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Pedestrians' perceptions of automated vehicle movements and light-based eHMIs in real world conditions: A test track study

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ABSTRACT

The development of increasingly automated vehicles (AVs) is likely to lead to new challenges around how they will interact with other road users. In the future, it is envisaged that AVs, manually driven vehicles, and vulnerable road users such as cyclists and pedestrians will need to share the road environment and interact with one another. This paper presents a test track study, funded by the H2020 interACT project, investigating pedestrians' reactions towards an AV's movement patterns and external Human Machine Interfaces (eHMIs). Twenty participants, standing on the side of a test-track road and facing an approaching AV, were asked to raise their arm to indicate: (1) when they could perceive the AV's eHMI, which consisted of either a Full Light Band (FLB) or a Partial Light Band (PLB); (2) when they perceived the deceleration of the AV (with eHMI vs. no eHMI); and (3) when they felt safe to cross the road in front of the approaching AV (with eHMI vs. no eHMI). Statistical analyses revealed no effects of the presence of an eHMI on the pedestrians' crossing decision or deceleration perception, but significant differences were found regarding the visibility of the FLB and PLB designs. The PLB design could be perceived at further distances than the FLB design. Both eHMI solutions were generally well-received, and participants provided high ratings of perceived safety, and confidence around the AV.

1. Introduction

The introduction of automated vehicles (AVs) on public roads is a major goal for vehicle manufacturers, governments, and academics in the automotive field (Frisoni et al., 2016). It has been argued that road user interactions in mixed traffic environments will change with the addition of "driverless" vehicles (Fekete et al., 2015), which are no longer controlled by a human operator (SAE Levels 4 & 5, SAE, 2018). To achieve safe and efficient integration of AVs in mixed traffic environments, they must gain both their passengers' trust and acceptance (Körber et al., 2018; Matthaei, 2015), and the trust, acceptance of other human traffic participants, such as manual car-drivers, cyclists and pedestrians (Rothenbücher et al., 2016).

Observations of pedestrian-driver communication in real-time traffic situations have shown that traffic participants' communications are mostly based on implicit cues. Vehicle movements are one of them and are commonly used in vehicle–pedestrian communication (Rasouli et al., 2017). Pedestrians' use the deceleration behaviour of a vehicle to decide whether to cross the road. However, the reaction time required to identify the deceleration depends on kinematic parameters and is quicker if the vehicle

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approaches with lower speed and a higher deceleration rate (Petzoldt et al., 2018; Beggiato et al., 2017b; Ackermann et al., 2019). Additional implicit factors include the use of the vehicle's time to arrival, or its' distance from the pedestrian, while explicit communication strategies include head movements, or vehicle-based lights and sounds (Ackermann et al., 2019; Dietrich et al., 2018; Lee et al., 2020a; Petzoldt et al., 2018; Sun et al., 2015). However, in congested traffic environments, such as urban settings, ambiguous situations are normally resolved through explicit interactions, via gestures, facial expressions, or eye contact, to help express intentions (Merten, 1977; Rasouli et al., 2018; Hölzel, 2008). The importance of visual search has been documented in a study by Schneemann and Gohl (2016), who demonstrated that pedestrians searched for eye-contact at lower speeds (in a 30 km/h zone) but made decisions based on vehicles' behaviour at faster speeds (in a 50 km/h zone). Explicit communications are also thought to be more useful in "stand-off" conditions (Rasouli et al., 2017; Sucha et al., 2017), for example, to resolve a conflict between two actors wishing to share the same road space at the same time (Markkula et al., 2020).

As high-level AVs are not yet ready for operation in suburban or urban environments, real-life interactions between pedestrians and AVs are rather unexplored, but a limited number of insights exist. Recent studies suggest that when it comes to interactions between pedestrians and AVs, pedestrians do not fully trust the AV's behaviour and prefer to receive some form of explicit information about its intention (De Clercq et al., 2019; Merat et al., 2018; Vissers et al., 2017). Pedestrians have also reported feeling uncomfortable when there is no possibility of communicating with the driver of a car (Lundgren et al., 2017, Hensch et al., 2019; Velasco et al., 2021). Therefore, it is critical to study future communication solutions that could promote pedestrians' understanding of AVs' intentions, which should also contribute to their acceptance (Färber, 2016).

External Human-Machine Interfaces (eHMIs) have been proposed as a means by which driver-pedestrian communication can be replaced in AVs (Schieben et al., 2019a; Fridman et al., 2017). These interfaces can be used to provide other road users with information about the AV's intended behaviour, by displaying visual or auditory messages on the outside of the vehicle. Studies have shown that they can enhance participants' perceived safety and comfort when encountering an AV (Böckle et al., 2017; de Clercq et al., 2019). Research has also shown that message design, and the visibility of light-based eHMIs can have a positive effect on how quickly pedestrians feel safe to cross in front of an approaching AV (e.g., Song, et al., 2018; Lee et al., 2020b; Wang, & Xu, 2020).

Much of the current research around eHMIs is devoted to investigating pedestrians' information needs, the best design options for eHMI signals, and how to gauge pedestrians' understanding of eHMI-signals (Böckle et al., 2017; Faas et al., 2020; Kaup et al., 2019; Hochman et al., 2020; Lee et al., 2020b). The literature presents several possible design solutions: LED-light signals, symbols, text-messages, head-mounted displays, projections on the street, etc. (Chang et al., 2017; Deb et al., 2018; Hillis et al., 2016; Lee et al., 2019; Song et al., 2018), with many studies showing higher willingness to cross the road in front of an AV when an eHMI is provided (e.g., Song et al., 2018; Ackermans et al., 2020; Dey et al., 2020). However, the visibility of these eHMI solutions must be taken into account (Lee et al., 2020b), and this is affected by the size of display, the distance between the pedestrian and AV, and the AV's approaching speed (Clamann et al., 2017). LED-based eHMI concepts which communicate information through light signals provide a good option in terms of visibility. In particular, sweeping and flashing lights can be perceived quite quickly, and learnt after a short training session (Faas and Baumann, 2019, Habibovic et al., 2018, Lee et al., 2019). Thereby the eHMI messages are easier to interpret if they are in line with the implicit information communicated by the vehicle (Dey et al., 2020) because pedestrians will probably do not over rely on emerging eHMI messages alone, especially at the initial contact. Rettenmaier & Bengler (2021) suggest that AVs should communicate information explicitly and implicitly simultaneously to provide safety and efficiency.

