Previous studies can provide important insights into the effects and design of eHMIs and pedestrian interaction with AVs. Based on previous findings and different evaluation criteria for eHMIs (Weber et al., 2019a), the interACT research project (interACT Project, n.d.) has developed different eHMI concepts. The concepts consist of two main components: a LED light-band and a directional signal lamp (Kaup et al., 2019; Weber et al., 2019a). The light-band is mounted around the test vehicle and is visible from any angle. Thus, it allows 360-degree communication with pedestrians. Different pulsating frequencies and amplitudes aim to communicate current or future vehicle maneuvers of the AV and can therefore be classified as "*intention-based*" (Weber et al., 2019a). A calm, slow pulsating of the light-band aims to communicate "I am giving way." In addition, it is possible to illuminate only segments of the light-band around a vehicle to specifically illuminate pedestrians, a so-called *perception-based light-band* (Weber et al., 2019a). This concept is mainly characterized by giving explicit information to other traffic participants that they have been detected by the AV. This is meant to replace information that is normally exchanged by interpreting eye contact or head rotation in human–human communication (Weber et al., 2019a). The two interaction concepts utilizing the LED light-band (*intention-* and *perception-based*) are described in detail by Sorokin et al. (2019). In contrast, the second main component of the developed eHMI concepts is a signal lamp only visible to relevant pedestrians. A specifically directed light beam lets her/him know that she/he has been detected and that the vehicle is aware of them (Kaup et al., 2019). In the interACT projects, the signal lamp was combined with the *intention-based light-band* to explicitly communicate that the pedestrian was detected, along with communicating the intentions of the AV (Weber et al., 2019a). Cyan was chosen as the color for the eHMI concepts because it emerges as the color of choice for novel AV lighting functions (Kaup et al., 2019).

Final concepts developed by the interACT project were assessed in several VR and test track experiments among others regarding the acceptance, usability, traffic efficiency, and perceived safety of other road users and passengers (Dietrich et al., 2020). Dietrich et al. (2020) summarizes the studies already conducted by the interACT project. The Institute for Transport Studies (ITS) in Leeds, for example, conducted a pedestrian simulator study to investigate the effect of one of the eHMI concepts developed in the interACT project on pedestrian crossing behavior. The authors compared the slow pulsating light-band to conventional flashing headlights and no eHMI by assessing among others the crossing initiation time. The results revealed a significantly shorter crossing initiation time for the flashing headlights than for the slow pulsating light-band. The authors suggested that signal familiarity played a role. Generally, crossing initiation time was significantly shorter when the eHMI was turned on compared to no eHMI. Furthermore, a study was conducted in BMW's pedestrian simulator to assess the influence of the three eHMIs developed by the interACT project on pedestrian crossing behavior. The results revealed no differences between the eHMIs on crossing initiation times without previous exposure or explanations to eHMIs. However, improved crossing times for the *intention-based light-band* were noted when participants were educated about the functionality of eHMIs. Perceived safety was at a high level in all groups, including the control group, which did not encounter an eHMI during the experiment. Different eHMI concepts were examined on pedestrian crossing behavior, intention recognition, subjective perception, and rating of the eHMIs in a Wizard-of-Oz study conducted by the Technical University of Munich on a test track. The results showed no significant differences between the eHMI concepts on pedestrians crossing initiation or intention recognition times. However, the *intention-based light-band* was ranked highest regarding their preference, with the *perception-based light-band* being a close second. The signal lamp was only perceived by a few participants. In general, most participants preferred to have an eHMI present on AVs. The purpose of another test track study at the Centro Ricerche Fiat (CRF) facilities in Torino was to evaluate the impact of the *intention-* and *perception-based light-band* on pedestrians' behaviors and perceptions. The results suggest that the different eHMIs may not impact road users crossing decisions but the *perception-based light-band*, in particular, may lead to greater confidence and comfort in the AV behavior compared to no eHMI (Dietrich et al., 2020).

Generally, these eHMIs have proven to be beneficial, in the interACT studies regarding the subjective perception of vehicle intention and AVs themselves. Most interACT studies revealed that these eHMIs lead to quicker interactions compared to encounters without eHMI. However, the different eHMI concepts did not result in different objective results among themselves. The results showed that participants almost unanimously preferred to have AVs equipped with one of the presented eHMIs. To clarify the previous findings that are partially contradictory, further research is needed. In addition, an examination of eHMI concepts in real-world road traffic scenarios is missing. This is the aim of the present work described as follows.

AIM AND RESEARCH QUESTIONS

The aim of this work is to investigate pedestrian reactions to the external communication concepts developed in the interACT research project (interACT Project, n.d.) in a real-world crossing scenario using a study design which we called *instructed walking*. The eHMIs were tested under the conditions that are less controlled but more realistic than test track environments. The focus of this work is to ascertain whether pedestrians can understand the intention of the vehicle ("I saw you" and "I'm letting you go ahead") through the different eHMI concepts on the outside of the vehicle. It is also examined which eHMI leads to better intelligibility and an earlier crossing decision. In

FIGURE 1 | The participants encountered the test vehicle with external human–machine interface (eHMI) at one of the two predefined interaction points.

addition, how these eHMIs affect acceptance and perceived safety is assessed. The specific research questions are as follows:

RQ1: How does the use of the eHMI concepts affect the comprehensibility of vehicle intention compared to no eHMI?

