Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrians' crossing behaviour

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ABSTRACT

In current urban traffic, pedestrians attempting to cross the road at un-signalised locations are thought to mostly use implicit communication, such as deceleration cues, to interpret a vehicle's intention to yield. There is less reliance on explicit driver- or vehicle-based messages, such as hand/head movements, or flashing lights/beeping horns. With the impending deployment of Automated Vehicles (AV), especially those at SAE Level 4 and 5, where the driver is no longer in control of the vehicle, there has been a surge in interest in the value of new forms of communication for AVs, for example, via different types of external Human Machine Interfaces (eHMIs). However, there is still much to be understood about how quickly a novel eHMI affects pedestrian crossing decisions, and whether it provides any additional aid, above and beyond implicit/kinematic information from the vehicle. The aim of this between-participant study, funded by the H2020 interACT project, was to investigate how the combination of kinematic information from a vehicle (e.g. Speed and Deceleration), and eHMI designs, play a role in assisting the crossing decision of pedestrians in a cave-based pedestrian simulator. Using an existing, well-recognised, message for yielding (Flashing Headlights - FH) as a benchmark, this study also investigated how quickly a novel eHMI (Slow Pulsing Light Band – SPLB) was learned. To investigate the effect of eHMI visibility on crossing decisions, the distance at which each eHMI was perceivable was also measured. Results showed that, compared to SPLB, the FH led to earlier crossings during vehicle deceleration, especially at lower approaching speeds, and smaller time gaps. However, although FH was visible earlier than SPLB, this visibility does not appear to be the only reason for earlier crossings, with message familiarity thought to play a role. Participants were found to learn the meaning conveyed by FH relatively quickly, crossing around 1 second earlier in its presence (compared to the no eHMI condition), across the three blocks of trials. On the other hand, it took participants at least one block of 12 trials for the new SPLB signal to affect crossing, which only accelerated crossing initiations by around 200ms, compared to the no eHMI condition. The role of comprehension, long-term exposure, and familiarity of novel messages in this context is therefore important, if AVs are to provide safe, trustworthy communication messages, which will enhance traffic flow and efficiency.

Keywords: pedestrian, AV, crossing, user experience, eHMI, Cave-based pedestrian simulator

1. INTRODUCTION

In conventional, mixed, road traffic situations, pedestrians are thought to interpret vehicle intentions mainly by using non-verbal/implicit communication cues from the vehicle, such as its speed, time-to-arrival, and stopping distance (Ackermann et al., 2019a; Petzoldt et al., 2018; Šucha et al., 2017; Varhelyi, 1998; Wang et al., 2014; Dey & Terken, 2017; Lee et al., 2020; Uttley et al., 2020). In addition, for example, during conflict situations, when two road users are likely to "*occupy the same region of space at the same time in the near future*" (Markkula et al., 2020), road users may also convey their intentions to one another by using hand/head gestures, facial expressions and/or eye contact (Rasouli et al., 2017; Šucha et al., 2017; Mahadevan et al., 2018). However, with the impending introduction of Autonomous Vehicles (AVs), especially those operating at Levels 4 and 5 (SAE, 2018), where a human is not necessarily in control of the driving task, pedestrian-driver communication is no longer possible.

Although there are currently conflicting findings on the extent to which explicit communication occurs between road users (e.g. Lee et al., 2020; Uttley et al., 2020, Dey & Terken, 2017; Rasouli et al., 2018), there is evidence that pedestrians and cyclists would appreciate some form of explicit communication from future automated vehicles, for example, to acknowledge their detection by an approaching AV, or for situations when the AV needs to communicate information about its future path (Merat et al., 2018; Schieben et al., 2018). In addition, research has shown that humans are not always very accurate at identifying implicit cues, such changes in speeds, especially when the vehicle is far away (e.g. Cavallo & Laurent, 1988; DeLucia, 2008; Smeets et al., 1996; Scialfa et al., 1991). Therefore, researchers and OEMs are investigating the design of various prototypes, and concepts, for externally facing interfaces that enable explicit communication by future AVs (e.g. Daimler, 2015; Nissan Motor Corporation, 2015; Semcon, 2016; Volvo Car, 2018; Daimler, 2017; Drive.ai, 2018; Jaguar Land Rover, 2018), see also overviews by Bazilinskyy et al., 2019; Rasouli & Tsotsos, 2019; Schieben et al., 2019.

The most common version of such designs, collectively called external Human Machine Interfaces (eHMIs), involves some form of light- or text-based message, either placed in different locations on the outside of the vehicle, or projected on the road (e.g. Bazilinskyy et al., 2019, Hillis et al., 2016). Auditory cues, involving pure tones or spoken word have also been used (e.g. Deb et al., 2018, Lee et al., 2019c). However, it is not currently clear what particular aspects of such eHMI are most successful for communicating the range of messages required from an AV when it is interacting with other road users. In addition, evaluating their benefits in terms of providing helpful, and timely, information to pedestrians and other Vulnerable Road Users is a major research gap.