Although a number of studies have investigated pedestrians' responses to new eHMI solutions, real-world investigations of the visibility of LED-based eHMIs, and pedestrians' interactions with these, are rare. To date, most studies in this context have evaluated the visibility of LED-based eHMIs in simulator environments (using pedestrian simulators, VR environments, or video-based analyses; Lee et al., 2020b; Deb et al., 2018), which do not sufficiently reflect the changes in natural lighting of a real-world setting. Clearly, for any design concepts to be deployed and used effectively, an investigation of pedestrians' perception of these designs in real-world lighting conditions is crucial. In addition, recent research has highlighted the need to consider the combined effects of vehicle movement patterns and eHMIs on pedestrian responses (e.g. De Clercq, Dietrich, Núñez Velasco, de Winter, & Happee, 2019; Dey et al., 2020; Lee et al., 2020a). To date, test-track studies in real-world conditions have used a Wizard-of-Oz (WOZ) method to simulate the impression of a driverless-car (e.g. Hensch et al., 2019; Palmeiro et al., 2018; Rothenbücher et al., 2016). However, the movement cues of a WOZ controlled vehicle are likely to be slightly different to a machine-controlled AV, and thus it is important to understand how AV movement cues are perceived by pedestrians.

The present study addressed these gaps in more detail, using a test-track study to explore participants' reactions to a machine-controlled AV with two different LED-based eHMI solutions. Specifically, the study aimed to answer three key questions:

(1) the distance at which pedestrians could perceive the LED-based eHMI solutions,
(2) the effect of eHMIs on the accuracy of pedestrians' perceptions about the AV's deceleration behaviour, and
(3) whether pedestrians felt safe to cross the road in front of an approaching AV (with eHMI vs. no eHMI).

A final goal of the study was to investigate how pedestrians interpret the meaning of these eHMI solutions, and how they rate them, in terms of perceived usability.

2. Method

2.1. Participants

Twenty-Four participants (14 males and 10 females) aged between 24 and 62 (M_{age} = 36.96 years, SD_{age}= 12.57) took part in the study. The data from two participants had to be eliminated as no video recordings were available. In addition, for some participants the GPS data dropped from time to time during their recordings, and therefore distance and time information was missing for some trials. This led to a difference in degrees of freedom between different conditions, as some single data points were missing for participants (see Fig. 4 for the number of data points included in each analysis). Due to ethical and security concerns about facilitating interactions with an automated vehicle, all participants were employees of Centro Ricerche FIAT - Stellantis (CRF-Stellantis) from Italy (with no expertise in the field of automated driving). Participants had a normal or corrected-to-normal vision. Ethical approval was obtained from the University of Leeds Research Ethics Committee (Reference Number AREA 19–058).

2.2. Location and demonstrator

The study took place on a dedicated straight test-track area at the FIAT Safety Centre, near the CRF-Stellantis facilities in Orbassano, Italy (see Fig. 1).

The experimental demonstrator vehicle for this study was an automated Jeep "Renegade" MY2018 (Fig. 2) provided by CRF-Stellantis, operated by a Cooperation and Communication Planning Unit (see Markowski et al., 2019), which controlled the trajectory and speed of the vehicle, and triggered the relevant eHMI when a pedestrian was detected in a pre-defined area of interest (AoI, see red marking in Fig. 1). The control strategy of the braking function used in the interACT project was based on the necessary deceleration rate to keep a safety distance to the pedestrian, depending on the speed and on the distance at which the pedestrian was detected. The participants were asked to stand at the side of the track due to constraints around safety requirements and the capabilities of the test vehicle. A safety driver was present in the driver's seat to intervene in the event of an emergency. The car was equipped with an LED-based light band (developed by interACT partner Hella, for information on design and implementation see Kaup et al., 2019) on the bottom of the windshield. Two eHMI solutions (see Fig. 2) were implemented through this light band, which was connected to the AV's control system. The eHMI designs were developed in the interACT research project as solutions for safe interactions between vulnerable road users and AVs (Weber et al., 2019). The eHMI solutions consisted of:

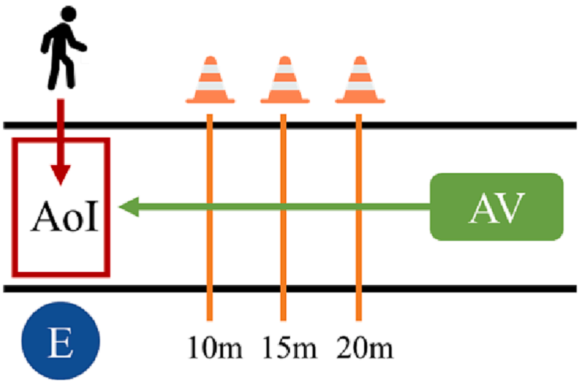

Fig. 1. Study set-up, including participant's starting position, their movement direction into the Area of Interest (AoI, red arrow), the experimenter's position (E), AV's approaching line (green arrow), and traffic cones at a 10 m, 15 m and 20 m distance from the participant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Ehmi solutions, the full light band design (left), and the partial light band design (right).

(i) A Full Light Band eHMI design (FLB), which consisted of a slow-pulsing cyan-coloured light band stretching across the bottom of the windscreen.
(ii) A Partial Light Band eHMI design (PLB), which was a smaller directed, cyan-coloured light band, that glowed in the direction of the addressee.

Both light bands pulsated at an average luminance of $\sim$ 1500 cd/m^2 at the highest luminance level, which dimmed to 2% of this value at the lowest luminance level. The light band pulsed between these two using a sinusoidal function, at two rates: slowly (0.4 Hz) and quickly (2 Hz). For the FLB, the entire light band was illuminated, whereas the directed light of the PLB was an illuminated moving block with a width of 35 pixels (35 cm). A dark cover was placed on the AV's bonnet to enhance the contrast of the cyan light of the eHMI, and to reduce reflections on the bonnet.

Both eHMI designs were developed and tested as part of the interACT project, along with other eHMI designs such as icons on a display or projections on the road. The most promising eHMI design was the light-based eHMI, as light is already used for vehicle communication, and it can potentially be placed around the whole vehicle to cover interactions with other road users in different directions (Sorokin et al., 2019). The FLB and PLB were both designed to indicate that the AV is giving the right-of-way (Weber et al, 2019). Thereby, two communication approaches were used: the FLB used an intention-based approach in pulsing to convey the AV's intention to yield and the PLB used a perception-based approach in following the movement of the pedestrian to reflect their detection. Lee et al. (2019) suggest that the design of a light-based eHMI doesn't impact the pedestrians' interpretation of the information displayed as pedestrians interpreted them both as signals communicating the right of way and the detection of the pedestrian. Thus, one key purpose of the current study was to understand if pedestrians interpreted these signals differently in a real-world context.

2.3. Procedure & study design

On arrival at the test track, participants were informed that the study aimed to examine pedestrians' interactions with automated vehicles, and their decision-making processes when crossing the road. They were told that for this experiment they would be interacting with a fully automated vehicle, which was driven autonomously, and that there would be a safety driver on board to monitor the system, but not control of the vehicle, apart from emergency situations. Participants started the experiment by standing at the side of the test track, and looking to their right, the opposite direction from the AV (see participant placement in Fig. 1). The experimenter stood opposite the participant, facing the direction of the vehicle (see experimenter placement in Fig. 1). The experimental procedure was as follows: On the experimenter's instruction, the participants were asked to step into the defined area of interest (AoI, the point at which the AV could detect the participant) and to turn their head to face the AV, which was approaching from their left at a maximum speed of $\sim$ 13 km/h. A within-participant design was used for the study, which required participants to respond to three potential eHMI design variations: no eHMI, Full Light Band eHMI (FLB), and Partial Light Band eHMI (PLB). Depending on the experimental test condition, participants were asked to raise their arm straight up:

(1) as soon as they could see the eHMI (eHMI Visibility);
(2) as soon as they noticed that the vehicle was decelerating (Deceleration Perception); or
(3) as soon as they felt safe to cross in front of the approaching AV (Crossing Decision).

