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eHMI on the Vehicle or on the Infrastructure? A Driving Simulator Study

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Abstract

Automated vehicles (AVs) may require the implementation of an external human-machine interface (eHMI) to communicate their intentions to human-driven vehicles. The optimal placement of the eHMI, either on the AV itself or as part of the road infrastructure, remains undetermined. The current driving simulator study investigated the effect of eHMI positioning on human driving behaviour, during the approach and execution of right turns at T-intersections. Forty-three participants drove under three conditions: absence of eHMI, eHMI on the AV (eHMIv), and eHMI integrated into the infrastructure (eHMIi). Participants encountered AVs that either yielded or did not yield to their vehicles. The results regarding the placement of the eHMI showed that both concepts are advantageous, but for different reasons. eHMIv was appreciated because implicit and explicit communication are congruent, although the AV must first be visually identified to respond to it. eHMIi was appreciated because a familiar cue is always at a known location in the environment; as a result, participants braked earlier for the intersection and came less close to the AV (which can be interpreted as a safety advantage or an efficiency disadvantage). Although there are limitations to the current driving simulator study, this research provides important insights into the fundamental question of how information placement affects drivers' visual attention demands and driving behaviour, topics that are important in view of the development of future cities.

1 Introduction

As automated vehicle (AV) technology progresses, it raises the question of how to design future traffic systems. During their initial deployment, AVs will coexist with human-driven vehicles (HDVs), potentially leading to communication and coordination challenges.

Researchers have suggested vehicle-to-vehicle communication to improve manoeuvre coordination among (semi-)automated vehicles (e.g., Bulumulle and Bölöni, 2016; Colley et al., 2022b; Zimmermann et al., 2018). Another approach involves improving the artificial intelligence of AVs to better anticipate HDV behaviour (Ohn-Bar and Trivedi, 2016; Rudenko et al., 2020, for literature surveys) or to improve the social interaction behaviour of AVs (for models, see e.g., Crosata et al., 2023; Schwarting et al., 2019; Taghavifar et al., 2024). The focus of the current study is an alternative solution involving visible lighting in the form of external human-machine interfaces (eHMIs) that communicate the intentions of AVs to HDVs. This research seeks to determine whether eHMIs should be situated on the AV or on the road infrastructure.

A large number of studies have previously investigated the effectiveness of eHMIs. Many of these have demonstrated the usefulness of eHMIs in clarifying the intentions of AVs when interacting with pedestrians (e.g., Bindschädel et al., 2021; Deb et al., 2018; De Clercq et al., 2019; Dey et al., 2020, 2022; Ferenchak and Shafique, 2022; Othersen et al., 2018). Nevertheless, the literature remains divided on the need for eHMIs (De Winter and Dodou, 2022; Dey and Terken, 2017; Lee et al., 2021).

While eHMIs have been examined for interactions between AVs and pedestrians (Bazilinskyy et al., 2019; Dey et al., 2020, for reviews), only a limited number of studies have examined eHMIs in AV-HDV interactions. Driving simulator research by Rettenmaier et al. (2019, 2020) found that eHMIs on the AV positively influenced driver acceptance and resulted in fewer accidents and reduced passing times in narrow road sections compared to the absence of an eHMI. Similarly, a simulator study by Avsar et al. (2021) found that eHMIs improved human drivers' perceived safety and trust. Mirnig et al. (2021) tested eHMIs on shuttles in real traffic and found that the impact on drivers was less pronounced than anticipated, with the shuttle's implicit communication (position, speed) likely playing a dominant role. Lastly, a test track experiment by Papakostopoulos et al. (2021) demonstrated that an eHMI on the AV aided manual vehicle drivers in making decisions more rapidly in intersection scenarios compared to the absence of an eHMI. These studies assessed eHMIs placed on the AV; however, the comparison between eHMIs on the AV and those on the road infrastructure remains relatively unexplored.

There has been limited research focusing on infrastructure-based eHMIs. In a review of 70 eHMI concepts, Dey et al. (2020) documented that most (51) concepts were situated on the vehicle, with 5 projected on the road, 3 carried by vulnerable road users, a single one placed exclusively on road infrastructure, and 10 featuring a combination of the aforementioned. Mahadevan et al. (2018) demonstrated a prototype LED-light eHMI designed for presentation on street infrastructure, in conjunction with an eHMI on the vehicle and another carried by the pedestrian. Participants indicated a preference for the combined presentation of signals, although a comparison of the different locations was not conducted. In a virtual reality study, Von Sawitzky et al. (2020) assessed a smart bicycle path that signalled whether a gap permitted safe crossing, and found that this eHMI received higher ratings of information quantity and quality than a baseline without eHMI. Umbrellium (2017) presented a prototype that interacted with road users by displaying messages on the road surface. Drawing inspiration from this, Löcken et al. (2019) tested a smart road eHMI, featuring a bright zebra crossing when crossing was safe and red icons when it was not. Their evaluation in virtual reality showed that the smart road resulted in faster crossing times and increased acceptance ratings compared to five other eHMI concepts, including those on the vehicle. However, definitive conclusions regarding eHMI placement remain elusive, as the vehicle-mounted eHMIs differed in brightness, colours, and symbols compared to the smart road.

Whether an eHMI is placed on the vehicle or the road infrastructure may influence a driver's expectations and attentional requirements in different ways. eHMIs on the infrastructure might match the drivers' expectations, similar to traditional traffic lights. However, a potential drawback is the increased attentional demands, as drivers must divide their attention between the eHMI and the AV. An eye-tracking study using animated video clips by Eisma et al. (2020) found that attention was divided between the AV and an eHMI message projected on the road. Similarly, Lee (2021; cited in Tabone et al., 2021) argued that with infrastructure-based eHMIs ('detached eHMIs'), there is a mental burden of mapping the eHMI to the object it refers to.

eHMIs on the AV may possess certain advantages. Manually controlled vehicles already emit signals through brake lights and turn indicators (e.g., Norman, 2014), and in line with this, eHMIs on the AV might be more intuitive for drivers, as vehicle motion (implicit communication) and the eHMI signal (explicit communication) coincide. However, a potential disadvantage of an eHMI on the AV is the need for visual search: identifying the moving AV may require time and effort. Moreover, drivers may overlook the AV or be unable to identify it if it is obscured by structures such as buildings. In contrast, infrastructure eHMIs can be positioned within the driver's forward view. In summary, there are arguments for and against eHMIs on the AV and on the infrastructure.

1.1 Study aim

The aim of this study was to examine the effect of eHMI positioning on the driving performance and subjective experience of human drivers during interactions with AVs at T-intersections. A driving simulator study was conducted in which participants were exposed to three conditions: eHMI situated on the AV (eHMIv), eHMI positioned on the road infrastructure (eHMIi), and a baseline condition without eHMI. The focus was on safety-related performance, which encompassed measures such as decelerating and avoiding hazardous crossings in front of non-yielding AVs.

Métayer and Coeugnet (2021) indicated the importance of assessing eHMIs using both subjective and objective measures. The current research used various subjective indicators, including emotional experience (Habibovic et al., 2018; Lau et al., 2021; Wilbrink et al., 2021), workload (e.g., Gruenefeld et al., 2019; Tran et al., 2022), perceived safety/criticality of the interaction (e.g., Colley et al., 2022a; Habibovic et al., 2018; Hensch et al., 2019), as well as trust (e.g., Faas et al., 2021; Hensch et al., 2019; Kaleefathullah et al., 2022), and acceptance (Faas et al., 2020; Mok et al., 2022; Rettenmaier et al., 2020). To gather more insights from participants, semi-structured interviews were conducted, in addition to the objective measures and questionnaires.

2 Methods

2.1 Independent variables

This within-subject study design incorporated two independent variables:

- *eHMI placement*, consisting of three levels: (1) no eHMI (Baseline), (2) eHMI on the vehicle (eHMIv), and (3) eHMI on the infrastructure (eHMIi). Each condition was provided as a distinct drive in the simulator, in a randomized order. This meant that the three conditions were presented to the participants in six possible order combinations. Consequently, the three different conditions (Baseline, eHMIv, eHMIi) were approximately equally likely to occur as the first, second, or third drive.
- *The AV's yielding behaviour*, with two levels: non-yielding (5 intersections per drive) and yielding (5 intersections per drive). In the non-yielding trials, the AV maintained speed. If the participant drove assertively, they could still cross in front of the AV. In the yielding trials, the AV decelerated but did not come to a complete halt. The AV's yielding behaviour was randomized across intersections but maintained the same order for all participants. Details on the speeds of non-yielding vehicles are available in the Supplementary Material.

Based on an online study that presented images of approaching AVs with different coloured bars on the front bumper (Bazilinskyy et al., 2020), the eHMIs were purple to signify that the AV would not yield, and green to indicate that the AV was yielding. Red was not used, as this colour has been considered confusing on a moving vehicle (Bazilinskyy et al., 2020; Dey et al., 2020) and may be perceived as a mandatory rather than an advisory signal.

2.2 *eHMI on the vehicle (eHMIv)*

The eHMIv conveyed the AV's intention through a cube placed on its roof (see Figures 1 and 2). The cube's design allowed targeting individual road users. Specifically, when the AV indicated non-yielding toward HDVs on its right side, the eHMI emitted a purple light on its right and front surfaces, which were visible to the HDV. The other two surfaces displayed a grey light to avoid inadvertently informing road users for whom the message was not intended. The eHMIv revealed the intention of the AV when the AV appeared, which occurred when the HDV had a distance of 70 m from the intersection. The eHMIv displayed the same colour on its right-front faces until it switched off (i.e., transitioning from purple/green to grey) after the AV exited the intersection. Note that the current study did not examine the effect of targeting other road users; participants only viewed the right-front surfaces of the eHMIv, and the back and left surfaces were never activated.