RQ2: How do the different eHMI concepts differ from each other regarding comprehensibility, acceptance, and perceived safety?

METHOD

Participants

In total, 30 participants (14 men, 16 women) with a mean age of 24.53 years [standard deviation (*SD*) = 2.37, min = 19, max = 30] participated in the experiment. Most of the participants were students. Apart from one participant with color vision deficiency, no participants had other uncorrected visual impairments. This participant had a red/green color vision deficiency. In the authors' opinion, this did not affect the interaction with the vehicle or the comprehensibility of the eHMIs, and thus the results of the study. Therefore, this person was not removed from the data set.

Study Design

The study employed a single-factor within-subject design. Three different eHMI concepts were tested (see section independent variable: eHMI concepts for a detailed description of the concepts) and compared to a baseline in which no eHMI was displayed. A Wizard-of-Oz approach (i.e., the driver hidden by a seat cover) was used to simulate an AV. In a real-vehicle study conducted at the private premises of the Technical University of Munich with other road users, participants encountered a test vehicle with eHMI in a specified road section at two predefined interaction points (see **Figure 1**). An attempt was made to conceal the actual purpose of the study with a cover story. The goal of this procedure was to reduce the possible bias in the expectations that participants had before entering the study to be able to investigate more natural interactions between the vehicle and participants. Participants were guided so that the interaction occurred at the appropriate time. We refer to this technique as *instructed walking*. With three encounters for each of the eHMI concepts and the baseline, each participant experienced 12 runs in total. The order of the eHMI concepts was randomized to counteract potential sequential effects.

Independent Variable: EHMI Concepts

The following three eHMI concepts were developed as part of the research project interACT (interACT Project, n.d.), and varied during this experiment: *intention-based light-band*, *perception-based light-band*, and *a combination of light-band and signal lamp*. Cyan was used as the color for the light of the signal lamp and of the light-band. The technical setup enabling the eHMIs comprised two components: First, a signal lamp placed in the top part of the windshield. The signal lamp could be partly occluded through an aperture to be visible only at a certain angle (only for a certain person, while others cannot see the light). In this experiment, the lamp's aperture was fully opened for maximum visibility, as there was only one participant. The second component was a light-band that run underneath the windshield, alongside the hood, and along the side of the test vehicle at the edge of the roof. The light-band could glow and pulsate as a whole. Furthermore, several lights could be activated at a certain location while the rest of the light-band was turned off. The co-driver adjusted both components in real time using

FIGURE 2 | eHMI concept *intention-based light-band* communicating "I'm letting you go ahead".

an experimenter interface on a tablet within the test vehicle. This was used to trigger the different eHMIs during the experiment.

The first eHMI concept *intention-based light-band* (see **Figure 2**) used the light-band that was pulsating slowly to indicate vehicle intention to stop in front of the participant and yield the right-of-way to the participant (Weber et al., 2019a).

The *perception-based light-band* (see **Figure 3**) was intended to signal to participants that they have been detected by the vehicle. For this purpose, a narrow section of the light-band was illuminated to indicate the position of the detected road user. If the participant moved, the illuminated section of the light-band also moved.

The third concept *combination of light-band and signal lamp* (see **Figure 4**) consisted of the pulsating light-band concept and the signal lamp that shone directly on the pedestrian by changing its direction depending on the participant's position relative to the vehicle. The signal lamp was visible only to relevant participants, communicating "I saw you." The combination of these two components should indicate that the participant was detected, along with communicating "I'm letting you go ahead" (Weber et al., 2019a).

In this study, the signal lamp was not investigated in combination with the *perception-based concept* because these two concepts aim to communicate the same message that the pedestrian is detected by the AV.

Dependent Variables

To gain insights into the crossing behavior, the reaction time in seconds, also called crossing initiation time, was assessed. Crossing initiation time is defined as the time at which the participant enters the road with the intention to cross. For this purpose, the video recording of vehicle-participant encounters was analyzed. Crossing initiation time represented the difference between the two points in time "step into the walking flow" and "reference point vehicle." The moment "step into walking flow" was defined as the moment when the leg, used to start the step into the fluent crossing of the road, was visibly angled in the video. The "reference point vehicle" is the moment when the right front wheel touches a virtual red line added to the footage. This moment was chosen because it was the point at which the eHMIs were switched on. To ensure comparability with the runs without eHMIs, we decided on a reference point for all runs. This reference point also represents the starting point of braking, which was 7 m away from the participant. At this point, the vehicle was already visible to the participant.

Furthermore, intention recognition was defined as a dependent variable, whereby a verbal statement from participants was used to record whether they understood what intention the vehicle was pursuing and what meaning the eHMI had. For this purpose, a structured interview was conducted at the end of this study to determine whether participants understood the intention of the eHMI concepts. First, participants were asked whether they noticed the different eHMI concepts during the study. This question served to ascertain which concepts were seen at all. After explaining the different concepts, participants were questioned which of the three concepts they found most understandable and which they found least understandable. An explanation of their assessment was also requested. Using this question, a comparison between the different eHMIs could be made. To examine whether participants generally prefer the use

FIGURE 3 | eHMI concept *perception-based light-band* that communicates "I saw you" following the participant.

of eHMIs, they were asked if this approach to communicate between the vehicle and the pedestrian is generally good. A further question was whether participants felt that they were adequately informed at all times about what the vehicle was going to do next (e.g., whether it was going to stop, etc.).