A trial ended with the response of the participant. Participants completed a total of 24 trials - the first 9 trials always consisted of Crossing Decision trials (randomized across 3 eHMI types $\times$ 3 AV distances) to avoid a situation where participants' crossing decision were affected by previous questions about eHMI Visibility or Deceleration Perception. The order of the remaining 15 trials was counterbalanced across eHMI Visibility (randomized across 2 eHMI designs $\times$ 3 AV distances) and Deceleration Perception trials (randomized across 3 eHMI types $\times$ 3 AV distances).

Prior to starting the main experiment, participants were allowed to complete as many practice trials as necessary to feel comfortable with the set-up. Additionally, participants were asked to provide their feedback through post-trial and post-experimental questionnaires (see Section 2.5). In order to investigate how intuitive the eHMI designs were, participants were not informed about their meaning. The experiment lasted approximately 1.5 h for each participant, with the chance for a break halfway through the experiment.

2.4. Objective measures

A video camera was placed in the windshield of the AV, recording the view from the front of the vehicle. GPS data was also recorded for the AV, along with absolute time in seconds, and distance to the detected pedestrian in meters for each trial. To establish how participants responded to each task, video recordings were analysed to extract data about participants' encounters with the approaching AV. The time of each arm raise (in seconds) was identified from participant videos as the moment at which the participant began to move their arm upwards. Therefore, the first little arm and hand movement was captured through the video data. The distance (in meters) between the participant and the AV at this moment was identified using the GPS data. Measurements of eHMI Visibility, Crossing Decision Time, and Deceleration Perception Time were calculated as follows:

(1) **eHMI Visibility** was measured by asking participants to raise their arms as soon as they perceived the eHMI. The distance (in meters) of the AV from the pedestrian was recorded at the time of each arm raise.

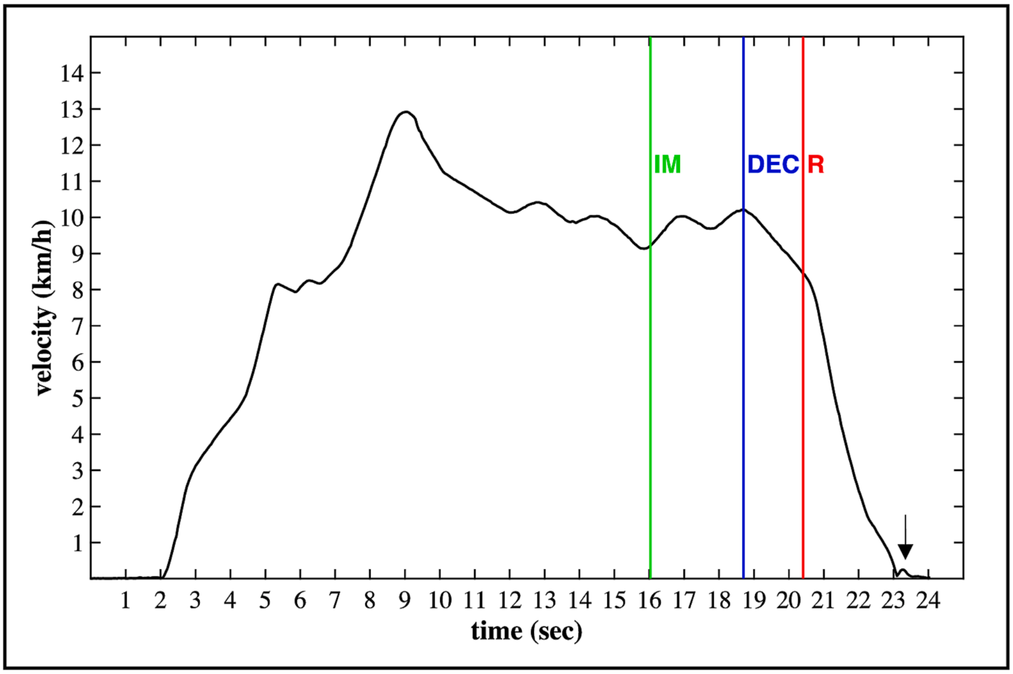

Fig. 3. AV velocity graph showing a sample trial for one participant. Markers identify the participant's initial movement into the AoI in green (IM), the AV's deceleration onset in blue (DEC), and the participant's response with an arm raise in red (R). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2) To investigate the pedestrians' **Crossing Decision Time** (*CDT*, in seconds), the AV's deceleration onset time was first identified, based on the point at which the AV began to brake evenly to come to a stop (see Fig. 3 for an example). This deceleration onset point was automatically identified using the findpeaks Matlab-function to detect the last peak in the velocity graph (see blue line in Fig. 3) for each trial. A threshold of 2 m/s (equivalent to 7.2 km/h) was set, to avoid the function returning the small peak before the AV stopped its' movement completely (see the peak after 23 s in the velocity graph shown in Fig. 3, marked with a black arrow). In order to incorporate an understanding of whether the AV kinematic behaviour affected pedestrians crossing decisions, CDT was calculated as the pedestrian arm raise onset time for the crossing trials (*R*, see red response time marker in Fig. 3), minus the AV deceleration onset time (DEC, see blue deceleration onset marker in Fig. 3):

$CDT = R – DEC$

(3) Similarly, **Deceleration Perception Time** (*DPT*, in seconds) was calculated as the pedestrian arm raise onset time (*R*) in the deceleration perception trials, minus AV deceleration onset time (*DEC*):

$DPT = R - DEC$

2.5. Subjective measures

After each of the Crossing Decision trials (first 9 trials), the participants were asked to provide a verbal rating on the following two items:

- *'I felt confident in my decision of when to cross the road.'*, and
- *'I felt safe during this encounter with the automated vehicle.'*,

using a 10-point-scale from 1- "Strongly Disagree" to 10- "Strongly Agree".

When the participants completed all 24 experimental trials, they were asked about their interpretation of the two eHMI solutions, and a questionnaire was provided to assess the effects of the eHMI designs on usability ratings. Usability was measured with the System Usability Scale (Brooke, 1986), a 10-item questionnaire rated from 1 (strongly disagree) to 5 (strongly agree).