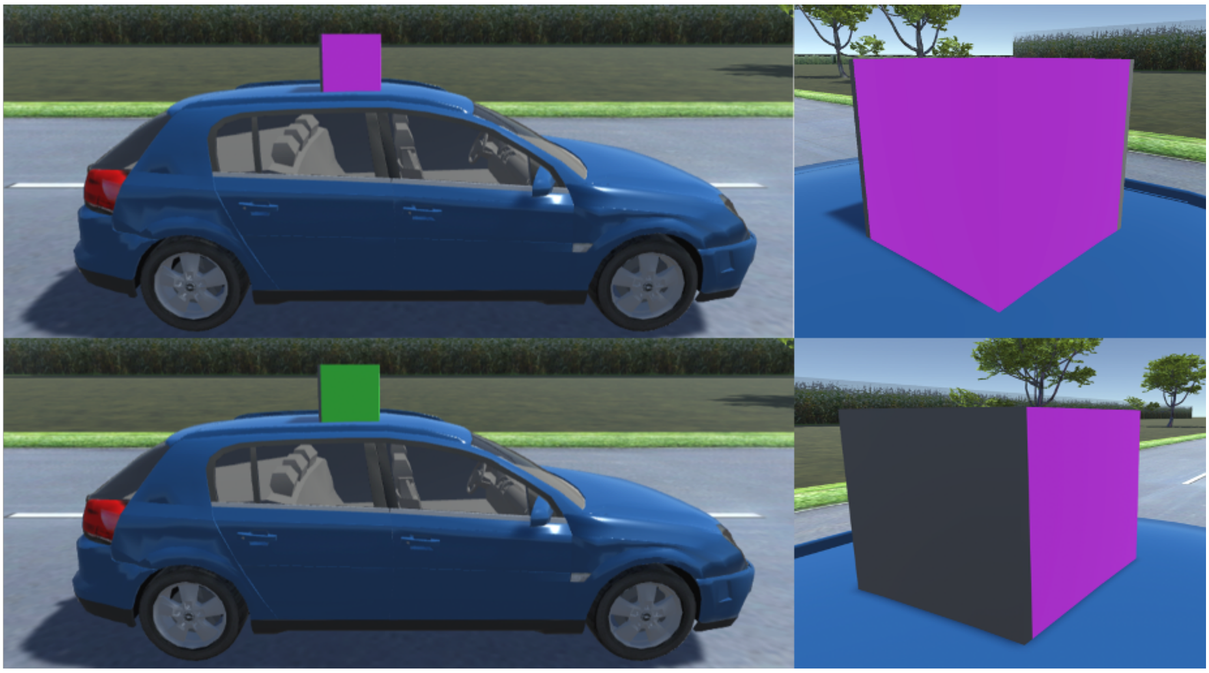

Figure 1. Left top: eHMIv in non-yielding state, Left bottom: eHMIv in yielding state, Right top: Right and front surfaces of eHMIv (i.e., the surfaces visible from the participant's perspective). Right bottom: Right and back surfaces of eHMIv (the back surface could not be seen from the participant's perspective).

2.3 *eHMI on the infrastructure (eHMIi)*

The eHMIi concept also conveyed the AV's intent at the intersection in the form of a light display (Figure 3). It resembled regular traffic lights to maintain familiarity with current traffic, and it used the same colours and onset timing as eHMIv. The eHMIi was triggered from a pre-existing green or purple colour to the designated colour when the HDV reached a distance of 70 m from the intersection. eHMIi did not switch off as the AV passed but remained the same, to avoid that the colour switching would affect the behaviour of the participants.

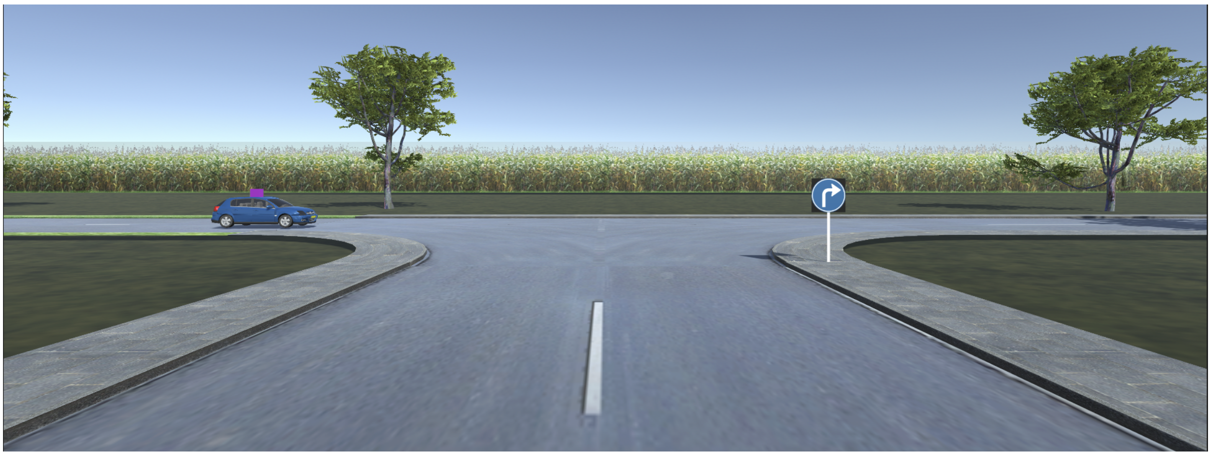

Figure 2. eHMIv in non-yielding state.

Figure 3. eHMI, in non-yielding (top) and yielding (bottom) state. The eHMIi was placed at 6 m from the start of the intersection.

2.4 Driving simulator

The participants drove in a fixed-base driving simulator (Figure 4). It featured three ultra-HD screens providing approximately a 180° field of view. The simulator was equipped with a Fanatec steering wheel, gas pedal, and brake pedal, with automatic gear changing. The simulator vehicle had a mass of 1600 kg. The dashboard, side mirrors, and rear-view mirrors were integrated into the virtual image. The experiment was developed using Unity 3D. The simulator recorded vehicle-related data at a frequency of 50 Hz.

Figure 4. Participant operating the driving simulator.

2.5 Driving route

All participants drove the same 8-km distributor road, consisting of straight road segments and 14 T-intersections. Participants made a right turn at ten of the T-intersections and a left turn at the remaining four. When turning right, participants interacted with an AV approaching from the left (Figure 5).

The left turns, which involved no AVs or other traffic, were included to reduce monotony for the participant. The road segments had different lengths (e.g., 1500 m or 500 m) to minimize predictability for participants. Furthermore, traffic was generated in the opposite lane of the AV for the 10 right-turn scenarios.

The lane width was 5 m and the distance between the centre of the intersection and the point where the HDV entered the intersection was 15 m. 80 km/h speed limit signs were placed adjacent to the road, 450 m from the intersection. Additionally, 50 km/h advisory speed signs were situated 140 m from the intersection.

In the Netherlands, for safety, a 70-m minimum clear-sight distance near intersections is recommended for roads with a 50 km/h speed limit (CROW, 2012). When the participant reached 70 m from the intersection, the approaching AV, previously hidden by a building or vegetation, became visible 70 m from the intersection (Figure 5).

2.6 Dependent variables

The dependent variables included measures from questionnaires and interviews, and measures from the simulator.

Subjective measures

Questionnaires were administered to assess trust, perceived criticality, emotions, acceptance, and workload following each drive. Participants completed the following questionnaires, designed in Qualtrics, on a tablet after each condition:

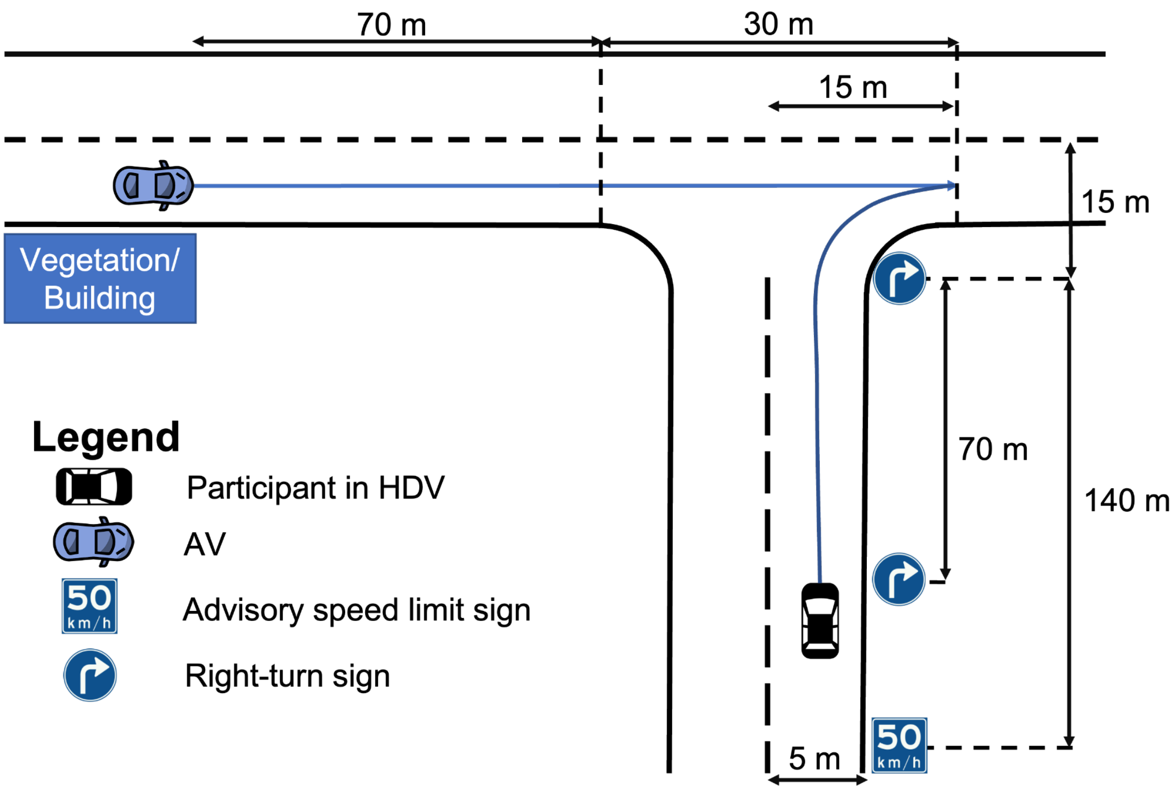

Figure 5. *Interaction between participant (human-driven vehicle; HDV) and automated vehicle (AV) at a T-intersection. When the HDV was 70 m from the intersection, the AV became visible, and the eHMI was activated.*