In addition, acceptance and perceived safety were assessed. The acceptance questionnaire of van der Laan et al. (1997) was used. The perceived safety questionnaire included one question about each eHMI concept and asked participants to rate on a 5-point Likert scale how confident they felt when interacting with each eHMI concept (i.e., "I felt very confident interacting with the *intention-based concept/perception-based concept/combination of light-band and signal lamp*").

Materials and Equipment

The study test vehicle was a BMW i3s with no driver automation and was therefore driven manually. However, an automated driving condition was simulated by using seat covers, under which the driver and co-driver were hidden from the participants' view to make the vehicle appear driverless (see **Figure 5**).

Furthermore, to examine the participants' behavior (i.e., crossing initiation time), wide-angle cameras were installed at fixed locations where participants walked across the street. A GoPro Hero 3 Silver Edition and APEMAN A79 action camera with a resolution of 1,920 × 1,080 pixels were used for this purpose.

Procedure

The study duration was ∼60 min per participant. Before starting the experiment, participants completed an online demographic questionnaire. Participants gave written informed consent and were instructed by the investigator before entering the study. The protocol was approved by the ethics committee of the Technical University of Munich under grant number 24/20 S. With the help of a cover story, participants were supposed to believe that they

FIGURE 4 | eHMI concept *combination of light-band and signal lamp* communicating "I saw you" and "I'm letting you go ahead".

were taking part in a GPS tracking experiment. According to the cover story, movement profiles of several users were to be recorded in a precisely measured street section *via* GPS using a smartphone. Participants were also told that their location would be monitored live, and that the accuracy of the location data would be checked regularly. The participants' instruction was to walk a predefined round course and stop at predefined points (see **Figure 6**). These points were necessary to control the timing of the participant–vehicle encounters. The vehicle drove in the opposite direction of participants and came from the right at each interaction point.

A trial run was conducted in which participants did not encounter the test vehicle. This served to show participants the defined route and all relevant markings on the ground. Participants were tasked to stop at certain markings until the experimenter told them to move on to the next marking. The experimenter was in constant communication with the driver via a walkie-talkie, coordinating the encounter between the participant and the vehicle.

The test vehicle approached the participant at a constant speed of 20 km/h, stopped in front of the participant on each of the runs, and waited until the participant had crossed the road before continuing. This was for participants' safety. The start of braking and switching on the eHMI took place simultaneously at fixed positions to keep these factors constant across all runs. This position was reached when the test vehicle was at a distance of 7 m from the participant, bringing it to a stop at a distance of 4 m from the participant. To ensure that deceleration was as constant as possible during braking, the recuperation function of the BMW i3s was used to stop in front of participants. Switching on the eHMI was manually controlled by the co-driver using a tablet.

After completion of the runs, a semi-structured interview was conducted. Participants were informed of the purpose of the study, and that the vehicle was not driving automatically at any time. Participants were then asked to complete the two questionnaires.

Statistical Procedure and Data Analysis

Statistical tests were conducted using the statistical software IBM SPSS Statistics (IBM Corp., 2017). It was determined whether there was a significant difference between the three eHMI concepts, including the difference to show no eHMI. Therefore, a one-way repeated measures analysis of variance (ANOVA) with eHMI as the within-subject factor and subsequent *post hoc* pairwise comparisons (Bonferroni-adjusted *t*-tests) were calculated for the crossing initiation time. The alpha error level was set to $\alpha = 0.05$.

The participant and the test vehicle encountered each other at two predefined interaction points. However, the evaluation showed that the comparability of these two interaction points is not guaranteed. During the execution of the experiment, an enormous data failure occurred at one interaction point due to the lack of a smooth interaction and crossing scenario, and thus these data could not be used. This leads to the fact that, in the following, only one interaction point is analyzed in more detail.

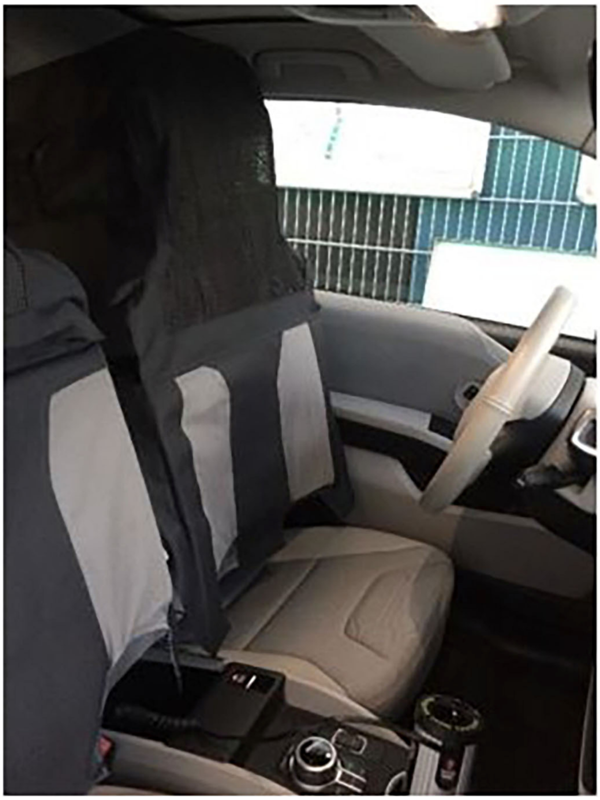

FIGURE 5 | The seat cover of a test vehicle to hide the driver and to simulate automated driving.