3. Results

3.1. Data Checking: Analysis of participants' initial movement distance

The instruction to step forward into the AoI was based on the experimenter's judgment of when the AV reached certain markers on the road (see traffic cones at a 10 m, 15 m, and 20 m distance from the participant in Fig. 1). It was anticipated that there would be

Dependent Variables	Independent Variables (IVs) Distance	eHMI type	Statistical test	n / N = 24 included in test
eHMI Visibility Distance	10 m →	FLB vs. PLB	t-test (IV: eHMI type)	21
	15 m →	FLB vs. PLB	t-test (IV: eHMI type)	19
	20 m →	FLB vs. PLB	t-test (IV: eHMI type)	17
Deceleration Perception Time	10 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	21
	15 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	19
	20 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	17
Crossing Decision Time	10 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	20
	15 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	20
	20 m →	FLB vs. PLB vs. no eHMI	ANOVA (IV: eHMI type)	17

Fig. 4. Statistical analysis plan for the step-forward distance data checking and the objective measures (eHMI Visibility Distance, Deceleration perception Time, and Crossing Decision Time) including the number of participants included in each test.

some variability in the participant's "Initial Movement Distance" to the AV across participants and trials, as each participant was likely to have a certain reaction time to the experimenter's instruction. Due to this variability, participants' initial movement distance to the AV for each eHMI condition were compared to ensure that this Initial Movement Distance did not differ significantly between the eHMI groups. The three distance conditions (10 m, 15 m, and 20 m) were analysed as separate measurement groups and not statistically compared to each other.

The resultant statistical analysis plan for the study's results is described in Fig. 4. The analysis plan includes the statistical tests conducted for each dependent variable and the number of participants included in each test. All quantitative data were analysed using IBM SPSS.

Following the statistical analysis plan in Fig. 4, separate analysis of the Initial Movement Distance for (1) the eHMI Visibility trials, (2) the Deceleration Perception trials, and (3) the Crossing Decision trials were conducted:

(1) For the eHMI Visibility trials, three separate paired-sample t-tests (IV: eHMI type) were performed between the two eHMI types (FLB vs. PLB), for each distance condition. A corrected alpha level of 0.02 was used to interpret the outcome. The results showed no significant difference in the participants Initial Movement Distance between FLB and PLB trials at 10 m ($t(20) = -0.49$, $p = .63$), 15 m ($t(18) = 0.74$, $p = .47$), or 20 m distance ($t(16) = 0.008$, $p = .99$). The results of this analysis suggest that any differences in response times for the eHMI Visibility trials are not due to differences in Initial Movement Distance. The actual distances at the participants' initial movement had a spread of approximately 4–5 m in each distance condition (see Appendix 1 for scatterplots of the eHMI Visibility trials for each distance condition).

(2) For the Deceleration Perception trials three ANOVAs (IV: eHMI type) were conducted for each distance condition between the three eHMI conditions (FLB vs. PLB vs. no eHMI). The pattern of results was similar to the eHMI Visibility trials (see Fig. 5). The results showed no significant differences between eHMI conditions in the 10 m ($F(2,20) = 0.45$, $p = .64$), and 20 m ($F(2,16) = 0.49$, $p = .61$) trials. However, there was a significant difference between the initial movement distances for PLB and FLB in the 15 m trials ($F(2,18) = 3.54$, $p = .04$, $r = 0.64$), with a large effect size (Rosenthal, 1991). A post-hoc-test with Bonferroni correction shows that the mean distance at the participant's initial movement into the AoI for the trial without eHMI was significantly longer than for the trials with PLB ($p = .04$). This could indicate that the AV was on average further away for trials without eHMI. Another reason could be the presence of an outlier data point in the PLB condition, at a distance of 8.90 m (see Fig. 5, second scatterplot). When this outlier was removed, the difference between PLB and no eHMI trials was no longer significant ($p > .5$). However, this significant effect for the 15 m condition was taken into account in the interpretation of the Deceleration Perception Time trials (see section 3.2.2), with the anticipation that if the initial movement distance influenced the Deceleration Perception Time, participants would have faster Deceleration Perception Times for the no eHMI condition than for the other two conditions.

(3) A check of the participant's Initial Movement Distance in the Crossing Decision trials (see scatterplots in Appendix 2), including three ANOVAs (IV: eHMI type) for each distance condition between three eHMI conditions (FLB vs. PLB vs. no eHMI), revealed no significant differences at the 10 m ($F(1,19) = 2.34$, $p = .11$), 15 m ($F(1,19) = 0.09$, $p = .91$), or 20 m ($F(1,16) = 1.22$, $p = .31$) distance conditions. The results of this analysis suggest that any differences in response times for the Crossing Decision trials are not due to differences in Initial Movement Distance.

3.2. Objective measures

3.2.1. Comparison of eHMI VISIBILITY DISTANCE between FLB and PLB

Fig. 6 shows the average eHMI Visibility Distance for the trials with FLB and PLB. Repeated measures t-tests were conducted separately for each of the distance conditions. Results revealed that the participants detected the PLB at a significantly further distance

