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From Visions to Reality: Investigating the Interplay of Vehicle Kinematics and Light-band eHMI in a Real Vehicle Study

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A R T I C L E I N F O

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A B S T R A C T

Highly automated vehicles (HAVs) will interact with pedestrians in urban environments. This requires efficient communication tools to ensure mutual understanding. Past research showed that pedestrians mostly used vehicle kinematics to communicate with vehicles, e.g., the vehicle's speed and distance. However, pedestrians required further explicit communication signals when the traffic situation was ambiguous. Light-band external human–machine interfaces (eHMIs) transmit additional explicit communication signals to pedestrians, e.g., the vehicle's yielding intent. To this point, the precise interplay of vehicle kinematics and eHMIs for HAVs has not yet been determined. Nevertheless, previous research showed that combining both means of communication has great potential to increase pedestrian perceived safety and to ensure a safe interaction. Only a little research used real vehicle studies to investigate the interaction between pedestrians and HAVs in a close-to-reality experimental setting. However, this would ensure the transferability of experimental results to future urban traffic. Therefore, this study aimed to address this research gap by investigating the effects of vehicle kinematics, eHMIs, and their interplay in a real-world pedestrian crossing on pedestrians' behaviors and subjective evaluations. In this field experiment, we applied a light-band eHMI on a Wizard-of-Oz test vehicle, an actual vehicle instructed as an HAV. We investigated the effects of vehicle kinematics (early yielding vs. late yielding) and the eHMI status (no eHMI, static eHMI, dynamic eHMI) on pedestrians' crossing behavior and subjective evaluation in a low-speed real-world setting. The static eHMI displayed the vehicle automation status by a static illuminated eHMI. The dynamic eHMI conveyed the automation status and the vehicle's yielding intent. This study focused particularly on the interplay of vehicle kinematics and eHMI status. We assumed that the crossing initiation was shorter when a dynamic eHMI was combined with an early yielding compared to a late yielding in this real-world setting. Moreover, we hypothesized that pedestrians' subjective evaluations are more positive for a well-coordinated interplay of eHMI and vehicle kinematics. The results showed that pedestrians initiated their crossing earlier with dynamic eHMI vs. no eHMI or static eHMI. Furthermore, they perceived a dynamic eHMI as safer and more trustworthy compared to no eHMI or a static eHMI. Combining an early yielding and dynamic eHMI increased participants' perceived safety of the vehicle behavior and trust and improved pedestrians' affective evaluations compared to a late yielding with dynamic eHMI. Overall, this real vehicle study highlighted the importance of implicit and explicit communication signals and their well-coordinated interplay for pedestrians' future interactions with HAVs in a real-world setting.

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1. Introduction

In future traffic, highly automated vehicles [HAVs; SAE level 4 (SAE International, 2021)] will share the same spaces with pedestrians, which requires communication with each other for safe interaction (Habibovic et al., 2018; Rasouli & Tsotsos, 2020). Communication in urban traffic means influencing others through the exchange of information, e.g., the vehicle could inform pedestrians via the vehicle's kinematics (Bengler et al., 2020; Rasouli et al., 2018; Rasouli & Tsotsos, 2020). With regard to current traffic, pedestrians primarily use vehicle kinematics as a source of information for safe interaction (Clamann et al., 2017; Lee et al., 2020; Dey & Terken, 2017). For example, if the vehicle maintains its speed, the pedestrians could anticipate the vehicle's intention not to give way. A reason why pedestrians interpret vehicle kinematics easily could be that they are familiar with it (Risto et al., 2017). Nevertheless, during low-speed traffic scenarios, the vehicle kinematics might not be identifiable anymore, so pedestrians might seek additional explicit communication signals, e.g., eye contact with the human driver (Rasouli et al., 2017).

In future HAVs, human drivers will become passengers not performing the driving task any longer, so they will no longer be available for meaningful or reliable communication with the interacting pedestrians (Merat et al., 2018; Schieben et al., 2019). Light-band external human–machine interfaces (eHMIs) have prevailed as a design solution for HAVs to present explicit communication signals, e.g., about the yielding intent (Dey, Habibovic et al., 2020; Faas et al., 2020; Lau et al., 2022a; Wilbrink et al., 2021). Past studies showed that eHMIs can increase pedestrians' perceived safety (Habibovic et al., 2018; Lau et al., 2022a) and trust (Faas et al., 2020; Lau et al., 2022a, 2022b). The vehicle kinematics as implicit communication signals will continue to contribute to successful communication. However, in low-speed scenarios with undefined right-of-way, additional explicit cues by the eHMI could contribute to a safe interaction (Bengler et al., 2020; Madigan et al., 2023; Schieben et al., 2019). Both communication means could contribute to secure future communication between pedestrians and HAVs (Rasouli & Tsotsos, 2020). Nevertheless, the question arises regarding how these two means of communication should be coordinated. The exact interplay of both communication signals towards a holistic communication strategy for HAVs needs further investigations in more realistic and external-valid interactions (Lee et al., 2022; Madigan et al., 2023). This study addressed the research question of how an efficient interplay of implicit and explicit communication signals should be coordinated for pedestrians' interactions with an HAV in a real-world setting.

1.1. Implicit and explicit communication signals

Highly automated vehicles will communicate with the traffic environment implicitly by their vehicle kinematics and explicitly by eHMIs (Bengler et al., 2020). The vehicle kinematics, e.g., the vehicle's speed or distance, transmit implicit communication signals that pedestrians could use as information sources about the vehicle's future behavior (Markkula et al., 2020; Schieben et al., 2019). External HMIs transmit explicit communication signals, e.g., the pulsation of the eHMI can inform about the vehicle's yielding intent (Bengler et al., 2020; Dey, Habibovic et al., 2020; Dey et al., 2022). Several studies manifested the importance of vehicle kinematics for HAVs' interactions with pedestrians (Dey, Habibovic et al., 2020; Risto et al., 2017; Rothenbucher et al., 2015). For instance, Risto et al. (2017) showed that pedestrians perceived an early deceleration combined with continuous slowing down as safety-increasing. The authors underlined that road users quickly understand vehicle kinematics and are used to interpret the vehicle's intention even in complex traffic situations (Risto et al., 2017).

In a study by Ackermann et al. (2019), the effect of vehicle speed, deceleration rate, and onset of deceleration on pedestrians' deceleration detection times was investigated. The participants had to press a button when they noticed a change in the vehicle movement. In the experimental trials, the starting velocity (20 km/h vs. 30 km/h), the deceleration rates (-2.1, -1.4, -0.7 m/s^2), and the onset of the vehicle's deceleration (early vs. late) were varied. Results showed that pedestrians detected the vehicle's deceleration faster when the vehicle drove at a higher speed and had an early onset of deceleration. Fuest et al. (2020) also underlined the importance of an early deceleration to indicate the vehicle's yielding intent. The authors investigated the effect of different intentions displayed by different driving profiles on pedestrians' intention-recognition times in a virtual reality (VR) setting. When the HAV intended to give the road user right-of-way, the pedestrians preferred an early deceleration starting at a distance of 25 m compared to a late deceleration starting at a distance of 16 m; the stopping point of the HAV was at a 5 m distance to the pedestrian. However, referring to the intention-recognition time, the participants needed more time to recognize the vehicle's intention in the early deceleration conditions. The authors explained that the participants might have taken more time to feel confident with their decision. Overall, current research underlines the importance of implicit communication signals for interaction with pedestrians and that pedestrians prefer an early deceleration to identify the vehicle's intention (Ackermann et al., 2019; Fuest et al., 2020). However, an early deceleration could also lead to longer intention-recognition times, giving pedestrians a longer time to decide (Fuest et al., 2020).

Pedestrians might require additional explicit communication signals in low-speed and low-distance traffic interactions to solve misunderstandings when the traffic interaction is ambiguous (Rasouli et al., 2017; Sucha et al., 2017). This has been found in today's interaction and pedestrians' future interactions with HAVs (Habibovic et al., 2018; Mahadevan et al., 2018; Merat et al., 2018; Schieben et al., 2019). For example, light-band eHMIs can inform explicitly by light signals in future interactions (Dey, Matviienko et al., 2020; Faas et al., 2020; Lau et al., 2022b). Pedestrians are already familiar with light signals from vehicles from today's traffic, e.g., turn indicators. This could help to interpret the light signals of a light-band eHMI (Faas & Baumann, 2019). Additional advantages of light-band eHMIs are that they provide high visibility for the surrounding traffic environment (Weber et al., 2019). Moreover, light-band eHMIs are cultural-independent as they do not require language skills (Schieben et al., 2019). Studies showed that the presence of a light-band eHMI could increase pedestrians' willingness to cross, perceived safety or trust compared to no eHMI (Dey, Matviienko et al., 2020; Habibovic et al., 2018; Lau et al., 2022a, 2022b; Loew et al., 2022). As a challenge, light-band eHMIs need to present the right amount of explicit communication signals at the correct timing (Dey, 2020). Therefore, different eHMI communication strategies were investigated in various studies to identify the right amount of information from a pedestrian's perspective (Faas et al., 2020; Lau et al., 2022a; Weber et al., 2019). Static (continuously enlightened) light-band eHMIs can inform the vehicle's automation status (Faas et al., 2020; Habibovic et al., 2018; Lau et al., 2022a). In addition, dynamic (static + intention-based) eHMIs can inform about the vehicle's yielding intent (Dey, Matviienko et al., 2020; Lau et al., 2022a; Lundgren et al., 2017; Wilbrink et al., 2021), e.g., by a slow pulsation of the light-band eHMI (Lau et al., 2022a; Wilbrink et al., 2021). Overall, results showed that dynamic intention-based eHMIs were perceived as safer and evaluated as affectively more positive compared to a static, continuously enlightened eHMI or no eHMI (Dey, Matviienko et al., 2020; Lau et al., 2022a; Wilbrink et al., 2021). As a limitation, previous studies focused primarily on the effect of the eHMI. Nevertheless, the effect of eHMIs cannot be considered on its own but is always formed by the interaction of vehicle kinematics and eHMIs (Lau et al., 2022b). Therefore, it needs further research on how the interplay takes place to define a holistic communication strategy for HAVs.