During the evaluation, one participant had to be completely excluded from the analysis because the participant did not show any natural interaction with the vehicle. Despite being told that it was a public road, this person did not pay any attention to the traffic. Therefore, it was assumed that this person did not normally exhibit such behavior in a crossing scenario. Therefore, it was decided to exclude this individual from further analyses because no natural crossing situation occurred.

The acceptance questionnaire was prepared according to the evaluation instructions of van der Laan et al. (1997) and analyzed. A coding system from +2 to −2 was used, with +2 being the most positive score. For the reversed items, the coding was adjusted accordingly. The questionnaire on perceived safety was scored from 1 (completely disagree) to 5 (completely agree). During the evaluation of the semi-structured interview, the statements of participants were collected and then clustered into categories. For each category, the number of mentions was recorded as absolute frequency so that frequently made statements could be identified. This categorization was based on inductive, thematic free coding according to Mayring (2015). The average inter-rater reliability was Cohen's $\kappa = 0.83$, reflecting a almost perfect agreement according to Landis and Koch (1977).

RESULTS

Crossing Initiation Time

Figure 7 shows the descriptive analysis of the data. The *intention-based light-band* was associated with the lowest average crossing initiation time ($M = 1.41$, $SD = 0.82$) and no eHMI with the highest ($M = 2.3$, $SD = 1.13$). The crossing initiation time of the *perception-based light-band* ($M = 1.71$, $SD = 1.17$) and of the *combination of light-band and signal lamp* ($M = 1.54$, $SD = 0.95$) lay between the *intention-based light-band* and no eHMI.

A repeated measures ANOVA showed a significant difference between the eHMI concepts [$F_{(3,66)} = 6.45$, $p < 0.001$, $\eta_p{}^2 = 0.23$]. The effect size can be classified as large according to Cohen (1988). *Post hoc* pairwise comparisons revealed a significant difference between the *intention-based light-band* and no eHMI ($p = 0.002$), as well as between the *combination of light-band and signal lamp* and no eHMI ($p = 0.031$). Hence, a significantly faster crossing initiation time was observed for the *intention-based light-band* and the *combination of light-band and signal lamp*, compared to no eHMI. No significance was found for the other comparisons.

Acceptance Questionnaire

The items were rated on a scale of −2 to +2, with +2 being the highest acceptance score. **Figure 8** displays the participants' scores on the two subscales. The examination of the descriptive analysis suggests that, on average, the *perception-based light-band* was rated best regarding usefulness ($M = 1.28$, $SD = 0.63$). The *intention-based light-band* was rated as slightly less useful ($M = 1.23$, $SD = 0.71$). The *combination of light-band and signal lamp* received the lowest rating ($M = 0.92$, $SD = 0.73$). Concerning ratings on user satisfaction with eHMIs, the *intention-based light-band* ($M = 1.16$, $SD = 0.72$) and the *perception-based light-band* received similarly high ratings ($M = 1.04$, $SD = 0.74$). The *combination of light-band and signal lamp* received the lowest rating ($M = 0.78$, $SD = 0.92$).

The two subscales of the acceptance questionnaire (i.e., usefulness and satisfying) were further evaluated with a repeated measures ANOVA. The statistical analysis revealed no significant effect on either usefulness [$F_{(2,56)} = 2.52$, $p = 0.09$, $\eta_p{}^2 = 0.08$] or satisfying [$F_{(1.53,42.95)} = 2.29$, $p = 0.13$, $\eta_p{}^2 = 0.08$].

Perceived Safety Questionnaire

Descriptive statistical analysis revealed that all three variants of the eHMI received high ratings. The *intention-based light-band* ($M = 4.24$, $SD = 0.87$) and the *perception-based light-band* ($M = 4.28$, $SD = 1.00$) received similar ratings. *The combination of light-band and signal lamp* received a slightly lower rating ($M = 3.90$, $SD = 1.08$). A repeated measures ANOVA showed no significant difference between the eHMI concepts [$F_{(2.55,38.78)} = 1.84$, $p = 0.17$].

Semi-Structured Interview

Participants were asked to name the different concepts they noticed during the study. Almost all participants named them as the *intention-based* ($n = 27$) and the *perception-based light-band*