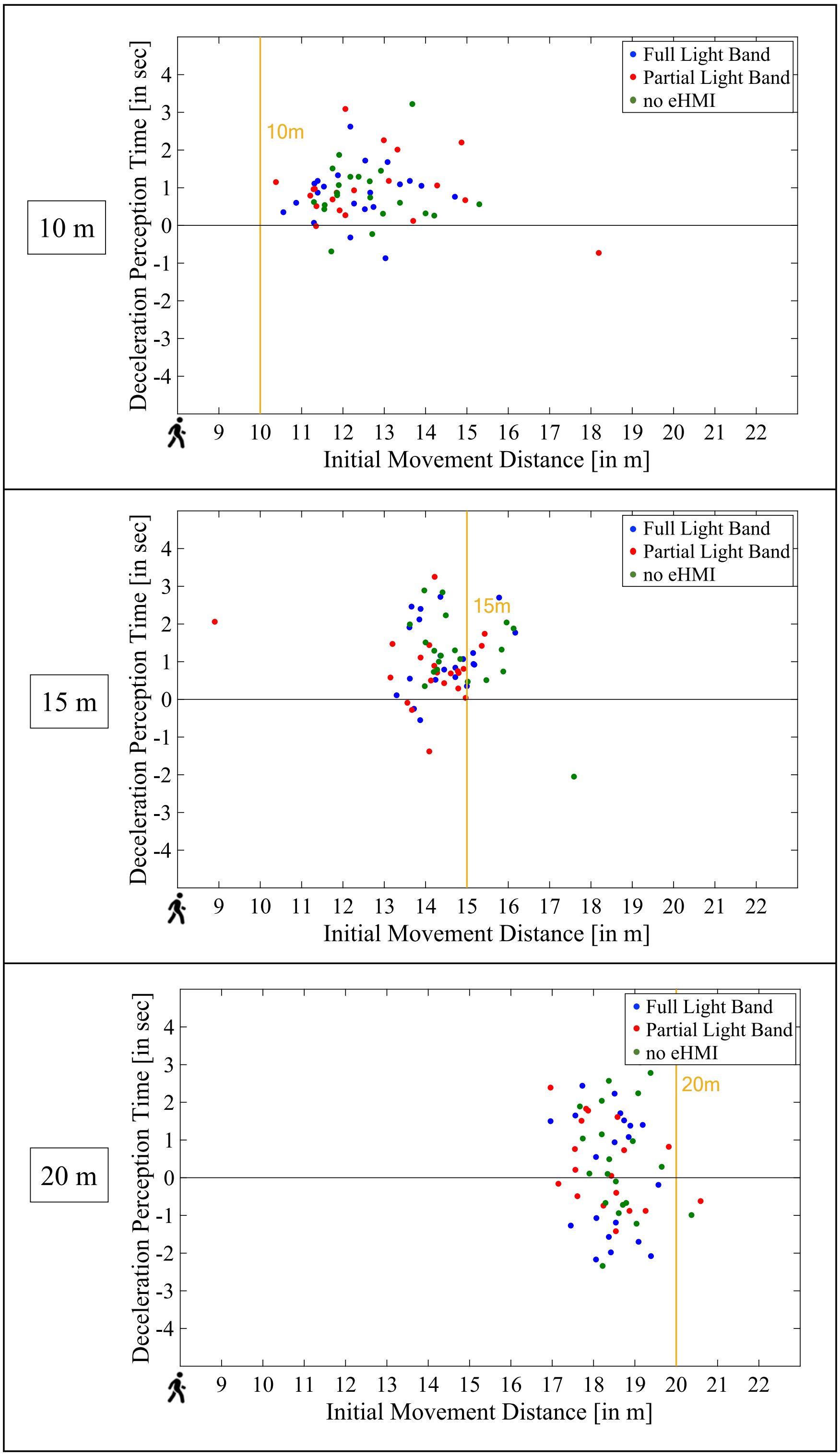

Fig. 5. Overview of the participant's **Initial Movement Distance** (x-axis) in the 10 m, 15 m, and 20 m conditions for the **Deceleration Perception** trials, against their **Deceleration Perception Time** (y-axis), including data for each participant (one scatter point equals one participant's trial) and all three eHMI conditions (FLB, PLB, and no eHMI). Deceleration Perception Time below zero incorporates participant's response before AV started to decelerate.

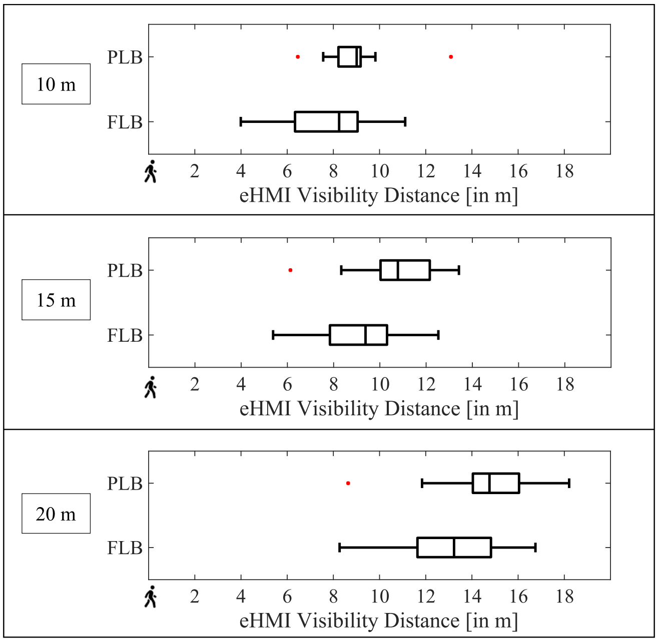

Fig. 6. Participant's eHMI Visibility Distance across three distance conditions (10 m, 15 m, 20 m), and two eHMI types (FLB and PLB), boxplots including median and outliers (red points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

than the FLB in the 15 m ($t(18) = -3.73$, $p = .002$, $r = 0.66$), and 20 m ($t(16) = -3.51$, $p < .003$, $r = 0.66$) distance conditions, with large effect sizes (Rossenthal, 1991). Using the corrected alpha level (significant for $p < .02$), results show no significant effect for the 10 m ($t(20) = -2.41$, $p = .023$, $r = 0.47$) distance condition. Tests for age effects on the perception task were conducted for each distance condition and revealed no effects ($p > .05$).

3.2.2. Comparison of DECELERATION PERCEPTION TIME between FLB, PLB and no eHMI

Three one-way ANOVAs were conducted to compare Deceleration Perception Times between eHMI conditions in the 10 m, 15 m, and 20 m trials. As a significant difference in the participant's Initial Movement Distance into the AoI was found between PLB and no eHMI conditions in the 15 m trials (see results pre-analysis in section 3.1), it could be expected that if the initial movement distance had an influence on deceleration perception, the participants would have perceived the deceleration for the no eHMI trial condition quicker. However, results showed that there was no effect of the presence of an eHMI on how quickly the participants perceived the

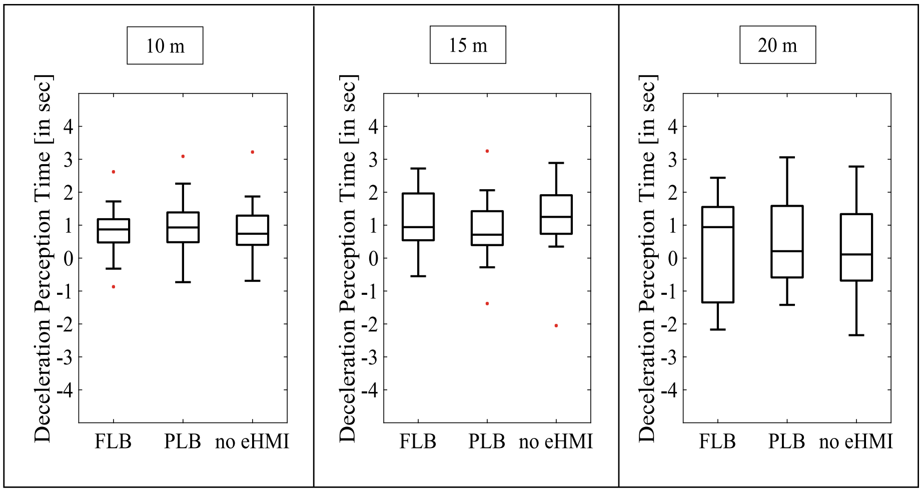

Fig. 7. Participant's Deceleration Perception Time across the three distance conditions (10 m, 15 m, 20 m), and three eHMI conditions (FLB, PLB, no eHMI), boxplots including median and outliers (red points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

