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Effectiveness of eHMI for Conveying Autonomous Vehicle Intentions to Multiple Pedestrians

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Abstract

In recent years, the development of automated vehicles has progressed, which is expected to reduce human errors that contribute to traffic accidents. However, in automated vehicles without a human driver, pedestrians may face difficulties in decision-making because the vehicle's driving intentions are unclear. To address this issue, external Human-Machine Interfaces (eHMIs) have been proposed to present the intentions of automated vehicles to pedestrians. Nevertheless, existing eHMIs mainly assume a one-to-one interaction between a single vehicle and a single pedestrian, and they do not adequately consider complex traffic environments in which multiple vehicles and pedestrians coexist. Therefore, this study proposes two eHMI designs: the Aggregated eHMI, which aggregates information from all vehicles and displays a single eHMI for each pedestrian, and the Distributed eHMI, which aggregates information on a per-lane basis and displays lane-specific eHMIs for each pedestrian. These designs aim to improve pedestrian safety and perceived comfort in complex traffic environments. A pedestrian crossing experiment was conducted in a virtual reality (VR) environment with 15 participants, and crossing willingness was evaluated together with a questionnaire survey using a seven-point Likert scale. The results showed that the Distributed eHMI significantly increased crossing willingness during crossing opportunities compared with existing methods, except for the Aggregated eHMI. Furthermore, in the questionnaire evaluation, the Distributed eHMI achieved the highest mean scores across all items, with statistically significant differences compared with other methods for many items. These results confirm that, in complex traffic environments, clearly conveying each vehicle's intentions toward each pedestrian is important for improving both safety and perceived comfort.

Keywords

Vehicle-Pedestrian Interaction, External Human-Machine Interface (eHMI), Automated Vehicle

1. Introduction

In recent years, the development of automated vehicles has progressed, and it is expected to reduce human errors that cause traffic accidents [1]. However, in automated vehicles without a human driver, pedestrians may have difficulty understanding the vehicle's driving intentions, which can negatively affect pedestrian safety and perceived comfort [2]. For example, when interacting with a manually driven vehicle, pedestrians can determine when it is safe to cross not only from vehicle speed information but also through nonverbal communication with the driver, such as gestures and eye contact. In contrast, for automated vehicles without a driver, pedestrians cannot engage in such nonverbal communication. As a result, pedestrians find it difficult to understand whether the vehicle intends to proceed or stop, which makes crossing decision-making more challenging.

To address this issue, external Human-Machine Interfaces (eHMIs) have been proposed as a method to convey the behavioral intentions of automated vehicles to pedestrians. eHMIs are used to visually present vehicle movements and intentions to pedestrians, and previous studies have reported improvements in pedestrian safety and perceived comfort as well as reductions in decision-making time [3]-[5]. In addition, projection-based approaches that directly project information onto the road surface have also been proposed, and some have already been commercialized [6] [7]. However, many existing eHMIs mainly assume one-to-one situations involving a single vehicle and a single pedestrian, and they do not consider complex traffic environments in which multiple pedestrians and multiple automated vehicles coexist. For instance, if a vehicle displays an eHMI that indicates it is safe to cross while two pedestrians are present on the sidewalk, it must be clearly understood whether the eHMI is directed to one pedestrian or both. Otherwise, a pedestrian who is not intended to receive the message may misunderstand the eHMI and create a dangerous situation [8]. Moreover, when multiple vehicles are present, displaying eHMIs from all vehicles may increase the amount of information pedestrians receive, potentially delaying their decision-making [9]. Therefore, it is necessary to investigate eHMIs that are effective in such complex traffic environments.

In this study, to address the limitation that existing eHMIs do not consider complex environments with multiple pedestrians and multiple automated vehicles, we propose two designs: the Aggregated eHMI, which aggregates information from all vehicles and displays a single eHMI for each pedestrian, and the Distributed eHMI, which aggregates information on a per-lane basis and displays lane-specific eHMIs for each pedestrian. We evaluate the effectiveness of these eHMIs in terms of pedestrians' crossing willingness and questionnaire-based assessments by comparing them with a baseline condition without eHMIs (No eHMI), related work that assumes one-to-one interactions between an automated vehicle and a pedestrian, and related work that assumes one-to-many interactions between a vehicle and pedestrians.

2. Related Work

2.1. Improving Pedestrian Comfort Using an Eye-Like eHMI

Tagawa *et al.* developed an external communication unit that resembles human eyes (an eye-like eHMI) to address pedestrians' anxiety caused by the lack of explicit communication of intent from automated vehicles and to resolve the issue that conventional eHMIs do not clearly indicate whom the vehicle recognizes and targets with its message [10]. Their approach provides pedestrians with the feeling of "being watched," which was shown to improve perceived comfort.

Chang *et al.* investigated whether installing eyes on automated vehicles could reduce pedestrian traffic accidents [11]. Their results indicated that vehicle-mounted eyes can reduce potential traffic accidents for male pedestrians and improve traffic efficiency for female pedestrians. They also reported that pedestrians tend to feel safer when the vehicle's gaze is directed toward them. However, when multiple pedestrians are present, it is difficult for a vehicle to recognize all pedestrians and direct its gaze toward each of them. Therefore, these approaches may improve perceived comfort only for pedestrians within a limited range.