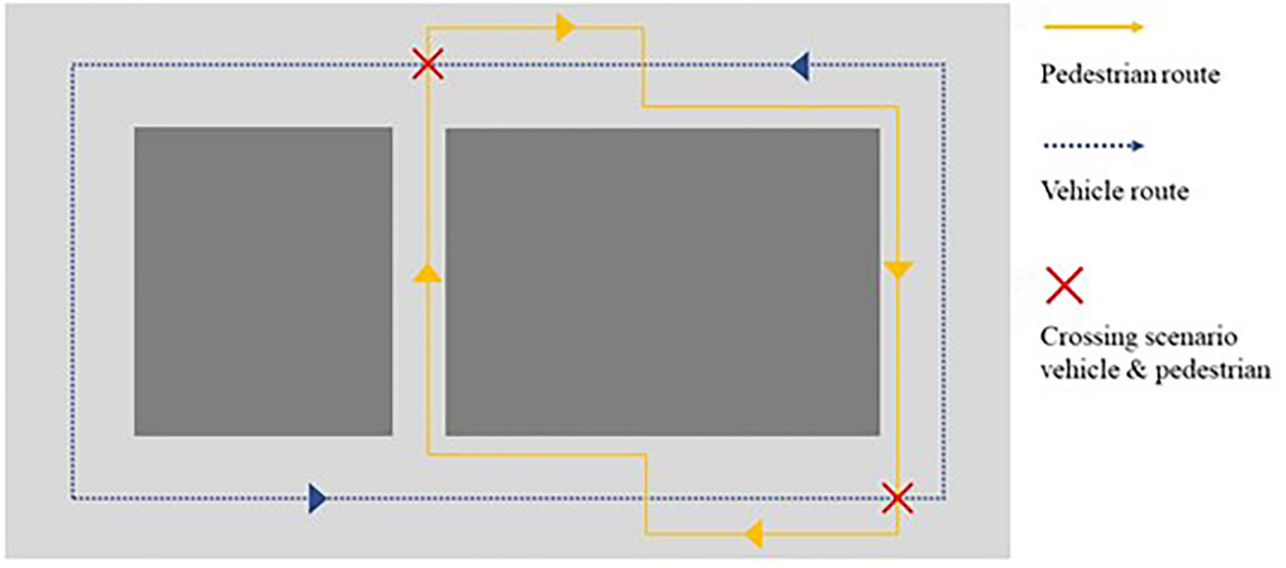

FIGURE 6 | Visualization of the test procedure with the predefined interaction points (red *x*).

($n = 27$). The signal lamp as part of the concept *combination of light-band and signal lamp* was mentioned only 13 times. After the three eHMI concepts were presented in terms of videos and explained, participants were asked which concept they found most or least understandable. Most participants named the *intention-based light-band* ($n = 13$) or the *perception-based light-band* ($n = 13$) as most understandable. The *combination of light-band and signal lamp* was rarely rated as the most understandable ($n = 3$). As a reason for the comprehensibility of the *intention-based light-band*, five participants mentioned the strong saliency of the concept, as the area in which the vehicle lights up green is large and thus easily perceivable. Regarding the *perception-based light-band*, eight participants noted as positive that the vehicle detects the participant's position and feeds back its detection. In total 11 participants described the *combination of light-band and signal lamp,* and ten the *perception-based light-band* as the least comprehensible. The *intention-based light-band*, on the other hand, was rather rarely described as incomprehensible ($n = 6$). Two participants rated none of the eHMIs as non-understandable. The main reasons given for a negative evaluation of the *perception-based light-band* were ambiguity of the concept ($n = 4$) and the lack of saliency ($n = 6$). The signal lamp was also criticized for its unobtrusiveness ($n = 5$), and four saw no added value or need for it. Five participants also noted that the signal lamp could be quickly misinterpreted. For example, three participants mistook the point-shaped light for that of a camera.

In general, almost all participants ($n = 25$) rated the approach of using eHMIs to communicate between vehicles and pedestrians as good. Eight participants commented that this was a very useful and intuitive communication option, which was especially good as a replacement for driver–pedestrian communication. The comprehensibility ($n = 6$), feedback ($n = 6$), and the feeling of safety ($n = 7$) that the external concept can provide were also mentioned. In total, 21 of the 29 participants said they felt adequately informed about what the vehicle was going to do next at any point in the study. One of the reasons cited was eHMI ($n = 11$), but another very common reason was the vehicle's implicit communication in the form of braking ($n = 16$).

DISCUSSION

Three different eHMI concepts were investigated in a real-world crossing scenario regarding their comprehensibility and their influence on the timing of the crossing decision. They were compared to a baseline without eHMI. For this reason, two research questions were posed (see section method), which are answered as follows:

RQ1: How does the use of the eHMI concepts affect the comprehensibility of vehicle intention compared to no eHMI?

The results showed a significant effect on the crossing initiation time between the *intention-based light-band* and no eHMI. This could be due to the good perceptibility and comprehensibility of this concept. Furthermore, there was a significant effect between the *combination of light-band and signal lamp* and no eHMI. This concept includes the concept of *intention-based light-band*, which can be an explanation for this significance, despite the poor subjective evaluation of the *combination of light-band and signal lamp* in the interview. Because only 13 participants noticed the signal lamp during the experiment, it is presumed that the other participants based their crossing decisions on the pulsating light-band and the signal lamp did not negatively influence it. In general, participants crossed the road earlier when the vehicle was communicating with the *intention-based light-band* or the *combination of light-band and signal lamp*. This is in line with the results of Matthews et al. (2017), Othersen et al. (2018), and Clercq et al. (2019)