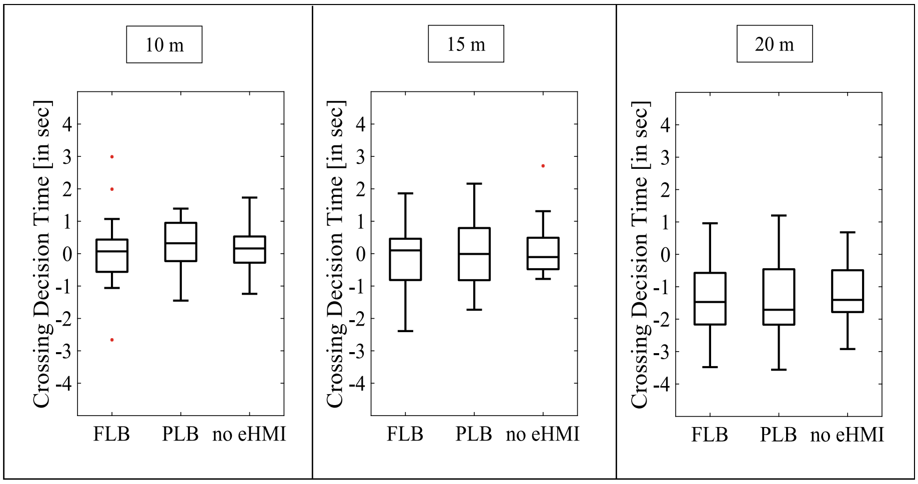

Fig. 8. Participant's Crossing Decision Time across the three distance conditions (10 m, 15 m, 20 m), and three eHMI conditions (FLB, PLB, no eHMI), boxplots including median and outliers (red points). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deceleration of the AV in the 10 m ($F(1,20) = 0.40$, $p > .68$), 15 m ($F(1,18) = 1.40$, $p = .26$) or 20 m trial ($F(1,16) = 0.44$, $p = .65$).

Overall, the results revealed that, the closer the AV, the faster the Deceleration Perception Time (see Fig. 7). Negative values indicate that participants responded/raised their arm before the AV started to decelerate. The spread of the data in the 20 m distance condition is larger than in the 10 m or 15 m distance condition, suggesting participants had greater difficulty identifying AV behaviour at further distances.

3.2.3. Comparison of Crossing Decision Time between FLB, PLB, and no eHMI

When looking at the results for the Crossing Decision task (see Fig. 8), the three one-way ANOVAs showed that there was no significant effect of the presence of an eHMI on participants' Crossing Decision Time in the 10 m ($F(1,19) = 0.65$, $p = .53$), 15 m ($F(1,19) = 1.25$, $p = .28$), or 20 m distance condition ($F(1,16) = 0.24$, $p = .78$). At further distances (20 m) the majority of the participants indicated a willingness to cross before the AV started the deceleration process (Crossing Decision Time < 0 sec).

3.3. Comparison of subjective responses

3.3.1. Perceived confidence & safety

After each Crossing Decision trial (the first 9 trials for each participant), participants were asked to provide ratings of their perceived confidence in their crossing decision and their perceived safety, on a 10-point-scale from 1 (strongly disagree) to 10 (strongly agree), while encountering the AV. Three one-way ANOVAs showed no significant differences between the three eHMI conditions (FLB, PLB, no eHMI) on the perceived confidence or safety ratings of participants for any of the distance conditions (see Table 1). These findings suggest that there was no effect of the presence of an eHMI on how safe or confident participants felt when crossing the road in front of an approaching AV. Participants gave somewhat higher ratings of safety and confidence in their crossing decisions the further away the AV was. However, the ratings were high for both scales on the whole, and above the scale midpoint of 5.5.

Table 1
Results for perceived confidence and safety including means for each of the eHMI conditions (FLB, PLB, no eHMI), within each distance condition for N = 24 participants.

		CONFIDENCE	
	10 distance condition	15 distance condition	20 distance condition
Means	$M_{FLB} = 8.83(SD = 1.34)$ $M_{PLB} = 8.75(SD = 1.15)$ $M_{noeHMI} = 8.96(SD = 1.12)$	$M_{FLB} = 9.21(SD = 1.10)$ $M_{PLB} = 9.00(SD = 1.14)$ $M_{noeHMI} = 9.17(SD = 1.09)$	$M_{FLB} = 9.33(SD = .96)$ $M_{PLB} = 9.38(SD = .77)$ $M_{noeHMI} = 9.38(SD = .88)$
ANOVA	$F(2,23) = .65, p = .29$	$F(1.55,23) = 1.25, p = .29$*	$F(2,23) = .06, p = .94$
		SAFETY	
	10 distance condition	15 distance condition	20 distance condition
Means	$M_{FLB} = 8.92(SD = 1.21)$ $M_{PLB} = 8.88(SD = 1.23)$ $M_{noeHMI} = 8.88(SD = 1.19)$	$M_{FLB} = 9.29(SD = 1.19)$ $M_{PLB} = 9.00(SD = 1.35)$ $M_{noeHMI} = 9.38(SD = .92)$	$M_{FLB} = 9.33(SD = 1.01)$ $M_{PLB} = 9.33(SD = .96)$ $M_{noeHMI} = 9.21(SD = 1.06)$
ANOVA	$F(2,23) = .06, p = .94$	$F(2,23) = 1.82, p = .17$	$F(2,23) = .38, p = .69$

* Greenhouse-Geisser correction due to Mauchly's test of sphericity was not satisfied.

Table 2
Interpretation categories of the FLB and PLB, including number of participants' answers.

FLB - interpretation categories	n / 29	PLB - interpretation categories	n / 24
AV detected me	13	AV detected me	6
safe to cross	4	AV detected me and my position	8
AV is braking	5	AV is braking	3
AV works correctly	1	safe to cross	2
distance to user	1		
AV's driving mode (automation on)	1		
no interpretation	4	no interpretation	5

3.3.2. *Interpretation of the signal*

Responses to open-ended questions about the participants' interpretation of the eHMI solutions ('*During the experiment how did you interpret the eHMI displayed in* Fig. 1*/2?*') were categorized and counted by two independent referees (see Table 2). Multiple responses were possible for the participants, and, in total, 24 participants provided 29 responses regarding the FLB and 24 responses regarding the PLB. Results showed that, when observing the FLB signal, more than half of the participants' ($n = 13$) thought that the signal indicted 'AV detected me', with comments such as "Indication that the vehicle saw me" or "I think the eHMI switches on when it sees me". The other half of the participants provided less specific answers and interpreted the FLB signal as "a safe signal, to cross the road" ($n = 4$) or as the "beginning of braking action" ($n = 5$). Similarly, the most common interpretation categories for the meaning of the PLB signal were 'AV detected me' ($n = 6$) and 'AV detected me and my position' ($n = 8$) with comments such as "Indication that the vehicle saw me" and "It was like an eye. I knew exactly where the vehicle was looking at.".

3.3.3. *Usability*

System Usability Scores for each item were converted to an aggregated score ranging from 0 (worst) to 100 (best). The mean System Usability Score (SUS) across all participants was 68.05 ($SD = 4.23$) for the FLB and 66.17 ($SD = 4.06$) for the PLB. According to other literature in this area (Sauro, & Lewis, 2016), scores under 68 are considered to be average, and systems scoring above 68 are considered to be over average. Our results suggest that overall participants were rather indecisive regarding the usability of the presented eHMIs. A *t*-test did not reveal a statistical difference between the average SUS rating of the FLB and PLB ($t\,(23) = 0.71$, $p = .49$).

