Pedestrian Carelessness toward Traffic Environment Due to External Human–Machine Interfaces of Automated Vehicles

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***Abstract*—To determine whether external human–machine interfaces (eHMIs) make pedestrians careless toward the traffic environment, we examined the following four hypotheses: H1, the pedestrian decides to cross earlier after seeing a yielding message on an eHMI; H2, the pedestrian perceives safety after seeing a yielding message on an eHMI; H3, the pedestrian's confirming behavior before crossing is suppressed after the pedestrian sees a yielding message on an eHMI; H4, miscommunication between pedestrians and automatic vehicles can be caused by yielding messages on an eHMI.**

***Index Terms*—Automated Vehicle (AV), external human–machine interface (eHMI), road safety, pedestrians, vulnerable road users**

I. Introduction

The design of communication between automated vehicles (AVs) and other road users is important for implementing AVs in the current traffic environment. In conventional vehicles, drivers communicate with other road users through eye contact, gestures, and voice to assess who has priority at intersections and in shared spaces [1]. AVs must be able to communicate with other road users without the eye contact, gestures, or voice of the driver. Moreover, the safety of other road users [2] and traffic efficiency [3] must be ensured after the introduction of AVs into the traffic environment.

The behavior of AVs and the external human–machine interface (eHMI) has been discussed as a communication solution without driver action (e.g., eye contact, gesture, or voice). Previous studies have examined the effects of the behavior of AVs and eHMIs on the emotions and behaviors of road users. Dey *et al*. [4] conducted a video-based study indicating that vehicle behavior (i.e., the vehicle speed) was the predominant factor influencing pedestrian road-crossing decisions, rather than the appearance of vehicles (ordinal or futuristic appearance) and the driving mode (manual or automated). Several studies have revealed that vehicle behavior is an important cue for pedestrian decisions [5]-[7]. In some studies, several types of eHMIs (light, beep, and text-based messages) that present status information (such as running, stopping, and turning) and the yielding intention of AVs were examined. The researchers investigated the effects of the eHMIs on the decisions (e.g., pedestrian deciding to cross a crosswalk earlier) and perceived safety (e.g., pedestrian perceives a high level of safety) of road users [8]-[10]. Moreover, several studies have suggested the importance of eHMIs for efficient and safe traffic environments [10], [11].

As mentioned above, most previous research has focused on positive aspects (e.g., earlier crossing decision and higher perceived safety) of the vehicle behavior (i.e., the vehicle speed) and the eHMIs of AVs. However, some studies focused on the negative aspects of eHMI. Kaleefathullah *et al*. [12] focused on pedestrian misuse of the eHMI caused by repeated exposure to the eHMI. They reported that explicit communication (message of eHMI) made pedestrians ignore implicit communication (behavior of AV). Similar results were obtained in a study conducted by Holländer *et al*. [13], who reported pedestrians' overtrust in eHMI. Moreover, Wang et al. [14] indicated that some eHMI designs may result in traffic inefficiency because road users are confused and need time to confirm the information provided by the eHMI.

Negative aspects of eHMIs have been examined, as mentioned previously; however, few studies have focused on whether eHMIs make road users careless in the traffic environment. It is possible that eHMI causes road users to behave carelessly, because collisions sometimes occur as a result of yielding behavior [15]-[17]. A right-turn accident (vehicles drive on the left side of the road in Japan) is a typical case (Fig. 1). Here, two vehicles face each other across an intersection. One vehicle (vehicle A) exhibits yielding behavior by flashing its headlights, and the other vehicle (vehicle B) starts turning right at the intersection. A motorcycle then moves from the side of the vehicle that exhibited the yielding behavior. The

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turning vehicle (vehicle B) does not pay sufficient attention to the traffic environment and collides with the motorcycle. In this case, the yielding behavior causes the collision. Right-turn accidents account for the third-highest mortality rate in Japan, following head-on collisions and overtaking accidents [18], and this type of accident also occurs frequently internationally [19]. Approximately 10% of right-turn accidents are caused by a failure to yield, as in the case of Fig. 1 [15]. Research indicates that yielding by a conventional vehicle can cause a risk of collision between pedestrians and other non-yielding vehicles [16], [17].