As one of the few studies, Dey, Matviienko et al. (2020) investigated the interplay of eHMI and vehicle kinematics on pedestrian willingness to cross in a realistic vehicle study. The stopping point was at a 5 m distance to the pedestrian for all conditions. Three different braking behaviors were investigated. First, early braking was initiated at a 45 m distance and performed within 16 m (deceleration rate of -5.17 m/s^2). After the braking, the vehicle drove slowly toward the participant before stopping at a 5 m distance from the pedestrian. Second, there was a gentle continuous braking, initiated at a 45 m distance and performed within 40 m (deceleration rate of -2.4 m/s^2). Third, an aggressive braking started at a distance of 24 m and was performed within 19 m (deceleration rate of -5.17 m/s^2). Moreover, the test vehicle was equipped with a light-band eHMI showing no eHMI, a static eHMI displaying the automation mode, or a dynamic eHMI displaying the yielding intent. Overall, pedestrians felt safer with dynamic eHMI compared to no eHMI. The results showed that gentle and early braking combined with dynamic eHMI leads to a higher willingness to cross than aggressive behavior or no braking (Dey, Matviienko et al., 2020). The authors stated that the vehicle's yielding intent is communicated most effectively when both communication signals, implicit and explicit, are in accordance with each other (Dey, Matviienko et al., 2020). As a limitation, the authors investigated a traffic interaction in which the vehicle approached from the left-hand side, which might have affected their willingness to cross (Dey, Matviienko et al., 2020). Additionally, this study investigated the mental processes of pedestrians when they think about whether to cross. However, the pedestrians did not actually cross the street in this study. Therefore, future research should focus more on traffic interactions where pedestrians do not have right-of-way and can cross the street naturally.

1.2. Effects on pedestrian crossing behavior

The consideration of pedestrians' objective crossing behavior can help to make statements about pedestrians' perceived safety (Faas et al., 2021). In a realistic vehicle study, Loew et al. (2022) investigated pedestrians' crossing initiations, their acceptance, and their perceived safety when interacting with an HAV equipped with light-band eHMI. This study followed a Wizard-of-Oz (WoZ) approach, i.e., the participants were instructed that the vehicle was highly automated, although it was driven manually. The eHMI showed different eHMI communication strategies, e.g., an intention-based eHMI, which pulsated slowly to indicate the vehicle's yielding intent. In the experimental trials, the test vehicle approached from the left-hand side, i.e., the pedestrian had the right-of-way. The results showed that the pedestrians initiated their crossings significantly earlier with an intention-based light-band eHMI compared to no eHMI (Loew et al., 2022). This finding stands in line with a study conducted by Wilbrink et al. (2021), who investigated the timing of pedestrians' crossing decisions and showed that pedestrians decided to cross the road earlier when the HAV communicated the vehicle's intention via dynamic eHMI (Wilbrink et al., 2021).

In contrast, previous studies found no significant differences in pedestrians' crossing onsets (Faas et al., 2020) or crossing initiation times (Dietrich et al., 2020). In a real vehicle study, Faas et al. (2020) investigated pedestrians' crossing onsets and their perceived safety and trust in their interaction with an HAV. The vehicle presented different eHMI communication strategies via light-band eHMI. The participants stood at an uncontrolled and unsignalized four-way intersection and saw the test vehicle approaching from the left-hand side. Initially, the test vehicle drove with a constant speed of 30 km/h toward the pedestrian and started to yield at a distance of 25 m. The test vehicle stopped at a distance of 7 m. Results showed that pedestrians felt safer and described a higher trust when the HAV was equipped with eHMI compared to conditions without eHMI. Additionally, the participants perceived the information about the vehicle's yielding intent as additional support for their safety (Faas et al., 2020). Regarding pedestrians' crossing onsets, the authors described differences on a descriptive level, i.e., the participants initiated their crossing earliest with a dynamic (static + intention-based) eHMI and the latest without eHMI. Nevertheless, they did not find statistically significant differences for the crossing onsets (Faas et al., 2020). As a limitation, this study only varied the eHMI status and not the vehicle kinematics. Hence, the interplay of both communication signals was not varied. In a simulator study by BMW as part of the interACT project, pedestrians' crossing initiation times did not differ for different eHMI communication strategies (Dietrich et al., 2020). Nevertheless, the authors pointed out that additional instructions on the eHMI functions enhanced pedestrians' crossing initiation times, i.e., they initiated their crossing earlier (Dietrich et al., 2020). A previous study on the learnability of eHMIs showed that participants quickly understood the correct meaning of a light-band eHMI, i.e., after a maximum of three interactions (Avsar et al., 2021). Derived from the results, pedestrians might need instructions on the eHMI functions to initiate their crossing accordingly and successfully interact with the eHMI (Dietrich et al., 2020; Liu et al., 2021).

Crossing the road consists of different phases, including the actual crossing of the road. Little published research has addressed the effect of eHMI status and vehicle kinematics on pedestrians' crossing durations. As one of a few studies, Faas et al. (2020) showed on a descriptive level that when the eHMI presented more information, the pedestrians needed more time for their crossing, i.e., an eHMI that transmitted information about the vehicle automation status (VAS), the pedestrian's detection and vehicle's intention increased pedestrians' crossing durations compared to a static eHMI (Faas et al., 2020). The crossing durations for all other experimental conditions did not differ. The authors attributed this finding to the communication of the vehicle's perception (Faas et al., 2020). In this experimental condition, the eHMI tried to build up eye contact and followed the pedestrians while crossing the street. Results of a structured interview after the experiment emphasized that when the eHMI conveyed information about the pedestrian's detection ("vehicle's perception"), it could lead to an information overload because the eHMI draws too much attention (Faas et al., 2020). From this derived, the right amount of information by eHMIs is highly important to ensure a safe crossing for pedestrians. Focusing on the effect of vehicle kinematics on pedestrians' crossing durations, Lee et al. (2019) stated that pedestrians required the same amount of time to cross the street, even when the vehicles' speed profiles differed. According to the results, when pedestrians decide to cross the street and feel safe enough to do so, they do so in the same amount of time. To this point, current research lacks studies focusing on the interplay of eHMI and vehicle kinematics and its effect on pedestrians' crossing durations. Additionally, most studies on eHMIs only addressed some phases of a crossing process, e.g., the crossing initiation (Dietrich et al., 2020). However, the crossing process consists of different phases (Ezzati Amini et al., 2019), and pedestrians should be able to experience the whole crossing.

Overall, light-band eHMIs seem to be promising communication tools for HAVs regarding pedestrians ' subjective evaluations. However, contrasting results exist on the effect of eHMIs on crossing initiation times. On the one hand, pedestrians initiated their crossings earlier with dynamic eHMI, which provided information about the yielding intent and vehicle automation status (Loew et al., 2022; Wilbrink et al., 2021). On the other hand, no differences were found in terms of the pedestrians' crossing initiation times (Dietrich et al., 2020; Faas et al., 2020). Additionally, no clear assumptions about the effects of eHMI and vehicle kinematics on the crossing duration can be derived from the latest studies. One of the reasons for such a contrasting image might be that most of the previously named studies were conducted in a VR setting. However, there might be a discrepancy between VR and real-world settings regarding the light emission, which also might affect the visibility of eHMIs (cf. Lee et al., 2022). The evaluation of new communication strategies for HAVs in real-world settings ensures the transferability of these communication strategies before HAVs enter the roads of tomorrow (Dey, Habibovic et al., 2020). Therefore, the effect of eHMIs in combination with vehicle kinematics on pedestrians' crossing initiations and crossing durations needs further elaboration in real-world settings to enable pedestrians to perform a natural crossing.