1. Participants' level of trust in the interacting vehicle was measured on a scale of 1 (not at all) to 10 (extremely) using a single-item question.
2. Participants' perception of the criticality of the interactions was measured on a scale of 1 to 10, where 1 to 3 represent 'harmless', 4 to 6 represent 'unpleasant', 7 to 9 represent 'dangerous', and 10 represents 'uncontrollable' (Neukum et al., 2008, as cited in Siebert et al., 2014; see also Tscharn et al., 2018).
3. Participants' feelings/emotions regarding the interacting vehicle were measured using Bradley and Lang's (1994) questionnaire. It captured three facets: pleasure, arousal, and dominance, on a scale ranging from 1 to 9.
4. Participants' acceptance of "the interaction system (i.e., communicating display (if any) + vehicle behaviour of driverless blue cars" was measured using a semantic differential questionnaire introduced by Van der Laan et al. (1997). It captured acceptance on two dimensions: usefulness (4 items) and satisfaction (3 items), on a five-point scale of -2 to +2. The items 'pleasant/unpleasant' and 'raising alertness/sleep-inducing' were not asked to avoid redundancy with the Bradley and Lang (1994) questionnaire, which already captured pleasure and arousal.
5. The NASA-Task Load Index (NASA-TLX) was used to assess participant workload (Hart and Staveland, 1988). Workload was measured on six dimensions: mental demand, physical demand, temporal demand, effort, and frustration, on a scale of 1 (low) to 10 (high), while performance was measured on a scale of 1 (good) to 10 (poor). The mean of the six items was calculated.

Furthermore, in an oral question after the experiment, participants were asked to rank their preference for the three eHMI conditions. Preferences were coded on a scale of 1 to 3, where 1 is the first-ranked preference and 3 the last-ranked preference.

Driving Behaviour Measures

Four driving behaviour measures were extracted from the simulator for each eHMI condition and participant (see Table 1). The first two pertain to the speed at which the participant approached the intersection, providing an indication of the eHMI's interpretability. The third and fourth reflect the safety of the interaction, with crossing in front of the non-yielding AV deemed hazardous.

Table 1. Driving behaviour measures and their calculation method

Behavioural measure	Unit	Definition
Time to enter the intersection	s	Elapsed time from the moment the AV was activated to when the HDV entered the intersection.
Time to speed < 30 km/h	s	Elapsed time from the first moment the AV was activated to when the HDV's speed was below 30 km/h. No value was computed if the HDV did not reduce speed to below 30 km/h before arriving at the intersection. 30 km/h signifies a substantial decrease in speed compared to the instructed approach speed of 50 km/h.
Crossing before the AV	0 or 1	Whether the HDV crossed before (coded as 1) or after (coded as 0) the AV. This variable was determined at the moment the HDV entered the intersection.
Close interaction	0 or 1	Whether the absolute value of the post-encroachment time (PET) was less than 2 s (coded as '1') or not (coded as '0') (Tang and Kuwahara, 2011). PET was defined as the duration from the moment the HDV entered the intersection to the moment the AV crossed the same HDV position. A negative PET indicates that the participant crossed after the AV, while a positive PET indicates the participant crossed before the AV.

Interviews

Semi-structured interviews were conducted after the experiment. Participants were asked to reflect on the eHMIs' usefulness in decision-making, their motivations behind their selected preferences, any perceived changes in their driving behaviour, any additional information required besides vehicle intention, and their overall experience with the experiment.

2.7 Participants

A total of 46 individuals, all holding a driver's license, participated. Three women were excluded. Two exhibited symptoms of simulator sickness, while the third requested exclusion. The remaining 43 participants (31 males, 12 females) had between 2 and 53 years of driving experience (M = 13.5; SD = 14.4). Participants had considerable experience with Advanced Driver Assistance Systems: 30 reported having driven with cruise control, 11 with adaptive cruise control, and 9 with lane-keeping assistance; none had driven with automated lane change systems. Ten participants had no experience with any of the aforementioned Advanced Driver Assistance Systems.

Of the 43 participants, 21% were over 45 years old, 49% were between 25 and 45 years old, and 30% were between 18 and 24 years old. In response to the query, "*What is your highest level of education? (include ongoing education)*", 2 participants indicated secondary education, 5 bachelor's education, 32 master's education, and 4 doctoral education. All participants provided written informed consent, and the study was approved by the Human Research Ethics Committee of TU Delft.

2.8 Procedure

Before the experiment, a questionnaire was used to collect information on the participants' characteristics. The participants were informed that the study aim was to understand the interactions between HDVs and AVs.

After providing written informed consent, participants received a briefing form. The form instructed them to follow the directional signals and drive to an office for an important meeting. The form stated that participants should remain aware of other traffic, drive responsibly, and adhere to traffic rules. It informed them that, at intersections, AVs would communicate their intentions through a display on top of the vehicle or a signalling device on the road. The colour purple would indicate an AV's intention to cross the intersection first at a speed of around 50 km/h, while green would represent its intention to slow down. Additionally, the briefing form depicted a screenshot of the eHMIv and of the eHMIi conditions. The form mentioned that these eHMIs indicated the vehicles' intent, and were not traffic rules. It clarified that participants were free to choose whether or not to comply with the AVs' intent. Participants were instructed to maintain a speed of approximately 50 km/h while approaching the intersection, marked by a right-turning sign at a distance of 70 m. Beyond this point, they were allowed to make independent driving decisions.

The experimenter also summarized the instructions, and indicated to the participant they had freedom to comply or not with the AV's intent. They were explicitly told that the eHMI lights were advisory, and that they were allowed to pass through the purple light without stopping.

Participants completed a 10-min practice drive to familiarize themselves. The practice session took place in a similar environment to the experiment, without eHMI. Participants then completed three experimental drives, one for each eHMI condition. After each drive, participants completed the questionnaire on a tablet.

Upon finishing the driving task, participants completed a 16-item Simulator Sickness Questionnaire (Bimberg et al., 2020; Kennedy et al., 1993), and a 19-item Presence Questionnaire (Witmer et al., 2005) (results included in the Supplementary Material). Participants were then interviewed and given a €10 gift voucher. The experiment duration, including questionnaires and interviews, was approximately 70 minutes, with optional 5-minute breaks after each drive.

2.9 *Analyses*

Out of 1290 trials (43 participants × 3 eHMI conditions × 10 interactions), one trial in the Baseline condition and one trial in the eHMIi condition were removed from the behavioural data due to erratic participant behavioir (collision with infrastructure and inappropriate deceleration, respectively). Consequently, 643 and 645 trials were available for non-yielding and yielding AVs, respectively. For the non-yielding AV trials, the 'time to speed < 30 km/h' measure was available for 534 of the 643 trials; in the remaining 109 trials, the participant did not reach a speed below 30 km/h.

The analysis was conducted solely on the non-yielding AV trials. Of the 645 yielding AV trials, participants let the AV to cross first in only 29, 6, and 5 trials for the Baseline, eHMIv, and eHMI conditions, respectively. Data exploration revealed that pre-programmed intersection-specific variations in AV approach speed affected the likelihood of participants crossing before the AV (i.e., the slower the AV approached, the more likely HDVs would cross first). Consequently, although the eHMIs appeared effective at encouraging participants to proceed, the AV-yielding trials were not considered usable for further analysis.

The four driver behaviour measures detailed in Table 1 were computed by averaging the five interactions with non-yielding AVs per participant per eHMI condition. For the two binary measures (Crossing before the AV, Close interaction), this became a percentage (i.e., 0%, 20%, 40%, 60%, 80%, or 100%). Pairwise comparisons were made among the three eHMI conditions using paired-samples *t*-tests. *t*-tests were used because they are known to be robust to mild deviations from normality, also for Likert item data (De Winter and Dodou, 2010). A Bonferroni correction was applied to account for multiple comparisons, and the result was considered significant for a *p*-value lower than $0.05/3 \approx 0.0167$.

A thematic analysis (Braun and Clarke, 2006) was performed of the transcribed interview data to obtain insights into the participants' preferences for the three different eHMI conditions. The thematic analysis was tailored towards understanding participants' experiences with the eHMIi and eHMIv conditions.

3 Results

3.1 Subjective measures

Table 2 presents the means, standard deviations, and pairwise comparisons among the three eHMI conditions. Out of 43 participants, 2 preferred no eHMI, 23 preferred eHMIv, and 18 preferred eHMIi. Participants perceived significantly lower criticality under the eHMIv condition compared to the Baseline. No significant differences were identified in perceived criticality scores between eHMIi and Baseline or between eHMIi and eHMIv.

Perceived trust, usefulness, satisfaction, and pleasure ratings were higher in the eHMI conditions than in the Baseline condition, but did not reveal statistically significant differences between eHMIi and eHMIv. Participants perceived a significantly lower workload in interactions involving eHMI compared to the Baseline. Furthermore, eHMIi resulted in a significantly lower arousal score than eHMIv. Pairwise comparisons did not reveal significant differences in dominance among the three eHMI conditions.