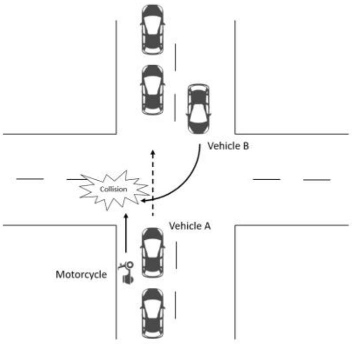

Figure 1. Example of a right-turn accident. Vehicle A yields to Vehicle B at the intersection. Vehicle B turns right without careful attention to the environment and collides with a motorcycle coming from behind Vehicle A.

The present study focuses on communication between AVs and pedestrians, because pedestrian safety is prioritized over the safety of other road users [4], [10]. Therefore, to determine whether eHMIs make pedestrians careless in the traffic environment, we examine the following four hypotheses (H1–H4).

- H1: the pedestrian decides to cross earlier after seeing a yielding message on an eHMI.
- H2: the pedestrian perceives safety after seeing a yielding message on an eHMI.
- H3: the pedestrian's confirming behavior before crossing is suppressed after the pedestrian sees a yielding message on an eHMI.
- H4: miscommunication between pedestrians and AVs can be caused by yielding messages on an eHMI.

II. Method

To examine the hypotheses, we conducted a virtual reality (VR) experiment. In the experiment, participants could cross a virtual crosswalk, and we examined their crossing behavior in various scenarios. In each experiment, the participants decided to cross the crosswalk while the AV and conventional vehicle approached from the right- and left-hand directions.

A. *Study Areas*

The experiment was conducted at a laboratory at Keio University. The experiment environment was developed by Unity, SteamVR, and Vive Pro (Fig. 2). In the environment, a pedestrian stands at a crosswalk with no signal on a double-lane road.

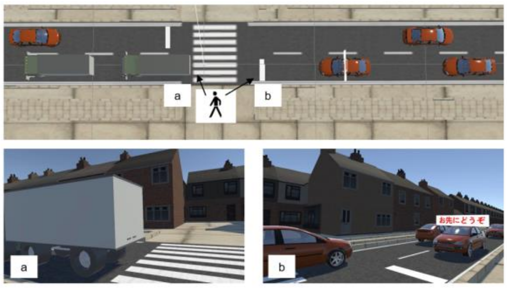

Figure 2. Virtual environment used in the VR experiment.

B. *AVs' Behaviors and eHMI Displays*

The AV approached at 15 km/h and decelerated 10 m from the center of the crosswalk, finally stopping 4.5 m from the center of the crosswalk, in front of the stop line (Fig. 3). Three different messages (with the same AV behavior) were displayed on the eHMI: "I will stop," "After you," and "In automated mode," as shown in Fig. 4. The message "I will go" was displayed in the fourth trial (Table I), but we did not use this trial in the analysis. These messages were shown 10 m from each participant. We examined four scenarios: no eHMI, "After you," "I will stop," and "In automated mode."

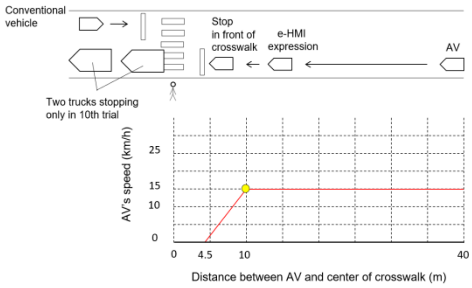

Figure 3. Behavior of the AV and the point where the eHMI displayed the message during the VR experiment. The red line shows the deceleration of the AV from a low speed (15 km/h-0 km/h). The yellow point shows where the eHMI message was displayed.

a. Message of "I will stop"

b. Message of "After you"

c. Message of "In automated mode"

Figure 4. Displays on the eHMI during the VR experiment.

C. *Participants*

We selected 40 participants ranging from 19 to 39 years old. In the experiment, each participant underwent 10 trials (i.e., the participant crossed the crosswalk 10 times). The first nine trials were for imprinting, and the tenth trial was used for analysis (Table I). The participants were grouped into four categories, depending on the eHMI display in the tenth trial (Table I and Table

II). The participants had to decide to cross at the crosswalk during congestion. The AV approached from the right-hand direction in the front lane, and the conventional vehicle approached from the left-hand direction in the back lane. During the tenth trial, it was difficult for the pedestrian to observe the conventional vehicle approaching from the left, because trucks approached from the right and stopped on the left side of the crosswalk, obscuring the motion of the conventional vehicle from the left side in the back lane. In each trial, participants were first instructed to wear a head-mounted display (HMD). Then, they stood at the crosswalk and crossed after confirming that it was safe to do so. The crossing behavior was controlled by pressing the button of the controller in each hand (the participant did not walk physically but walked virtually by pressing the button). After completing the trial, the participants were instructed to answer questions concerning their perceived safety, as experienced in the HMD. The next trial began after they answered the questions.