1.3. Research aim

This real vehicle study aimed to extend previous research on the interplay of vehicle kinematics and eHMIs for HAVs in a real-world pedestrian crossing scenario. This study builds on previous video-based studies addressing pedestrians' interactions with differently sized HAVs (Lau et al., 2022a, 2022b). In contrast to video-based studies, this realistic vehicle study conveyed a high degree of realism by focusing on the entire crossing of the pedestrians and not only on the crossing decision. Past realistic vehicle studies mainly focused on traffic interactions in which the vehicles approached from the left-hand side (Dey, Matviienko et al., 2020; Loew et al., 2022). In this realistic vehicle study, the vehicle approached from the right-hand side of the pedestrian, i.e., the pedestrian did not have right-of-way. The motivation for our research was three-fold. First, we focused on how the effect of a light-band eHMI, which displayed three different eHMI statuses (no eHMI, static eHMI, dynamic eHMI), affects pedestrians' subjective evaluations and crossing behaviors for their interaction with the HAV in a real-world setting. Second, we focused on how the timing of the vehicle kinematics might affect pedestrians' crossing behaviors and their subjective evaluations in this pedestrian crossing scenario. Third, we investigated how the interplay of both means of communication (eHMI and vehicle kinematics) affects pedestrians' behaviors and subjective evaluations in a real-world setting.

1.4. Research questions and hypotheses

The following hypotheses address the effect of eHMI status (hypotheses 1.1 and 1.2), the effect of vehicle kinematics (hypotheses 2.1 and 2.2), and the interplay of eHMI status and vehicle kinematics (hypotheses 3.1 and 3.2). Furthermore, we address the crossing durations in a research question.

Previous studies underlined that pedestrians crossed significantly earlier with a dynamic intention-based eHMI than without an eHMI or a static eHMI (Loew et al., 2022; Wilbrink et al., 2021). However, other studies did not find significant effects of eHMIs on pedestrians' crossing initiations when there were no instructions about the eHMI functionalities available (Dietrich et al., 2020). In this study, we instructed the participants about the eHMI designs. We hypothesized that pedestrians' crossing initiation times are shorter depending on a dynamic eHMI compared to a static eHMI or no eHMI:

Hypothesis 1.1. **(H 1.1): Pedestrians' crossing initiation times** are shorter for a dynamic eHMI compared to a static eHMI and no eHMI.

Previous studies manifested positive effects of eHMIs on the willingness to cross, trust, and perceived safety of pedestrians (Dey, Matviienko et al., 2020; Faas et al., 2020; Habibovic et al., 2018; Lau et al., 2022b; Loew et al., 2022). Additionally, pedestrians evaluated a dynamic intention-based eHMI with a more positive affective evaluation than a static eHMI or no eHMI (Lau et al., 2022b). From this derived, we assumed that pedestrians evaluate their subjective experience as more positive when the test vehicle is equipped with dynamic eHMI compared to a static eHMI or no eHMI:

Hypothesis 1.2. **(H 1.2):** Pedestrians evaluate their **trust, perceived safety, affective valence, arousal, and dominance** more positively for a dynamic eHMI than a static eHMI and no eHMI.

In general, previous studies highlighted that vehicle kinematics are an essential indicator of pedestrian crossing behavior (Dey & Terken, 2017; Lee et al., 2020). The study by Ackermann et al. (2019) emphasized that pedestrians' deceleration detection times were faster when the vehicle had an early onset of deceleration. Moreover, pedestrians generally preferred to be informed early about the yielding intent (Fuest et al., 2020) and evaluated a continuous slowing down as safety-enhancing (Risto et al., 2017). Overall, these studies focused on the effect of the deceleration, i.e., the vehicle kinematics, on pedestrians' crossing behavior. From this derived, we assumed that an early deceleration of the HAV leads to an earlier initiated crossing compared to a late yielding when there is no eHMI:

Hypothesis 2.1. **(H 2.1):** For no eHMI conditions, pedestrians' **crossing initiation times** are shorter when the vehicle yields early vs. late.

Hypothesis 2.2. **(H 2.2):** For no eHMI conditions, pedestrians evaluate their **trust, perceived safety, affective valence, arousal, and dominance** more positively when the vehicle yields early vs. late.

Previous studies highlighted that pedestrians seek additional explicit communication signals, e.g., eye contact, in low-speed scenarios for further clarification (Rasouli et al., 2017; Sucha et al., 2017). External HMIs are design solutions to ensure explicit communication between pedestrians and HAVs in the future without the need for a human driver (Habibovic et al., 2018; Schieben et al., 2019). In particular, dynamic intention-based eHMIs informing about the vehicle automation status and the vehicle's intent could help to clarify the vehicle's yielding intent (Faas et al., 2020; Lau et al., 2022b; Wilbrink et al., 2021), particularly when the right-of-way is unclear (Madigan et al., 2023). To use the full potential of eHMIs, a coordinated interplay between eHMI and vehicle kinematics is required (Dey, Matviienko et al., 2020). Dey, Matviienko et al. (2020) showed that employing gentle and early braking alongside a dynamic eHMI significantly increased the willingness to cross compared to aggressive behaviors or no braking. Therefore, we assumed the following in this study:

Hypothesis 3.1. **(H 3.1)**: For conditions with dynamic eHMI, pedestrians' **crossing initiation times** are shorter when the vehicle yields early compared to when the vehicle yields late.

Hypothesis 3.2. **(H 3.2):** For conditions with dynamic eHMI, pedestrians evaluate their **trust, perceived safety, affective valence, arousal, and dominance** more positively when the vehicle yields early compared to when the vehicle yields late.

Focusing on individual road crossings, it should be noted that the actual crossing is also part of the process in addition to the crossing initiation (Geruschat et al., 2003). In a study by Lee et al. (2019), pedestrians needed the same time to cross the street, even when the vehicle performed different driving profiles. This finding aligns with Faas et al. (2020), who did not find significant differences in pedestrians' crossing durations when interacting with an HAV without eHMI, with a static eHMI, or with an intention-based eHMI. The studies focused on the effect of vehicle kinematics (Lee et al., 2019) and the effect of eHMIs (Faas et al., 2020) on crossing durations. As a limitation, the studies did not focus on the interplay of eHMI and vehicle kinematics. Moreover, since no clear statements can yet be made about the crossing duration, we wanted to investigate further the effect of eHMI and vehicle kinematics on crossing durations. The following explorative research question for pedestrians' crossing duration was derived: How do the crossing durations differ depending on the vehicle kinematics or the eHMI status?

2. Method

2.1. Sample

In total, 43 participants (16 female, one not specified) with an average age of $M = 34.14$ years ($SD = 13.56$ years) participated in the study. The Affinitiy-of-Technology Interaction (ATI) was measured with the ATI questionnaire by Franke et al. (2018) and was ranked with $M = 4.53$ ($SD = 0.69$) from completely disagree (1) to completely agree (6) on a 6-point Likert scale. None of the participants had a red-green deficiency. This was an exclusion criterion for participation to ensure that the participants perceived the color cyan of the eHMI. All participants indicated that they had heard of HAVs before. Moreover, the participants rated their interest in HAVs with $M = 4.16$ ($SD = 0.79$) from not at all (1) to very much (5) on a 5-point Likert scale. This study followed a WoZ approach, i.e., the test vehicle was instructed as an HAV, although it was manually driven. Therefore, the participants had to answer if they believed it was an HAV at the end of the experiment. Only one participant did not believe it was a HAV and was excluded from further analysis. The participants were recruited from an internal test database and at the University of Braunschweig. We conducted the study in line with the Declaration of Helsinki. The participation was voluntary, and all participants could cancel their participation without giving any reasons. Moreover, the participants received 15 euros as compensation for expenses.

2.2. Study design

The study design was a 3 (eHMI status) × 2 (vehicle kinematics) repeated-measures design with two independent variables, eHMI status and vehicle kinematics. The eHMI status varied in three stages, i.e., no eHMI, static eHMI and dynamic eHMI. No eHMI means that the eHMI was turned off. The static eHMI lightened steadily and indicated the vehicle's automation status (VAS). The dynamic eHMI informed about the VAS and, additionally, about the vehicle's yielding intent by a pulsating eHMI (0.66 Hz frequency). The pulsation frequency of 0.66 Hz was based on Lau et al. (2022b). The pulsation of the dynamic eHMI started when the vehicle was at a 27.5 m distance, measured from the center point (CP) of the pedestrian's straight walking line (Fig. 1). In the no eHMI conditions, the eHMI was turned off. The vehicle kinematics varied in two stages, i.e., early yielding and late yielding. The initial speed of the test vehicle was 30 km/h. The early yielding started at a 27.5 m distance from the pedestrians with a deceleration rate of -1.73 m/s^2 (Fig. 1). The late yielding started at a distance of 20 m with a deceleration rate of -2.77 m/s^2. In all experimental trials (except the distractor trials), the vehicle stopped at a distance of 7.5 m from the participants (Fig. 1). Each participant experienced six experimental conditions once (no eHMI – early yielding, no eHMI – late yielding, static eHMI – early yielding, static eHMI – late yielding, dynamic eHMI – early yielding, dynamic eHMI – late yielding) and two distractor trials. The vehicle did not yield in the distractor trials, and the eHMI was turned off. The distractor trials always took place as the second and fifth trials. The distractor trials were included in the experiment to prevent the participants from believing that the vehicle would always stop for them and to prevent sequence effects. Due to ethical reasons, a major concern was placed on the fact that the participants did not cross during these trials. Therefore, they were informed about the occurrence of these distractor trials before the experimental trials. None of the participants did initiate a crossing in the distractor trials. All other experimental trials were randomized with the latin-squared method (J. V. Bradley, 1958).