Table 2. Mean and standard deviations (*SD*) of the dependent variables, for each eHMI condition. 1: Baseline (no eHMI), 2: eHMIv, 3: eHMIi. Also reported are the *t*-statistic of pairwise comparisons at the level of participants (*n* = 43)

Variables	Unit	Mean			*SD*			Pairwise comparison		
		1	2	3	1	2	3	*t* (1 vs 2)	*t* (1 vs 3)	*t* (2 vs 3)
Subjective measures										
Preference rank[a]	1 to 3	2.74	1.59	1.66	0.54	0.67	0.66	7.35***	7.09***	-0.37
Perceived criticality	1 to 10	3.86	2.95	3.35	1.96	1.68	2.05	2.89**	1.36	-1.22
Trust	1 to 10	4.91	7.12	7.35	2.15	1.75	1.66	-5.43***	-6.36***	-0.66
Pleasure	1 to 9	4.95	6.49	6.53	1.84	1.49	1.37	-4.60***	-5.41***	-0.17
Arousal	1 to 9	5.14	4.26	3.67	1.81	1.16	1.55	3.39**	4.79***	2.60*
Dominance	1 to 9	4.95	5.09	5.26	1.90	2.06	2.11	-0.45	-1.04	-0.70
Usefulness	-2 to +2	-0.19	0.91	0.87	0.97	0.69	0.77	-6.94***	-6.71***	0.38
Satisfaction	-2 to +2	-0.12	1.02	1.02	1.04	0.78	0.80	6.98***	-6.67***	0.00
NASA-TLX workload	1 to 10	4.83	4.28	4.09	1.81	1.89	1.56	2.14	3.39**	0.70
Driving measures (non-yielding AVs)										
Time to enter the intersection	s	6.85	7.20	7.76	0.99	0.91	1.28	-2.71*	-5.80***	-3.83***
Time to speed < 30 km/h[b]	s	4.18	3.93	3.54	0.49	0.55	0.72	2.90**	6.24***	4.58***
Crossing before the AV	%	21.16	13.02	14.53	27.45	18.46	22.01	1.97	1.65	-0.50
Close interaction	%	56.98	60.00	42.91	36.42	36.25	35.54	-0.57	2.93**	3.97***

****p* < 0.001. ***p* < 0.01. **p* < 0.05/3.

[a] Out of 129 ranks coded (43 participants × 3 ranks), 18 ranks were implied from the entirety of the interview. For instance, some participants reported their favourite condition (e.g., eHMIv or eHMIi) but did not explicitly rank the conditions, yet it was still clear that Baseline was their least preferred condition.

[b] The number of trials for which this measure was available was 534 (Baseline: 170; eHMIv: 182; eHMIi: 182). The corresponding sample sizes used in the statistical tests were 42, 43, and 42 for the Baseline, eHMIv, and eHMIi conditions.

3.2 *Driving behaviour*

Figure 6 shows the mean approach speed for the three eHMI conditions, for non-yielding AVs. It is noteworthy that at the trigger moment, the mean approach speed was already lower for eHMIi and eHMIv than for the Baseline.

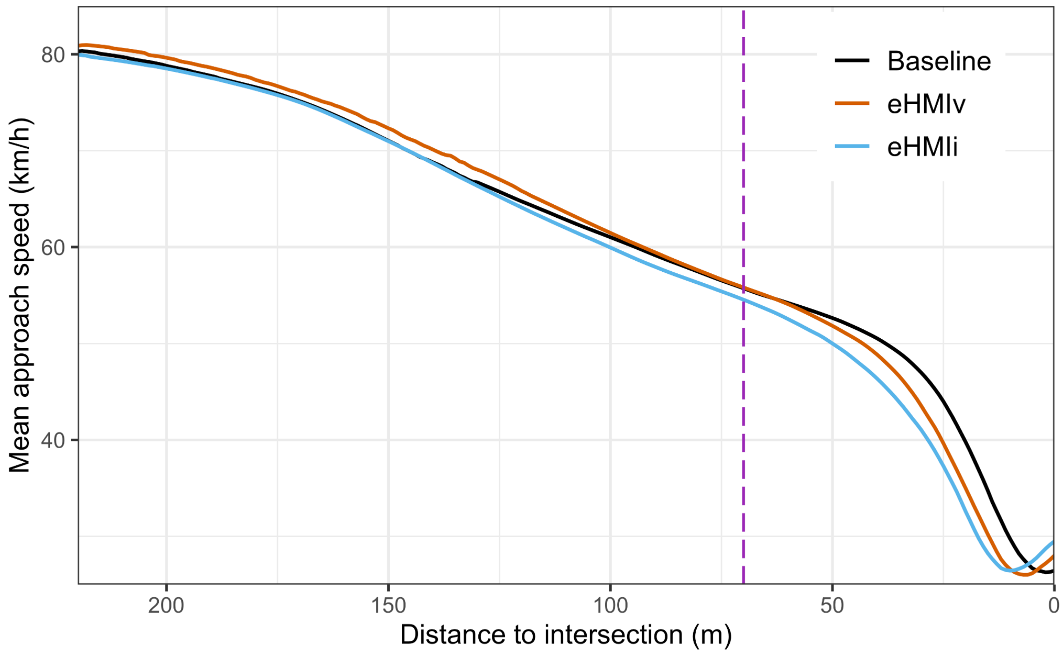

Figure 6. Mean approach speed when enring non-yielding AVs, for the three conditions. The vertical dashed line at 70 m is the moment the AV (with eHMI in the eHMIv condition) became visible, and when the eHMIi switched to the correct state.

Figure 7 depicts the HDVs' trajectories and events (first moment when the participant's speed fell below 30 km/h, and crossing behaviour) for the three experimental conditions. It can be seen that participants in the eHMIi condition slowed down earlier compared to the eHMIv and Baseline conditions.

Table 2 indicates that the time taken to reach the intersection was longer with eHMI compared to without eHMI. Moreover, participants took significantly more time to reach the intersection in the eHMIi condition compared to the eHMIv condition. The results also show that the time taken to slow down to a threshold speed of 30 km/h was shortest in the eHMIi condition, followed by the eHMIv condition and the Baseline condition.

Figure 8 provides the distribution of post-encroachment time (PET) values. Firstly, there are more positive PET values in the Baseline condition (n = 45), than in the eHMIv condition (n = 28) and eHMIi condition (n = 31), consistent with the 'crossing before the AV' measure shown in Table 2. Secondly, there are more values between -2 and 0 s for the Baseline condition (n = 79) and the eHMIv condition (n = 104) compared to the eHMIi condition (n = 64), indicating that in the former two conditions, the participant merged closely after the passing AV. This is consistent with Table 2, in which it is shown that the number of close interactions ($|PET| < 2$ s) was significantly lower for eHMIi compared to Baseline and eHMIv.

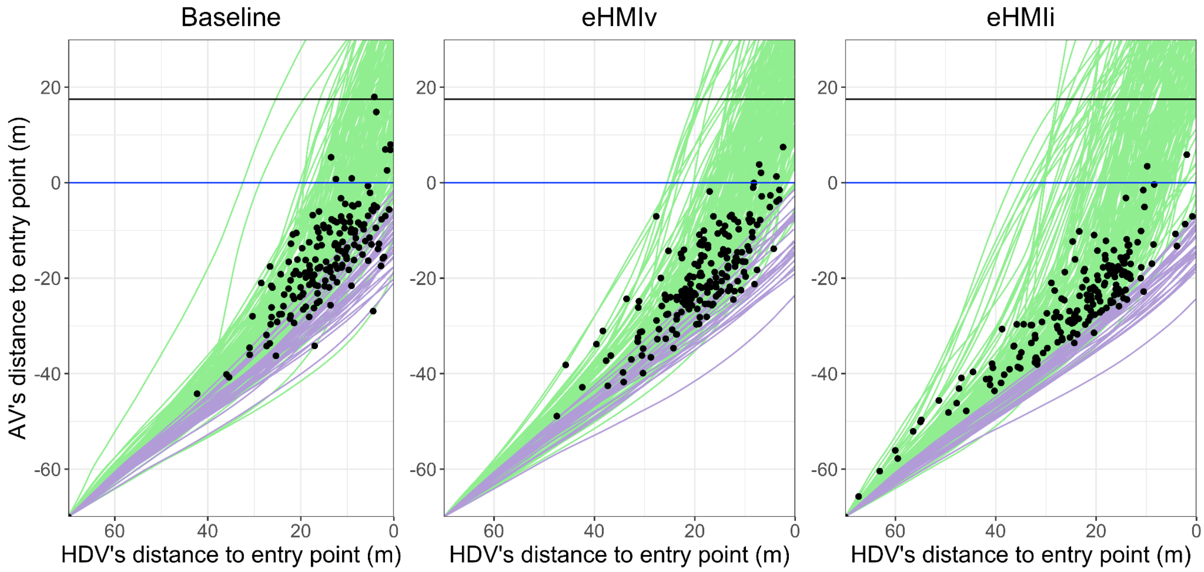

Figure 7. *Distance to the entry point of the intersection for the participants (HDVs) and non-yielding AVs, per HDV-AV encounter for the three conditions. The blue and black horizontal lines represent the entry point and the center of the intersection for the AV. Purple and green lines represent the crossing of participants before and after the AV, respectively. Black markers represent the first moment the HDV reached a speed below 30 km/h. The numbers of visible markers are 170, 182, and 182 for the left, middle, and right subfigures, respectively.*