TABLE I. EXPERIMENTAL CONDITIONS FOR EACH TRIAL IN THE VR EXPERIMENT

Trial	Message displayed by eHMI	Behavior of conventional vehicle coming from left side
1	No eHMI	Stop in front of stop line
2	“In automated mode”	Stop in front of stop line
3	“After you”	Conventional vehicle was not present
4	“I will go”	Go through stop line
5	“I will stop”	Stop in front of stop line
6	“In automated mode”	Go through stop line
7	“After you”	Stop in front of stop line
8	“I will stop”	Stop in front of stop line
9	No eHMI	Stop in front of stop line
10	Group 1: “I will stop” Group 2: “After you” Group 3: “In automated mode” Group 4: No eHMI	Go through stop line

TABLE II. SAMPLE SIZE IN THE VR EXPERIMENT

Participant	Display of eHMI	Sample size	Mean age	Age range	SD
Group 1	“I will stop”	10	22.90	20–39	3.62
Group 2	“After you”	10	22.30	20–39	2.45
Group 3	“In automated mode”	10	22.90	19–33	5.75
Group 4	No eHMI	10	22.90	20–29	5.43

D. Procedure

In the experiment room, the researcher first explained the following to the participants: the aim of the experiment was to investigate the crossing decisions of pedestrians when they interact with an AV; in the situation presented, the AV was to come from the right side of the crosswalk in various traffic environments; AVs are not perfect; the participants should use the controller to cross when they can do so safely. Next, before the experiment, the researcher instructed the participants to walk across a crosswalk as usual and measured their walking speed. In this experiment, we conducted a between-subject study; thus, the participants completed 10 trials (Table I). At the beginning, the participants stood at the crosswalk and then looked at the AV on the right side before crossing. After each trial, the participants rated their perceived safety.

E. Analysis

First, we examined the distance between the pedestrian and the AV when the pedestrian decided to cross (H1: the pedestrian decides to cross earlier after seeing a yielding message on an eHMI). In this analysis, we measured the distance between the AV and the participant when the pedestrian made the crossing decision.

Second, we examined the pedestrians’ perceived safety (H2: the pedestrian perceives safety after seeing a yielding message on an eHMI). After each trial, the

participants rated their perceived safety by selecting one of five levels (Verbal Rating Scale): “Strongly agree with feeling safe,” “Agree with feeling safe,” “Slightly agree with feeling safe,” “Disagree with feeling safe,” and “Strongly disagree with feeling safe.”

Third, we examined the pedestrians’ confirming behavior before crossing (H3: the pedestrian’s confirming behavior before crossing is suppressed after the pedestrian sees a yielding message on an eHMI). We measured their focus time on the vehicles coming from the left (conventional vehicle).

Finally, we examined miscommunications between the pedestrians and AVs (H4: miscommunication between pedestrians and AVs can be caused by yielding messages on an eHMI). We focused on the frequency of miscommunications and collisions when the pedestrian crossed in specific situations (10th trial in Table II). Miscommunication was measured by observation of non-smooth crossing behavior (e.g., going back and forth at the crosswalk) and by reports of miscommunication in the post-trial interview. Collision between the participant and AV was measured by overlap of their locations (x and y coordinates) in the virtual environment.

We discussed the results with consideration of the reasons for the decisions reported by each participant in the post-trial interview.

III. RESULTS

A. Distance between Pedestrian and AV When Pedestrian Decides to Cross (H1)

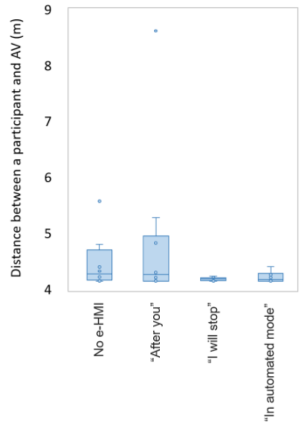

Figure 5. Crossing decision of participants during the VR experiment.

