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Investigating Implicit and Explicit Communication of Highly Automated Vehicles in Japan: How do Light-band eHMIs affect Pedestrians' Willingness to Cross, Trust and Perceived Safety?

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ABSTRACT

In the near future, pedestrians will face highly automated vehicles on the roads. Highly automated vehicles (HAVs) should have safety-enhancing communication tools to guarantee traffic safety, e.g., vehicle kinematics and external human–machine interfaces (eHMIs). Pedestrians, as highly vulnerable road users, depend on communication with HAVs. Miscommunication between pedestrians and HAVs could quickly result in accidents, and this, in turn, could cause severe impairments for pedestrians. Light-band eHMIs have the potential to enhance traffic safety. However, eHMIs have been less explored in Japan so far. As a first-time approach, this experimental online study shed light on the effect of a light-band eHMI on Japanese pedestrians (N=99). In short video sequences, the participants interacted with two differently sized HAVs equipped with light-band eHMI. We investigated the effect of vehicle size (small vs. large), eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI), and vehicle kinematics (yielding vs. non-yielding) on pedestrians' willingness to cross, trust, and perceived safety. To investigate possible side effects of eHMIs, we also included experimental conditions in which the eHMI mismatched the vehicle's kinematics. Results revealed that Japanese were more willing to cross the street and indicated higher trust- and safety ratings when they received information about the vehicle's intention and automation status (dynamic eHMI) compared to when they received no information (no eHMI) or only about the vehicle automation status (static eHMI). Surprisingly, Japanese participants tended to rely on the eHMI when there was mismatching information between eHMI and vehicle kinematics. Overall, we concluded that light-band eHMIs could contribute to a safe future interaction between pedestrians and HAVs in Japan under the requirement that the eHMI is in accordance with vehicle kinematics.

1. Introduction

Highly automated vehicles [HAVs; SAE 4 (SAE International, 2021)] have the potential to enhance safety with other traffic participants in the future (Edelmann et al., 2021). Focusing on today's traffic, pedestrians, cyclists, and motorcyclists are involved in more than half of all fatal traffic accidents. The total annual number of deaths due to traffic accidents was approx. 1.3 million (World Health Organisation, 2022). Pedestrians highly depend on communication with other traffic participants in the road environment, e.g., to anticipate the vehicle's future behavior (Habibovic et al., 2018; Rasouli & Tsotsos, 2020). Thus, the potential of HAVs will depend to a large extent on the communication capabilities of the HAVs (Dey et al., 2022; Habibovic et al., 2018; Schieben et al., 2019). While a human driver still controls the vehicle today, HAVs will execute the driving task in the future (SAE International, 2021; Schieben et al., 2019). Therefore, HAVs should have tools to communicate with pedestrians to enhance safe interactions (Bengler et al., 2020; Lau et al., 2022b). Moreover, those communication tools should be investigated not only in one country but in multiple countries to globally ensure traffic safety in the future (Atchley et al., 2014).

Derived from today's interactions, vehicle kinematics are a significant indicator for pedestrians to understand the vehicle's intention and to plan their future behavior (Dey & Terken, 2017; Y. M. Lee et al.,

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2021). Focusing on future interactions, other studies also underlined the importance of vehicle kinematics for pedestrians' interactions with HAVs (Ackermann et al., 2018; Ackermann et al., 2019; Dey, Matviienko et al., 2020; Lau et al., 2022b). Soshiroda et al. (2021) showed that the vehicle's deceleration impacted pedestrians' crossing behavior, i.e., pedestrians crossed the street faster with an early deceleration. External human–machine interfaces (eHMIs) are an additional source of information and could present explicit communication signals, e.g., about the vehicle's yielding intent (Dey et al., 2022; Faas & Baumann, 2019; Faas, Mathis, & Baumann, 2020; Lau et al., 2022a). Different eHMI approaches stand in the focus of current research, e.g., projection-based, text-based, or light-band eHMIs (Bazilinskyy et al., 2019; Bengler et al., 2020; Dey, Habibovic et al., 2020). Light-band eHMIs can communicate with pedestrians through light patterns (Dey, Habibovic et al., 2020; Faas, Mathis, & Baumann, 2020; Lau et al., 2022a) and are culturally independent (Weber et al., 2019). The light-band eHMI approach proved particularly promising as it is easy to learn (Avsar et al., 2021) and increased perceived safety and trust (Lau et al., 2022b). As design recommendations for eHMIs, Wilbrink et al. (2023) described several eHMI principles, addressing situations, in which an eHMI should communicate. One principle is the "identification of the automation level (p. 8; Wilbrink et al., 2023)", meaning that the eHMI should communicate the vehicle automation status when the vehicle drives in automated mode. This could be communicated, e.g., by a LED light-strip positioned around the vehicle (Wilbrink et al., 2023). As an additional eHMI principle, the vehicle's yielding intent should be communicated via eHMI, which could be communicated by light signals to inform the surrounding traffic environment (Wilbrink et al., 2023). Lau et al. (2022b) investigated a 360° LED light-band eHMI, which was positioned on the vehicle's outer body, for the interaction between pedestrians and differently sized HAVs (car, bus). The eHMI presented different explicit information to the pedestrian, e.g., information about the automation status and the vehicle's yielding intent. The vehicle automation status was presented by a continuously enlightened light-band eHMI, and, in addition, the yielding intent was presented by a pulsation of the light-band eHMI (Lau et al., 2022b). The results revealed that pedestrians perceived an eHMI that transmitted information about the vehicle automation status and the vehicle's yielding intent as safety-enhancing (Lau et al., 2022b).