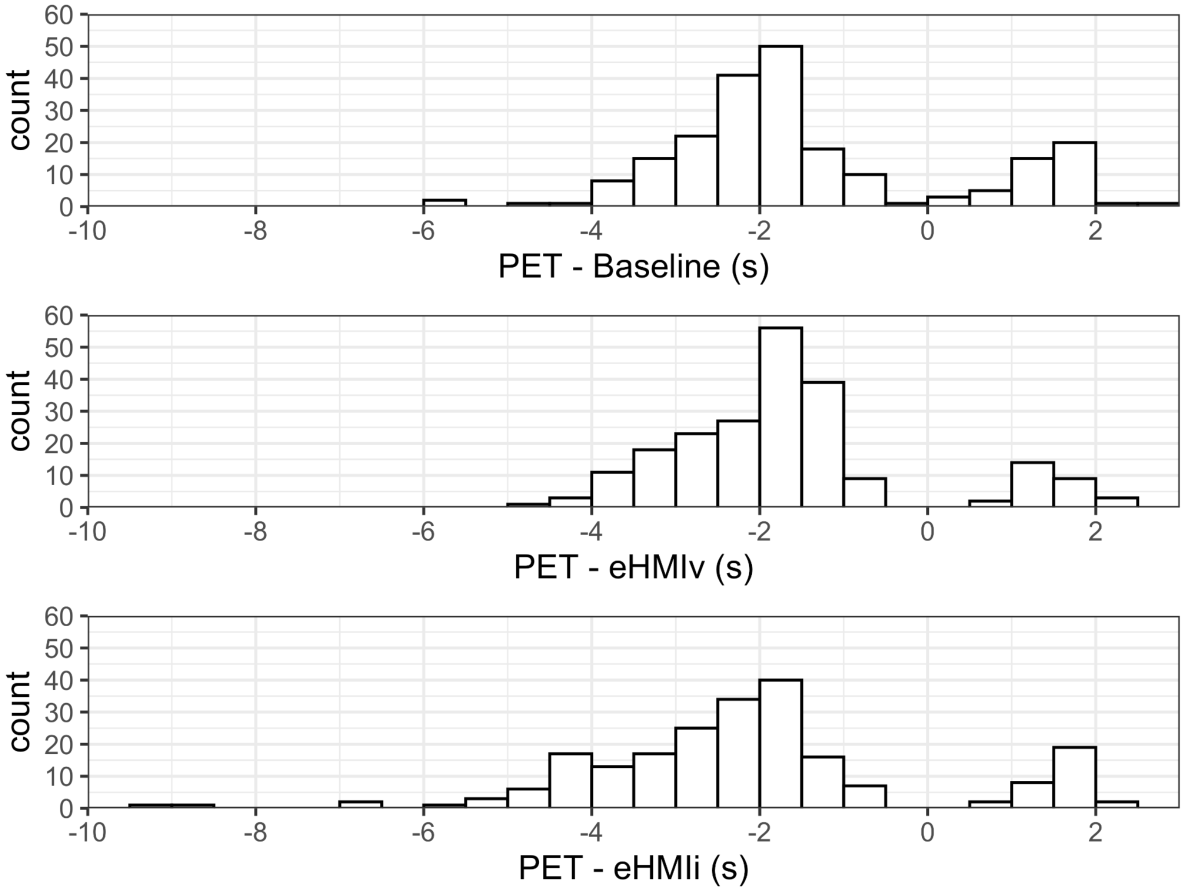

Figure 8. *Histograms of post-encroachment time (PET) for intersections where the AV did not yield. A negative value means that the participant crossed after the AV; a positive value means that the participant crossed before the AV. The total sample size is 214, 215, and 214 for the Baseline, eHMIv, and eHMIi conditions, respectively.*

3.3 *Interviews*

This section provides quotes corresponding to the thematic analysis. The reported participant numbers correspond to the order in which participants were recruited (1 to 46). Overall, participants preferred to have an eHMI compared to no eHMI at all.

- "*I trusted more vehicles with the communication system, because you have to, like I said earlier, you have to less interpret what it's doing.*" (Participant 3).
- "*I noticed in that base scenario that you are more uncertain, simply because, you don't know what the other vehicle is going to do unless you recognise it and it's speed, which is more difficult to realise than just a block on top of a car or a light.*" (Participant 10).

Only two participants preferred the Baseline condition over the eHMIi and eHMIv conditions. Their rationale included a preference to make their own judgments, and a generic aversion to processing supplementary information.

- "*Because then you have to rely on your own judgement, you have to decide for yourself and … if it is safe, or if it is not safe.*" (Participant 17).
- "*because we have to look at the light and be like, wait, purple, green. Like, you have to kind of think about it.*" (Participant 30).

Those who favored the eHMIv condition cited the proximity of the eHMI and the AV as reasons for their preference.

- "*I thought the cube was nice because you know … which car it's talking about … with the traffic light, you might think like: 'okay, about which car are we talking?*" (Participant 3).
- "*on the roof, I found the most helpful because I would look at the car anyways, and check how fast it's going before I take a turn, so I would see it and then I could take that into account when making a decision whether I would take the turn or not, and whereas with the traffic lights, I had to check the traffic light and then the car and then sometimes I would already have slowed down more because the traffic light showed purple. But in the end, the car was not super aggressive, so I could have still taken the turn*" (Participant 26).
- "*Because it's on the car itself, and you can watch through the car what car does." (Participant 28).*
- "*when it is on the car, then I'm more focused on what is happening around me. And yeah, so I think that's more safe than the traffic lights.*" (Participant 31).

One participant considered the eHMIi more effective but still deemed the eHMIv their favourite, stating they preferred it "*because it's different.*" (Participant 8).

A drawback of the eHMIi concept is that drivers must distribute their visual attention between the eHMI and the AV:

- "*for cube it was more like, I saw the colour and then I stopped. But with the traffic light, I wasn't actually looking at the traffic light, I was looking at the car.*" (Participant 8).
- "*when you get more confident about the driving, I realised that you stop looking at the car, because you already know it's there, but you don't really, you tend not, like you tend to forget to look at it.*" (Participant 20).
- "*although you would still have to check both.*" (Participant 42).

Some participants pointed out the high perceptual demands of the eHMIv:

- "*because the object is moving … it has some … implication on your driving.*" (Participant 4).
- "*for the visual box on top, I think it was a bit more demanding in terms of getting the speed right and then see what type of colours (is) in top*" (Participant 13).
- "*Because the vehicle was kind of out of my line of vision. So I had to really take my focus off to see where is it?*" (Participant 30).
- "*that's directly … the Achilles' heel for this thing; I still have to see the moving object. … if … objects are in … the blind spot … so you would need a solution for that*" (Participant 2).

Several participants noted that the eHMIi was easier to localize:

- *"the signal system … was straight up ahead in front of me. So, I look at that, and then …I'll decide that, fine, there are lights and I'll follow the lights and I'll be safe" (Participant 16).*
- *"Because I don't have to search for the car, look for the car where it was and search for the cube. I could just look at a signal. And if it was purple, I stopped. If it was green, I would go." (Participant 38).*
- *"I can see straight in my vision without having to turn left. And you know, that gap allows me to have a split second extra in making my decision." (Participant 40).*
- *"for me is the traffic light was easier because it's in your direct vision and you don't have to look left or right towards it … it's easier for me, as the driver to not have to focus on multiple things." (Participant 42).*

Moreover, the familiarity of the eHMIi concept was viewed positively:

- *"I did like the traffic light more because it is more familiar. … okay, maybe the colours were not familiar, but seeing a traffic light and seeing like, stop or go that does help interacting with it"* (Participant 3).
- *"if the signals were green, I felt confident in accelerating. …. and that felt very intuitive. It's like a real traffic light"* (Participant 16).
- *"with the signal, it feels more natural, because we are used to a signal, but also like, you can keep your eyes on the road, kind of, like what's in front of you."* (Participant 30).

Nonetheless, some participants experienced confusion, as the eHMIi resembled a traffic light but had an advisory function and displayed a purple colour instead of red. Participants suggested that such confusion could be detrimental during moments of distraction:

- *"I think the traffic lights are confusing in the way they're set up now like this. Too close to the normal traffic light system. … if you're not paying enough attention, only the difference in colour makes, has to indicate that it's about automated vehicles. And that's not enough."* (Participant 14).
- *"I feel like it's kind of close to the regular stoplight, so it's confusing."* (Participant 35).
- *"I'm used to normal traffic signs, so this is, this is the same thing, but with a different meaning, so that's quite hard to... well, it is not really hard to understand but … if you get distracted … "* (Participant 36).

The eHMIv and eHMIi trigger signals occurred simultaneously. However, the eHMI, in its default state (green or purple), was already visible while approaching the intersection. This aspect of the eHMIi was generally, but not always, regarded positively:

- *"with the traffic lights, I was way more careful when driving up to the intersection, because it was going to change"* (Participant 10).
- *"they are very useful, especially the traffic light, because it switched, so you can see like the changes"* (Participant 20).
- *"when you were at a distance, they were sometimes purple. But when you got closer, it changed. … I actually liked the one with the cubes more. They were a bit more static."* (Participant 34).
- *"you can see the signal from a distance even if you don't see a car. So you know that if it's green maybe there is a car coming … but if it's purple, then you know definitely, that there's gonna be a car, driverless car coming towards you. But you don't necessarily need to see that car."* (Participant 41).

Some participants commented on the technological challenges of implementing the eHMIv and eHMIi concepts in future traffic situations. They highlighted that the eHMIi system would require vehicle-to-infrastructure communication:

- *"I'm not sure if it's, it's, it's going to work when you have multiple cars. Because then, then, a sign on a car would be, would make more sense, I think. But in this scenario, I would choose the traffic lights."* (Participant 23).

- "*… just from a technical perspective, that it's way more difficult to have everything interacting and communicating at the right times when it's this this static traffic light.*" (Participant 29).
- "*because it's closer to the driver. And the signal doesn't need to travel in the air and can less easily be disturbed by others, other cars signalling to that system. … So it was more trustworthy to me.*" (Participant 44).

Additionally, participants observed that relying on the eHMIi signal could be difficult when multiple vehicles are involved:

- "*now, it was only one car. So the traffic light is good. … but if there are multiple, it's hard to distinguish for which one it is.*" (Participant 13).
- "*I prefer … the cubes on the car … because the traffic light could be wrong, and you're not looking at the car, but you're looking at the traffic light*" (Participant 22).