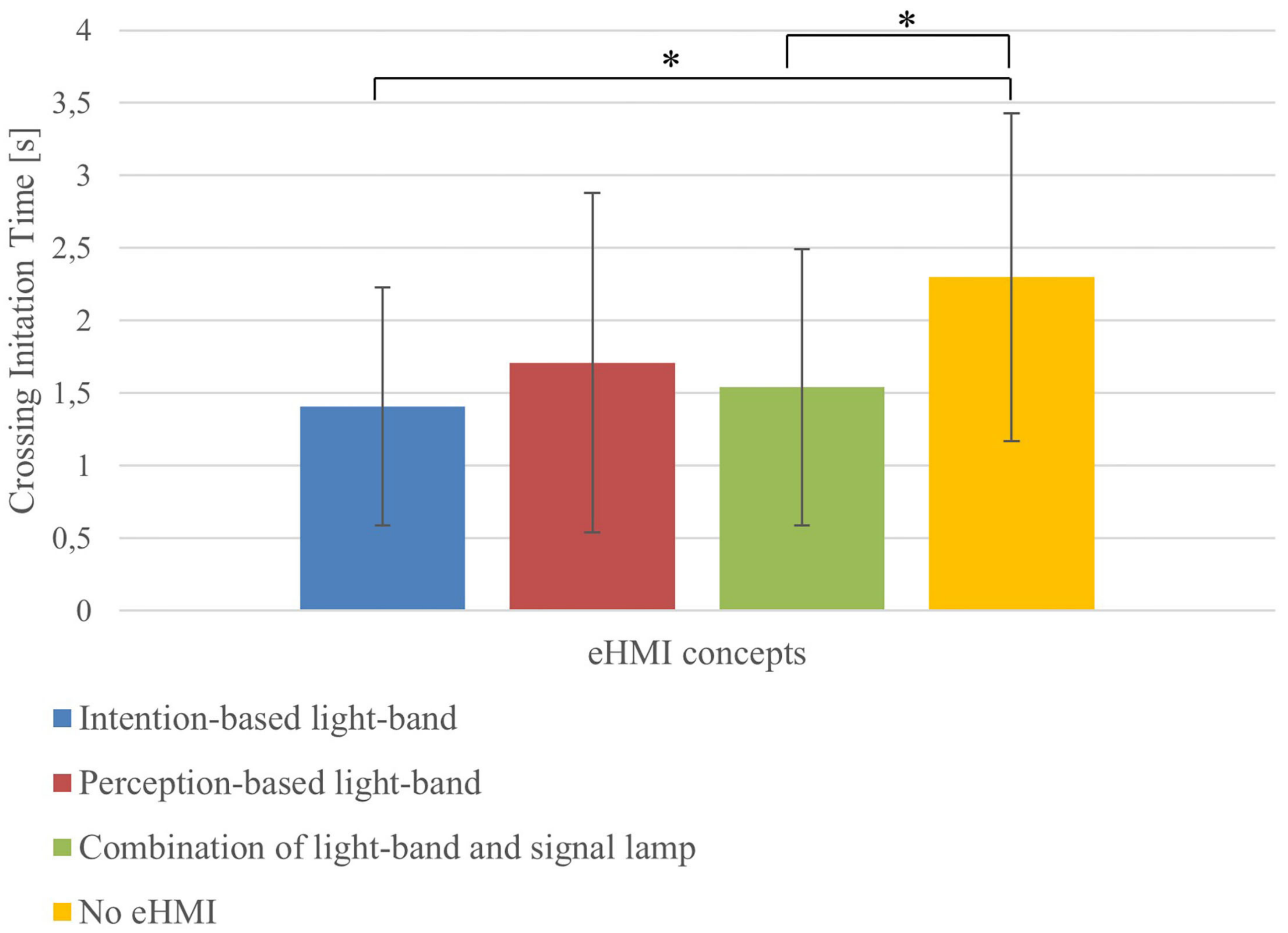

FIGURE 7 | Mean crossing initiation time in seconds across the different eHMI concepts. Error bars reflect ± 1 *SD*. *Reflects $p < 0.05$.

who were able to demonstrate in their studies that the presence of an eHMI led to an earlier crossing decision. This was also confirmed by ITS in Leeds as part of the interACT project (Dietrich et al., 2020). No significant difference was found between the *perception-based light-band* and the baseline. One reason for this could be the perceptibility and the partial lack of comprehensibility of this concept, which was criticized by participants. Another reason could be that participants needed time to infer from the eHMI statement, "I saw you," to the intention of the vehicle. However, there was no significant difference between the concepts *per se*. This can be due to the fact that the concepts are similar in their implementation and thus do not differ strongly enough from each other. This is in line with a test track study conducted by the TUM as part of the interACT project (Dietrich et al., 2020).

Another important factor to consider is vehicle movement. A finding of the interview was that participants also cited implicit communication through braking as a reason to infer the vehicle's intention. This is also consistent with the results of other studies. Clamann et al. (2017), for example, found that the use of external displays for communication with pedestrians influenced the crossing decision of only 12% of participants, while most pedestrians mainly used other information, such as vehicle speed and distance, for their crossing decision. This was also evident in the interview analysis, where several participants mentioned implicit communication as an additional reason for the comprehensibility of the vehicle's intention. The results of Rothenbucher et al., 2016 study also suggested that pedestrians' crossing decision depended solely on vehicle movement, but at the same time, pedestrians wished for clear signals to show them that they had been detected and could safely cross the street. This is in accordance with Mahadevan et al. (2018) who recommended to use explicit communication of vehicle intention rather than just implicit communication. Thus, it can be concluded that the use of eHMIs is not a substitute for implicit communication, but can be supportive and helpful to pedestrians in making crossing decisions. Therefore, an interplay of both means of communication should be aimed for, whereby the eHMI communication must in no case contradict the behavior of the vehicle.