A number of methods have been used to investigate if eHMIs are suitable and effective for conveying the AV's intentions and behaviour, to pedestrians. Examples include self-report studies, using questionnaires and interviews (e.g. Ackermann et al., 2019b; Deb et al., 2018; Otherson et al., 2018), computer-screen based tasks (e.g. Ackermann et al., 2019b; Fridman et al., 2017; Bazilinskyy et al., 2019; Lee et al., 2019c; Dey et al., 2020a), field tests, real-world experiments (e.g. Clamann et al., 2017; Matthews et al., 2017; Habibovic et al., 2018; Faas & Baumann, 2019; Hensch et al., 2019), and various forms of pedestrian simulator studies (e.g. Chang et al., 2017; Böckle et al., 2017; De Clercq et al., 2019; Holländer et al., 2019a; Lee et al., 2019b; Löcken et al., 2019; Deb et al., 2018; Feldstein et al., 2016; Ackermann et al., 2019b; Kooijman et al., 2019).

In particular, researchers have started to investigate if eHMIs affect pedestrians' crossing behaviour, and subjective experience, such as whether they are accepted, trusted and liked. For example, Chang, Toda, Sakamoto and Igarashi (2017), found that their eHMI concept (a pair of eyes on the car) decreased the mean decision-making time of pedestrians asked to consider crossing in front of an AV (by pressing a button), compared to crossing in front of AVs without these eyes. Similarly, using a Head-Mounted Display (HMD), Holländer et al. (2019a) reported that eHMIs significantly reduced pedestrians' crossing initiation time, and concluded that eHMIs improve feelings of comfort, trust and acceptance about AVs. Using an HMD, Deb et al. (2018) found that eHMIs increased participants' willingness to interact with AVs, whereby participants felt more comfortable and more positive about sharing the same space with these AVs if eHMIs were included. Finally, using a video-based approach, and a handheld slider for recording responses, Dey et al. (2020a) reported that distance-based eHMI, used to inform of the AV's yielding behaviour, such as "I have seen you and I am yielding" or "I am yielding and here is an estimate of when I will come to a full stop", improved understanding of the AV's intentions, and increased pedestrians' willingness to cross. In terms of the success of different eHMIs for conveying the correct message, results are mixed, with some studies showing the same response by pedestrians to a range of very different looking/sounding eHMIs (e.g. Deb et al., 2018; de Clercq et al., 2019; Kooijman et al., 2019), and others suggesting that one eHMI can be perceived as portraying two very different, and contradictory, messages (Lee et al. 2019c).

Despite the large interest in this area, and a surge in recent studies, a number of research gaps still remain. For example, many studies on pedestrian-vehicle interactions suggest that pedestrians typically use implicit cues from the vehicle, such as its deceleration profile, to help with their crossing decisions (e.g. Ackermann et al., 2019a; Petzoldt et al., 2018; Šucha et al., 2017; Varhelyi, 1998; Wang et al., 2014; Dey & Terken, 2017; Lee et al., 2020). However, as highlighted above, humans are not very good at identifying subtle changes in kinematic behaviour, especially if the vehicle is far away. In addition to being associated with positive affect (e.g. Deb et al., 2018; Kooijman et al., 2019; Chang et al., 2017; Böckle et al., 2017; De Clercq, 2019), eHMI messages may, therefore, be useful as an additional aid for improving the speed and accuracy of crossing decisions, particularly if the messages are clearly visible and comprehensible from afar. In a Wizard-of-Oz test track study, Dey et al. (2020b) investigated the effect of eHMIs and yielding behaviours on pedestrians willingness to cross by using a slider as input. Authors found an effect of eHMI when the approaching AV was in the 'Gentle Brake' and 'Early Brake' conditions, but no effect of eHMI was shown in the 'Aggressive' braking and 'Constant Speed' conditions. Conversely, in a CAVE-based pedestrian simulator study, Kaleefathullah et al. (2020) demonstrated that after a series of exposures to a functioning eHMI conveying a yielding message, approximately 35% of pedestrians walked onto the road when the eHMI was presented but the approaching vehicle was not decelerating. This suggests that pedestrians may become over-reliant on information conveyed through eHMI, to the point where they start to ignore the vehicle movement behaviour. Together, these studies provide valuable insights as to how a conflict between eHMI messages and AV yielding patterns may cause confusion for pedestrians. This then raises the question of how to best present the combination of eHMI and kinematic information (i.e. different speed and deceleration profiles) from a vehicle, in order to reduce confusion for the pedestrian, and ensure that both sources of information are interpreted the same way. Knowledge on how implicit and explicit messages from future AVs are received at different approaching speeds and distances is also valuable, and is, at present, an under-researched topic.. Some research has suggested that crossing decisions are faster if an eHMI is easily perceivable from a distance, or if it can be pre-attentively processed (Treisman, 1985), by using the right form, colour and position (Holländer et al. 2019b). The current study will investigate this in more detail. It is also important to investigate pedestrians' actual crossing behaviour in response to AV cues.