2.2. Effectiveness Comparison of Vehicle-Mounted eHMIs in Multi-Pedestrian Environments

Alhawiti *et al.* investigated the effectiveness of vehicle-mounted eHMIs in situations involving a single pedestrian and those involving multiple pedestrians [12]. Their study showed that, in both situations, an eHMI combining a flashing green LED, a robotic sign, and a countdown timer was more effective than an eHMI using only a green LED and one combining a green LED with a robotic sign. They also found that pedestrians' willingness to cross decreased in multi-pedestrian situations compared with single-pedestrian situations. Furthermore, in terms of perceived comfort and the extent to which pedestrians felt that the eHMI was directed at them, lower scores were obtained in the multi-pedestrian condition than in the single-pedestrian condition. These results suggest that more effective eHMIs are required in environments where multiple pedestrians are present.

2.3. Challenges of eHMIs in Multi-Pedestrian Environments and Road-Projection Approaches

Dey *et al.* investigated eHMIs that can communicate which pedestrian an automated vehicle intends to yield to in situations with multiple pedestrians [13]. Their VR (Virtual Reality) experiment showed that conventional vehicle-mounted eHMIs make it difficult to understand to whom the vehicle's yielding intention is directed, which may lead to misunderstandings. In contrast, an eHMI that projects the vehicle's stopping position onto the road surface was found to be effective even in scenarios with multiple pedestrians, as it explicitly indicates where the vehicle will stop and helps reduce misunderstandings about the intended yielding target. This finding highlights that, in multi-pedestrian situations, clearly indicating to whom an eHMI message is intended is essential for improving safety. However, a limitation of their study is that the effectiveness of such approaches was not examined in environments where multiple vehicles are present.

3. Proposed Method

3.1. Overview

In this study, we propose two methods for displaying eHMIs to pedestrians after their positions have been detected: the Aggregated eHMI and the Distributed eHMI. The Aggregated eHMI aggregates crossing-permission information from all vehicles within a certain distance of each pedestrian and displays a single eHMI at the roadway closest to the pedestrian. When all vehicles determine that crossing is permitted, an eHMI indicating that crossing is allowed is displayed. Otherwise, an eHMI indicating that crossing is not allowed is displayed. No eHMI is displayed when a pedestrian is not detected. The Distributed eHMI determines crossing permission on a per-lane basis for each pedestrian and displays lane-specific eHMIs for each pedestrian. Several approaches can be considered for displaying eHMIs on the road surface, such as projection from roadside infrastructure or embedded LEDs in the pavement. However, this study does not restrict the implementation method [14] [15].

3.2. Aggregated eHMI

The operating procedure of the Aggregated eHMI is shown in **Figure 1(a)**. The numbers in the figure correspond to the following steps.

1. When an automated vehicle detects a pedestrian who intends to cross, it sends the following information to the server:
- Pedestrian location information.
- Crossing permission information.
2. The server aggregates the crossing permission information from all vehicles and determines the eHMI to be displayed to the pedestrian:
- If all vehicles permit crossing, the server selects an eHMI indicating that crossing is allowed.
- If at least one vehicle does not permit crossing, the server selects an eHMI indicating that crossing is not allowed.
3. Based on the pedestrian's location information, the server determines the nearest eHMI display device and activates it.
4. Steps 1 - 3 are repeated for all pedestrians who intend to cross.

3.3. Distributed eHMI

The operating procedure of the Distributed eHMI is shown in Figure 1(b). The numbers in the figure correspond to the following steps.

1. When an automated vehicle detects a pedestrian who intends to cross, it sends the following information to the server:
- Pedestrian location information.
- Crossing permission information.
- Lane ID.
2. The server aggregates crossing permission information for each lane and determines the eHMI to be displayed to the pedestrian for each lane:
- If all vehicles in the same lane permit crossing, the server selects an eHMI indicating that crossing is allowed.
- If at least one vehicle in the same lane does not permit crossing, the server selects an eHMI indicating that crossing is not allowed.
3. Based on the pedestrian's location information, the server determines the nearest eHMI display device for each lane and activates it.
4. Steps 1 - 3 are repeated for all pedestrians who intend to cross.