2.3. Dependent variables

This study used a mixed-method approach to evaluate pedestrians' interactions with the HAV, i.e., objective and subjective measurements. The objective measurements were crossing initiation times and crossing durations. The subjective measurements were trust, perceived safety, and affective dimensions.

The calculation of the crossing initiation times followed a similar methodological approach by Loew et al. (2022). *Pedestrians' crossing initiation times* [in seconds (s)] were calculated as the time differences between two reference time points, i.e., reference point "pedestrian initiated crossing" and reference point "vehicle". The reference point "pedestrian-initiated crossing" was determined in two steps. First, all movement patterns of the participants for all experimental trials for one day were clustered in a scatterplot. Second, based on the scatterplots, we individually defined a starting line for each day. The reason was that the LiDAR sensor was set up and calibrated daily. Thus, the starting line had to be recalculated for each day, as changes in the lidar position, even if minimal, could occur and affect the calculation. The criteria for establishing this starting line were that it was perpendicular to the pedestrians' moving path and considered all trials of each participant. The trajectory of the starting line defined a position that the pedestrian had to reach, so the movement of the pedestrian was classified as crossing initiation. The reference point "vehicle" was set at the time when the vehicle started to yield. For the early yielding conditions, the yielding onset was at a 27.5 m distance from the pedestrian (measured from the center of the pedestrians' straight walking line). For the late yielding conditions, the yielding onset was at a 20 m distance from the pedestrian. *Pedestrians' crossing durations* [in seconds (s)] were calculated as the time differences between the time point when the pedestrians initiated their crossing and the time point when they reached the other side of the road in a 5.20 m distance (width of the street).

Regarding subjective measurements, *trust* ("I trust the vehicle's behavior.") was assessed on a 7-point Likert scale from disagree (1) to agree (7). Pedestrians' perceived safety was evaluated in two ways, i.e., their *perceived safety of vehicle behavior* ["For my personal safety, I found the behavior of the vehicle to be safety enhancing."; on a 7-point Likert scale from disagree (1) to agree (7)] and their *perceived safety during the crossing* [("How safe did you feel during the crossing?"; on a 7-point Likert scale from very unsafe (1) to very safe (7)]. Furthermore, *affective valence* in the interaction with the HAV [unpleasant (1) to pleasant (9)], *affective arousal* [calm (1) to aroused (9)], and *affective dominance* [subjectively perceived no control (1) to full control (9)] was assessed with the Self-Assessment Manikin (M. M. Bradley & Lang, 1994).

2.4. Experimental setting and apparatus

This study took place on an enclosed test track on the DLR campus in Braunschweig, Germany. In each trial, the participants stood at a standardized predefined starting point at the roadside (Fig. 2). During the experiment, all participants wore ear muffs as the sounds of the electric vehicle's recuperation could indicate the vehicle's deceleration and could have influenced the interaction. In the following, we give detailed information about the test vehicle, light-band eHMI, LiDAR sensor, and the study system architecture.

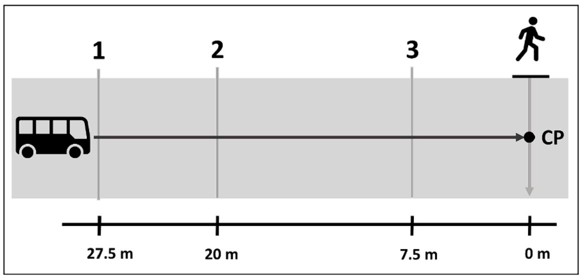

Fig. 1. Distance marker for this study's setting: 1. Dynamic eHMI activation and deceleration start for early yielding conditions, 2. Deceleration start for late yielding conditions, 3. Stopping point of the vehicle. *Note.* All distances were measured in meters (m) from the center point of the straight walking line of the pedestrian (CP).

2.4.1. Wizard-of-Oz test vehicle

The test vehicle was a WoZ vehicle, which means that the test driver was hidden to create the illusion that the vehicle was highly automated (Rothenbucher et al., 2015). Moreover, the test vehicle was a silver Mercedes-Benz EQV 300 with automatic transmission and speed limiter (Fig. 2). We applied blackout foils on the vehicle's windshield and the front side windows to avoid eye contact between the participants and the test driver. Furthermore, a non-functioning dummy magnet antenna was placed on the vehicle's roof to simulate an HAV. The test driver practiced the trajectories extensively before the experiment.

2.4.2. Light-band eHMI

A light-band eHMI prototype (length 166 cm × width 3 cm × height 6 cm) was positioned under the windshield of the test vehicle (Fig. 3). The eHMI prototype aligned with the light-band eHMI in the interACT project (Kaup et al., 2019). The light-band eHMI consisted of 162 light emitting diodes (LEDs) and shone in the colour cyan.

2.4.3. LiDAR sensor

A Light Detection and Ranging (LiDAR) sensor detected the vehicle's and pedestrian's position during the experimental trials. In general, LiDAR sensors are a highly reliable method to generate 3D information about the position of surrounding objects, e.g., road users (Li & Ibanez-Guzman, 2020). The LiDAR sensor emits light signals to the environment and detects the backscattered signals of the surrounding objects. The time elapsed between emission and detection provides information about the exact distance to the surrounding objects (Li & Ibanez-Guzman, 2020; Royo & Ballesta-Garcia, 2019). The LiDAR sensor in this study was an Ouster OS1 with a maximum detection range of 45 m (Ouster, 2022). Moreover, the LiDAR sensor stood at the road side opposite to the pedestrian and captured the vehicle's and the pedestrian's position during the experimental trials. We positioned the LiDAR sensor on a tripod, which was 1.62 m high. The sample frequency rate was 20 Hz. The Augmented LiDAR Box (ALB) unit, which is a hardware-software solution by Ouster, enabled the data preprocessing (Ouster, 2022). We defined several event zones within the ALB unit, i.e., the vehicle registration zone, pedestrian registration zone, and an exclusion zone (Fig. 4). The vehicle and pedestrian registration zones ensured the vehicle and pedestrian detection. The exclusion zone avoided the detection of other irrelevant objects in the environment. All event zones were active during all experimental trials. Moreover, the LiDAR sensor continuously measured the distance between the vehicle and the center of the pedestrian's straight walking line. This distance determined the activation of the dynamic eHMI (see Section 2.2).

2.4.4. Study system architecture

The study system architecture consisted of four main components: the LiDAR sensor system (A) [including the ALB unit (A.1) and the LiDAR sensor (A.2)], the study control computer (B), the eHMI controller (C) inside the vehicle, and the pedestrian (D; Fig. 5). A Wireless Local Area Network (WLAN) Access Point T750 by COMMSCOPE established a WLAN connection between the components. The LiDAR sensor (A.2) detected the vehicle (C) and pedestrian (D), and forwarded the data to the ALB unit (A.1). A website hosted by the ALB unit preprocessed the data. The website enabled the preview the incoming LiDAR sensor data and to setup the preprocessing, e.g., the definition of event zones for the pedestrian and vehicle (see Fig. 4). Furthermore, the ALB unit supplied the LiDAR sensor with power. By using the ALB unit, the data was encoded in Open Serialization Format (OSEF) in frames and per object, e.g., location, velocity, and object classification (e.g., car, person). OSEF is a binary format to read and analyze the data of the ALB (Foundation, 2022). The study control computer (B) was connected to the ALB unit and the WLAN. The study control computer (B) hosted a software component that received OSEF data from the ALB unit (A.1). This software component was also connected to the ALB unit, received the preprocessed data, and forwarded the data to our data model. Our data model processed and logged the data, and requested the activation of the dynamic eHMI in 27.5 m (see Section 2.2). The request was sent via WLAN using Message Queuing Telemetry Transport (MQTT). MQTT is a network protocol for the communication between machines or sensors (Khan et al., 2021). The eHMI controller (C) received and handled the requests from the study control computer (B) via MQTT.

Fig. 2. Interaction between the participant and the test vehicle equipped with light-band eHMI in this study.

Fig. 3. Close-up view of the light-band eHMI in this study.