Based on the above research gaps, one aim of the current study, (funded by the H2020 interACT project; Grant number 723395), was to investigate the impact of two different eHMIs on pedestrians' crossing behaviour, and how/if this was affected by the speed and deceleration behaviour of the approaching vehicle. The aim was, therefore, to understand the circumstances in which crossing pedestrians use an eHMI for decision-making, versus those where vehicle kinematics are used.

With the plethora of eHMI concepts being tested, another aim of the current study was to investigate how quickly the meaning of messages conveyed from a novel eHMI can be learned by crossing pedestrians, when compared to a more conventionally used message: A Flashing Headlight. In order to avoid the possibility of carry-over effects, and transferrable learning from one eHMI to another, we used a between-participants approach. Finally, the distance at which each eHMI was perceived was also measured, to provide a more concrete understanding of how eHMI visibility plays a role in crossing decisions.

2. METHOD

2.1 Participants

Ethical approval was obtained from the University of Leeds Research Ethics Committee (Ref: LTTRAN-107). Forty participants were recruited for this study, via the University of Leeds Driving Simulator database, notices posted in the University's students' union building, and social media posts. Participants were divided into two groups based on the two eHMI Designs: Slow Pulsing Light Band group, and Flashing Headlights group. These groups were matched in terms of age and gender. The demographic information for each group is shown in Table 1.. The study lasted 1.5 hours and participants were paid £15 for taking part in the study.

Table 1. Demographic information for the participants recruited in this study

Groups	N	Age			Years spent in the UK		
		Range	M	S.D	Range	M	S.D
Slow Pulsing Light Band (SPLB)	12M, 8F	20-34	28.1	4.18	1-34	24.43	10.04
Flashing Headlights (FH)	12M, 8F	19-34	27.85	4.69	1-34	21.08	10.12

2.2 Apparatus and Virtual Environment

The experiment was conducted in the University of Leeds Highly Immersive Kinematic Experimental Research (HIKER) laboratory, an advanced CAVE-based pedestrian simulator, funded by the UK EPSRC (EP/T008833/1, see Figure 1). The HIKER lab is a controlled and safe environment which provides walking space to pedestrians in a 9-metre-long by 4-metre-wide physical space, which incorporates an array of 4k projectors, providing an immersive Virtual Reality (VR) environment that responds to the participant's head position. Participant tracking is achieved using a pair of tracking glasses (see Figure 2).

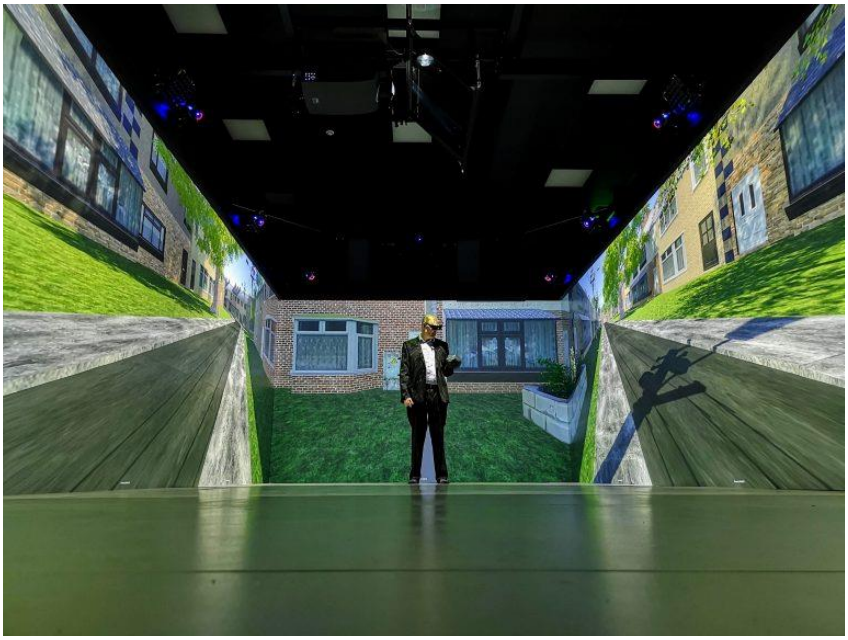

Figure 1. The Highly Immersive Kinematic Experimental Research (HIKER) laboratory at The University of Leeds

The Virtual Environment was created using Unity cross-platform game engine (unity.com). It consisted of a one-way, 3.5 m wide, single-lane road (UK standard), and depicted a daytime environment, in a residential area with houses on both sides of the road. A row of trees was created on one side of the road, to indicate the starting position for the pedestrian prior to each crossing. Two bollards were placed at each side of the road, to guide participants across the path.

Figure 2. The participant waiting to cross the road, between the two approaching vehicles. If present, the eHMI was always displayed on the second vehicle. This figure also shows the tracking glasses worn by participants.