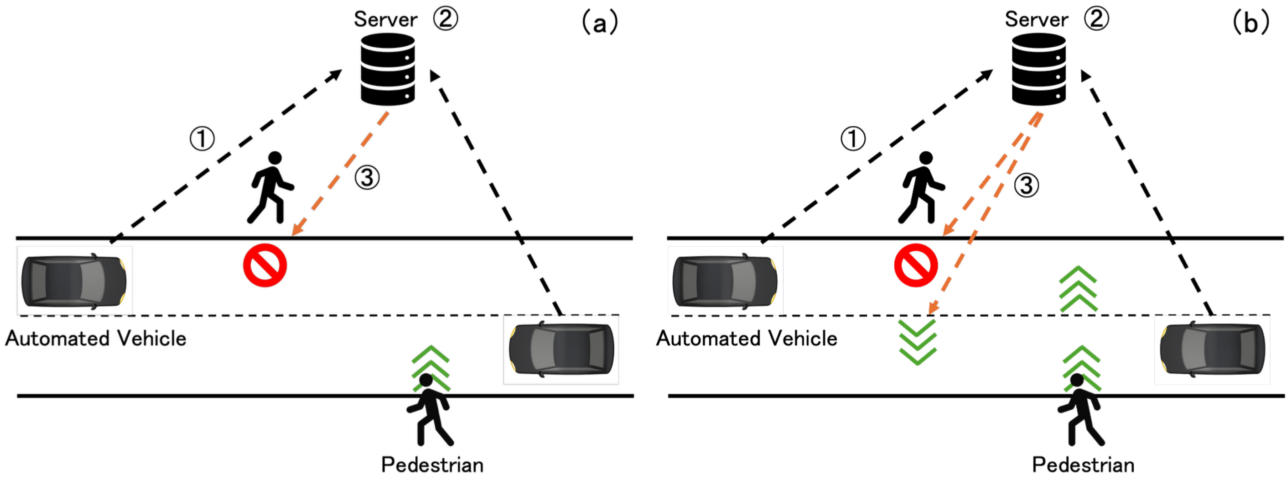


Figure 1. (a) Aggregated eHMI procedure; (b) Distributed eHMI procedure.

4. Evaluation

4.1. Experimental Environment

The evaluation in this study was conducted using a system in which a VR environment was created in Unity 6.0 running on a PC and displayed on an HMD (Meta Quest 3). The evaluation environment used in this study is illustrated in Figure 2. The main assets used in Unity to construct the environment are listed in Table 1.

In the scenario, two automated vehicles and two pedestrians were assumed. The participant automatically moved along the direction indicated by the orange arrow in Figure 2 and stopped at the position indicated by the orange square. The other virtual pedestrian automatically moved in the direction indicated by the white arrow and stopped at the position indicated by the white square. The distance between the two pedestrians was set to 10 m. The lane width was set to 3 m. Vehicle A approached from the right side of the figure, starting from a position 100 m away from the participant, while Vehicle B approached from the left side, starting from a position 105 m away. Each vehicle approached at a speed of 40 km/h. Each vehicle began decelerating at 33 m before the target pedestrian and stopped 3 m before the pedestrian. In this study, an eHMI corresponding to each pedestrian was displayed when the vehicle came within 33 m of that pedestrian.

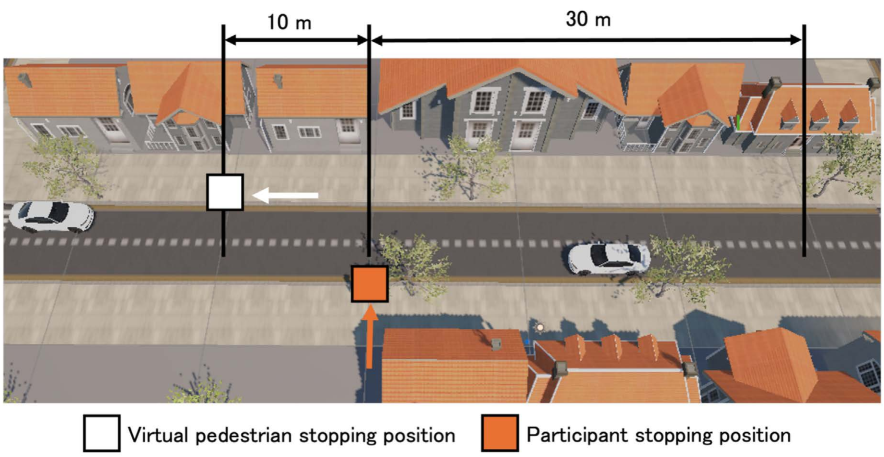


Figure 2. Experimental environment reproduced in the VR space.

Table 1. Assets used in Unity.

Item	Specification
Buildings	House Pack Asset (provided by Mehdi Rabiee)
Roads	Modular Lowpoly Streets Asset (provided by EVPO Games)
Automated Vehicles	Realistic Mobile Car #26 (Demo) Asset (provided by Surdov Vadym)
Pedestrians	UMA 2 Asset (provided by UMA Steering Group)

4.2. Comparison Conditions

To evaluate the effectiveness of the proposed methods, we compared six conditions: No eHMI and five eHMI-based methods, as described below.

- VA eHMI: Arrow on the vehicle

The design of the VA eHMI is shown in **Figure 3(a)**. Based on the eHMI proposed by Ackermann *et al.*, we designed the display for crossing-permitted situations [16]. To support multiple pedestrians, the vehicle displays the message only to the pedestrian closest to the vehicle: a green arrow when crossing is permitted and a red prohibition symbol (a red circle with a diagonal slash) when crossing is not permitted.

- AT eHMI: Arrow on the vehicle + remaining time to arrival

The design of the AT eHMI is shown in **Figure 3(b)**. Based on the eHMI proposed by Ackermann *et al.* and Alhawiti *et al.*, we designed the display by adding the remaining time until the vehicle stops, in addition to the arrow displayed on the windshield in the VA eHMI [12] [16].