Fig. 4. Example illustration of the interaction between pedestrians and HAV created with the Outsight's ALB unit. *Note.* Green = vehicle registration zone; red = test vehicle; orange = pedestrian registration zone; light-blue = pedestrian; purple = exclusion zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

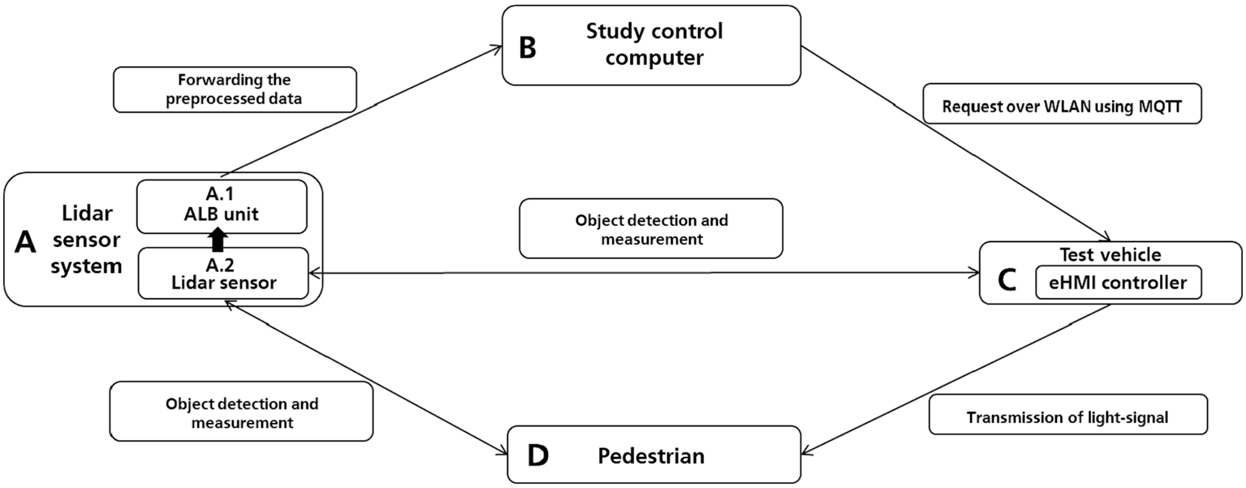

Fig. 5. Study system architecture consisting of the LiDAR sensor system (A), the study control computer (B), the eHMI controller inside the test vehicle (C), and the pedestrian (D).

2.5. Procedure

The total duration time of this experiment was 90 minutes. The participants were welcomed and informed about the hygiene measures during the experiment. Moreover, they were asked to fill out the consent and data protection notice. This was followed by a demographical and the ATI questionnaire (Franke et al., 2018). We put a great emphasis on the training phase of the eHMIs, which is recommended by Holländer et al. (2019). In the first part of the training, the main focus was to let the participants familiarize themselves with the test vehicle, the experimental setting, and their task. The test vehicle was introduced as HAV, and the participants were informed about a technical supervisor inside the vehicle (not visible to them) who would intervene during an emergency. The participant's task was to cross the street as soon as they recognized the vehicle's intention to yield to them. The task was formulated this way to prevent pedestrians from crossing the road early, e.g., before deceleration started or the dynamic eHMI began to pulse. Two practice trials took place in which the vehicle yielded and not yielded without eHMI. In the second part of the training, the light-band eHMI and the different eHMI statuses (static eHMI, dynamic eHMI) were introduced. For demonstration purposes, the test vehicle stopped at a 37.5 m distance, and the investigator switched the eHMI on via remote control. The static and dynamic eHMI were presented. All participants ($N = 43$) confirmed that they could identify both eHMI statuses from this distance (37.5 m). Additional three practice trials took place with eHMI (dynamic eHMI + yielding, no eHMI + non-yielding, static eHMI + yielding). The main part consisted of eight experimental trials (six experimental trials and two distractor trials). After each trial, the participants completed an online questionnaire via tablet, including the subjective measurements.

3. Results

We conducted a 3 (eHMI status) × 2 (vehicle kinematics) repeated-measures ANOVA. The requirements for the calculation of the ANOVA were checked and given. The assumption of the normal distribution was not given for all dependent variables. However, we assumed that the ANOVA with repeated measures is robust to violations of the normal distribution due to the sample size ($N = 43$) (Pagano, 2013; Salkind, 2017). When the assumption of sphericity was violated, we applied Huynh-Feldt corrections (Huynh & Feldt, 1976). Post-hoc pairwise comparisons were conducted with Bonferroni correction. The effect size was partial-eta squared (η_p^2), which was classified as follows: small effect with $\eta_p^2 \leq 0.01$; medium effect with $\eta_p^2 \leq 0.06$; large effect with $\eta_p^2 \leq 0.14$. The interpretation of the effect size Cohen's d_z was as follows: small effect with $|d_z| = 0.2$; medium effect with $|d_z| = 0.5$; large effect with $|d_z| = 0.8$ (Cohen, 1988).

3.1. Crossing initiation times and crossing durations

The results showed a significant main effect for eHMI status on pedestrians' crossing initiation times [$F(2, 84) = 78.63, p < .001, \eta_p^2 = 0.65$; Fig. 6]. Pedestrians initiated their crossings significantly earlier when the HAV was equipped with a dynamic eHMI [$M = 1.52$ s, $SD = 0.82$ s] compared to no eHMI [$M = 2.50$ s, $SD = 0.79$ s; $p_{Bonf} < .001$] and the static eHMI [$M = 2.66$ s, $SD = 0.67$ s; $p_{Bonf} < .001$]. Pedestrians' crossing initiation times did not differ significantly for static eHMI vs. no eHMI ($p > .05$). Moreover, a significant main effect was found for vehicle kinematics [$F(1, 42) = 244.04, p < .001, \eta_p^2 = 0.85$]. Pedestrians initiated their crossings earlier when the HAV yielded late [$M = 1.71$ s, $SD = 0.66$ s] compared to when the HAV yielded early [$M = 2.75$ s, $SD = 0.74$ s; $p_{Bonf} = .001$; Fig. 6]. For no eHMI conditions, the crossing initiation was significantly shorter for a late yielding [$M = 1.94$ s, $SD = 0.96$ s] than for early yielding [$M = 3.06$ s, $SD = 0.92$ s; $t(42) = 7.17, p < .001, dz = 1.09$]. There was no significant interaction between eHMI status and vehicle kinematics [$F(1.61, 67.52) = 1.22, p = .29, \eta_p^2 = 0.03$]. When the HAV was equipped with dynamic eHMI, the participants initiated their crossing earlier when there was a late yielding [$M = 1.08$ s, $SD = 0.90$ s] compared to an early yielding [$M = 1.96$ s, $SD = 0.90$ s; $t(42) = 8.06, p < .001, dz = 1.23$]. For conditions with dynamic eHMI and late yielding, seven participants crossed the road before the yielding onset (20 m) and relied on the explicit communication to initiate their crossing.

Regarding pedestrians' crossing durations, no significant effect for eHMI status [$F(1.62, 68.00) = 0.76, p = .45, \eta_p^2 = 0.02$], for vehicle kinematics [$F(1, 42) = 0.33, p = .57, \eta_p^2 = 0.01$] or the interaction of eHMI status and vehicle kinematics [$F(1.47, 61.84) = 0.004, p = .99, \eta_p^2 = 0.00$] was found (Fig. 7).

Overall, the results showed that pedestrians' crossing initiation times were shorter for a dynamic eHMI than for a static eHMI and no eHMI (hypothesis 1.1). For no eHMI conditions, the crossing initiation times were shorter when the vehicle yielded late vs. early, under the consideration of the yielding onset (hypothesis 2.1). Hypothesis 1.1 was confirmed, and hypothesis 2.1 was declined. Hypothesis 3.1 was declined as the results showed that for conditions with dynamic eHMI pedestrians' crossing initiation times were

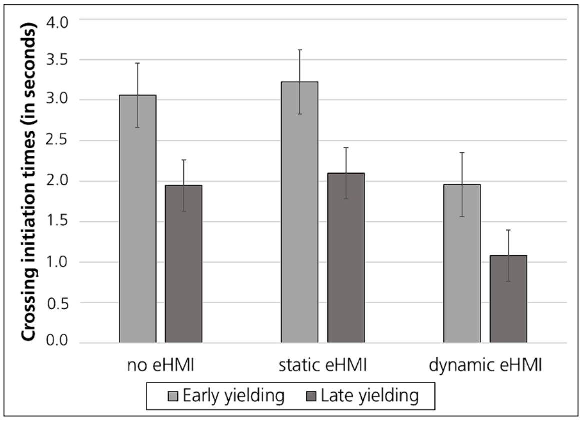

Fig. 6. Descriptive statistics for pedestrians' crossing initiation times (in seconds) depending on the eHMI status (no eHMI, static eHMI, dynamic eHMI) and the vehicle kinematics (early yielding, late yielding). *Note.* Error bars ± 1 *SE*.

shorter for a late yielding than for an early yielding (hypothesis 3.1). The results showed that the eHMI and vehicle kinematics did not affect pedestrians' crossing durations.

3.2. Trust

We found significant main effects for eHMI status [$F(2, 84) = 9.09, p < .001, \eta_p^2 = 0.18$] and vehicle kinematics [$F(1, 42) = 7.24, p = .010, \eta_p^2 = 0.15$]. Pairwise comparisons showed that pedestrians' trust ratings were significantly higher with dynamic eHMI [$M = 5.53$, $SD = 0.85$] compared to static eHMI [$M = 4.74$, $SD = 1.22$; $p_{Bonf} < .001$]. No significant differences were found between dynamic eHMI vs. no eHMI and static eHMI vs. no eHMI (p >.05). Moreover, the participants trusted an early yielding [$M = 5.24$, $SD = 0.92$] more than a late yielding [$M = 4.99$, $SD = 0.95$; $p_{Bonf} = .01$]. For no eHMI conditions, there was no difference between an early yielding [$M = 5.14$, $SD = 1.32$] or a late yielding [$M = 5.00$, $SD = 1.50$; $t(42) = 0.76$, $p = .453$, $dz = 0.12$] for their trust. The interaction between eHMI status and vehicle kinematics was significant with a medium-sized effect [$F(2, 84) = 3.50, p = .035, \eta_p^2 = 0.08$]. According to the results, this was an ordinal interaction (Fig. 8). Pedestrians' trust ratings were significantly higher for an early yielding with dynamic eHMI [$M = 5.84$, $SD = 0.84$] compared to a late yielding with dynamic eHMI [$M = 5.23$, $SD = 1.21$; $t(42) = 3.31$, $p = .002$, $dz = 0.50$]. The results showed that the pedestrians indicated a higher trust for their interaction with HAV equipped with dynamic eHMI than static eHMI or no eHMI (hypothesis 1.2). When there was no eHMI, the trust ratings did not differ between early and late yielding (hypothesis 2.2). Moreover, the results showed that, for conditions with dynamic eHMI, the pedestrians trusted the HAV more when it yielded early vs. late (hypothesis 3.2).