2.3 Design

The design was adapted from a study by Lobjois & Cavallo (2007). The main task of each participant was to cross the road between two approaching vehicles (white followed by blue- as shown in Figure 2), if they felt comfortable to do so. A mixed design approach was used, with four within-participant variables: (i) the speed of the approaching vehicles (25/30/35 mph); (ii) the time gap between the vehicles (2/3/4/5 s) (iii) the deceleration behaviour of the second vehicle (deceleration/no deceleration), and (iv) Block order (1/2/3), and one between-participant variable: eHMI Design (Slow-Pulsing Light Band/Flashing Headlight). For each group, the eHMI-Status was randomly manipulated, whereby half of the decelerating vehicles had their respective eHMI present, while for the other other half the eHMI was absent. The rationale for this manipulation was to simulate a more realistic traffic situation, where not all decelerations are accompanied by external messages. This design also allowed a comparison between crossings in response to vehicle deceleration only, versus those accompanied by an eHMI. Table 2 shows the range of behaviours and eHMI combinations experienced by the two groups.

Table 2. The deceleration behaviour/eHMI combination presented to the two groups

Number of Scenarios per block	**Slow Pulsing Light Band (SPLB) group**		**Flashing Headlights (FH) group**	
	Behaviour	**eHMI-Status**	**Behaviour**	**eHMI-Status**
12	Decelerating	Present	Decelerating	Present
12	Decelerating	Absent	Decelerating	Absent
24	Non-Decelerating	Absent	Non-Decelerating	Absent

Each of the above conditions was presented at three different approaching speeds, and there were four different time gaps between the approaching vehicles, as outlined above, leading to 12 initial kinematic variations in total, repeated twice for the non-decelerating trials, to achieve an even number of deceleration and non-decelerating trials. Each participant experienced three repetitions of this block of 48 trials, with a short rest between each block, resulting in 3 x 48 = 144 crossings for each participant. The order of trials was randomised per participant, within each block.

2.3.1 eHMI Designs

Two eHMI designs were implemented in this study. Results from a forced-choice, paired-comparison, study on 20 participants in our laboratory showed that conventional Flashing Headlights and a Slow Pulsing Light Band were both associated with the message '*I am giving way*', when presented on a vehicle, in a PC-based Head Mounted Display study (Lee et al., 2019c). Therefore, these two messages were chosen for further investigation in the current study, to understand the effect of context and actual crossing behaviour, on the perception and comprehension of each signal. Flashing Headlights is a commonly understood and accepted message for giving way (at least in the west; Honest, 2004). The Slow Pulsing Light Band, which was developed as part of the interACT project (Weber et al., 2019), was a cyan light-band, presented at a pulsing rate of 0.4 Hz, and placed around the front windscreen of the vehicle, as shown in Figure 3 (left). The Flashing Headlights (Figure 3, right), were implemented by using a combination of texture and Unity spotlights, turning on and off over a 300ms period.

Figure 3. The two eHMI used for this study: Slow Pulsing Light Band (left) and the Flashing Headlight (right) eHMI

2.3.2 Behaviour of the decelerating/non-decelerating vehicles

Figure 4 provides a schematic of each trial, which involved the approach of two vehicles from the right (white, followed by blue), at three different speeds, and three different time gaps. For the non-decelerating trials, the second vehicle did not decelerate, and the two approaching vehicles continued to drive past the pedestrian, at their initial speed of 25, 30, or 35 mph. For the decelerating trials, the second approaching vehicle started to decelerate when it was 38.5 m away from the pedestrian (Point A in Figure 4), and stopped 2.5 m away from the pedestrian (Point B in Figure 4). This design was based on the typical stopping distance suggested in the UK Department for Transport's Rule 126 (DFT, 2019 August 20). This created the same stopping distance for all trials, even though the deceleration rate differed for the three approaching speeds (1.73, 2.50 and 3.40 m/s^2, for 25, 30, 35 mph respectively). When the eHMI was present, it was activated at the same time as the vehicle started to decelerate.