- GS eHMI: Vehicle stopping position projected on the ground

The design of the GS eHMI is shown in **Figure 3(c)**. Based on the eHMI proposed by Dey *et al.*, the vehicle's stopping position is displayed using a turquoise frame and an animated arrow [13].

- Aggregated eHMI

The design of the Aggregated eHMI is shown in **Figure 3(d)**. Based on the work of Ackermann *et al.*, we designed the display for crossing-permitted situations. For each pedestrian, a green arrow is displayed when crossing is permitted, and a red prohibition symbol is displayed when crossing is not permitted [16].

- Distributed eHMI

The design of the Distributed eHMI is shown in **Figure 3(e)**. Based on the work of Ackermann *et al.*, we designed the display for crossing-permitted situations. For each pedestrian, a green arrow is displayed when crossing is permitted, and a red prohibition symbol is displayed when crossing is not permitted [16].

(a) VA eHMI design (b) AT eHMI design (c) GS eHMI design

(d) Aggregated eHMI design (e) Distributed eHMI design

Figure 3. eHMI designs for each method: (a) VA eHMI; (b) AT eHMI; (c) GS eHMI; (d) Aggregated eHMI; and (e) Distributed eHMI.

4.3. Participant Experiment

Fifteen participants aged 21 - 25 years (14 males and 1 female) took part in the experiment. The total experiment time was approximately 30 minutes per participant. The pre-experiment briefing lasted about 10 minutes and mainly explained the situation in the VR environment, the experimental overview, and the operation procedure. Specifically, participants were informed that they would automatically approach the roadway as a pedestrian who intends to cross and that they could freely move their viewpoint in the VR environment. Next, the experimental environment and the designs of the six comparison conditions were presented. However, to evaluate intuitive comprehensibility, the specific intentions behind each design were not explained. After the briefing, participants wore the HMD and performed position adjustment and gaze calibration in the VR environment. After completing these settings, participants performed a practice session under the No eHMI condition, in which the vehicles did not stop, in order to become familiar with the environment and operation. After the practice, the main experiment was conducted. An overview of the system configuration used in this experiment is shown in Figure 4. At the beginning of the experiment, a start screen was displayed, and the experiment began when the participant pressed the A button on the Meta Quest 3 controller. For each method, four trials were conducted. In each set of four trials, the vehicle yielded twice to the participant and twice to the virtual pedestrian in a randomized order. After each trial, the screen was paused, and the participant pressed the A button again to start the next trial. After completing the trials for each method, participants answered a questionnaire, and they were also asked to provide free-form comments about any issues or concerns regarding the method.

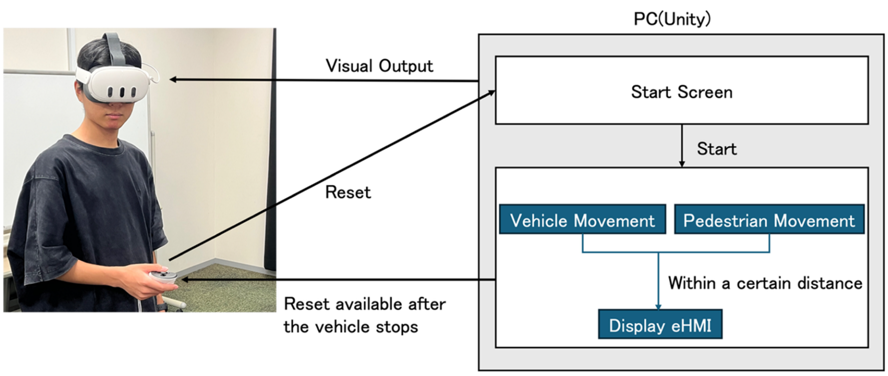


Figure 4. Overview of the system configuration.

4.4. Evaluation Metrics

In this study, we conducted both quantitative and qualitative evaluations as follows.

- Crossing willingness

As a quantitative measure, we evaluated crossing willingness. While the vehicles were approaching, participants continuously pressed a controller button during the period in which they judged that they could cross. The button-press state was recorded at 0.25 s intervals. Trials were conducted in which the vehicle yielded either to the participant or to the virtual pedestrian, and safety was evaluated based on crossing decision errors.

- Questionnaire evaluation

As a qualitative measure, we conducted a questionnaire evaluation. Using a seven-point Likert scale, the following four items were evaluated to examine whether the proposed methods improved perceived comfort compared with conventional methods.

- Perceived safety: I felt that the interaction with the vehicle was safe.
- Willingness to use: The interaction with the vehicle was comfortable (I would like to use this method).
- Understanding of the intended recipient: When the vehicle approached, it was clear to whom the vehicle was presenting its intention.
- Clarity of the stopping target: When the vehicle approached, it was clear whether the vehicle would stop for me or for the other pedestrian.

Based on these evaluation metrics, we compared the proposed eHMIs with related work eHMIs as well as No eHMI.