The effect of eHMIs has been investigated in different countries, e.g., in the United Kingdom (Kaleefathullah et al., 2020; Y. M. Lee et al., 2022), in Germany (Lau et al., 2022a; Wilbrink et al., 2021), in the United States (Faas, Kao, & Baumann, 2020) or as a cultural comparison between Germany and China (Lanzer et al., 2020). In an intercultural study, Lanzer et al. (2020) investigated different eHMI interaction messages for an autonomous delivery vehicle in an experimental online study in Germany and China. The vehicle projected six interaction messages on the ground to communicate with the surrounding traffic environment. The results revealed cultural differences between Germany and China, i.e., the Chinese participants were more compliant when the autonomous delivery vehicle communicated politely than the German participants. The authors concluded that a cross-cultural transferability of eHMI designs is not directly possible (Lanzer et al., 2020). However, as a limitation of this study, the eHMI communicated via text messages in different languages, i.e., the eHMI was culturally dependent. Overall, research on eHMIs still needs further investigation in different countries to provide safe and efficient communication tools for HAVs globally (Weber et al., 2019).

To the best of our knowledge, light-band eHMIs have not been under investigation in Japan. Recent eHMI studies in Japan mainly focused on the design of text-based eHMIs (J. Lee & Daimon, 2023, 2024; J. Lee et al., 2021, 2022; Suzuki et al., 2022). For instance, J. Lee et al. (2021) investigated possible side effects of a text-based eHMI showing "After you" and "I will stop" messages in a virtual reality experiment. The results showed that when the eHMI presented information, pedestrians scanned the ongoing traffic less and showed a more careless crossing behavior than when the eHMI was off (J. Lee et al., 2021). The question arises of whether those side effects also occur for light-band eHMIs and could influence pedestrians' willingness to cross, trust, and perceived safety in Japan. Focusing on cultural differences in pedestrians' traffic behavior, past research showed that Japanese people have a high demand for traffic safety, follow the rules, and tend to avoid uncertainties (Atchley et al., 2014; Hell et al., 2021; Hofstede Insights, 2021; Money & Crotts, 2003). Moreover, Hell et al. (2021) reported that Japanese have a greater aspiration to avoid traffic risks than Germans. Building on this, Money & Crotts (2003) described that Japanese show more risk-avoiding behavior than Germany and other European countries. Overall, current research on eHMIs lacks the applicability of light-band eHMIs in Japan to make assumptions on the transferability of eHMIs. The overall goal is to create communication tools that solve ambiguities and make future traffic safe for pedestrians.

As an additional limitation of current eHMI research, most studies on cross-cultural differences in terms of eHMI have focused on only one vehicle size so far (Joisten et al., 2021; Lanzer et al., 2020). Nevertheless, vehicle size can impact pedestrians' perceived safety (Edwards & Leonard, 2022; Lau et al., 2022a). Petzoldt et al. (2017) showed that larger vehicles are perceived as more threatening than smaller vehicles. Moreover, pedestrians felt safer and were more willing to cross when interacting with a smaller HAV vs. a larger AV (Lau et al., 2022b). Soshiroda et al. (2021) designed text-based eHMIs for service automated mobilities, i.e., golf carts and bus. The results revealed that Japanese pedestrians showed higher anxiety when interacting with an automated bus than with an automated golf cart during the crossing. As a general implication for future communication solutions in Japan, Hell et al. (2021) suggested that yielding intents should be explicitly communicated to meet their high need for traffic safety, e.g., via vehicle deceleration or lights (Hell et al., 2021). Overall, the critical challenge is to ensure safe future interactions between pedestrians and differently sized HAVs globally, and the prospective investigation of communication tools is one key solution to master this challenge.

2. Objectives

To this point, light-band eHMIs have not been investigated in Japan. As a replication of Lau et al. (2022b), this study investigated the effects of light-band eHMIs, vehicle kinematics, and the interplay of both for differently sized HAVs with a Japanese sample. Overall, this study had two main objectives. First, we wanted to extend existing eHMI research to achieve the overall goal of a safe future interaction of pedestrians with HAVs. Thus, we examined if using light-band eHMIs for differently sized HAVs contributed to pedestrians' willingness to cross, trust, and perceived safety in Japan. Second, we investigated the effects of the interplay of eHMI and vehicle kinematics on pedestrians' interactions with HAVs in Japan. Current studies revealed side effects of eHMIs (e.g., Kaleefathullah et al., 2020; Lau et al., 2022b; J. Lee et al., 2021), e.g., pedestrians felt safe even if the eHMI communicated contradictory signals to the vehicle kinematics (Lau et al., 2022b). Therefore, we wanted to investigate how the interplay of vehicle kinematics (yielding vs. non-yielding) and eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI) subjectively affected Japanese participants. Additionally, we contrasted the results of this study of the Japanese sample with the results of the German sample based on Lau et al. (2022b) regarding possible cultural differences and similarities between both countries.

3. Method

This study's approach is based on Lau et al. (2022b), who conducted an experimental online study focusing on the interplay of eHMI and vehicle kinematics in Germany. In multiple steps, the German questionnaire was translated from German into Japanese by native speakers. In addition, the stimulus material was adjusted to Japanese traffic rules, i.e., driving on the left hand. This research was approved by the

Institutional Review Board at Keio University (REF No. 2022-053 and No. 2022-124). Informed consent was obtained from each participant.

3.1. Sample

In total, 128 participants participated in the experimental online study. We excluded 29 participants from the analysis as they did not pass the manipulation check after the experiment. The manipulation check at the end of the experiment included four check questions with a dichotomous answer format (yes vs. no): (1) Could you perceive the vehicles in the videos well?; (2) Could you perceive the light-band in the videos well?; (3) Did you notice any changes in the vehicle behavior of the car in the videos?; (4) Did you notice any changes in the vehicle behavior of the bus in the videos? Participants were excluded from the analysis when they denied one of the manipulation check questions.

This study's sample included in the further analyses 99 (42 female) Japanese participants with an average age of $M = 44.66$ ($SD = 18.13$; age range $= 18 - 77$ years). The Affinity-for-Technology Interaction questionnaire (Franke et al., 2018) was rated higher than average with $M = 3.69$ ($SD = 0.68$) on a 6-point Likert scale from completely disagree (1) to completely agree (6). Eighty-three participants possessed a driver's license. Moreover, 66 participants indicated that they would run their errands in urban areas, and 33 said they would run their errands in rural areas. Of all the participants, five had not heard of HAVs before. The interest in HAVs was rated with $M = 3.72$ ($SD = 1.14$) on a 5-point Likert scale from not at all (1) to very strong (5). Moreover, we asked how carefully the participants conducted the questionnaire on a 5-Likert scale, from very careless (1) to very careful (5). All participants included in the analysis answered with "rather careful" ($N = 27$), "careful" ($N = 54$), and "very careful" ($N = 18$).