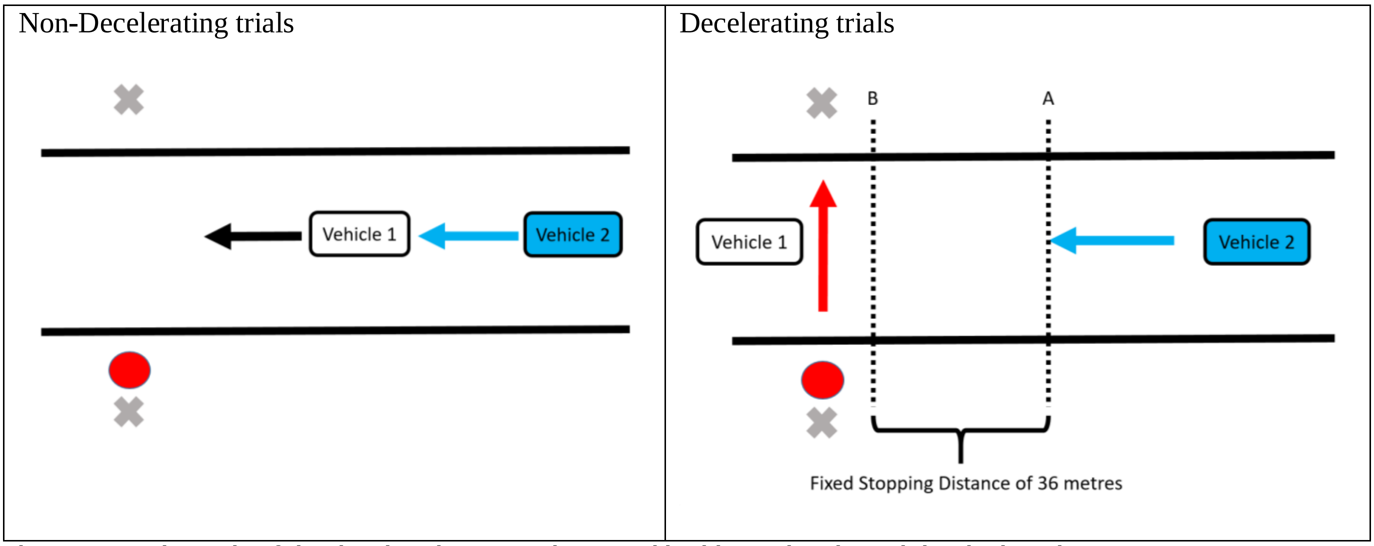

Figure 4. A schematic of the deceleration procedure used in this study. The red dot depicts the pedestrian standing at the edge of the road, waiting to cross between the approaching vehicles (Vehicle 1 and Vehicle 2). The grey X are bollards, which guided pedestrians during their intended crossing, a path depicted by the red arrow. During the decelerating trials, Vehicle 2 started to decelerate at Point A, which was 38.5 m from the crossing path, and stopped at Point B, which was 2.5 m from the crossing path.

2.4 Procedure

Upon arrival, participants gave their informed consent to take part in the study, and were given the opportunity to ask any questions. They were then provided with a written description of their task, which was also explained by the researcher, as follows: *'You will begin by standing at the edge of the road when you are ready, and you will have to press a button on the controller to trigger the trial. You will then see two cars approaching from the right. Your task is to cross (or decide not to cross) between the two approaching cars (pictures were provided). Please cross naturally when you feel comfortable to do so, such as you would in real traffic. If you cross the road before the second car arrives, we will want you to rate afterwards how safe this road crossing situation felt to you'.*

Participants were then randomly assigned to one of the two groups, matched according to their age, number of years spent in the UK, and gender. All participants were provided with the same information sheet, which contained no information about the eHMI so that any learning effects could be explored. Participants started with a practice block, to make sure they understood the instructions for the task, and to give them an opportunity to familiarise themselves with the virtual environment. The practice block stopped as soon as participants confirmed that they understood the task (usually after about three trials), and did not contain any trials with eHMI. For the experimental trials, if participants crossed the road after the first vehicle had passed, they heard a short beep once they reached the other side of the road, which prompted them to give their perceived safety rating. Here, they were asked to provide a rating of Perceived Safety from 1 to 4, to indicate their agreement with the following statement: 'I felt safe during this road crossing situation, both while standing and walking', where 1 = 'Disagree', 2 = 'Mostly disagree', 3 = 'Mostly agree', and 4 = 'Agree', after which they walked back to the starting point and triggered the next trial. If they decided not to cross the road, they were asked to press the button to trigger the next trial. Each block of 48 trials took approximately 15 minutes to complete, with a short break between each block. To ensure that participants were not experiencing any motion sickness, or unease, during the experiment, they were asked to complete the Misery scale (Bos et al., 2010) after each experimental block. A score of four or higher would suggest that the participant should not continue the study, but this did not occur.

Finally, a fourth block was added for the two eHMI groups, to investigate the visibility of each eHMI used in the simulated environment. In this block of trials, the vehicles again approached participants at three speeds, with four time gaps. Participants were asked to press a button on the hand-held controller as soon as they saw the eHMI. The distance of the approaching vehicle to the pedestrian was recorded at the time the button was pressed.

3. RESULTS AND DISCUSSION

Participants' age and years living in the UK were carefully matched between groups, to ensure these variables were not a contributing factor to any differences found between the two groups. Two independent samples t-tests were conducted to confirm that there were no significant differences between the groups in terms of age ($t(38) = .18$, $p = .86$; SPLB: M = 28.1, S.D. = 4.18; FH: M = 27.85; S.D. = 4.69) or years of living in the UK ($t(38) = 1.05$, $p = .30$; SPLB: M = 24.43, S.D. = 10.04; FH: M = 21.08, S.D. = 10.12).

3.1 Comparison of crossing behaviour between SPLB and FH

A total of 5760 trials were conducted (40 participants x 144 trials each). There were 69 missing trials (data were not recorded), and, therefore, there were a total of 5691 usable trials included in the analyses.

3.1.1 Percentage of Crossings

Figure 5 shows the percentage of pedestrian crossings, in relation to the location of the second vehicle, for the non-deceleration trials (a) and deceleration trials (b). For ease of understanding, the crossings are plotted for each 2.5 m bin, starting from when the vehicle was 42.5 m away, which is 4 m away from the deceleration point. Figure 5a illustrates that 40% of participants crossed the road in the non-decelerating trials, when the vehicle was over 42.5 m away, and, therefore, before it started to decelerate. This finding is similar to the results reported in Lee et al (2019b), which showed that 51 % of pedestrians crossed the road before the vehicle started to decelerate (see also Giles et al., 2019, Markkula et al., 2018; Schneemann & Gohl., 2016).