5. Results

5.1. Crossing Willingness

When the vehicle yields to the participant, it is expected that the participant will notice at an early stage that the vehicle is yielding to them, feel safe, and begin crossing early. Therefore, a higher crossing willingness before the vehicle comes to a complete stop indicates a stronger effect of the eHMI. **Figure 5** shows the mean button-press rate over a 7-s period from the moment Vehicle A approached within 33 m of the participant until all vehicles stopped. The results indicate that the No eHMI produced the lowest crossing willingness, whereas the Distributed eHMI produced the highest crossing willingness. To examine statistical differences in the 7 s data, we conducted the Friedman test, a non-parametric statistical test. The results showed a chi-square statistic of 41.644 with a p-value of less than 0.001, indicating a significant difference among the methods. We then performed pairwise comparisons using the Wilcoxon signed-rank test, and the results are shown in **Table 2**. The significance level was set to $\alpha = 0.05$, and Bonferroni correction was applied for 15 comparisons, resulting in a significance threshold of $p < 0.05/15$ for each comparison. The results showed that the Distributed eHMI produced statistically significant differences compared with all methods except the Aggregated eHMI. Significant differences were also observed between No eHMI and the VA eHMI, and between No eHMI and the Aggregated eHMI.

When the vehicle does not yield to the participant, it is desirable for the participant to notice at an early stage that the vehicle is not yielding to them and decide not to cross. Therefore, a lower crossing willingness before the vehicle arrives indicates a stronger effect of the eHMI. **Figure 6** shows the mean button-press rate over a 4-s period from the moment Vehicle A approached within 33 m of the participant until it arrived. The results showed similar trends across all methods. In addition, the Friedman test yielded a chi-square statistic of 4.456 with a p-value of

0.486, indicating that no significant differences were observed among the methods.

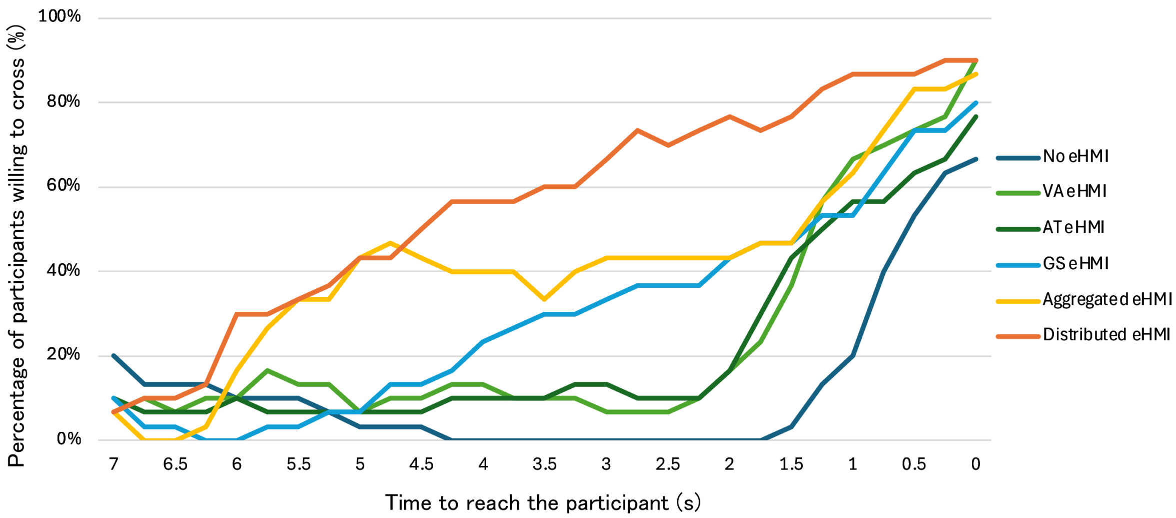


Figure 5. Crossing willingness (yielding to the participant).