However, it was also noted that standardizing the eHMIv may present challenges:

- "*with the signals, you can make it standard, you can integrate it with the traffic light system. So I find that more testable rather than saying every manufacturer will provide a different kind of signalling system on his car.*" (Participant 16).

4 Discussion

This study aimed to determine whether the eHMI should be placed on the automated vehicle (AV) itself (eHMIv) or on road infrastructure (eHMIi). A driving simulator experiment was conducted, in which participants turned right at T-intersections while an AV approached from the left. Participants were exposed to AVs under three conditions: no eHMI (Baseline), eHMIv, and eHMIi.

The results showed that when the AV maintained its speed, participants adopted a slower approach speed and entered the intersection later when an eHMI was present compared to its absence. Moreover, with an eHMI, participants tended to cross after the AV rather than before it, which is expected to benefit safety. Ultimately, 95% of participants preferred AVs with eHMIs. The current results suggest that safety-related benefits of eHMIs, typically found among pedestrians, also apply to human-driven vehicles.

Regarding eHMI placement, both eHMIv and eHMIi received equivalent preference rankings and produced similar crossing decisions. However, reasons for preference differed substantially. Participants who preferred eHMIv typically did so because they could focus on the AV without having to distribute their attention between the eHMI and the AV. Although identifying the AV is visually challenging, once the AV has been identified, its yielding state can readily be seen.

The eHMIi concept appeared to offer some advantages over eHMIv. Specifically, compared to eHMIv, eHMIi resulted in a lower self-reported arousal level and the participants slowed down earlier and reached the intersection later for eHMIi compared to eHMIv. Several possible reasons for these beneficial effect are:

1. As pointed out, the eHMIv requires the driver to first identify the AV by rotating their head or eyes. This is time-consuming, and there may be a risk of overlooking the AV. In contrast, when approaching the intersection, the eHMIi is already in the participant's field of view, i.e., directly ahead. This interpretation is consistent with Wickens et al. (2008) and Eisma et al. (2018), who argued that physical effort affects the probability that a stimulus is glanced at.
2. The eHMIi attracted the driver's attention even before the AV was visible, while eHMIv could only be seen when the AV appeared from behind a building/vegetation. That is, although the trigger location was the same (when the participant was 70 m from the intersection), the traffic-light-like structure is a cue to which participants could respond early. This is supported by Figure 6, which shows that the HDV speed in the eHMIi condition is already reduced at the eHMI trigger moment compared to eHMIv and Baseline.

3. The eHMIi remained visible as the AV passed, whereas the eHMIv display turned grey as the AV passed. Thus, the eHMIi may deter entering the intersection early, since the participant had to run the purple light. On the other hand, visual inspection of Figure 7 reveals that participants rarely came to a full stop (i.e., the lines in the figure do not run vertically), so participants did not interpret the eHMIi as a traffic light for which they had to stop.

The question of how the eHMIv and eHMIi conditions should be implemented in future traffic is a topic of further discussion, which relates to whether future cities will adopt connectivity of infrastructure elements. Our findings suggest that positioning signals on the infrastructure is of benefit compared to signals on the AV, as they encourage the driver to slow down early. However, it may also be argued that high driving speeds near intersections and short PET values (as found in the current study for the eHMIv condition) could be seen as an efficiency benefit.

In future traffic, eHMIi and eHMIv may be used in combination. Online and virtual reality studies have shown that eHMIs on the AV are useful in supporting crossing decisions, especially when infrastructure elements, such as traffic lights and pedestrian crossings, are lacking (Eisele and Petzoldt, 2022; Madigan et al., 2022; Métayer and Coeugnet, 2021; Sadeghian et al., 2020). Eisele and Petzoldt (2022) found that pedestrians are likely to cross (or not) at a green (or red) traffic light, disregarding the eHMI on the AV entirely. This suggests that the eHMIv concept may become redundant if traffic lights are already in place at the site.

Our experiment focused only on one-to-one interactions at T-intersections in a rural environment. Further research is needed to determine the validity of the results for different vehicle behaviours and road configurations, including left-turn interactions. As traffic density increases, drivers will have to divide their attention among multiple elements. It can be expected that if many AVs are present, or if there are visual obstructions such as buildings, the eHMIv condition may become less preferred. Other challenges for the eHMIv condition include standardization between vehicle brands and the question of whether the eHMIv should signal the intentions of the ego-vehicle or also take into consideration the intentions of surrounding traffic.

Future research should explore whether the eHMIi should be functionally and perceptually distinct from traffic lights (by using, e.g., a purple light in a different infrastructural form or location). Another challenge of the eHMIi concept is that it would require vehicle-to-infrastructure communication. However, the eHMIi does not need to be restricted to a physical traffic light; it could also be displayed on the driver's dashboard (BMW, 2021; Kettwich et al., 2016; Winzer et al., 2018), on a head-up display (Yang et al., 2016), through augmented reality (Von Sawitzky et al., 2019), or on a wearable device (Martins et al., 2019).

A limitation of this study is that the participant sample is not representative of the general population, with most participants having an engineering education. Additionally, the study design has a limitation, in that although the presentation order of the three eHMI conditions was randomized, the order of yielding and non-yielding AVs within each condition was the same for all participants, which may introduce some bias (due to, e.g., presentation order, and length of the straight that preceded the intersection). However, further analyses of the mean times to enter the intersection (see Table S5 of the Supplementary Material) indicate that the results are robust.

5 Conclusion

The current driving simulator study among manual drivers investigated where eHMI information should be placed: on the AV or on the road infrastructure. This is an important question that relates to how future cities should be developed in regard to vehicle-to-infrastructure connectivity. The current study has shown that there are pros and cons to both concepts. An eHMI on the AV (eHMIv) has advantages in terms of divided attention, as all necessary information is available on the AV. Participants made tighter crossing decisions in the eHMIv condition, something that can be interpreted as unsafe, but also as an efficiency advantage. An eHMI on the infrastructure (eHMIi), on the other hand, has advantages in terms of familiarity and also fixedness in placement, making visual search easier. Technically, however, it is challenging for this concept to replace traffic lights. Despite its limitations, the current study provides an important first step in the process of thinking about how safety, efficiency, and the visual attention demands of car drivers should be optimized towards the future.

Data availability

Data underlying the statistical tests and illustrative videos of the three eHMI conditions can be accessed here: https://doi.org/10.4121/8e1c6604-53c7-4905-8ef9-4a6b2acc4e7a

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Conflict Of Interest

There is no conflict of interest.

References

Avsar, H., Utesch, F., Wilbrink, M., Oehl, M. and Schießl, C. (2021). Efficient communication of automated vehicles and manually driven vehicles through an external human-machine interface (eHMI): Evaluation at t-junctions. In Stephanidis, C., Antona, M. and Ntoa, S. (eds) *HCI*

International 2021 - Posters. HCII 2021 (pp. 224–232), Springer, Cham. https://doi.org/10.1007/978-3-030-78645-8_28

Bazilinskyy, P., Dodou, D. and De Winter, J. (2019). Survey on eHMI concepts: The effect of text, color, and perspective. *Transportation Research Part F: Traffic Psychology and Behaviour,* 67, 175–194. https://doi.org/10.1016/j.trf.2019.10.013

Bazilinskyy, P., Dodou, D. and De Winter, J.C.F. (2020). External Human-Machine Interfaces: Which of 729 colors is best for signaling 'Please (do not) cross'? *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics (SMC)* (pp. 3721–3728). Toronto, Canada. https://doi.org/10.1109/SMC42975.2020.9282998

Bimberg, P., Weissker, T. and Kulik, A. (2020). On the usage of the Simulator Sickness Questionnaire for virtual reality research. *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 464–467). Atlanta, GA. https://doi.org/10.1109/VRW50115.2020.00098

Bindschädel, J., Krems, I. and Kiesel, A. (2021). Interaction between pedestrians and automated vehicles: Exploring a motion-based approach for virtual reality experiments. *Transportation Research Part F: Traffic Psychology and Behaviour,* 82, 316–332. https://doi.org/10.1016/j.trf.2021.08.018

BMW. (2021). Owner's handbook. The BMW X7. https://ownersmanuals2.com/bmw-auto/x7-2021-owners-manual-80712

Bradley, M.M. and Lang, P.J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

Braun, V. and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology,* 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Bulumulle, G. and Bölöni, L. (2016). Reducing side-sweep accidents with vehicle-to-vehicle communication. *Journal of Sensor and Actuator Networks*, 5(4), 19. https://doi.org/10.3390/jsan5040019

Colley, M., Bajrovic, E. and Rukzio, E. (2022a). Effects of pedestrian behavior, time pressure, and repeated exposure on crossing decisions in front of automated vehicles equipped with external communication. *Proceedings of the CHI Conference on Human Factors in Computing Systems*. New Orleans, LA. https://doi.org/10.1145/3491102.3517571

Colley, M., Fabian, T. and Rukzio, E. (2022b). Investigating the effects of external communication and automation behavior on manual drivers at intersections. *Proceedings of the ACM on Human-Computer Interaction,* 6(MHCI), 176. https://doi.org/10.1145/3546711

Crosato, L., Tian, K., Shum, H.P.H., Ho, E.S.L., Wang, Y. and Wei, C. (2023). Social interaction-aware dynamical models and decision-making for autonomous vehicles. *Advanced Intelligent Systems*, 6(3), 2300575. https://doi.org/10.1002/aisy.202300575

CROW. (2012). *ASVV 2012 : Aanbevelingen voor verkeersvoorzieningen binnen de bebouwde kom* [ASVV 2012: Recommendations for traffic facilities in built-up areas]. CROW Kenniscentrum voor Verkeer, Vervoer en Infrastructuur, Ede.