3.3. Perceived safety

Perceived safety was evaluated in two ways, i.e., perceived safety of vehicle behavior and perceived safety during crossing. Regarding the perceived safety of vehicle behavior, we found a main effect of eHMI status [$F(2, 84) = 22.17, p < .001, \eta_p^2 = 0.35$]. Pairwise comparisons revealed significant differences for no eHMI [$M = 4.88$, $SD = 1.26$] vs. static eHMI [$M = 4.42$, $SD = 1.24$; $p = .03$], no eHMI vs. dynamic eHMI [$M = 5.73$, $SD = 0.88$; $p_{Bonf} = 0.002$] and static eHMI vs. dynamic eHMI ($p_{Bonf} < 0.001$). No significant main effect for vehicle kinematics was found [$F(1, 42) = 2.00, p = .16, \eta_p^2 = 0.05$]. For no eHMI conditions, the perceived safety of the vehicle behavior did not differ between an early [$M = 4.81$, $SD = 1.42$] or a late yielding [$M = 4.95$, $SD = 1.33$; $t(42) = -0.83$, $p = .412$, $dz = -0.13$]. However, we found a significant interaction between eHMI status and vehicle kinematics [$F(1.83, 76.71) = 5.96$, p = .005, $\eta_p^2 = 0.12$; Fig. 9]. Post-hoc tests revealed that pedestrians felt safer for an early yielding with dynamic eHMI [$M = 6.21$, $SD = 0.99$] compared to a late yielding and dynamic eHMI [$M = 5.81$, $SD = 1.05$; $t(42) = 2.20$, $p = .033$, $dz = 0.33$].

Regarding the perceived safety during the crossing, we found significant main effects for eHMI status [$F(1.75, 73.43) = 13.89, p < .001, \eta_p^2 = 0.25$] and vehicle kinematics [$F(1, 42) = 4.98, p = .031, \eta_p^2 = 0.11$]. Pairwise comparisons manifested significant differences between no eHMI [$M = 5.21$, $SD = 1.48$] vs. dynamic eHMI [$M = 6.01$, $SD = 0.83$; $p_{Bonf} = .01$] and static eHMI [$M = 4.99$, $SD = 1.13$] vs. dynamic eHMI ($p_{Bonf} < .001$). Moreover, the participants felt safer when the test vehicle yielded early [$M = 5.51$, $SD = 0.90$] than late yielding [$M = 5.29$, $SD = 0.98$, $p_{Bonf} = .03$]. When there was no eHMI, their perceived safety during the crossing did not differ between an early [$M = 5.28$, $SD = 1.56$] or the late yielding [$M = 5.14$, $SD = 1.64$; $t(42) = 0.735$, $p = .467$, $dz = 0.11$]. The interaction between eHMI status and vehicle kinematics was not significant [$F(1.99, 83.52) = 0.62, p = .54, \eta_p^2 = 0.01$]. In conditions with dynamic eHMI, the perceived safety during the crossing differed significantly between an early yielding [$M = 6.21$, $SD = 0.99$] and a late yielding [$M = 5.81$, $SD = 1.05$; $t(42) = 2.20$, $p = .033$, $dz = 0.34$]. All in all, pedestrians' perceived safety was more positive for a dynamic eHMI compared to a static eHMI or no eHMI which can be confirmed for both measures, pedestrians' perceived safety for vehicle behavior and the perceived safety during crossing (hypothesis 1.2). Moreover, the results highlighted that the perceived safety for the vehicle behavior and the perceived safety during the crossing did not differ in conditions without eHMI when the vehicle

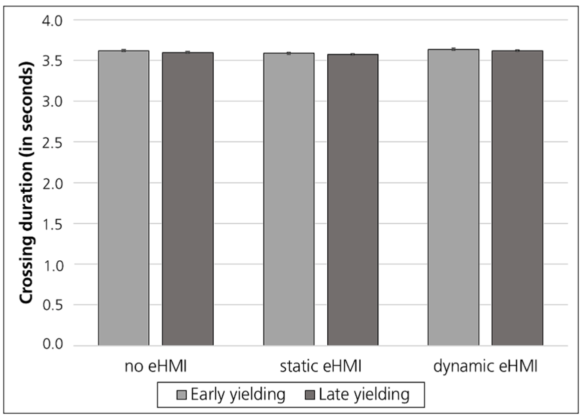

Fig. 7. Descriptive statistics for pedestrians' crossing durations (in seconds) depending on the eHMI (no eHMI, static eHMI, dynamic eHMI) and the vehicle kinematics (early yielding, late yielding). *Note.* Error bars ± 1 *SE*.

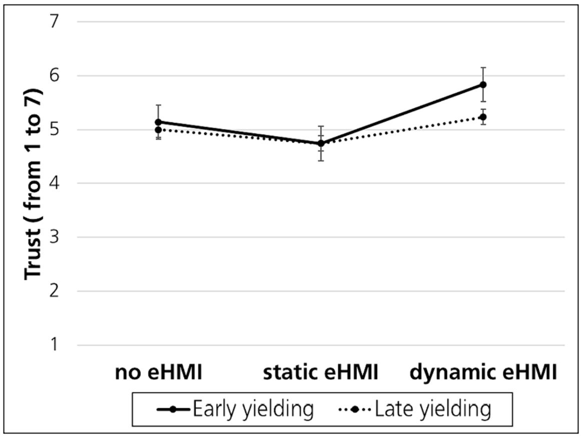

Fig. 8. Significant interaction for eHMI status (no eHMI, static eHMI, dynamic eHMI) and the vehicle kinematics (early yielding, late yielding) for the participants' mean trust ratings. *Note.* Error bars ± 1 *SE*.

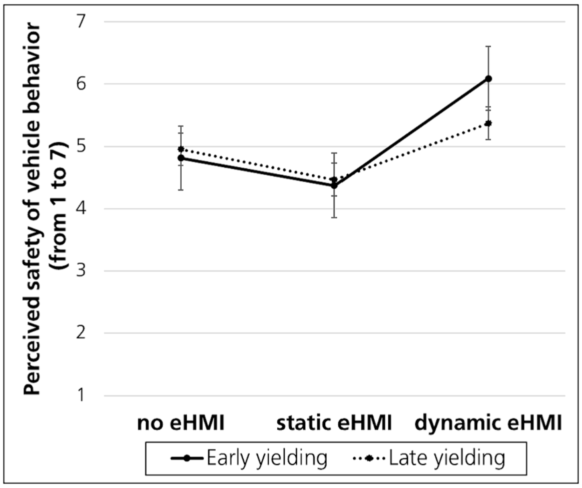

Fig. 9. Significant interaction for eHMI status (no eHMI, static eHMI, dynamic eHMI) and the vehicle kinematics (early yielding, late yielding) for pedestrians' mean perceived safety of vehicle behavior ratings. *Note.* Error bars ± 1 *SE*.

yielded early vs. yielded late (hypothesis 2.2). Furthermore, pedestrians evaluated their perceived safety more positively for conditions with dynamic eHMI and when the vehicle yielded early compared to late (hypothesis 3.2).

3.4. Affective dimensions

For affective valence, we found significant main effects for eHMI status [$F(2, 84) = 37.15$, $p < .001$, $\eta_p^2 = 0.47$] and vehicle kinematics [$F(1, 42) = 13.76$, $p = .001$, $\eta_p^2 = 0.25$]. Pairwise comparisons revealed significant differences between pedestrians' interactions with the HAV depending on the eHMI status. The participants indicated a more positive affective valence for their interaction when the HAV was equipped with dynamic eHMI [$M = 7.41$, $SD = 1.16$] vs. static eHMI [$M = 5.09$, $SD = 1.06$; $p_{Bonf} < .001$], dynamic eHMI vs. no eHMI [$M = 6.53$, $SD = 1.56$; $p_{Bonf} = .009$] and no eHMI vs. static eHMI ($p < .001$). Moreover, the pedestrians indicated a more positive affective valence when they indicated with the early yielding HAV [$M = 6.01$, $SD = 0.80$] compared to the late yielding HAV [$M = 6.69$, $SD = 1.11$; $p_{Bonf} = .001$]. When there was no eHMI, the affective valence did not differ between early yielding conditions [$M = 6.35$, $SD = 1.82$] and late yielding conditions [$M = 6.72$, $SD = 1.64$; $t(42) = -1.597$, $p = .118$, $dz = -0.24$]. Additionally, the interaction between eHMI status and vehicle kinematics was significant [$F(1.81, 76.20) = 22.45$, $p < .001$, $\eta_p^2 = 0.35$; Fig. 10]. Pedestrians perceived an early yielding with dynamic eHMI [$M = 7.74$, $SD = 1.24$] as affectively more pleasant compared to late yielding with dynamic eHMI [$M = 7.09$, $SD = 1.63$; $t(42) = 2.47$, $p = .018$, $dz = 0.38$]. The results show a decrease in pedestrians' affective valence ratings for static eHMI with an early yielding (Fig. 10).