3.2. Experiment design

This study followed a 2 x 2 x 3 repeated-measures research design with vehicle size (smaller vehicle vs. larger vehicle), vehicle kinematics (yielding vs. non-yielding), and eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI), which were manipulated within-participants. For the dynamic eHMI condition, the non-yielding condition was considered a non-matching condition since the eHMI provided explicit information that indicated the vehicle would yield, but the actual behavior was non-yielding. Two non-matching trials were provided, one for the smaller vehicle and one for the larger vehicle. The other eHMI conditions did not provide yielding information. Thus, the non-yielding conditions would not be perceived as a conflict.

3.3. Independent variables

3.3.1. Vehicle size

The videos showed two differently sized HAVs (Fig. 1). The smaller vehicle was a BMW i3, and the larger vehicle was a Mercedes Benz bus.

3.3.2. Vehicle kinematics

The distance of the vehicles to the pedestrian was 32.5 m when the video started. All reported distances (in meters, m) are measured from the pedestrians' position. Vehicle kinematics varied in two stages: yielding and non-yielding. In the yielding conditions, the HAVs performed a two-step deceleration. First, the HAVs decelerated at a 25 m distance from 30 to 20 km/h (deceleration rate: $-$ 1.92 m/s^2). Second, the vehicles decelerated at a 15 m distance from 20 to 2 km/h (deceleration rate: $-$ 3.83 m/s^2). In the non-yielding conditions, the vehicles did not decelerate, and the vehicle drove continuously at 30 km/h toward the pedestrian. All videos stopped when the vehicle was 11 m from the pedestrian. This point was called the *freezing point* and should represent a point in time with high uncertainty for the pedestrians without frightening the participants (Fig. 2).

3.3.3. eHMI status

The light-band eHMI used in this study was based on Dietrich et al. (2018). The eHMI lit up in the color cyan, which is a color that is not occupied in the traffic context so far (de Clercq et al., 2019; Faas, Mathis, & Baumann, 2020). Moreover, the light-band was positioned under the windshield (Fig. 3). We investigated three different eHMI statuses, i.e., no eHMI, static eHMI, and dynamic eHMI. The *no eHMI* condition served as a baseline, and the eHMI was completely turned off in this condition. The *static eHMI* condition showed a continuously enlightened light-band eHMI from the beginning of the trial. The continuously enlightened eHMI indicated the vehicle's automation status (Fig. 3). The *dynamic eHMI* condition presented the vehicle's automation status and the yielding intent (Fig. 3). The pulsation of the light-band indicated the vehicle's intent and started at a 25 m distance from the pedestrian. The light-band eHMI pulsated at a frequency of 0.66 Hz. In two experimental conditions (one condition with the car and one with the bus), the message of the dynamic eHMI did not match the vehicle's kinematics, referred to as "non-matching" conditions.

3.4. Dependent variables

After each experimental condition, the participants indicated their willingness to cross ("How willing are you to cross the street?"; 7-Likert scale from 1 = low to 7 = high), trust ("I would trust the vehicle to stop for me"; 7-Likert scale from 1 = disagree to 7 = agree) and perceived safety ("For my personal safety, I perceived the behavior of the vehicle as safety-enhancing."; 7-Likert scale from 1 = disagree to 7 = agree).

3.5. Procedure

This study was an experimental online study conducted with the online questionnaire platform SoSci (Leiner & Leiner, 2022). Initially,

Fig. 1. The smaller HAV (left) and the larger HAV (right) in this study.

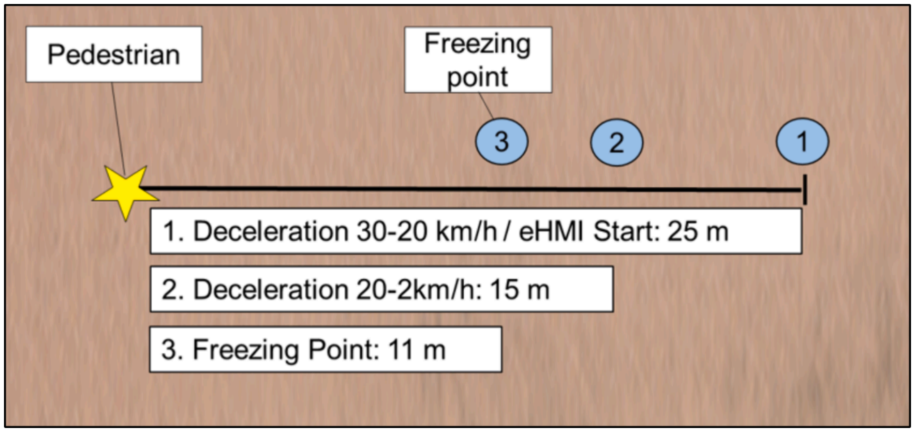

Fig. 2. Description of the vehicle kinematics in the yielding conditions of this study. *Note.* Distances are measured from the pedestrians' positions in meters (m).

Fig. 3. Demonstration of the static eHMI (left) and pulsation of the dynamic eHMI (right) for the bus.

participants started the online questionnaire independently and were guided throughout the experiment via written instructions. In the beginning, the participants gave their written informed consent for their participation. Afterward, the training phase started, in which the participants received written information about the study environment and the presented HAVs. The study environment was a shared space where explicit communication between pedestrians and AV is essential (Dey et al., 2017; Lau et al., 2022b; Y. M. Lee et al., 2021). A shared space is a traffic-calmed area without traffic signs or lane markings. However, the central principle of a shared space is mutual consideration (Clarke, 2006; Hamilton-Baillie, 2008).