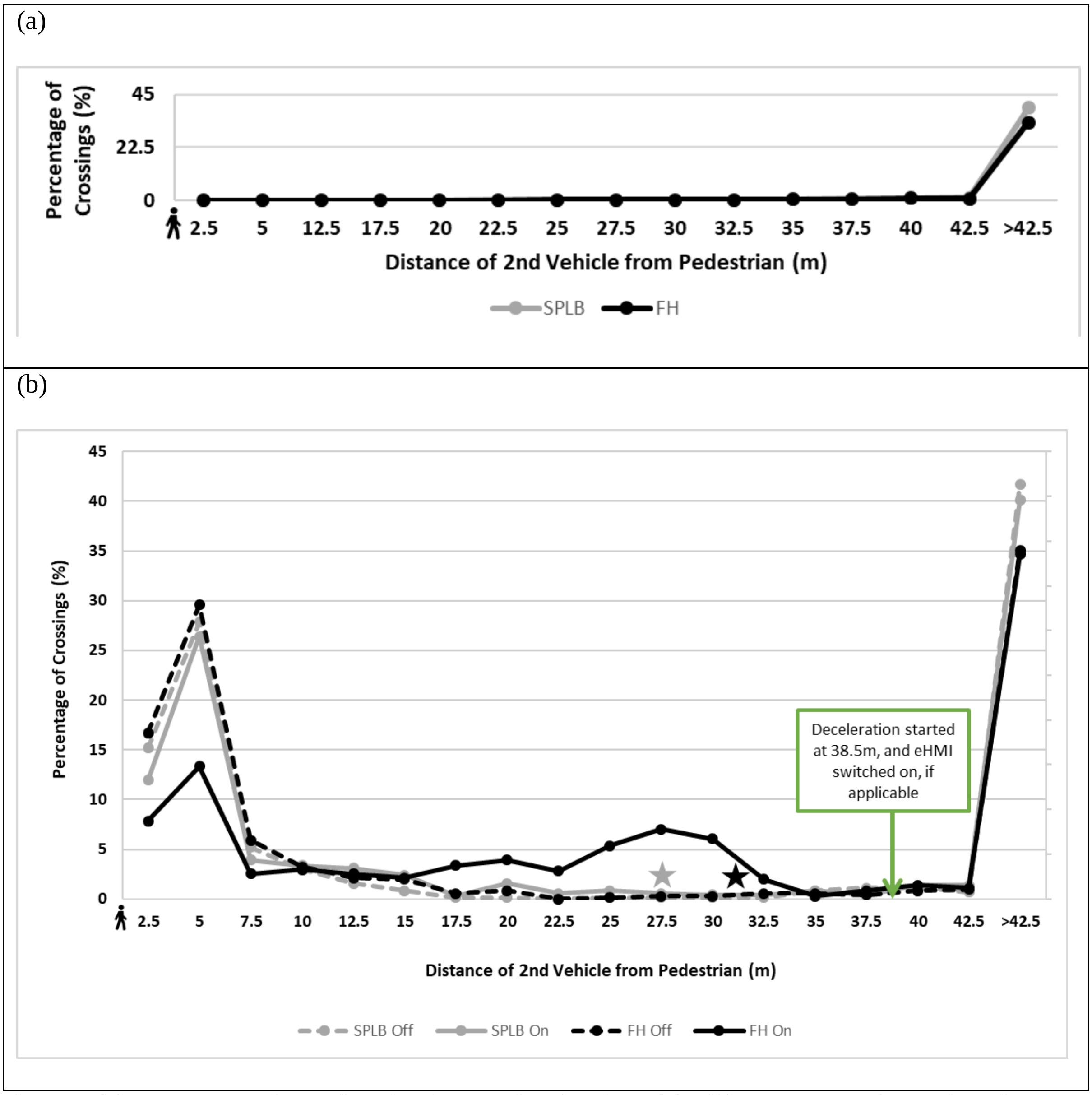

Figure 5. (a) Percentage of crossings for the non-decelerating trials. (b) Percentage of crossings for the decelerating trials, where the green vertical line represents the distance at which deceleration started (38.5 m away from pedestrians). The black star represents the average distance at which FH was perceptible to the participants, as measured in the fourth block (31.30 m away from pedestrians), the grey star represents the average distance at which SPLB was perceptible (27.76 m away from pedestrians). The vehicle always stopped at 2.5 m away from the pedestrian.