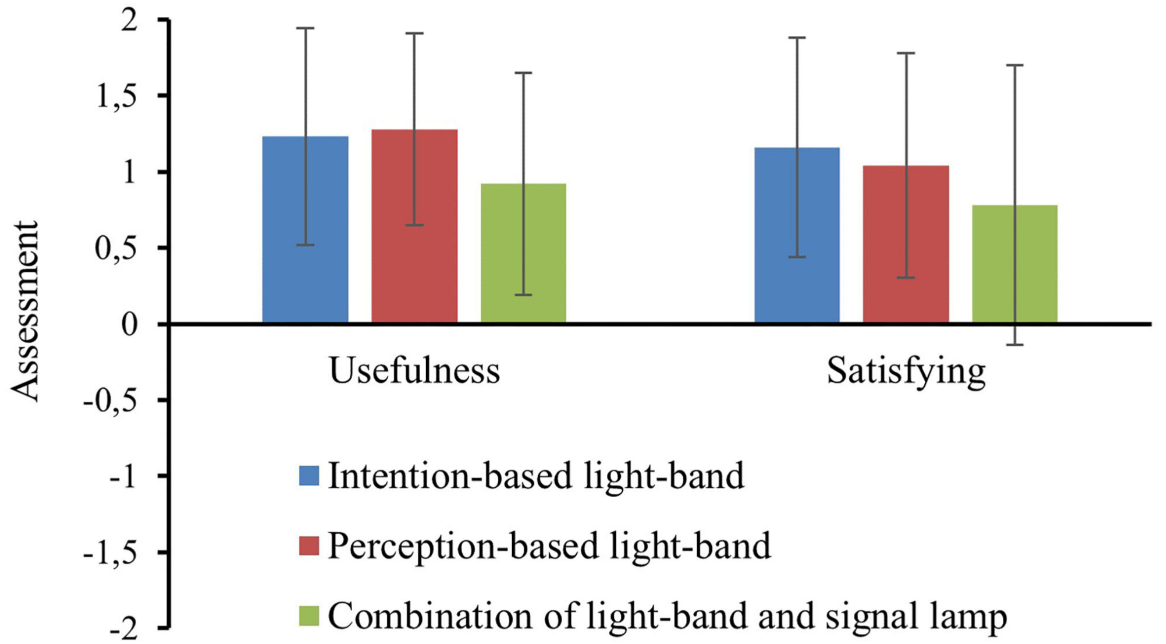

FIGURE 8 | Mean acceptance rating across the eHMI concepts. Error bars reflect ± 1 *SD*.

In summary, the present results provide evidence that the evaluated eHMI concepts have a positive effect on the comprehensibility of the vehicle's intention. The subjective evaluation of participants reveals that explicit communication using these eHMIs is helpful. This is also reflected in the objective data, showing that participants crossed the road earlier when either the *intention-based light-band* or the *combination of light-band and signal lamp* was present. However, there were no significant differences in crossing initiation times between the absence of eHMI and the *perception-based light-band*. Also, implicit vehicle communication probably contributes to the comprehensibility of the concepts.

RQ2: How do the different eHMI concepts differ from each other regarding comprehensibility, acceptance, and perceived safety?

The interview showed that the *intention-based light-band* was perceived by almost all participants and could therefore be noted as the most salient concept. This might be due to the large area of the light along the entire vehicle contour and should be emphasized as positive. For this reason, it can be assumed that this concept is easily recognizable by participants. High perceptibility could be a prerequisite for good comprehensibility because this concept was often evaluated as positive in this respect. Overall, the *intention-based light-band* can be rated as comprehensible.

In the evaluation of the *perception-based light-band*, the interview did not reveal any clear tendency among participants. This concept was perceived by some participants as the most comprehensible one. The continuous display of the detected participant position was mentioned positively. However, the *perception-based light-band* was also rated as the least understandable by some participants. This could be an indication that not all participants understood the running light-band as an indication of their own position or did not perceive it as soon as they crossed the street and turned their gaze forward. The designation of the concept by some participants as a "small green bar" also suggested that the salience of this concept was not sufficient for several participants. This finding is consistent with the results of a study conducted by Faas and Baumann (2020). They stated that a steady or flashing light was better suited to indicate the intention of an AV, or to give pedestrians the right of way, than a "sweeping light." Thus, the comprehensibility of the *perception-based light-band* has to be questioned.

The interview showed that the *signal lamp* was only perceived by 13 participants and could therefore be noted as the least salient component of the eHMIs concepts. The *combination of light-band and signal lamp* was often described as the least understandable concept after explanation. The interview showed that the signal lamp was misunderstood and had a negative impact on the comprehensibility of the concept. It was not clear to all participants what message the signal lamp communicated. Therefore, this eHMI scored the worst in the evaluation regarding its comprehensibility. However, it can be assumed that this poor rating is due to the signal lamp and not to the entire concept, including the *intention-based light-band* concept.

The evaluation of the acceptance questionnaire showed that all three eHMIs scored high ratings. No significant differences were found between the concepts in the evaluation of usefulness and satisfaction. Therefore, it can be assumed that they do not differ greatly from one another in terms of subjective acceptance. The evaluation of perceived safety did not indicate any major differences between the three eHMI variants, with only the *combination of light-band and signal lamp* being rated slightly lower. Although participants might not see or understand the signal lamp, they would still rate this concept quite high regarding acceptance and perceived safety. This could be explained by the fact that the well-understood and well-rated pulsating light-band was additionally present, which positively influenced the evaluation of this concept. Because this rating was high on average for all eHMI variants, it could be assumed that the presence of eHMIs conveyed a sense of safety to participants, regardless of the concept. This is also in line with the results of Habibovic et al. (2018), who were able to demonstrate that participants feel safer when information is communicated *via* eHMIs in addition to implicit communication. Thus, it can be assumed that all concepts can contribute to a higher subjective perception of safety.