As part of the training phase, we explained the different eHMI statuses in tutorial videos (Fig. 4). Hence, the participants were not naïve before starting the experimental phase. This study did not focus on first contact with eHMIs or the learnability of the eHMIs, and therefore, we decided to provide information about the different eHMI statuses. The learnability of eHMIs was already investigated by Avsar et al. (2021), who showed that participants could understand different eHMI statuses shortly after only a few interactions. In the experimental phase, the participants experienced twelve experimental trials in randomized order. As part of the experimental trials, the participants experienced two "non-matching" conditions (for each vehicle size one trial), in which the HAVs did not yield; however, the eHMI started to pulsate to indicate a yielding intent. These trials were considered to investigate possible side effects of a malfunctioning eHMI. The experimental trials consisted of short video sequences from the pedestrians' egocentric perspective. At the beginning of each video sequence, the participants looked to the other street side, turned their heads to the right-hand side, and faced the approaching HAV. The movement should increase the immersion. Following Lau et al. (2022b), pedestrians should have the right of way in the experiment. In Japan, the vehicles drive on the left-hand side (Hell et al., 2021), and thus, the vehicles in this study approached from the right-hand side (Fig. 5).

After each video, the participants evaluated their willingness to cross, trust, and perceived safety. The experiment ended with a final questionnaire in which the participants had to evaluate both AVs in the videos. Based on Petzoldt et al. (2017), the participants evaluated the smaller and larger HAVs based on selected adjectives (threatening, large, pleasant, dangerous, strong, familiar, safe, close) on a 7-point Likert scale from disagree (1) to agree (7). The experiment lasted 30 min, and the participants received 1200 Yen (approximately 9 euros) for their participation.

3.6. Statistical approach

The statistical approach aligns with Lau et al. (2022b). Firstly, we conducted a data validation check and multiple *t*-tests to investigate if participants' evaluations of specific adjectives differed for both vehicle sizes in this study. Therefore, eight *t*-tests were conducted with a Bonferroni-adjusted $p < 0.006$. The used effect size for the *t*-tests was Cohen's d_z and interpreted with $d_z = 0.2$ as a small effect, with $d_z = 0.5$ as a medium effect, and $d_z = 0.8$ as a large effect (Cohen, 1988). Moreover, we conducted a repeated-measures ANOVA with vehicle size (small vs. large), vehicle kinematics (yielding vs. non-yielding), and eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI). The three independent variables were manipulated within the participants. The prerequisites of a repeated-measures ANOVA were tested and were given. Huynh-Feldt correction was used when sphericity was not given (Field, 2013). For the interpretation of the ANOVA, we used partial eta-squared (η_p^2) as effect size with $\eta_p^2 \leq 0.01$ as small effect, with $\eta_p^2 \leq 0.06$ as medium effect, and with $\eta_p^2 \leq 0.14$ as large effect (Cohen, 1988). All statistical analyses were implemented in the statistical software IBM SPSS Statistics Version 26 (IBM Corp., 2019).

Fig. 4. Extract from the online questionnaire: Experimental condition showing the dynamic eHMI for the bus.

4. Results

4.1. Data validation check

The goal of the data validation check was to check if the participants perceived the HAVs differently, as found in previous work (Dey et al., 2017; Petzoldt et al., 2017). Petzoldt et al. (2017) showed that a larger vehicle was evaluated as more threatening than a smaller vehicle. The present study was conducted online. Thus, we wanted to see if the participants perceived similar differences for both vehicles in terms of eight adjectives. The results are presented in Fig. 6. T-tests showed a significant difference that a larger vehicle was evaluated as more *threatening* compared to a smaller ($t\,(98) = -6.74$, $p < 0.001$, $d_z = 0.68$; *Ms* = 4.78 vs. 3.81, *SDs* = 1.44 vs. 1.55), as *larger* ($t\,(98) = -14.01$, $p <$ 0.001, $d_z = 1.42$; *Ms* = 5.72 vs. *Ms* = 3.09, *SDs* = 1.44 vs. 1.37), as *more dangerous* ($t\,(98) = -4.42$, $p < 0.001$, $d_z = 0.44$; *Ms* = 4.65 vs. 4.01, *SDs* = 1.33 vs. 1.43) and *as stronger* ($t\,(98) = -8.39$, $p < 0.001$, $d_z = 0.84$; *Ms* = 4.91 vs. 3.82, *SDs* = 1.25 vs. 1.16). These results stand in accordance with previous research (Lau et al., 2022b; Petzoldt et al., 2017).

4.2. Willingness to cross

The repeated-measures ANOVA revealed that the main effects for vehicle kinematics [$F(1, 98) = 94.74$, $p = 0.001$, $\eta_p^2 = 0.49$] and for eHMI status [$F(1.57, 153.70) = 54.99$, $p = 0.001$, $\eta_p^2 = 0.36$] were significant. Regarding the vehicle kinematics, post-hoc tests with Bonferroni corrections showed that the willingness to cross was significantly higher in yielding conditions ($M = 3.92$, $SD = 1.44$) than in non-yielding conditions ($M = 2.66$, $SD = 1.37$; $p_{Bonf} < 0.001$). Regarding the eHMI status, the participants were more willing to cross with dynamic eHMI

Fig. 5. Egocentric view of the smaller HAV, which approached from the right-hand side.