Deb, S., Strawderman, L.J. and Carruth, D.W. (2018). Investigating pedestrian suggestions for external features on fully autonomous vehicles: A virtual reality experiment. *Transportation Research Part F: Traffic Psychology and Behaviour,* 59, 135–149. https://doi.org/10.1016/j.trf.2018.08.016

De Clercq, G.K., Dietrich, A., Núñez Velasco, P., De Winter, J.C.F. and Happee, R. (2019). External human-machine interfaces on automated vehicles: Effects on pedestrian crossing decisions. *Human Factors,* 61(8), 1353–1370. https://doi.org/10.1177/0018720819836343

De Winter, J.C.F. and Dodou, D. (2010). Five-point Likert items: t test versus Mann-Whitney-Wilcoxon (Addendum added October 2012). *Practical Assessment, Research, and Evaluation,* 15(1), 11. https://doi.org/10.7275/bj1p-ts64

De Winter, J.C.F. and Dodou, D. (2022). External human–machine interfaces: Gimmick or necessity? *Transportation Research Interdisciplinary Perspectives*, 15, 100643. https://doi.org/10.1016/J.TRIP.2022.100643

Dey, D., Ackermans, S., Martens, M., Pfleging, B. and Terken, J. (2022). Interactions of automated vehicles with road users. In Riener, A., Jeon, M. and Alvarez, I. (eds) *User Experience Design in the Era of Automated Driving* (pp. 533–581), Springer, Cham. https://doi.org/10.1007/978-3-030-77726-5_20

Dey, D., Habibovic, A., Löcken, A., Wintersberger, P., Pfleging, B., Riener, A., Martens, M. and Terken, J. (2020). Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, 7, 100174. https://doi.org/10.1016/J.TRIP.2020.100174

Dey, D. and Terken, J. (2017). Pedestrian interaction with vehicles: Roles of explicit and implicit communication. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 109–113). Oldenburg, Germany. https://doi.org/10.1145/3122986.3123009

Eisele, D. and Petzoldt, T. (2022). Effects of traffic context on eHMI icon comprehension. *Transportation Research Part F: Traffic Psychology and Behaviour*, 85, 1–12. https://doi.org/10.1016/j.trf.2021.12.014

Eisma, Y.B., Cabrall, C.D.D. and De Winter, J.C.F. (2018). Visual sampling processes revisited: Replicating and extending Senders (1983) using modern eye-tracking equipment. *IEEE Transactions on Human Machine Systems,* 48(5), 526–540. https://doi.org/10.1109/THMS.2018.2806200

Eisma, Y.B., Van Bergen, S., Ter Brake, S.M., Hensen, M.T.T., Tempelaar, W.J. and De Winter, J.C.F. (2020). External human-machine interfaces: The effect of display location on crossing intentions and eye movements. *Information,* 11(1), 13. https://doi.org/10.3390/info11010013

Faas, S.M., Kao, A.C. and Baumann, M. (2020). A longitudinal video study on communicating status and intent for self-driving vehicle–pedestrian interaction. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu, HI. https://doi.org/10.1145/3313831.3376484

Faas, S.M., Kraus, J., Schoenhals, A. and Baumann, M. (2021). Calibrating pedestrians' trust in automated vehicles: Does an intent display in an external HMI support trust calibration and safe crossing behavior? *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama, Japan. https://doi.org/10.1145/3411764.3445738

Ferenchak, N.N. and Shafique, S. (2022). Pedestrians' perceptions of autonomous vehicle external human-machine interfaces. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 8(3), 034501. https://doi.org/10.1115/1.4051778

Gruenefeld, U., Weiß, S., Löcken, A., Virgilio, I., Kun, A.L. and Boll, S. (2019). VRoad: Gesture-based interaction between pedestrians and automated vehicles in virtual reality. *11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings* (pp. 399–404). Utrecht, The Netherlands. https://doi.org/10.1145/3349263.3351511

Habibovic, A., Malmsten Lundgren, V., Andersson, J., Klingegård, M., Lagström, T., Sirkka, A., Fagerlönn, J., Edgren, C., Fredriksson, R., Krupenia, S., Saluäär, D. and Larsson, P. (2018). Communicating intent of automated vehicles to pedestrians. *Frontiers in Psychology*, 9, 1336. https://doi.org/10.3389/fpsyg.2018.01336

Hart, S.G. and Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In Hancock, P.A. and Meshkati, N. (eds) *Human Mental Workload* (pp. 139–183), North Holland Press, Amsterdam.

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J. and Krems, J.F. (2019). Effects of a light-based communication approach as an external HMI for automated vehicles – A Wizard-of-Oz Study. *Transactions on Transport Sciences*, 10(2), 18–32. https://doi.org/10.5507/tots.2019.012

Kaleefathullah, A.A., Merat, N., Lee, Y.M., Eisma, Y.B., Madigan, R., Garcia, J. and De Winter, J.C.F. (2022). External human–machine interfaces can be misleading: An examination of trust development and misuse in a CAVE-based pedestrian simulation environment. *Human Factors*, 64(6), 1070–1085. https://doi.org/10.1177/0018720820970751

Kennedy, R.S., Lane, N.E., Berbaum, K.S. and Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology,* 3(3), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kettwich, C., Haus, R., Temme, G. and Schieben, A. (2016). Validation of a HMI concept indicating the status of the traffic light signal in the context of automated driving in urban environment. *Proceedings of the 2016 IEEE Intelligent Vehicles Symposium (IV)* (pp. 1374–1379). Gothenburg, Sweden. https://doi.org/10.1109/IVS.2016.7535569

Lau, M., Le, D.H. and Oehl, M. (2021). Design of external human-machine interfaces for different automated vehicle types for the interaction with pedestrians on a shared space. In Black, N.L., Neumann, W.P. and Noy, I. (eds) *Proceedings of the 21st Congress of the International Ergonomics Association* (pp. 710–717), Springer, Cham. https://doi.org/10.1007/978-3-030-74608-7_87

Lee, Y.M., Madigan, R., Giles, O., Garach-Morcillo, L., Markkula, G., Fox, C., Camara, F., Rothmueller, M., Vendelbo-Larsen, S.A., Holm Rasmussen, P., Dietrich, A., Nathanael, D., Portouli, V., Schieben, A. and Merat, N. (2021). Road users rarely use explicit communication when interacting in today's traffic: implications for automated vehicles. *Cognition, Technology & Work,* 23, 367–380. https://doi.org/10.1007/s10111-020-00635-y

Löcken, A., Golling, C. and Riener, A. (2019). How should automated vehicles interact with pedestrians? A comparative analysis of interaction concepts in virtual reality. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 262–274). Utrecht, The Netherlands. https://doi.org/10.1145/3342197.3344544

Madigan, R., Lee, Y.M., Lyu, W., Horn, S., De Pedro, J.G. and Merat, N. (2023). Pedestrian interactions with automated vehicles: Does the presence of a zebra crossing affect how eHMIs and movement patterns are interpreted? *Transportation Research Part F: Traffic Psychology and Behaviour*, 98, 170–185. https://doi.org/10.1016/j.trf.2023.09.003

Mahadevan, K., Somanath, S. and Sharlin, E. (2018). Communicating awareness and intent in autonomous vehicle-pedestrian interaction. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Montréal, Canada. https://doi.org/10.1145/3173574.3174003

Martins, V., Rufino, J., Silva, L., Almeida, J., Fernandes Silva, B.M., Ferreira, J. and Fonseca, J. (2019). Towards personal virtual traffic lights. *Information*, 10(1), 32. https://doi.org/10.3390/info10010032

Métayer, N. and Coeugnet, S. (2021). Improving the experience in the pedestrian's interaction with an autonomous vehicle: An ergonomic comparison of external HMI. *Applied Ergonomics*, 96, 103478. https://doi.org/10.1016/j.apergo.2021.103478

Mirnig, A.G., Gärtner, M., Wallner, V., Gafert, M., Braun, H., Fröhlich, P., Suette, S., Sypniewski, J., Meschtscherjakov, A. and Tscheligi, M. (2021). Stop or go? Let me know! A field study on visual external communication for automated shuttles. *Proceedings of the 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 287–295). Leeds, UK. https://doi.org/10.1145/3409118.3475131

Mok, C.S., Bazilinskyy, P. and De Winter, J.C.F. (2022). Stopping by looking: A driver-pedestrian interaction study in a coupled simulator using head-mounted displays with eye-tracking. *Applied Ergonomics*, 105, 103825. https://doi.org/10.1016/J.APERGO.2022.103825

Neukum, A., Lübbecke, T., Krüger, H.-P., Mayser, C. and Steinle, J. (2008). ACC-Stop&Go: Fahrverhalten an funktionalen Systemgrenzen. In Maurer, M. and Stiller, C. (eds) *5. Workshop Fahrerassistenzsysteme (FAS) (2008)* (pp. 141–150).

Norman, D. (2014). *Turn Signals Are the Facial Expressions of Automobiles.* Diversion Books, New York.

Ohn-Bar, E. and Trivedi, M.M. (2016). Looking at humans in the age of self-driving and highly automated vehicles. *IEEE Transactions on Intelligent Vehicles*, 1(1), 90–104. https://doi.org/10.1109/TIV.2016.2571067

Othersen, I., Conti-Kufner, A.S., Dietrich, A., Maruhn, P. and Bengler, K. (2018). Designing for automated vehicle and pedestrian communication: Perspectives on eHMIs from older and younger persons. In De Waard, D., Brookhuis, K., Coelho, D., Fairclough, S., Manzey, D., Naumann, A., Onnasch, L., Röttger, S., Toffetti, A. and Wiczorek, R. (eds) *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference* (pp. 135–148).