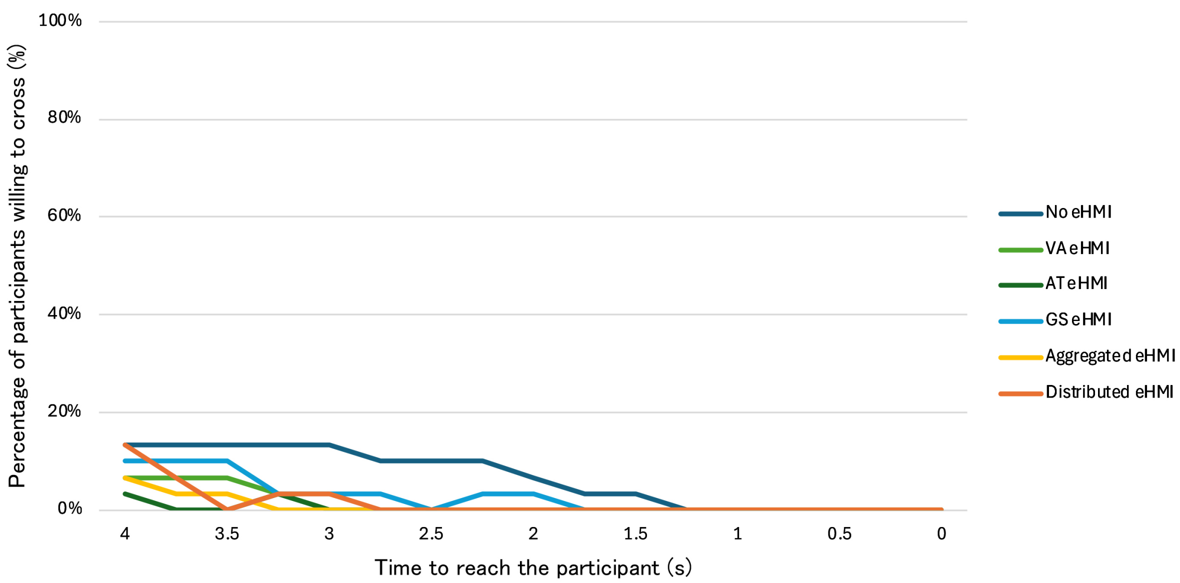


Figure 6. Crossing willingness (not yielding to the participant).

Table 2. Results of the Wilcoxon test when the vehicle yielded to the participant.

Comparison	p-Value
N - VA	0.001*
N - AT	0.096
N - GS	0.050
N - Aggregated	<0.001*
N - Distributed	<0.001*

Continued

VA - AT	0.875
VA - GS	0.451
VA - Aggregated	0.006
VA - Distributed	0.002*
AT - GS	0.149
AT - Aggregated	0.013
AT - Distributed	<0.001*
GS - Aggregated	0.064
GS - Distributed	0.002*
Aggregated - Distributed	0.031

Note: *indicates $p < 0.05/15$ (Bonferroni corrected). Abbreviations: N = No eHMI, VA = Vehicle-mounted arrow, AT = Vehicle-mounted arrow + time to arrival, GS = Ground-projected stopping position, Aggregated = Aggregated eHMI, Distributed = Distributed eHMI.

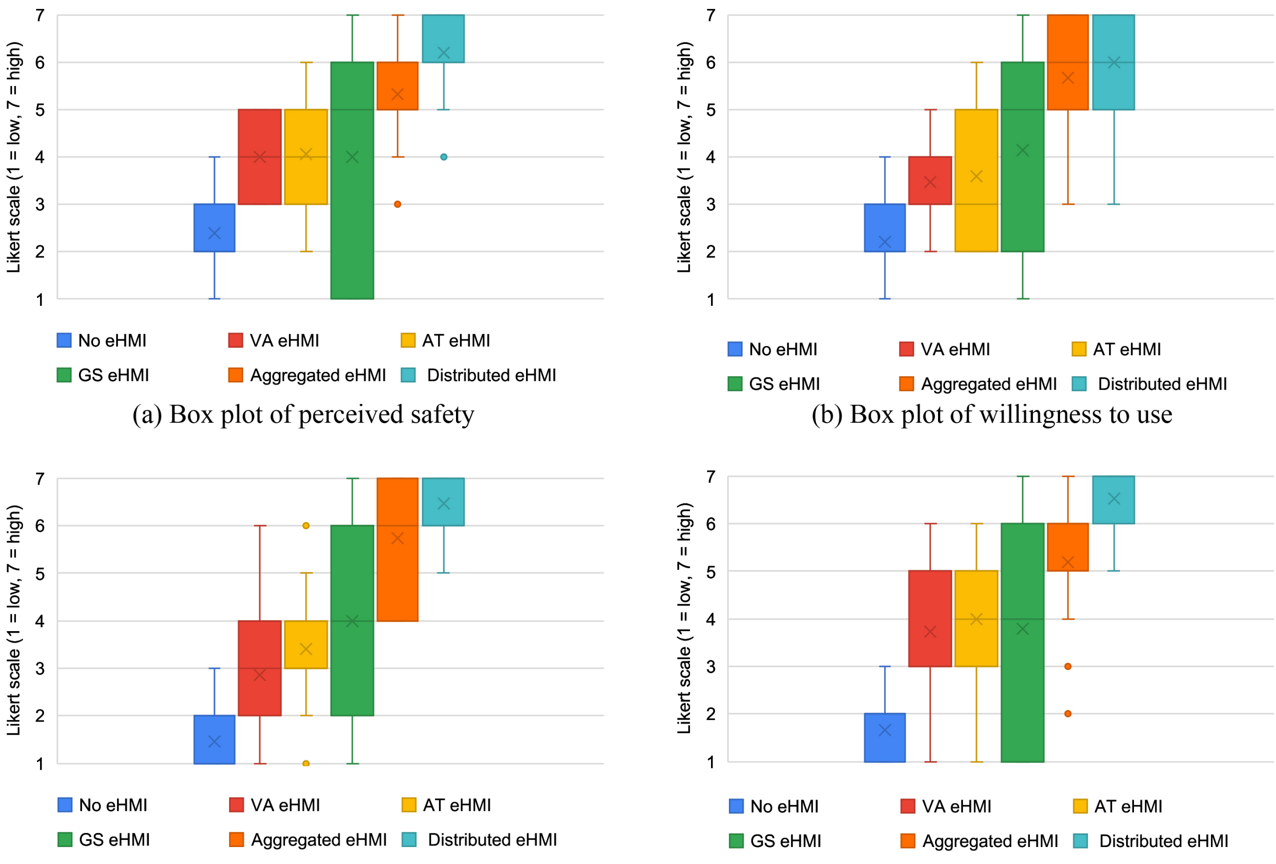
5.2. Questionnaire Evaluation

Figure 7(a) shows the results for perceived safety, Figure 7(b) shows the results for willingness to use, Figure 7(c) shows the results for understanding of the intended recipient, and Figure 7(d) shows the results for clarity of the stopping target. The results of the Wilcoxon pairwise comparisons for these questionnaire items are presented in Table 3.