(M = 4.12, SD = 1.56) vs. static eHMI (M = 3.00, SD = 1.50, p_{Bonf} < 0.001) and vs. no eHMI (M = 2.75, SD = 1.38; p_{Bonf} < 0.001). Moreover, the participants were more willing to cross with static eHMI than without eHMI (p_{Bonf} = 0.03). Moreover, we found a significant interaction between eHMI status and vehicle kinematics [F(1.96, 192.39) = 5.50, p = 0.005, η_p^2 = 0.05], as shown in Fig. 7. For yielding and non-yielding conditions, pedestrians' willingness to cross was higher with dynamic eHMI (yielding: M = 4.86, SD = 1.80; non-yielding: M = 3.37, SD = 1.70) than with static eHMI (yielding: M = 3.50, SD = 1.68; non-yielding: M = 2.50, SD = 1.63) or no eHMI (yielding: M = 3.38, SD = 1.72; non-yielding: M = 2.12, SD = 1.50; Fig. 7). Moreover, pedestrians reported a mid-ranged willingness to cross in the non-matching condition, i.e., non-yielding vehicle kinematics with dynamic eHMI (M = 3.37, SD = 1.70; the condition is marked in bold frames in Fig. 7). This finding indicated that the eHMI influenced pedestrians' willingness to cross, although it presented contradictory information about the vehicle's kinematics. No significant differences were found for vehicle size [F(1, 98) = 3.68, p = 0.06, η_p^2 = 0.04], the interactions vehicle size * vehicle kinematics [F(1, 98) = 0.00, p = 1.00, η_p^2 = 0.00], vehicle size * eHMI status [F(2, 196) = 2.40, p = 0.09, η_p^2 = 0.02], and vehicle size * vehicle kinematics * eHMI status [F(1.91, 187.48) = 1.69, p = 0.19, η_p^2 = 0.02].

4.3. *Trust*

We found a significant main effect for vehicle kinematics [F(1, 98) = 58.14, p < 0.001, η_p^2 = 0.37]. The participants perceived a higher trust when the vehicle yielded (M = 4.02, SD = 1.29) compared to when it did not yield (M = 3.06, SD = 1.42; p_{Bonf} < 0.001). Moreover, pedestrians' trust significantly differed depending on the eHMI status [F(1.79, 175.50) = 57.46, p = 0.001, η_p^2 = 0.37]. Post-hoc comparisons revealed that the participants trusted the vehicle with dynamic eHMI significantly more (M = 4.37, SD = 1.33) compared to static eHMI (M = 3.24, SD = 1.53; p_{Bonf} < *0.001*) or no eHMI (M = 3.02, SD = 1.43; p_{Bonf} < *0.001*). There was no significant difference between static eHMI and no eHMI (p_{Bonf} = *0.12*). The interaction between eHMI status and vehicle kinematics was also significant for pedestrians' trust [F(2, 196) = 3.44, p = 0.03, η_p^2 = 0.03; Fig. 8]. For the non-yielding conditions, the results showed that the participants perceived the vehicles with dynamic eHMI (M = 3.79, SD = 1.69) as more trustworthy vs. the static eHMI (M = 2.86, SD = 1.67) or no eHMI (M = 2.54, SD = 1.66; Fig. 8). For the yielding conditions, the results revealed that the participants also evaluated the vehicles with dynamic eHMI (M = 4.96, SD = 1.49) with higher trust ratings than with static eHMI (M = 3.61, SD = 1.63) or without eHMI (M = 3.49, SD = 1.62). Overall, we did not find any

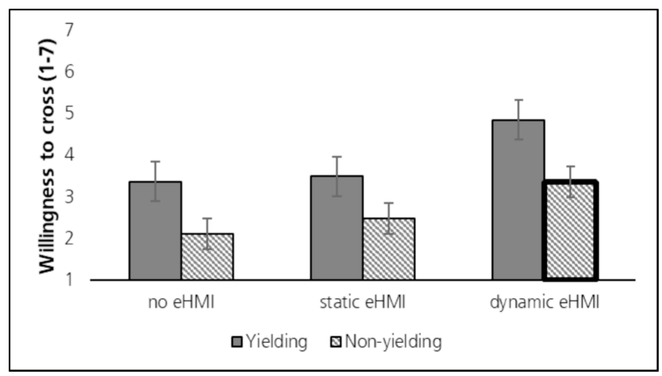

Fig. 7. Significant interaction for vehicle kinematics and eHMI status on pedestrians' willingness to cross. *Note.* The **bold** frame marks the non-matching condition (dynamic eHMI, non-yielding), Error bars ± 1 SE.

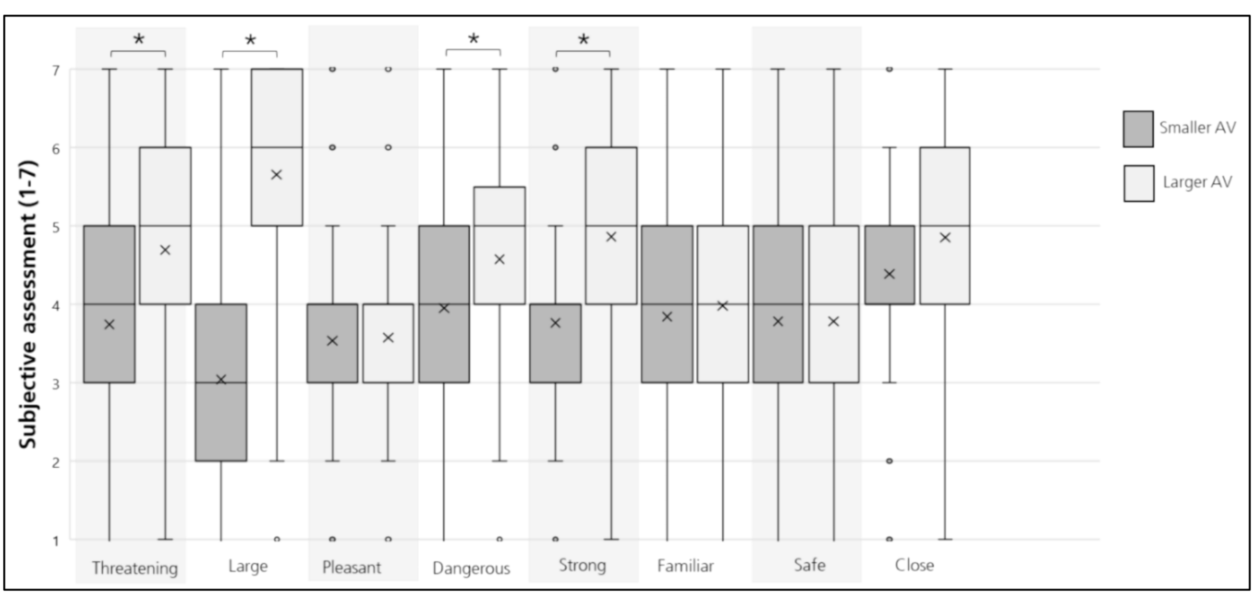

Fig. 6. Boxplots for the subjective assessment of the selected adjectives for the smaller and larger vehicles. *Note.* Crosses = Means; lines = medians. Bonferroni-corrected p-value * < 0.006.