For affective dominance, we found a significant main effect of eHMI status [$F(2, 84) = 8.53$, $p = .001$, $\eta_p^2 = 0.17$]. Pairwise comparisons showed that the participants perceived subjectively more control over the situation with dynamic eHMI [$M = 6.55$, $SD =$

1.70] compared to no eHMI [$M = 5.73$, $SD = 1.82$; $p_{Bonf} = .02$]. We found no significant differences for vehicle kinematics [$F(1, 42) = 3.90$, $p = .06$, $\eta_p^2 = 0.09$] and no significant interaction of eHMI status and vehicle kinematics [$F(2, 84) = 1.24$, $p = .30$, $\eta_p^2 = 0.03$]. When there was no eHMI, the evaluation of the affective dominance did not differ between the early [$M = 5.77$, $SD = 1.86$] and the late yielding [$M = 5.70$, $SD = 1.98$; $t(42) = 0.368$; $p = .714$, $dz = 0.56$]. In conditions with dynamic eHMI, the participants evaluated their affective dominance for their interaction with the HAV higher for the early [$M = 6.84$, $SD = 1.93$] than for the late yielding [$M = 6.26$, $SD = 1.93$; $t(42) = 2.12$; $p = .040$, $dz = 0.32$].

For affective arousal, we found a significant main effect of vehicle kinematics [$F(1, 42) = 7.25$, $p = .01$, $\eta_p^2 = 0.15$]. Pairwise comparisons showed that the participants felt more aroused when the HAV yielded late [$M = 3.91$, $SD = 1.89$] compared to when the HAV yielded early [$M = 3.54$, $SD = 1.67$; $p_{Bonf} = .01$]. For no eHMI conditions, we did not find any difference between the early [$M = 3.63$, $SD = 1.95$] and the late yielding condition [$M = 3.86$, $SD = 2.24$; $t(42) = -1.094$, $p = .280$, $dz = -0.17$]. We found no significant differences between the eHMI statuses [$F(2.00, 83.98) = 2.87$, $p = .062$, $\eta_p^2 = 0.06$] and no significant interaction between eHMI status and vehicle kinematics [$F(2.00, 83.94) = 1.35$, $p = .265$, $\eta_p^2 = 0.03$]. Overall, hypothesis 1.2 can be partially confirmed as the results showed that the pedestrians evaluated their interaction with the HAV equipped with dynamic eHMI as with a higher affective valence and higher affective dominance compared to their interaction with the HAV equipped with static eHMI or no eHMI. However, the results did not show differences in affective arousal. Moreover, the results underlined that when there was no eHMI, vehicle kinematics (early vs. late yielding) did not affect the affective valence, dominance, and arousal (hypothesis 2.2). For conditions with dynamic eHMI, the pedestrians evaluated a more positive affective valence when the HAV yielded early vs. when it yielded late (hypothesis 3.2).

4. Discussion

In this real vehicle study, we investigated the effect of vehicle kinematics and eHMI status on pedestrians' interactions with an HAV using the WoZ approach. Thus, pedestrians' safety was ensured throughout the experiment by simulating the interaction with the HAV. This real vehicle study followed a multi-method approach and combined the investigation of objective (pedestrians' crossing initiation times, crossing durations) and subjective measurements (trust, perceived safety, and affective dimensions) in a real-world pedestrian crossing scenario.

Regarding the effect of the eHMI status, the results of both measurements highlighted the positive impact of a dynamic eHMI. The participants initiated their crossing earlier, trusted the vehicle with dynamic eHMI more, and felt safer with dynamic eHMI compared to no eHMI or static eHMI. Additionally, they perceived a more positive affective valence and more control when interacting with an HAV that communicated with dynamic eHMI compared to the other two eHMI statuses. These findings stand in line with previous VR studies (cf. Lau et al., 2022a, 2022b; Wilbrink et al., 2021) and real vehicle studies that investigated pedestrians' interaction with HAVs (Dey, Matviienko et al., 2020; Faas et al., 2020; Loew et al., 2022). This real vehicle study extended current research in real-world settings by addressing a traffic interaction in which the pedestrian did not have right-of-way, i.e., the vehicle approached from the right-hand side. Surprisingly, pedestrians' arousal levels did not differ when the participants interacted with the HAV equipped with different eHMIs. A possible explanation for why the pedestrians did not feel aroused for their interaction with the HAV when the eHMI conveyed different information could be that the participants were well-instructed about the traffic interaction. We ensured that the pedestrians did not feel uncertain about the traffic interaction and that they received information about the different eHMIs in the training phase. As pointed out in previous studies, instructions about the different eHMI functions are essential to ensure mutual understanding between pedestrians and HAVs (Dietrich et al., 2020; Liu et al., 2021). In future research, we should investigate first contacts with the eHMI and how fast participants without prior knowledge would learn the eHMI functions.

Our results showed that pedestrians' crossing durations did not differ between the experimental trials. From this, we concluded that the participants did not feel uncertain in the experimental trials so that, for example, they would rush over the street (cf. Lee et al.,

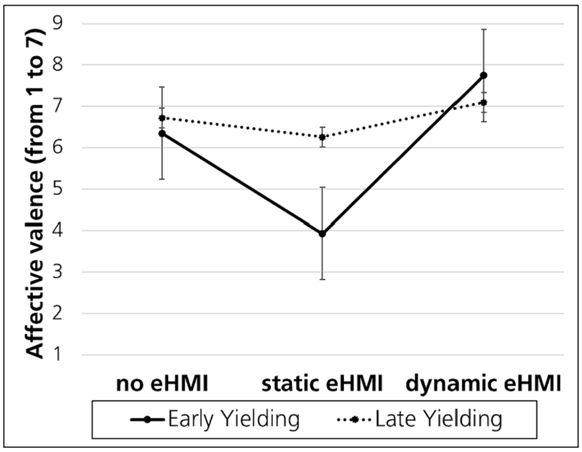

Fig. 10. Significant interaction for eHMI status (no eHMI, static eHMI, dynamic eHMI) and the vehicle kinematics (early yielding, late yielding) for affective valence. *Note.* Error bars ± 1 *SE*.

2019). Moreover, we assumed that when the participants decided to cross the street, they used the same time in all experimental trials. The participants' interest in HAVs was generally high, which could also have influenced their crossing behavior and affective evaluation, i.e., pedestrians did not feel aroused due to previous experiences. Overall, the participants perceived a static eHMI as less trustful, safe, and affectively less pleasant than no eHMI or dynamic eHMI. This finding stands in line with previous studies, which showed that participants preferred an HAV that communicated a yielding intent via dynamic eHMI compared to a static eHMI that only informed about the automation status (Faas et al., 2020; Lau et al., 2022a; Wilbrink et al., 2021). In this real vehicle study, the experimental trials with dynamic eHMI started similar to those with static eHMI, i.e., the light-band eHMI was continuously enlightened. The only difference was that the dynamic eHMI began to pulsate at a 27.5 m distance. In conditions with static eHMI, the participants might have expected a pulsation, which did not occur. Hence, their expectations and the actual behavior of the HAV are mismatched, which might have led to low trust, perceived safety, and affective valence. The mismatch could also be related to human-limited visual sensitivity in detecting positive and negative accelerations (Gottsdanker et al., 1961; Snowden & Braddick, 1991; Werkhoven et al., 1992) and their inability to utilize visual acceleration information for temporal and spatial judgments (Benguigui & Bennett, 2010; Benguigui et al., 2003; Bennett & Benguigui, 2016; Kaiser & Hecht, 1995; Senot et al., 2003; Wessels et al., 2023).