As shown in Figure 7(a), the Distributed eHMI achieved the highest median and mean scores for perceived safety. The Friedman test yielded a chi-square statistic of 50.722 with a p-value of less than 0.001, indicating a significant difference among the methods. As shown in Table 3, the Distributed eHMI exhibited statistically significant differences compared with all methods except the Aggregated eHMI. The Aggregated eHMI showed significant differences compared with the VA eHMI and the No eHMI. In addition, the VA eHMI and the AT eHMI also showed significant differences compared with the No eHMI.

As shown in Figure 7(b), the Distributed eHMI and the Aggregated eHMI achieved the highest median scores for willingness to use, and among them, the Distributed eHMI achieved the highest mean score. The Friedman test yielded a chi-square statistic of 48.423 with a p-value of less than 0.001, indicating a significant difference among the methods. As shown in Table 3, the Distributed eHMI exhibited significant differences compared with all methods except the Aggregated eHMI and the GS eHMI. Similarly, the Aggregated eHMI exhibited significant differences compared with all methods except the Distributed eHMI and the GS eHMI. A significant difference was also observed between the VA eHMI and the No eHMI.

As shown in Figure 7(c), the Distributed eHMI achieved the highest median and mean scores for understanding of the intended recipient. The Friedman test yielded a chi-square statistic of 58.753 with a p-value of less than 0.001, indicating a significant difference among the methods. As shown in Table 3, the Distributed eHMI exhibited significant differences compared with all methods except the Aggregated eHMI. The Aggregated eHMI exhibited significant differences compared with all methods except the Distributed eHMI and the GS eHMI. In addition, the VA eHMI, the AT eHMI, and the GS eHMI each exhibited significant differences compared with the No eHMI.



(a) Box plot of perceived safety

(b) Box plot of willingness to use

(c) Box plot of understanding of the intended recipient

(d) Box plot of clarity of the stopping target

Figure 7. Box plots of questionnaire results.

Table 3. Results of the Wilcoxon test for each questionnaire item.

Comparison	p-Value			
	Perceived Safety	Willingness to Use	Intended Recipient	Stopping Target
N - VA	<0.001*	0.002*	0.003*	<0.001*
N - AT	0.001*	0.005	<0.001*	<0.001*
N - GS	0.015	0.005	0.002*	0.008
N - Aggregated	<0.001*	0.001*	<0.001*	<0.001*
N - Distributed	<0.001*	<0.001*	<0.001*	<0.001*

Continued

VA - AT	0.773	0.603	0.085	0.334
VA - GS	0.968	0.216	0.048	0.898
VA - Aggregated	0.002*	<0.001*	0.001*	0.040
VA - Distributed	<0.001*	<0.001*	<0.001*	0.001*
AT - GS	0.746	0.233	0.257	0.751
AT - Aggregated	0.007	0.003*	0.001*	0.068
AT - Distributed	<0.001*	<0.001*	<0.001*	<0.001*
GS - Aggregated	0.023	0.031	0.009	0.017
GS - Distributed	0.002*	0.004	<0.001*	0.002*
Aggregated - Distributed	0.005	0.374	0.013	0.002*

Note: *indicates p < 0.05/15 (Bonferroni corrected). Abbreviations: N = No eHMI, VA = Vehicle-mounted arrow, AT = Vehicle-mounted arrow + time to arrival, GS = Ground-projected stopping position, Aggregated = Aggregated eHMI, Distributed = Distributed eHMI.

Finally, from **Figure 7(d)**, the Distributed eHMI achieved the highest median and mean scores for clarity of the stopping target. The Friedman test yielded a chi-square statistic of 47.230 with a p-value of less than 0.001, indicating a significant difference among the methods. As shown in **Table 3**, the Distributed eHMI exhibited significant differences compared with all other methods. In addition, the Aggregated eHMI, the AT eHMI, and the VA eHMI each exhibited significant differences compared with the No eHMI.

6. Discussion

6.1. Discussion on Crossing Willingness

As described in Section 5.1, in the crossing-permitted condition, the Distributed eHMI showed significant differences compared with all methods except the Aggregated eHMI, and it produced higher crossing willingness at an early stage after the vehicles began decelerating. This result can be attributed to the fact that lane-specific eHMIs were displayed for each pedestrian, allowing pedestrians to easily judge the intentions of all vehicles. The Aggregated eHMI also showed a significant difference compared with No eHMI, as indicated in **Table 2**. In addition, **Figure 5** shows that crossing willingness increased at an early stage; however, no improvement was observed during the period when the remaining time to arrival decreased from 5 s to 2 s. This is because pedestrians could not determine that the crossing-permission information from all vehicles was aggregated into a single eHMI, and therefore, they could not understand the intentions of vehicles in lanes where no eHMI was displayed.