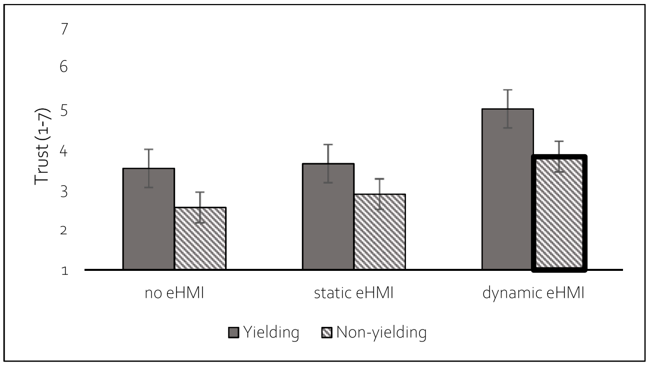

Fig. 8. Significant interaction for vehicle kinematics and eHMI status on trust. *Note.* The **bold** frame marks the non-matching condition (dynamic eHMI, non-yielding), Error bars ± 1 SE.

significant differences for vehicle size [$F(1, 98) = 0.007$, $p = 0.93$, $\eta_p^2 = 0.00$], the interactions vehicle size * vehicle kinematics [$F(1, 98) = 1.06$, $p = 0.31$, $\eta_p^2 = 0.01$], vehicle size * eHMI status [$F(2, 196) = 1.22$, $p = 0.30$, $\eta_p^2 = 0.01$], and vehicle size * vehicle kinematics * eHMI status [$F(1.87, 183.30) = 1.81$, $p = 0.17$, $\eta_p^2 = 0.02$].

4.4. Perceived safety

The results manifested a significant main effect for vehicle kinematics [$F(1, 98) = 45.59$, $p < 0.001$, $\eta_p^2 = 0.32$] and for eHMI status [$F(1.75, 171.01) = 41.17$, $p = 0.001$, $\eta_p^2 = 0.30$]. The participants perceived a higher safety when the vehicle yielded ($M = 4.15$, $SD = 1.27$) compared to when it did not yield ($M = 3.47$, $SD = 1.46$; $p_{Bonf} < 0.001$). Moreover, participants perceived a higher safety when there was a dynamic eHMI ($M = 4.48$, SD=1.37) vs. static eHMI ($M = 3.67$, $SD = 1.57$; $p_{Bonf} < 0.001$) vs. no eHMI ($M = 3.29$, $SD = 1.53$; $p_{Bonf} < 0.001$). Moreover, post-hoc comparisons with Bonferroni corrections revealed that the perceived safety was higher for the static eHMI than no eHMI ($p_{Bonf} = 0.001$). Additionally, the interaction for eHMI status and vehicle kinematics was significant [$F(1.93, 189.48) = 5.69$, $p = 0.004$, $\eta_p^2 = 0.06$; Fig. 9]. For non-yielding conditions, pedestrians' perceived safety was the highest with dynamic eHMI ($M = 4.96$, $SD = 1.46$) vs. static eHMI ($M = 3.46$, $SD = 1.78$) vs. no eHMI ($M = 2.97$, $SD = 1.74$), although the dynamic eHMI presented contradictory signals in the non-yielding condition (Fig. 9). For the yielding conditions, the pedestrians felt safer with dynamic eHMI ($M = 3.99$, $SD = 1.65$) vs. static eHMI ($M = 3.87$, $SD = 1.59$) vs. no eHMI ($M = 3.61$, $SD = 1.61$). We found no significant differences for vehicle size [$F(1, 98) = 0.64$, $p = 0.43$, $\eta_p^2 = 0.01$], the interactions vehicle size * vehicle kinematics [$F(1, 98) = 0.24$, $p = 0.62$, $\eta_p^2 = 0.002$], vehicle size * eHMI status [$F(2, 196) = 0.26$, $p = 0.77$, $\eta_p^2 = 0.003$], and vehicle size * vehicle kinematics * eHMI status [$F(1.92, 188.05) = 1.67$, $p = 0.19$, $\eta_p^2 = 0.02$].

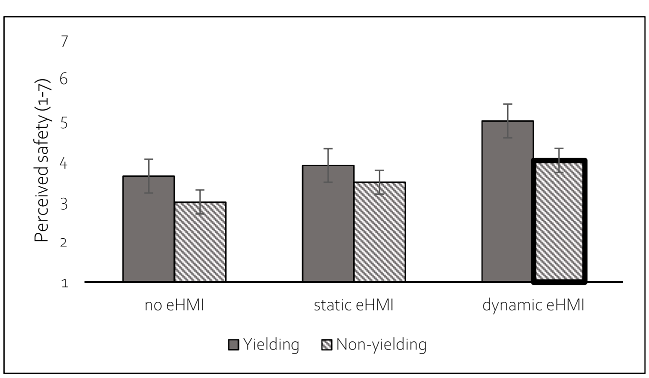

Fig. 9. Significant interaction for vehicle kinematics and eHMI status on perceived safety. *Note.* The **bold** frame marks the non-matching condition (dynamic eHMI, non-yielding), Error bars ± 1 SE.