For the decelerating trials, 100% of pedestrians crossed the road, although different patterns were observed for the different eHMI conditions. Figure 5b shows a bimodal, and very similar crossing pattern for the eHMI-absent, and SPLB-present conditions. Most of the crossings were made either when the approaching vehicle was more than 42.5 m away, or when the vehicle had come to a near- (between 2.5 – 5 m away) or complete- (2.5 m away) stop. These bimodal crossing patterns have been observed in previous simulation models and test-track studies (Giles et al., 2019; Lee et al., 2019, Markkula et al., 2018; Schneemann & Gohl., 2016), and support suggestions that the vehicle does not need to come to a full stop for a crossing pedestrian (Lee et al., 2020). This bimodal crossing pattern also suggests that pedestrians were more comfortable crossing the road either when the vehicle was quite far away, or waited until the yielding behaviour of the vehicle was more prominent, i.e. when it was closer.

To understand the influence of eHMI visibility on this behaviour, and how it interacted with the vehicles' deceleration cues, the participants were asked to press a button as soon as they perceived the two eHMI, in Block 4 of the experiment (see Section 2.4). Both eHMIs were activated when the vehicle started decelerating, at a distance of 38.5 m away from the pedestrian. Using an independent samples t-test, the perceived distance of SPLB (labelled by a grey star in Figure 5b) and FH (labelled by a black star in Figure 5b) was compared. Results showed that the FH was perceived significantly further away than the SPLB (M = 31.30 m, S.D. = 2.54, vs M = 27.76 m, S.D. = 2.39 m, respectively, $t(38) = 4.54$, $p < .001$). This visibility explains the different pattern seen for the FH condition, with some crossings occurring when the vehicle was as far as 32 m away, and generally more early crossings in response to this eHMI. This finding suggests that the FH was more efficient as an explicit communication cue, compared to the SPLB. Of course, visibility of eHMI is perhaps not the only factor to explain this phenomenon, since the SPLB was perceived around 27.5 m away, yet did not prompt as many crossings. A previous study (Lee et al., 2019c), showed FH to be ranked significantly higher than SPLB for conveying the message '*I am giving way*', and, at least in the west (Honest, 2004), this cue is associated with such a communication message. Although the UK Highway Code, Rule 110, states that: "*Only flash your headlights to let other road users know that you are there*" (DFT, 2019, August 20), this method is used often by drivers to communicate that they are letting others go first (Fitzsimons, 2019). Therefore, the implicit or learnt meaning of an eHMI is also important when considering its effect on pedestrians' crossing behaviour.

3.1.2 Crossing Initiation Time (CIT)

Crossing Initiation Time (CIT) was measured as the time taken for participants to start crossing the road, after the rear end of the first vehicle had passed the crossing point (Lee et al., 2019; Lobjois & Cavallo, 2007, 2009). To understand how the presence of eHMIs affected Crossing Initiation Time, a new metric, termed CIT-Change (ΔCIT), was computed. This was achieved by subtracting the CIT values for the eHMI-absent conditions from those for the eHMI-present conditions, for both SPLB and FH. Here, a negative value meant that switching on the eHMI advanced the CIT, and provided additional cues about the vehicle behaviour to any kinematic/implicit cues. A positive ΔCIT meant that switching on the eHMI delayed the CIT, while a zero value meant there was no effect of eHMI on participants' CIT. This metric was used to study how crossing behaviour changed across blocks in the two groups, and how quickly participants learnt the meaning of the message conveyed by each eHMI.

a) Response to each eHMI, across the three blocks

To investigate the learning effect of each eHMI, and to establish if there was a different response to the novel eHMI (SPLB), compared to the more conventionally used Flashing Headlights, we examined crossing behaviour across the three blocks, by conducting a mixed ANOVA, with a between- participants factor of eHMI (SPLB, FH), and a within-participants factor of Block (1^{st}, 2^{nd}, 3^{rd}), see Figure 6.

Results showed no main effect of Block ($F(2,76) = 0.63$, $p = .538$, $\eta p^2 = .016$), but there was a main effect of eHMI Design ($F(1,38) = 17.10$, $p < .001$, $\eta p^2 = .31$), whereby the ΔCIT was larger for FH (M = -1.10, S.D. = 1.01) than SPLB (M = -0.21, S.D. = 0.60), confirming the power of the Flashing Headlights in conveying the "give way" message, which then initiated earlier crossings, compared to conditions with SPLB. There was also an interaction between Block and eHMI Design ($F(2,76) = 1.54$, $p = .017$, $\eta p^2 = .102$). Further investigation showed that the interaction was caused by ΔCIT being significantly larger for FH than SPLB for Block 1 ($t(38) = 5.30$, $p < .001$) and Block 3 ($t(38) = 3.10$, $p = .004$), but not in Block 2 ($t(38) = 2.00$, $p = .055$).

Figure 6 shows that the effect of FH on crossings decreases across blocks. This could be caused by the overall learning effect of the kinematic cues provided across the trials, with participants learning the overall behaviour of the approaching vehicle, which "washes out" the power of the FH. This argument is confirmed by the fact that the Crossing Initiation Time also decreased across blocks for the eHMI-absent conditions (see Appendix 1). Overall, these results show that the presence of both eHMI accelerated Crossing Initiation Time, compared to the no eHMI conditions, but that FH was much more effective, accelerating CIT by an average of 1 s across the trials, compared to an average of 200 ms for the SPLB trials.