Regarding the effect of vehicle kinematics, the pedestrians initiated their crossing earlier with late yielding than early yielding when there was no eHMI. A possible explanation for why the late yielding led to an earlier crossing initiation compared to the earlier yielding could be the systematic difference in the distance of the yielding onset. The late yielding occurred closer to the participants and they may have been detected the strong deceleration more clearly as the vehicle was closer to them. Additionally, the deceleration rate was lower in the early yielding condition than in the late yielding condition. The perception of (negative) acceleration is influenced by comparing the velocity at two time points (Brouwer et al., 2002). If the deceleration rate is low, more time between these two time points may be required to reach a threshold for the velocity change. This might have resulted in longer crossing initiation times for the early yielding than late yielding. In future studies, more gradations of the deceleration rate and braking distance should be investigated to analyze the effect of vehicle kinematics on pedestrians' crossing initiation times further. Under all circumstances, aggressive braking behavior should be avoided (cf. Dey, Matviienko et al., 2020). In this study, we measured the crossing initiation time with the LiDAR, which enabled us to determine the exact time the pedestrians started to cross the street naturally. Closely related to the actual crossing decision might be the detection yielding time (Tian et al., 2023). Future studies should investigate the relation between the detection of the yielding intent of an approaching vehicle and the initiated crossing of pedestrians, e.g., with respect to elderly pedestrians. For instance, Dommes et al. (2013) showed that sensory and cognitive abilities decreased for elderly pedestrians, e.g., leading to misperceptions in time-to-arrival estimations of vehicles. Regarding pedestrians' subjective experiences, we did not find differences in pedestrians' subjective evaluations of trust, perceived safety, and their affective experience for early and late yielding, i.e., they felt equally safe and trusted the HAV in both conditions. This study aimed to investigate authentic and unthreatening decelerations, with no intention of inducing fear or safety–critical situations for the participants, e.g., no aggressive braking behavior. Overall, this study highlighted that a late-initiated deceleration with a stronger deceleration rate could lead to an early-initiated crossing when there was no eHMI.

This study extended previous research (cf. Ackermann et al., 2019; Fuest et al., 2020; Risto et al., 2017) by looking at both the effect of the vehicle kinematics and the eHMI and how it affects the actual crossing initiation time, not just the effort to cross at that moment in a real-world setting, and their subjective experience. In future traffic, the vehicle kinematics could be combined with explicit communication signals by the eHMI in low-speed and low-distance traffic situations to ensure safe interaction between pedestrians and HAVs (Dey, Matviienko et al., 2020; Lau et al., 2022b). Focusing on subjective measurements, the participants perceived an early yielding intent and dynamic eHMI as safer and more trustful than a late yielding with the same dynamic eHMI. This could be explained by the fact that, in the conditions with dynamic eHMI and late yielding, the mismatch of implicit and explicit communication signals was reinforced with the strong deceleration (-2.77 m/s^2). In contrast, the deceleration rate in the early yielding conditions was -1.73 m/s^2. Focusing on the objective measurements, we found that the use of a dynamic eHMI, in general, leads to a faster crossing initiation time. The participants initiated their crossing significantly earlier when the dynamic eHMI was combined with a late yielding than an early yielding. Hence, the vehicle kinematics seem to be a sufficient source of information for pedestrians' crossing initiation times in this study. However, in the conditions where the HAV communicated via dynamic eHMI (started at 27.5 m distance) and yielded late (started at 20 m distance), seven participants initiated their crossing before the HAV decelerated. This might show that those participants relied on explicit communication via the dynamic eHMI without waiting for an implicit communication signal, which aligns with findings by Lau et al. (2022b). Nevertheless, these results contrast findings by Dey, Matviienko et al. (2020), which showed that pedestrians relied on vehicle kinematics to indicate their willingness to cross. Future studies should address possible side effects of eHMIs and the risk of pedestrians overtrusting the eHMI in further detail.

Moreover, pedestrians perceived an early yielding combined with static eHMI as affectively unpleasant. The set-up of the experiment might influence this finding. As previously described, the participants were well-instructed about all eHMI functions, and they knew that the HAV could inform about a yielding intent by the pulsation of the eHMI. The participants might have expected a pulsation of the eHMI, which did not occur in conditions with static eHMI. In this case, pedestrians preferred a late yielding as this communicated how the HAV would behave. In line with previous studies (Ackermann et al., 2019; Fuest et al., 2020), vehicle kinematics were a decisive factor for pedestrians' crossing behaviors in this study. Although a previous study found that an early deceleration is preferred, it also took pedestrians longer to understand the vehicle's intention, as they wanted to be sure about the yielding intent (Fuest et al., 2020). This might lead to the conclusion that additional eHMI signals could contribute to a better understanding of the intention by communicating the vehicle's intention early. On a subjective level, pedestrians evaluated their trust and perceived safety as highest when the HAV communicated via dynamic eHMI and early yielding. However, on an objective level, the fastest initiation was when the HAV communicated its yielding intent via the dynamic eHMI and a late deceleration. One reason for this could be that the HAV performed a stronger deceleration in the late yielding, which occurred closer to the pedestrians. Under all circumstances, the communication of the vehicle's intention must be considered holistically considering other road users, e.g., vehicles traveling behind. Therefore, further research should address the vehicle kinematics combined with eHMI in more detail to focus on a holistic communication strategy for HAVs, e.g., speed or braking distance variations.

All in all, the results highlighted the potential of a dynamic eHMI presenting explicit information about the vehicle's yielding intent and the vehicle automation status can improve pedestrians' interaction with HAVs in terms of their crossing initiation times, their perceived safety, trust, and affective valence, their affective arousal and affective dominance in a real-world setting. Nevertheless, we found no differences between the eHMI status for the crossing durations. Comparing our results of this study with previous video-based experimental studies (Lau et al., 2022a, 2022b), we found similar results for this study in a real-world setting, i.e., pedestrians felt safer with the dynamic eHMI compared to static or no eHMI. For the standardization of eHMIs, two facts can be derived from this real vehicle study. First, if explicit communication signals about the vehicle's yielding intent are presented, they should be combined with implicit communication signals. Second, future eHMIs should be capable of communicating the VAS and the yielding intent, i.e., dynamic eHMIs. Static eHMIs, which only inform about the VAS, did not fulfill the pedestrians' information needs in this study and increased uncertainty on an emotional level. Nevertheless, static eHMIs can still help distinguish between manually driven vehicles and HAVs in mixed-traffic environments. For instance, some road users might continue to try to build up eye contact with a human driver in future traffic. The information about the vehicle automation status could prevent confusion (Schieben et al., 2019). The challenge is to design communication tools for HAVs as close as possible to the existing and established communication means but still leave enough room to experience new communication means embedded in the current state of technology.

5. Limitations

At the beginning of each experimental trial, pedestrians stood at a predefined point at the side of the road. Therefore, the starting position was the same for all participants. However, we did not include an approaching phase, which would have represented a more natural crossing behavior. Furthermore, the participants wore ear muffs in combination with face masks during the experimental trials (this study was conducted during COVID-19), which might have influenced their subjective feelings. Ear muffs had to be worn because the participants should focus primarily on the visual signals and not be affected or distracted by environmental sounds, e.g., the vehicle's recuperation noises. However, ear muffs could influence the individual perception of the scene, considering that integrating both auditory and visual information is crucial in assessing the motion of approaching objects (DeLucia et al., 2016; Wessels et al., 2022). The setup of this experiment was very complex, including the LiDAR sensor, the light-band eHMI, and the network connection. On the one hand, the complexity enabled the standardized triggering of the dynamic eHMI, which is, until now, a new approach to applying eHMIs in a real-world setting. Nevertheless, the network connection and the LiDAR sensor were prone to interruptions, e.g., due to weather conditions. We determined the timing of pedestrians' initiations in a standardized procedure with defined criteria and predefined event zones. This had to be done since the LiDAR sensor was set up daily. In future studies, the LiDAR sensor should be combined with camera systems to compare sensor data (Li & Ibanez-Guzman, 2020). As a further limitation, this study was conducted at different times of the day, which could have affected the visibility of the eHMI. However, we checked for each participant to see if he/she could see the eHMI and its different eHMI statuses. Moreover, we applied the light-band eHMI on only one vehicle size in this study and did not focus on the effect of vehicle size. Therefore, future studies should be conducted with more than one vehicle to focus on the effect of vehicle size. In this study, the eHMI functionalities were explained in the training phase so that the participants understood the meaning of the eHMI correctly and that all participants started at the same level of knowledge. Nevertheless, the learnability of eHMI signals should be investigated in future studies to address how the integration of eHMIs could occur.

6. Conclusion

This study investigated the interplay of eHMI and vehicle kinematics for pedestrians' future interactions with HAVs in a realistic vehicle study by following a new methodological approach. This study went one step further toward implementing and evaluating communication tools for HAVs by investigating both the effects of eHMI and vehicle kinematics in a real-world setting. This methodological approach consisted of a system architecture that enabled the simultaneous detection of the WoZ test vehicle and pedestrians, and the automated activation of the light-band eHMI. The results of this study highlighted the importance of a well-coordinated interplay of vehicle kinematics and eHMI for pedestrians' subjective evaluations regarding their trust, perceived safety, and affective valence. When there was no eHMI, the pedestrians initiated their crossing significantly earlier when the HAV yielded late than when it yielded early. This finding might be explained by the fact that the late yielding occurred with a stronger deceleration rate and in closer distance to the pedestrians. The combination of the dynamic eHMI with a late yielding lead, objectively, to the fastest crossing initiation. Subjectively, the combination of the dynamic eHMI with an early yielding leads to the highest level of perceived safety, trust, and affective valence in a real-world setting. From this, HAVs should clearly communicate their intention to pedestrians via vehicle kinematics and dynamic eHMIs in low-distance and close-range scenarios. Moreover, the timing of the dynamic eHMI should be precisely coordinated with the vehicle kinematics.

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CRediT authorship contribution statement

Merle Lau: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hoai Phuong Nguyen:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis. **Meike Jipp:** Writing – review & editing, Supervision, Conceptualization. **Michael Oehl:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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