4.5. Contrasting the Japanese and German sample

In this section, we contrasted our results to those of Lau et al. (2022b), who conducted the study with German participants using the same methodological approach. In Table 1, we present the inferential statistics of the Japanese sample from this study and the results of the German sample based on Lau et al. (2022) in terms of pedestrians' willingness, trust, and perceived safety. The results demonstrated similar effects for the Japanese and German sample. For both samples, pedestrians' willingness to cross, trust, and perceived safety different depending on the eHMI status, i.e., the dynamic eHMI was evaluated with a higher willingness, higher trust ratings, and a higher perceived safety compared to a static eHMI or no eHMI. From this, we concluded that the use of a dynamic light-band eHMI that presented the vehicle's automation status and the vehicle's intention could contribute to a safe future interaction between pedestrians and HAVs in both countries. Moreover, pedestrians were more willing to cross, trusted the HAVs more, and felt safer when the vehicles yielded compared to when they did not yield in Japan the same way as we found in Germany (Table 1). For the Japanese sample, the interaction between eHMI status and vehicle kinematics was significant for pedestrians' willingness to cross, trust, and perceived safety. However, for the German sample, the interaction between eHMI status and vehicle kinematics was only significant for pedestrians' perceived safety (Table 1). There were significant differences in vehicle size for the German sample (Lau et al., 2022b); however, there were no significant differences for the Japanese sample.

5. Discussion

This study investigated the interplay of eHMI status and vehicle kinematics for pedestrians' interactions with two differently sized HAVs in Japan. This study was conducted in Japan and was a follow-up with Japanese participants of the study by Lau et al. (2022b), which took place in Germany. Light-band eHMIs have great potential to support the communication between HAVs and pedestrians (Faas, Mathis, & Baumann, 2020; Lau et al., 2022a,b; Wilbrink et al., 2021). However, light-band eHMIs were primarily under investigation in Europe (Faas, Mathis, & Baumann, 2020; Habibovic et al., 2018; Wilbrink et al., 2021) and have not been investigated in Japan yet. The overall goal is to design eHMIs that are culturally independent and easily understood (Avsar et al., 2021; Tabone et al., 2021). Therefore, we wanted to examine the effects of light-band eHMIs, vehicle kinematics, and their interplay in Japan as one step toward a global communication strategy for HAVs.

Miscommunication with larger vehicles can have fatal consequences for pedestrians due to their high vulnerability (Edwards & Leonard, 2022). In this study, we included two differently sized HAVs to examine the effect of vehicle size on pedestrians' future interactions with HAVs. The results showed that the Japanese participants perceived larger HAVs as more threatening, larger, dangerous, and stronger. The results align with findings by Petzoldt et al. (2017) and Lau et al. (2022b), which also highlighted differences in the subjective assessment of differently-sized vehicles in video-based experimental studies. We expected that differences in vehicle sizes would also influence pedestrians' subjective assessments of automated vehicles. However, the effect of vehicle size on pedestrians' willingness to cross, trust, and perceived safety did not become significant in this study. One explanation for the significant effect of vehicle size in Germany but no significant effect in Japan could be the different sample sizes, i.e., 99 in Japan and 149 in Germany. Nevertheless, the results revealed a similar trend regarding the vehicle size for both samples, i.e., similar effect sizes for the Japanese and the German samples. Future research should vary the vehicle size in more detail to learn how different automated vehicles, as part of the road

Table 1
Test statistics for the Japanese sample (*N*=99) and German sample (*N*=149) based on Lau et al. (2022b).

	Effect	Japan (*N*=99)					Germany (*N*=149)				
		df_1	df_2	*F*	*p*	η_p^2	df_1	df_2	*F*	*p*	η_p^2
Willingness to cross	Vehicle size	1	98	3.68	0.06	0.04	**1**	**148**	**6.69**	**0.006****	**0.04**
	Vehicle kinematics	**1**	**98**	**94.74**	**0.001****	**0.49**	**1**	**148**	**255.67**	**0.001****	**0.63**
	eHMI status	**1.57**	**153.70**	**54.99**	**0.001****	**0.36**	**1.48**	**216.49**	**136.09**	**0.001****	**0.48**
	Vehicle size x vehicle kinematics	1	98	0.00	1.00	0.00	1	148	1.29	0.26	0.01
	Vehicle size x eHMI status	2	196	2.40	0.09	0.02	1.96	290.13	1.17	0.31	0.01
	Vehicle kinematics x eHMI status	**1.96**	**192.39**	**5.50**	**0.005***	**0.05**	1.88	278.84	0.17	0.84	0.00
	Vehicle size x vehicle kinematics x eHMI status	1.91	187.48	1.69	0.19	0.02	1.99	295.79	1.82	0.16	0.01
Trust	Vehicle size	1	98	0.007	0.93	0.00	1	148	2.21	0.07	0.02
	Vehicle kinematics	**1**	**98**	**58.14**	**0.001****	**0.37**	**1**	**148**	**212.59**	**0.001****	**0.59**
	eHMI status	**1.79**	**175.50**	**57.46**	**0.001****	**0.37**	**1.53**	**226.34**	**133.85**	**0.001****	**0.48**
	Vehicle size x vehicle kinematics	1	98	1.06	0.31	0.01	1	148	1.59	0.21	0.01
	Vehicle size x eHMI status	2	196	1.22	0.30	0.01	2	296	0.78	0.39	0.01
	Vehicle kinematics x eHMI status	**2**	**196**	**3.44**	**0.03***	**0.03**	1.90	281.40	1.46	0.23	0.01
	Vehicle size x vehicle kinematics x eHMI status	1.87	183.30	1.81	0.17	0.02	1.97	291.41	1.62	0.20	0.01
Perceived safety	Vehicle size	1	98	0.64	0.43	0.01	1	148	0.05	0.41	0.00
	Vehicle kinematics	**1**	**98**	**45.59**	**0.001****	**0.32**	**1**	**148**	**129.70**	**0.001****	**0.48**
	eHMI status	**1.75**	**171.01**	**41.17**	**0.001****	**0.30**	**1.57**	**232.96**	**120.99**	**0.001****	**0.45**
	Vehicle size x vehicle kinematics	1	98	0.24	0.62	0.00	1	148	0.37	0.54	0.00
	Vehicle size x eHMI status	2	196	0.26	0.77	0.003	1.91	282.50	0.73	0.48	0.01
	Vehicle kinematics x eHMI status	**1.93**	**189.48**	**5.69**	**0.004****	**0.06**	**1.59**	**234.61**	**19.33**	**0.001****	**0.12**
	Vehicle size x vehicle kinematics x eHMI status	1.92	188.05	1.67	0.19	0.02	2	295.37	2.14	0.12	0.014