Fig. 5 shows the distance between a participant and the AV when the participant started crossing the crosswalk. The results indicated that none of the messages supported early crossing decisions (the Dwass–Steele–Critchlow–Fligner test) [20]. We used this nonparametric test because it can be applied to non-Gaussian distributed data and did not show significant differences between the no-eHMI and message conditions.

B. Pedestrians' Perceived Safety (H2)

Fig. 6 shows the perceived safety when participants decided to cross. Messages of "After you" enhanced the perceived safety (the Dwass–Steele–Critchlow–Fligner test indicated significant differences between no eHMI and "After you" ($p < 0.1$)). However, the message of "In automated mode" did not enhance the perceived safety (the Dwass–Steele–Critchlow–Fligner test did not indicate significant differences between no eHMI and "In automated mode").

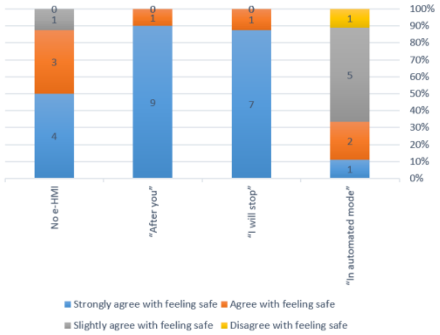

Figure 6. Perceived safety when participants decided to cross. The perceived safety was classified as "Strongly agree with feeling safe," "Agree with feeling safe," "Slightly agree with feeling safe," or "Disagree with feeling safe." "Strongly disagree with feeling safe" is not shown, because no participants responded in this manner.

C. Pedestrian Confirmation Behavior before Crossing (H3)

Fig. 7 shows the focus time of the participants on the conventional vehicle approaching from the left-hand direction in the VR experiment. The focus time was not influenced by the eHMI (the Dwass–Steele–Critchlow–Fligner test did not indicate significant differences between the cases with an eHMI (messages of "After you," "I will stop," and "In automated mode") and those without).

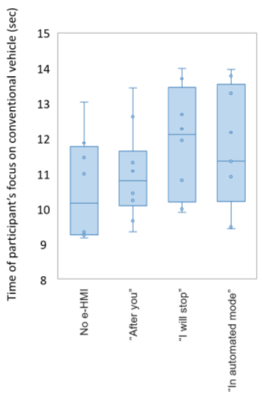

Figure 7. Focus time of participants for the conventional vehicle approaching from the left during the VR experiment.

D. Miscommunication between Pedestrians and AVs (H4)

Fig. 8 shows the miscommunication between the pedestrian and the AV in VR experiments. Messages of "After you" and "I will stop" on the eHMI caused four cases of miscommunication. For the "After you" message, the participants reported in the interviews that they expected the conventional vehicle from the left-hand direction to recognize the eHMI message of the AV and therefore to stop in front of the stop line. However, the conventional vehicle did not stop (in three cases, the participants miscommunicated with the AV, and in one case, the participant collided with the conventional vehicle from the left side). For the "I will stop" message, the participants reported that they expected the conventional vehicle from the left-hand direction to decelerate and stop in front of the stop line. However, the conventional vehicle did not stop (in one case, the participant misunderstood the behavior of the conventional vehicle coming from the left side).

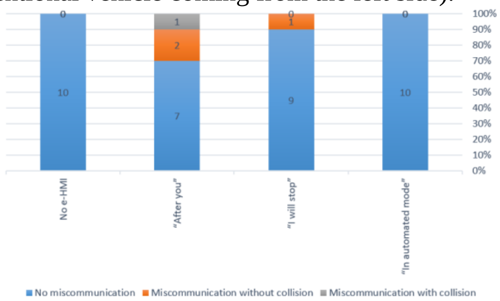

Figure 8. Crossing decision of participants during the VR experiment.

IV. Discussion

To determine whether the eHMI made the pedestrians careless in the traffic environment, we examined four hypotheses (H1–H4). Two hypotheses (H2 and H4) were confirmed as expected, depending on the messages displayed on the eHMI.