4. Discussion and conclusions

The aim of this test-track study was to investigate pedestrian reactions to LED-based eHMI solutions and AV movement patterns in natural daylight conditions. We investigated three main topics: (1) the visibility of the two eHMI designs, (2) the impact of the presence of an eHMI on participants' ability to perceive the deceleration behaviour of an AV, and (3) the impact of an eHMI on pedestrians' crossing decisions around an approaching AV.

Overall, the findings suggest that participants can see the Partial Light Band (PLB) design from a further distance than the Full Light Band (FLB) design. This finding was unexpected, as research into visual perception has generally suggested that larger objects or symbols appear in one's viewpoint earlier than smaller objects (e.g. De Lucia, 1991). However, it is possible that the movement of the PLB across the black LED band, and the contrast between the light and LED-band colour led to a greater contrast, that was easier to detect. This observation was also made by Hensch et al. (2019) who found that their moving light-based eHMI attracted more attention than a not moving eHMI signal.

There was no significant effect of eHMI on crossing decisions or deceleration perception, indicating that the eHMI had no effect on participants ability to judge the movement patterns of the AV, or their willingness to cross in front of the vehicle. Previous research has shown that participants made faster crossing decisions in front of an AV with eHMI than without (e.g. Song, et al., 2018; Lee et al., 2020b; Wang, & Xu, 2020). However, our data revealed that the presence or design of the LED-based eHMIs didn't affect how quickly participants decided when it is safe to cross the road. Lee et al. (2020b) found that the effect of their flashing headlights eHMI only emerged at particular kinematic combinations (at speeds of 25, 30, and 35mph, equivalent to ~ 40 to 56 km/h, and smaller time gaps of 2 to 3 s). Thus, it is possible that differences might emerge at faster speeds than the 12 km/h the AV was travelling at in the current study.

Interview data revealed some ambiguity in how participants interpreted the eHMI signals portrayed in this study. Half of the participants interpreted the eHMIs as providing information about the AV's detection of the pedestrian (FLB and PLB) and the detection of the position of the pedestrian (PLB). A smaller group interpreted the signals as providing information that the AV was braking or that it was safe to cross (FLB and PLB), and a few participants were not able to infer any reasonable meaning. Thus, there was no consistent meaning assigned to either eHMI across participants. This rather low level of comprehensibility of LED- or light-based eHMI signals was also reported in previous research works (Ackermann et al., 2019; Lee et al., 2019, Schieben et al., 2019b, and Hensch et al., 2019). Regardless of the eHMI type or absence of the eHMIs, pedestrians generally provided feedback that they felt safe and confident in interacting with the AV. Taken together, these results suggest that participants did not use the eHMI to inform their crossing decisions. Indeed, although there was variance in crossing decisions and deceleration perception times at further distances, participants provided slightly higher ratings of perceived confidence and safety the further away the AV was. This suggests that pedestrians felt safer crossing at further distances from the AV, regardless of their perception of the eHMI or deceleration behaviour.

These results are supported by previous finding from Suh et al. (2013) and Clamann et al. (2017) that the distance is a main determinant in pedestrians' decision to cross. However, the slow speed of the AV must be taken into account, as research by Beggiato et al. (2017a) has shown that pedestrians' decisions to cross are affected by estimations of time to arrival.

4.1. Limitations

In the current study, the participant's initial movement distance to the AV had two sources of errors: First, the experimenter's judgment of when the AV reached the distance markers on the road (10 m, 15 m, 20 m) could vary, leading to some inconsistency in the participant's Initial Movement Distance towards the AV. Second, the participants' own reaction time to the experimenter's instruction also led to a small delay. In order to counteract this issue, we checked the participants' initial movements into the AoI for all three test conditions (eHMI Visibility, Deceleration Perception, and Crossing Decision) across all three distances (10 m, 15 m, and 20 m) and all three eHMI conditions (FLB, PLB, and no eHMI). As already mentioned, this difference did not have an evident influence on this study's outcome (see section 3.2.2), but it did limit the comparisons across the three distances, which is something future research should consider. It also could be possible that the study set up using pylons along the road confounded the perception task, because subjects might use these cues. Future studies should also allow more natural crossing scenarios. In this study participants were instructed to stand at the side of the track and asked to step in the AoI which is not as natural as found on the real road environment. Furthermore, our study was conducted with a small number of participants, and only involved one AV and therefore couldn't represent the realistic traffic environment where the pedestrian has to interact with several traffic participants at the same time.

4.2. Conclusions

To our knowledge, this is the first study evaluating pedestrians' responses to a machine-controlled AV and eHMI signals in real world conditions. Both eHMI solutions showed good visibility in daylight conditions across all distances examined, although the PLB design was perceived further away than the FLB design. This suggests that a moving light signal, with high contrast to the surrounding vehicle may be an optimal way to convey messages in a real-world setting. While there were no differences in crossing decision or deceleration perception times based on eHMI design or presence, both eHMI designs were rated highly, suggesting that their inclusion may aid perceived usability of AVs. Future research, in higher speed and more complex settings is required to understand how these factors influence visibility and perception of AV eHMIs and movement patterns in naturalistic environments.