Limitations and Future Research

Firstly, no pilot study was conducted beforehand. Prior to the experiment, preliminary studies were performed with several participants; however, not all limitations were discovered during these studies. The limitations of the study are reported below. The location of the experiment proved to be problematic. Spontaneous events along the test route, although favoring the impression of a real traffic situation, led to problems during the experiment. Other vehicles, e.g., trucks, parked on the sidewalk or car entering and exiting, interfered with the smooth test procedure. Pedestrians crossing participants' path also forced the repetition of the corresponding passes. Furthermore, this study can reflect the natural crossing behavior of a participant only to a certain extent. The planned and repetitive encounter between the vehicle and the participant led to a rather artificial flow of the experiment.

A central limitation of this study was that the two interaction points at which participants encountered the test vehicle were not identical. For this reason, the interaction points could not be compared and the results could not be merged. This resulted in a loss of data. A further study with more data is recommended.

Moreover, it could be assumed that the learning effect considering the behavior of the vehicle during the study was high. Because participants encountered the vehicle several times and the vehicle stopped for them each time, participants could have decided to cross the road completely independent of the display of an eHMI, but solely based on their previous experiences and lessons learned. Furthermore, it should be mentioned that the switching on of the eHMIs was done manually by the co-driver on a tablet. An automated solution would have been useful at this point to ensure standardized timing.

An additional limitation of this study is the composition of the present sample. This consisted mainly of students under 30 years of age, which corresponds to a very young and homogeneous group. Rasouli et al. (2017) noted that culture also plays a role in determining pedestrian behavior. In the future, communication with AVs must be intuitive, understandable, and easily learnable by all road users, regardless of culture, language, or age. Therefore, it would be important to replicate the results of this study by resurveying with a more heterogeneous sample. To rule out possible cultural influences on the intelligibility of eHMIs, the study should be repeated in other countries. The results presented must be considered with the reservation of low power. It cannot be ruled out that possible differences between the concepts cannot be detected due to the small sample size. Future experiments should take this aspect into account and be conducted with a larger sample size.

The results of this study indicate the potential for improvement and further development of eHMI concepts. Further research questions can be posed, which need to be examined in further studies. For example, it must be ensured that eHMI concepts are sufficiently perceptible and understandable for people with color vision impairment. Similarly, it should not be possible to confuse the display of an eHMI with the lighting system of emergency vehicles. Differently rated comprehensibility of eHMIs reinforces the call for cross-manufacturer communication concepts. Manufacturer-specific eHMIs could lead to ambiguity, lack of comprehensibility, and confusion when making crossing decisions. This could counteract the goal of increasing traffic safety through AVs. In a standardized solution approach, attention should be paid to an intuitive and easy-to-learn design. The need for a detailed explanation should be avoided. In addition, future studies should consider crossing situations where pedestrians have to interact with more than one AV, which might lead to conflicting yield/pass messages.

CONCLUSION

The introduction of AVs could lead to a lack of communication between drivers and pedestrians. New and intuitive communication concepts for achieving safe interactions between AVs and vulnerable road users, such as pedestrians, are needed. The present work aimed to investigate participants' reactions to external communication concepts in a real-world crossing scenario. Three different eHMI concepts developed in the interACT project (*intention-based light-band, perception-based light-band, and combination of light-band and signal lamp*) were varied and compared to a baseline without eHMI. The study investigated whether the use of eHMIs affects the comprehensibility of vehicle intention and leads to earlier road crossing. For this purpose, crossing initiation time in seconds was measured and the intention recognition was queried.

It was shown that participants crossed the road significantly earlier with the concepts of *intention-based light-band* and the *combination of light-band and signal lamp* compared to no eHMI. Moreover, all eHMIs were rated with high acceptance and perceived safety. The *intention-based light-band* was evaluated as well understandable and had high saliency. It communicated the vehicle intention "I'm letting you go ahead," which was explicit for most participants. This is preferable to the *perception-based light-band* that communicated "I saw you." The constant communication of the participant's position through the *perception-based light-band* was noted positively, but the lack of perceptibility and comprehensibility of the concept was evaluated negatively. This results in an ambiguous picture, which calls for a revision of this concept, especially regarding its saliency. The *combination of light-band and signal lamp* was subject to most criticism because the signal lamp was not salient enough and could be easily misinterpreted. Therefore, the signal lamp investigated in this study is neither suitable and nor recommended for communication between AVs and pedestrians.

Conclusively, the *intention-based light-band* investigated in this study can be rated as the best and most comprehensible concept and is therefore recommended for further application. This work makes an important contribution to clarify how communication between pedestrians and AVs can be designed and investigated in a safe and intuitive way. In addition, the present study design provides a novel approach for assessing eHMIs in a realistic traffic situation. However, future work is needed to enhance this approach.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethic commission of the Technical University of Munich; Grant No. 24/20 S. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AL wrote the first draft of the manuscript. JG, LH, AG, AB, and AD contributed to conception and design of the study. AL and JG performed the statistical analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

This project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 723395.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.