Note. * $p < 0.05$, ** $p < 0.01$. Significant effects are printed in **bold.**

environment, might affect pedestrians' perceptions. For instance, Soshiroda et al. (2021) manifested higher anxiety levels of pedestrians for an automated bus compared to an automated golf cart during the crossing. Hence, as presented in this study, Japanese pedestrians might regard golf carts as safer mobility than the BMW i3 or the automated bus. Therefore, a subsequent study should investigate cultural differences of vehicle size on pedestrians' perceived safety ratings in more detail. Moreover, pedestrians' attitudes toward automated vehicles could generally differ between Germany and Japan (Edelmann et al., 2021), which should also be investigated in future studies. Additionally, objective measures should be considered in combination with subjective measures to evaluate a holistic picture of the crossing behavior of pedestrians and their subjective well-being.

This study investigated how the eHMI status influenced pedestrians' willingness to cross, trust, and perceived safety. The results showed that pedestrians were more willing to cross when the vehicle had a dynamic eHMI than a static eHMI or no eHMI. Additionally, they trusted the vehicle more and felt safer with dynamic eHMI compared to the static eHMI or no eHMI. These findings are in line with previous studies (Habibovic et al., 2018; Lau et al., 2022b; Wilbrink et al., 2021). Our results underlined that light-band eHMIs can contribute to safe interactions between pedestrians with differently sized HAVs in Japan when the eHMI message is in accordance with the vehicle kinematics. To our knowledge, this study is the first experimental study investigating light-band eHMIs in Japan. As one of the few eHMI studies in Japan, J. Lee et al. (2021) investigated the effect of text-based eHMIs placed on an automated vehicle. The results revealed possible negative effects of eHMI, i.e., pedestrians focused less on the traffic and crossed the street less carefully when the eHMI was on vs. when the eHMI was off. In this study, the results also revealed possible side effects of eHMIs, i.e., Japanese participants relied on the explicit communication by the dynamic eHMI, which is underlined by a mid-ranged pedestrians' willingness to cross, trust, and perceived safety in conditions in which the dynamic eHMI indicated to yield, even though the vehicle did not yield. Such non-matching conditions represented high-risk traffic situations for pedestrians as vulnerable road users (Lau et al., 2022b). In contrast, Lau et al. (2022b) only found a significant effect of eHMI and vehicle kinematics on perceived safety, i.e., pedestrians felt safe with dynamic eHMI, even though the vehicle did not yield. A possible reason could be that the Japanese participants saw the dynamic eHMI and trusted the eHMI functions. Japanese drivers are highly reliable in following the rules in traffic (Atchley et al., 2014; Hell et al., 2021; Hofstede Insights, 2021). Thus, Japanese participants might have built up high confidence in eHMIs functionalities, which were explained in the training phase, so they assumed that the pulsating eHMI meant that the HAVs were stopping. Japanese and German participants received the same information about the eHMI functions in the training phase with online tutorials. In future studies, we would like to investigate such side effects in VR to enable pedestrians to interact in a more realistic traffic environment and in more complex traffic situations with more than one pedestrian. Overall, the interplay of eHMI and vehicle kinematics could support pedestrians' willingness to cross, trust, and perceived safety when both communication tools (eHMI and vehicle kinematics) are in accordance.

This study contributed to ongoing eHMI research and the standardization of eHMIs by giving insights into the effects of light-band eHMIs in Japan. Light-based eHMIs could be a cultural-independent communication solution for HAVs, and we demonstrated that Japanese participants could interact and understand light-band eHMI communication messages in this study. The participants received an online tutorial on how to understand the eHMI messages. We did not focus on first contact with eHMIs but whether light-band eHMIs are also beneficial in Japan. Overall, we saw similar findings when comparing Japan and Germany, i.e., a dynamic light-band eHMI indicating the vehicle's yielding intent and automation status contributed to pedestrians' willingness to cross. Pedestrians' willingness to cross was slightly higher in Germany compared to Japan (referring to Lau et al., 2022b). Nevertheless, a greater sample size in Germany could also explain higher ratings. Additionally, Japanese participants relied on explicit communication and indicated a high willingness to cross, high trust, and high perceived safety when the eHMI displayed a false yielding intent. In future studies, we would like to investigate the perceptual processes of pedestrians during the interaction with HAVs in more detail, e.g., by considering eye-tracking data.

5.1. Limitations

The current study presents several limitations. First, the German sample in the previous study (Lau et al., 2022b) was larger compared to the Japanese sample, which could influence the comparison of both samples. Also, the participants in this study conducted the online study independently by clicking on a weblink. Therefore, the test environment could not be fully controlled, e.g., light sources in the participants' surroundings. However, we provided written guidelines throughout the experiment and asked the participants to dim the lights in their current environment. Additionally, we conducted manipulation checks in both countries to ensure that all study participants understood the task and perceived the light-band and the vehicles. Participants were only included in the analysis when they answered the check questions in the affirmative. Additionally, this study investigated the interaction between pedestrians and HAV as a one-to-one interaction. Pedestrians' crossing behavior and their subjective evaluation in the interaction with HAVs can be influenced by the group size (Joisten et al., 2021). Therefore, future studies should address more than one participant in terms of pedestrians' interaction with HAVs.

Ethical approval

The authors have received approval from the Ethics Board of Keio University and followed appropriate ethical standards in conducting their research.

CRediT authorship contribution statement

Merle Lau: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jieun Lee:** Writing – review & editing, Validation, Investigation. **Satoshi Kitazaki:** Writing – review & editing, Project administration. **Tatsuru Daimon:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Michael Oehl:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, 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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Ethics statement

The study was approved by the Ethics Board of the Keio University, Faculty of Science and Technology/Graduate School of Science and Engineering. The participants provided their written informed consent to participate in this study.

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