CRediT authorship contribution statement

Stefanie Horn: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Ruth Madigan:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Yee Mun Lee:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – review & editing, Supervision. **Fabio Tango:** Conceptualization, Methodology, Software, Resources, Writing – review & editing, Project administration. **Natasha Merat:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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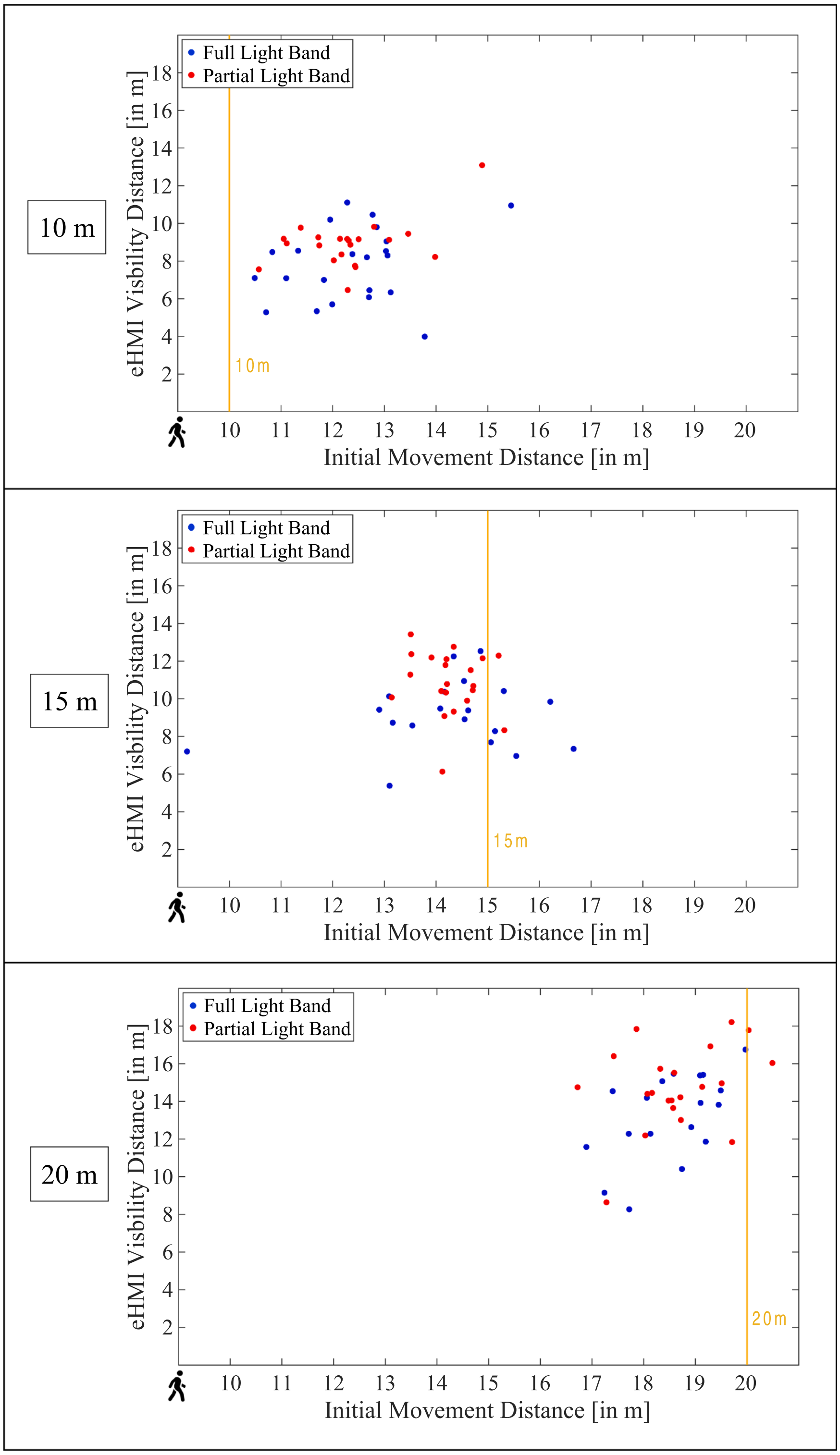
Appendix 1:. Overview of the participant's initial movement distance (x-axis) in the 10 m, 15 m, and 20 m conditions for the eHMI Visibility trials, against their eHMI Visibility distance (y-axis), including data for each participant (one scatter point equals one participant's trial) and two eHMI solutions (FLB and PLB).


10 m
Full Light Band
Partial Light Band
eHMI Visbility Distance [in m]
18
16
14
12
10
8
6
4
2
10 m
10
11
12
13
14
15
16
17
18
19
20
Initial Movement Distance [in m]
15 m
15 m
20 m
20 m

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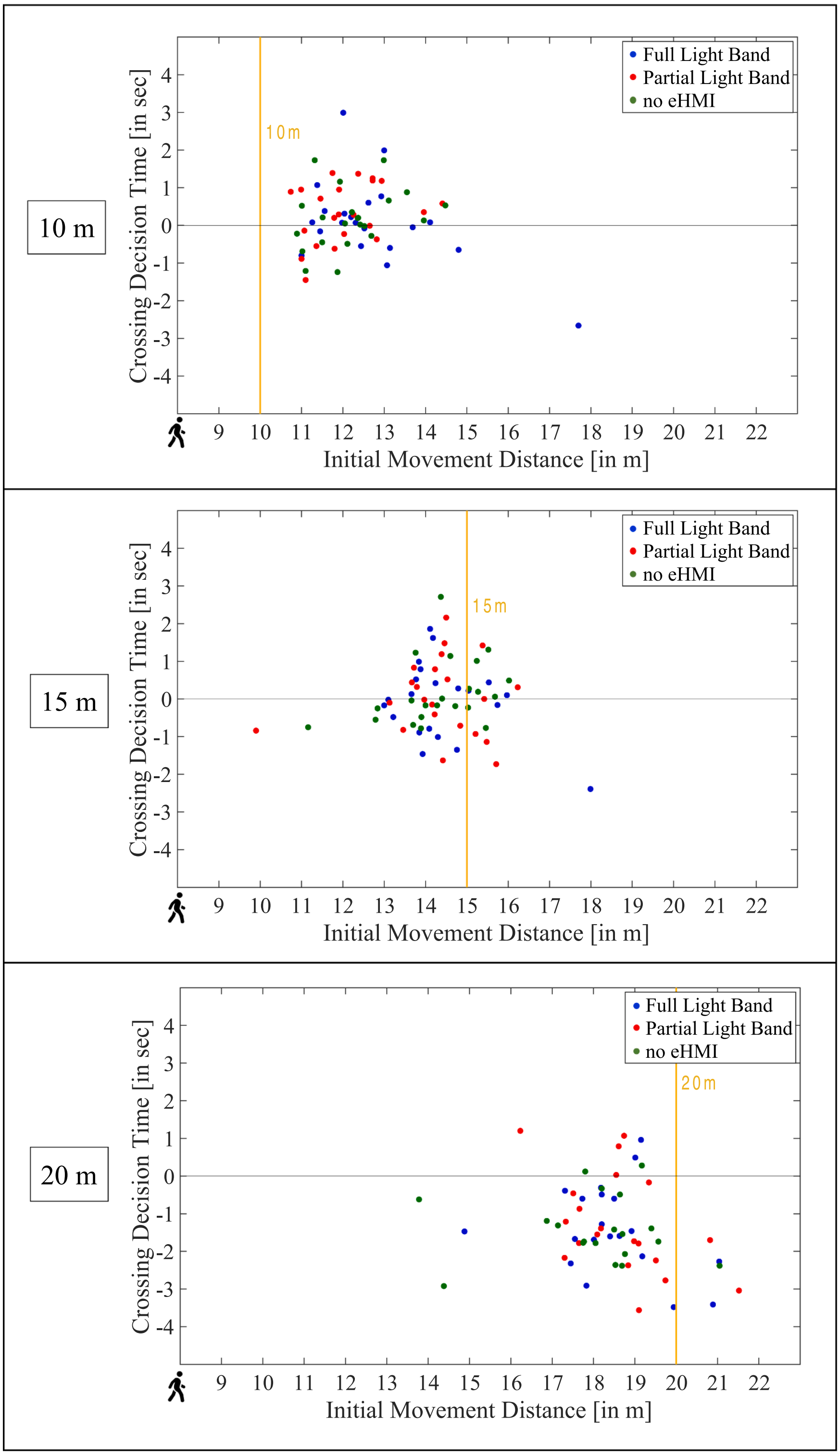
Appendix 2:. Overview of the participant's initial movement distance (x-axis) in the 10 m, 15 m, and 20 m conditions for the crossing Decision trials, against their crossing Decision time (y-axis). One scatter point equals one participant's trial in each of the three eHMI conditions (FLB, PLB and, no eHMI). Crossing Decision time below zero incorporates participant's crossing before AV started to decelerate.



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