In contrast, the No eHMI resulted in the lowest crossing willingness. This is because participants found it difficult to determine the vehicle's stopping position based solely on vehicle speed information. As shown in **Table 2**, the VA eHMI exhibited a significant difference compared with No eHMI, and **Figure 5** indicates that crossing willingness for the VA eHMI increased sharply from approximately 2.5 s before the vehicle reached the participant. This can be explained by the design in which the eHMI was displayed only to the pedestrian closest to the vehicle. After the vehicle passed the first pedestrian, it began displaying the eHMI to the participant, allowing the participant to recognize that the message was directed toward them.

No significant differences were observed between the AT eHMI and No eHMI, or between the GS eHMI and No eHMI. A possible reason is that these two methods made it difficult for participants to interpret the vehicle's intention intuitively. For the AT eHMI, some participants commented that it was unclear whether the displayed time indicated the time until the vehicle stopped or the remaining time during which crossing was allowed. For the GS eHMI, individual differences were observed in perceived clarity. While some participants felt that the stopping position could be understood visually, others interpreted the animated arrow motion as indicating that the vehicle intended to proceed without stopping.

When the vehicle did not yield to the participant, no significant differences were observed among the methods. According to **Table 3**, for understanding the intended recipient in the questionnaire evaluation, the Distributed eHMI showed significant differences compared with all methods except the Aggregated eHMI, and for clarity of the stopping target, it showed significant differences compared with all methods. These results suggest that, under the Distributed eHMI, participants refrained from crossing because they correctly judged that they could not cross, whereas under other methods, participants refrained from crossing because the vehicle behavior and intention were difficult to interpret.

6.2. Discussion on Questionnaire Evaluation

As described in Section 5.2, for willingness to use, the Distributed eHMI and the Aggregated eHMI achieved the highest median scores, while for the other questionnaire items, the Distributed eHMI achieved the highest median score. In addition, the Distributed eHMI achieved the highest mean scores across all items, and it showed significant differences in many comparisons with other methods. This can be attributed to the lane-specific eHMIs displayed in association with each pedestrian's position, which made it easier for pedestrians to understand which intention each vehicle had toward whom. On the other hand, some participants reported that it was difficult to determine how they should behave when different eHMIs were displayed for different lanes, and multiple free-form responses indicated that the Aggregated eHMI was preferable.

For the VA eHMI and the AT eHMI, because the eHMIs were displayed on the vehicles, participants had to pay attention to vehicles on both the left and right sides when making crossing decisions. Furthermore, they also needed to determine whether the displayed message was directed at them, which likely resulted in lower scores compared with the Distributed eHMI. In addition, in the comparison between the Distributed eHMI and the GS eHMI for willingness to use, no significant difference was observed. This supports the idea that road projection is an intuitive and easy-to-understand method for presenting vehicle intentions.

Overall, these results confirm that, in complex environments where multiple automated vehicles and pedestrians coexist, clearly conveying which intention each vehicle has toward which pedestrian is important for improving both safety and perceived comfort.

7. Conclusions

In recent years, the development of automated vehicles has progressed, and it is expected to reduce human errors that contribute to traffic accidents. However, in automated vehicles without a human driver, pedestrians may have difficulty interpreting the vehicle's driving intentions, making it challenging to make safe crossing decisions. To address this issue, external Human-Machine Interfaces (eHMIs) have been proposed to present vehicle intentions to pedestrians. Nevertheless, most previous studies have assumed one-to-one interactions between a vehicle and a pedestrian. In complex traffic environments where multiple vehicles and multiple pedestrians coexist, ambiguity regarding the intended recipient and an increase in information load may lead to misunderstandings and delayed decision-making.

To improve pedestrian safety and perceived comfort in such complex environments, this study proposed two eHMI presentation methods. The first is the Aggregated eHMI, which integrates crossing-permission information from all vehicles and presents a single eHMI for each pedestrian. The second is the Distributed eHMI, which integrates information on a per-lane basis and presents lane-specific eHMIs to pedestrians. We conducted experiments in a VR environment to compare the proposed methods with a baseline condition without eHMI and multiple comparison methods based on related work. Crossing willingness was evaluated with 15 participants, and a questionnaire was conducted to assess perceived safety, willingness to use, understanding of the intended recipient, and clarity of the stopping target.

The results showed that, in crossing-permitted situations, the Distributed eHMI most strongly increased crossing willingness and exhibited statistically significant differences compared with all methods except the Aggregated eHMI. In the questionnaire evaluation, the Distributed eHMI achieved the highest mean scores across all items and showed significant differences compared with many of the other methods. These results confirm that, in complex environments involving multiple vehicles and multiple pedestrians, clearly conveying which intention each vehicle has toward each pedestrian is important for improving both safety and perceived comfort.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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