When the eHMI displayed messages regarding the behavior of the AV ("I will stop") and yielding ("After you"), the pedestrians reported high perceived safety (Figs. 6). However, the message caused miscommunication between the pedestrian and the AV (Fig. 8). This is because the pedestrians felt safety owing to the vehicle yielding, suppressing their confirmation behavior. This miscommunication after yielding was observed in previous studies [16], [17]. A possible explanation is that the negative influence of the eHMI was caused by differences between the actions of traditional drivers (eye contact, gesture, and voice) and the eHMI. Generally, pedestrians decide to cross on the basis of cues from the driver of the vehicle, for example, eye contact and gestures [21], [22]. In most cases, drivers yield to pedestrians in safe traffic environments and do not yield in dangerous traffic environments. Pedestrians know that drivers communicate yielding after briefly confirming traffic safety. However, in the present experiment, the eHMI allowed yielding without confirmation of the safety of the traffic environment. This difference may cause confusion among pedestrians. Post-experiment interviews revealed that some participants who were confused and collided with the AV during the VR experiment thought the AV yielded after confirming the safety of the traffic environment (indicative of the pedestrian overtrusting the eHMI). This miscommunication suppressed the behaviors for checking the traffic environment. This result is relevant to previous research indicating that excessive information on an eHMI causes inefficient traffic [14]. Therefore, to reduce confusion, we must investigate the possibility of combining eHMIs and detection systems (camera and sensor) of other road users (e.g., pedestrians and vehicles). The detection system would allow the AV to display yielding message on the eHMI after confirming safety. To complement this system, education is important. The government must provide basic knowledge regarding the differences between conventional vehicles and AVs as well as the functions of AVs.

Conversely, when the eHMI did not display messages regarding the behavior of the AV and yielding ("In automated mode"), pedestrians reported lower perceived safety (Figs. 6). In previous studies, informing the participants of the driving mode (manual or automated driving) did not influence pedestrian decisions [4], [22], and direct instructions were preferred by pedestrians [8].

Although previous research indicated that eHMI made pedestrians cross earlier, Fig. 5 and 7 did not show significant differences in the distance of the AV with and without an eHMI when the pedestrian started crossing, and we could not examine H1 and H3. This may be because the AV started moving 15 m from the center of the crosswalk and displayed the eHMI at 10 m from the center of the crosswalk; thus, the participants did not have sufficient time for judgment, and we could not record diverse distances between the AV and participants, and focusing time in this trial. According to the foregoing discussion, eHMIs should be developed on the basis of their role in communication. As several studies have indicated, the most important vehicle cues for a pedestrian's decision are vehicle behaviors [4], [6], [22]. In most cases, pedestrians can communicate with vehicles without signals from the driver, e.g., at nighttime when the driver cannot be seen. In a previous AV test-track experiment (similar environment to the one used in this study), we did not observe miscommunication between pedestrians and the AV. Furthermore, the eHMI had no significant effects on the crossing decision. Therefore, if the behavior of the AV is apparent, the decision of the pedestrians mainly depends on the behavior of the AV (implicit communication). When developing eHMIs, car manufacturers must replace the actions of the driver (eye contact, gesture, and voice) and provide information that cannot be obtained from the behavior of the AV. Additionally, the eHMI message (explicit communication) must not disrupt information obtained from the behavior of the AV (implicit communication), as indicated by previous research [12], [13].

This study had several limitations. The behavior of the AV was only one case; therefore, we could not examine the influence of the behavior on the decisions of the pedestrians in detail. Additionally, the participants used virtual controllers to cross the road; they did not walk in the experiment. We selected participants with consideration of their age, because of important determinants of cognition [23]; however, other factors must be considered, such as gender and eyesight. The vehicle types were the same; therefore, we could not examine the influence of the appearance of the vehicle [4], [11]. Moreover, this study focused on the crossing behavior of pedestrians; therefore, the effects of other behaviors (avoidance and overtaking) and road users (drivers and cyclists) are unclear. Cultural differences in priority between pedestrians and vehicles influence the decisions made by pedestrians [10], [24]; however, we only conducted this study in Japan, where the pedestrian priority is comparatively low. Thus, it is important to examine the negative aspects of eHMIs in other countries. Further research needs to be conducted to examine the aforementioned limitations.

V. Conclusion

The objective of this study was to determine whether eHMIs make pedestrians careless in traffic environments through test-track and VR experiments. The results indicated that the messages displayed by an eHMI regarding the behavior of the AV ("I will stop") and yielding ("After you") can make pedestrians careless and cause miscommunication between pedestrians and AVs, although these messages were associated with high perceived safety.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Tasuru Daimon designed and conducted the experiment; Tasuru Daimon and Masahiro Taima analyzed the data; Masahiro Taima wrote the paper; all authors approved the final version.

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