Papakostopoulos, V., Nathanael, D., Portouli, E. and Amditis, A. (2021). Effect of external HMI for automated vehicles (AVs) on drivers' ability to infer the AV motion intention: A field experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, 82, 32–42. https://doi.org/10.1016/j.trf.2021.07.009

Rettenmaier, M., Albers, D. and Bengler, K. (2020). After you?! – Use of external human-machine interfaces in road bottleneck scenarios. *Transportation Research Part F: Traffic Psychology and Behaviour*, 70, 175–190. https://doi.org/10.1016/j.trf.2020.03.004

Rettenmaier, M., Pietsch, M., Schmidtler, J. and Bengler, K. (2019). Passing through the bottleneck – The potential of external human-machine interfaces. *Proceedings of the IEEE Intelligent Vehicles Symposium* (pp. 1687–1692). Paris, France. https://doi.org/10.1109/IVS.2019.8814082

Rudenko, A., Palmieri, L., Herman, M., Kitani, K. M., Gavrila, D.M. and Arras, K.O. (2020). Human motion trajectory prediction: A survey. *The International Journal of Robotics Research*, 39(8), 895–935. https://doi.org/10.1177/0278364920917446

Sadeghian, S., Hassenzahl, M. and Eckoldt, K. (2020). An exploration of prosocial aspects of communication cues between automated vehicles and pedestrians. *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 1687–1692). Virtual Event. https://doi.org/10.1145/3409120.3410657

Schwarting, W., Pierson, A., Alonso-Mora, J., Karaman, S. and Rus, D. (2019). Social behavior for autonomous vehicles. *Proceedings of the National Academy of Sciences*, 116(50), 24972–24978. https://doi.org/10.1073/pnas.1820676116

Siebert, F.W., Oehl, M. and Pfister, H.-R. (2014). The influence of time headway on subjective driver states in adaptive cruise control. *Transportation Research Part F: Traffic Psychology and Behaviour*, 25, 65–73. https://doi.org/10.1016/j.trf.2014.05.005

Tabone, W., De Winter, J.C.F., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock, P.A., Happee, R., Krems, J., Lee, J. D., Martens, M., Merat, N., Norman, D.A., Sheridan, T.B. and Stanton, N.A. (2021). Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transportation Research Interdisciplinary Perspectives*, 9, 100293. https://doi.org/10.1016/j.trip.2020.100293

Taghavifar, H., Wei, C. and Taghavifar, L. (2024). Socially intelligent reinforcement learning for optimal automated vehicle control in traffic scenarios. *IEEE Transactions on Automation Science and Engineering*. https://doi.org/10.1109/TASE.2023.3347264

Tang, K. and Kuwahara, M. (2011). Implementing the concept of critical post-encroachment time for all-red clearance interval design at signalized intersections. *Proceedings of the Eastern Asia Society for Transportation Studies*, 8, 299–299. https://www.jstage.jst.go.jp/article/eastpro/2011/0/2011_0_299/_pdf

Tran, T.T.M., Parker, C., Wang, Y. and Tomitsch, M. (2022). Designing wearable augmented reality concepts to support scalability in autonomous vehicle-pedestrian interaction. *Frontiers in Computer Science*, 4, 866516. https://doi.org/10.3389/FCOMP.2022.866516

Tscharn, R., Naujoks, F. and Neukum, A. (2018). The perceived criticality of different time headways is depending on velocity. *Transportation Research Part F: Traffic Psychology and Behaviour*, 58, 1043–1052. https://doi.org/10.1016/j.trf.2018.08.001

Umbrellium. (2017). Make roads safer, more responsive & dynamic. https://umbrellium.co.uk/case-studies/south-london-starling-cv

Van der Laan, J.D., Heino, A. and De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research Part C: Emerging Technologies*, 5(1), 1–10. https://doi.org/10.1016/S0968-090X(96)00025-3

Von Sawitzky, T., Wintersberger, P., Löcken, A., Frison, A.-K. and Riener, A. (2020). Augmentation concepts with HUDs for cyclists to improve road safety in shared spaces. *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. Honolulu, HI. https://doi.org/10.1145/3334480.3383022

Von Sawitzky, T., Wintersberger, P., Riener, A. and Gabbard, J.L. (2019). Increasing trust in fully automated driving: Route indication on an augmented reality head-up display. *Proceedings of the 8th ACM International Symposium on Pervasive Displays*. Palermo, Italy. https://doi.org/10.1145/3321335.3324947

Wickens, C.D., McCarley, J.S., Alexander, A.L., Thomas, L.C., Ambinder, M. and Zheng, S. (2008). Attention-situation awareness (A-SA) model of pilot error. In Foyle, D.C. and Hooey, B.L. (eds) *Human Performance Modeling in Aviation* (pp. 213–239), CRC Press, Boca Raton, FL.

Wilbrink, M., Lau, M., Illgner, J., Schieben, A. and Oehl, M. (2021). Impact of external human–machine interface communication strategies of automated vehicles on pedestrians' crossing decisions and behaviors in an urban environment. *Sustainability*, 13(15), 8396. https://doi.org/10.3390/su13158396

Winzer, O.M., Conti-Kufner, A.S. and Bengler, K. (2018). Intersection Traffic Light Assistant – An evaluation of the suitability of two human machine interfaces. *Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1687–1692). Maui, HI. https://doi.org/10.1109/ITSC.2018.8569708

Witmer, B.G., Jerome, C.J. and Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence: Teleoperators and Virtual Environments,* 14(3), 298–312. https://doi.org/10.1162/105474605323384654

Yang, B., Zheng, R., Yin, Y., Yamabe, S. and Nakano, K. (2016). Analysis of influence on driver behaviour while using in-vehicle traffic lights with application of head-up display. *IET Intelligent Transport Systems*, 10(5), 347–353. https://doi.org/10.1049/iet-its.2015.0179

Zimmermann, M., Schopf, D., Lütteken, N., Liu, Z., Storost, K., Baumann, M., Happee, R. and Bengler, K.J. (2018). Carrot and stick: A game-theoretic approach to motivate cooperative driving through social interaction. *Transportation Research Part C: Emerging Technologies*, 88, 159–175. https://doi.org/10.1016/j.trc.2018.01.017

Supplementary material

Table S1. Automated vehicle behavior for the ten intersections encountered by the participants

Intersection	Baseline	eHMIv	eHMIi	Transition of colours (eHMIi)
1	Non-yielding	Yielding	Yielding	Purple to Green
2	Yielding	Yielding	Non-yielding	**Purple to Purple**
3	Yielding	Non-yielding	Non-yielding	Green to Purple
4	Non-yielding	Non-yielding	Yielding	Purple to Green
5	Yielding	Yielding	Non-yielding	**Purple to Purple**
6	Non-yielding	Non-yielding	Yielding	**Green to Green**
7	Non-yielding	Non-yielding	Non-yielding	Green to Purple
8	Yielding	Yielding	Non-yielding	**Purple to Purple**
9	Non-yielding	Non-yielding	Yielding	**Green to Green**
10	Yielding	Yielding	Yielding	Purple to Green

Note. eHMIi colours that were already correct while the participant was approaching the intersection are marked in boldface (green to green, purple to purple).

The approaching AVs differed in their yielding behavior (i.e., non-yielding vs. yielding), and showed some variability in speed (see Table S2 for non-yielding AV).

Table S2. Mean speed of non-yielding AVs at 70 m and 0 m, and over the entire distance between 70 m and 0 m from the start of the intersection

Condition	AV speed (km/h)					
	AV at 70 m		AV at 0 m		AV from 70 to 0 m	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
Baseline (*n* = 214)	48.03	0.43	51.47	1.93	47.84	4.65
eHMIv (*n* = 215)	48.19	0.30	52.66	2.76	47.54	4.98
eHMIi (*n* = 214)	48.15	0.37	53.43	2.03	47.36	4.81

Note. The non-yielding AV braked if the participant cut in front of it, which can explain some of the variability between trials and conditions.

Table S3. Results of the Simulator Sickness Questionnaire (*n* = 42)

	Mean	*SD*
Nausea	14.3	14.3
Oculomotor	15.9	15.5
Disorientation	19.6	19.7
Total score	18.7	16.1

Note. Scoring was done according to Kennedy et al. (1993). Simulator sickness was rated on 16 items from 0 (none) to 3 (severe). The maximum possible score is 200.34, 159.18, 292.32, and 235.62 for the nausea, oculomotor, disorientation, and total score, respectively (Bimberg et al., 2020). One participant did not fill in the questionnaire.

Table S4. Results of the 19-item Presence Questionnaire (*n* = 42)

	Mean	*SD*
Involvement (9 items)	4.44	0.81
Visual fidelity (2 items)	4.96	1.28
Adaptability/immersion (6 items)	4.98	0.64
Interface quality (2 items)	3.04	1.17

Note. Presence was rated on a scale of 1 (none at all) to 7 (a great deal). One participant did not fill in the questionnaire.

Table S5. Mean and standard deviation (*SD*) of time to enter the intersection (s) for intersections in which the automated vehicle did not yield, specified per intersection (*n* = 43)

	Mean			*SD*		
	Baseline	eHMIv	eHMIi	Baseline	eHMIv	eHMIi
Intersection 1	6.93	–	–	1.39	–	–
Intersection 2	–	–	8.38	–	–	2.15
Intersection 3	–	7.30	7.31	–	1.36	1.98
Intersection 4	7.14	7.31	–	1.27	1.14	–
Intersection 5	–	–	7.79	–	–	1.61
Intersection 6	6.86	6.93	–	1.17	1.22	–
Intersection 7	6.57	7.07	7.64	1.32	1.18	1.26
Intersection 8	–	–	7.66	–		1.42
Intersection 9	6.74	7.38	–	1.44	1.27	–
Intersection 10	–	–	–	–	–	–

Note. It can be seen that, for the same intersection, the mean time to enter the intersection is longer for eHMIv than for Baseline (Intersections 4, 6, 7, 9), longer for eHMIv than for Baseline (Intersection 7), and longer for eHMIi than eHMIv (Intersections 3, 7), which corresponds to Table 2.