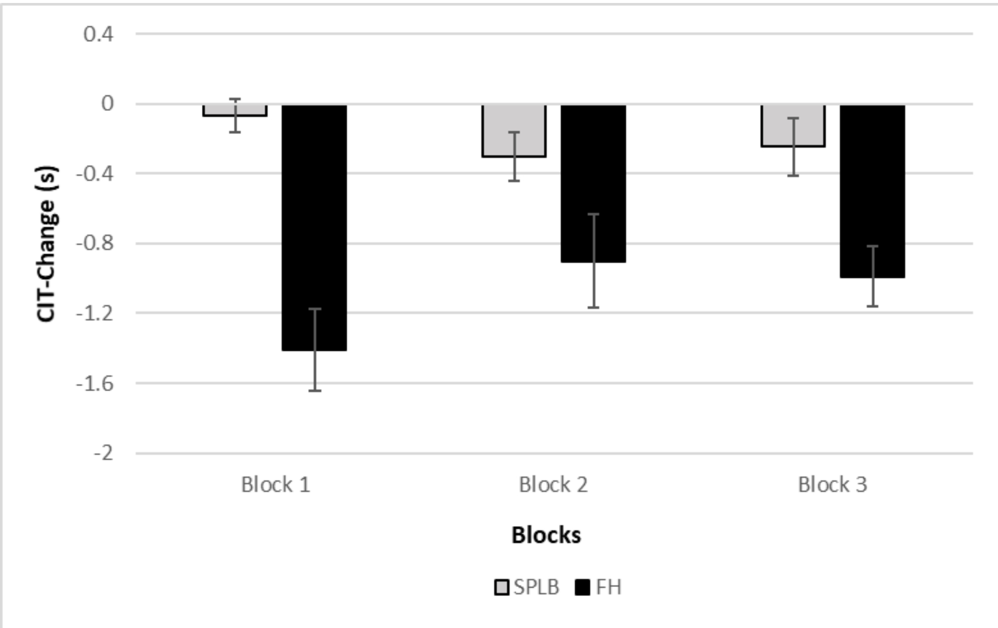

Figure 6. Crossing Initiation Time (s) across blocks, for SPLB and FH groups

b) The importance of each eHMI message, at the different speeds and time gaps

The aim of this analysis was to further understand the effect of each eHMI on CIT, for the different approaching speed and time gap conditions. Since the analysis described in section a, above, showed no main effect of Block for the two eHMI Designs, an average ΔCIT value across the three testing Blocks was calculated and used in the analysis. As stated earlier, a zero value for ΔCIT would indicate that there was no difference in CIT between the eHMI-present and eHMI-absent trials, and, therefore indicate no effect from the eHMI on crossing decisions. To understand whether there was an effect of eHMI-present on ΔCIT, a series of one-sample t-tests were conducted, to compare the ΔCIT value with zero, for each speed and time gap combination. Due to the large number of t-tests (24 one-sample t-tests), alpha level was adjusted to 0.001.

As shown in Table 3, and Figure 7a, SPLB-present led to a significant effect of ΔCIT only when the vehicle was travelling at 30 mph, with a 2s time gap, but evidence of ΔCIT influence was not found in any other speed and time gap combination, for this eHMI. On the other hand, there was a significant effect of FH-present on ΔCIT across more time gap and speed combinations. As seen in see Table 3 and Figure 7b, overall, these analyses showed that FH-present conditions were particularly helpful when the speed and time gap of the approaching vehicle was lower, leading to an earlier crossing, compared to the no eHMI conditions.

Table 3. Comparing CIT-Change with zero, across different speed and time gap combinations for SPLB and FH. Alpha level was adjusted to 0.001. Significant one-sample t-tests are bolded.

	SPLB	FH
25mph_2s	_t_(19) = 2.48, _p_ = .023	**_t_(19) = 7.24, _p_ < .001**
30mph_2s	**_t_(19) = 3.77, _p_ = .001**	**_t_(19) = 6.81, _p_ < .001**
35mph_2s	_t_(19) = 1.69, _p_ = .107	**_t_(19) = 5.74, _p_ < .001**
25mph_3s	_t_(19) = 1.10, _p_ = .284	**_t_(19) = 4.97, _p_ < .001**
30mph_3s	_t_(19) = .07, _p_ = .943	**_t_(19) = 4.44, _p_ < .001**
35mph_3s	_t_(19) = .49, _p_ = .631	_t_(19) = 2.83, _p_ = .011
25mph_4s	_t_(19) = .21, _p_ = .838	**_t_(19) = 4.29, _p_ < .001**
30mph_4s	_t_(19) = .71, _p_ = .485	_t_(19) = 1.62, _p_ = .121
35mph_4s	_t_(19) = .13, _p_ = .901	_t_(19) = .46, _p_ = .65
25mph_5s	_t_(19) = .15, _p_ = .884	_t_(19) = 1.57, _p_ = .134
30mph_5s	_t_(19) = .10, _p_ = .921	_t_(19) = 1.42, _p_ = .172
35mph_5s	_t_(19) = .72, _p_ = .478	_t_(19) = .92, _p_ = .371

(a)

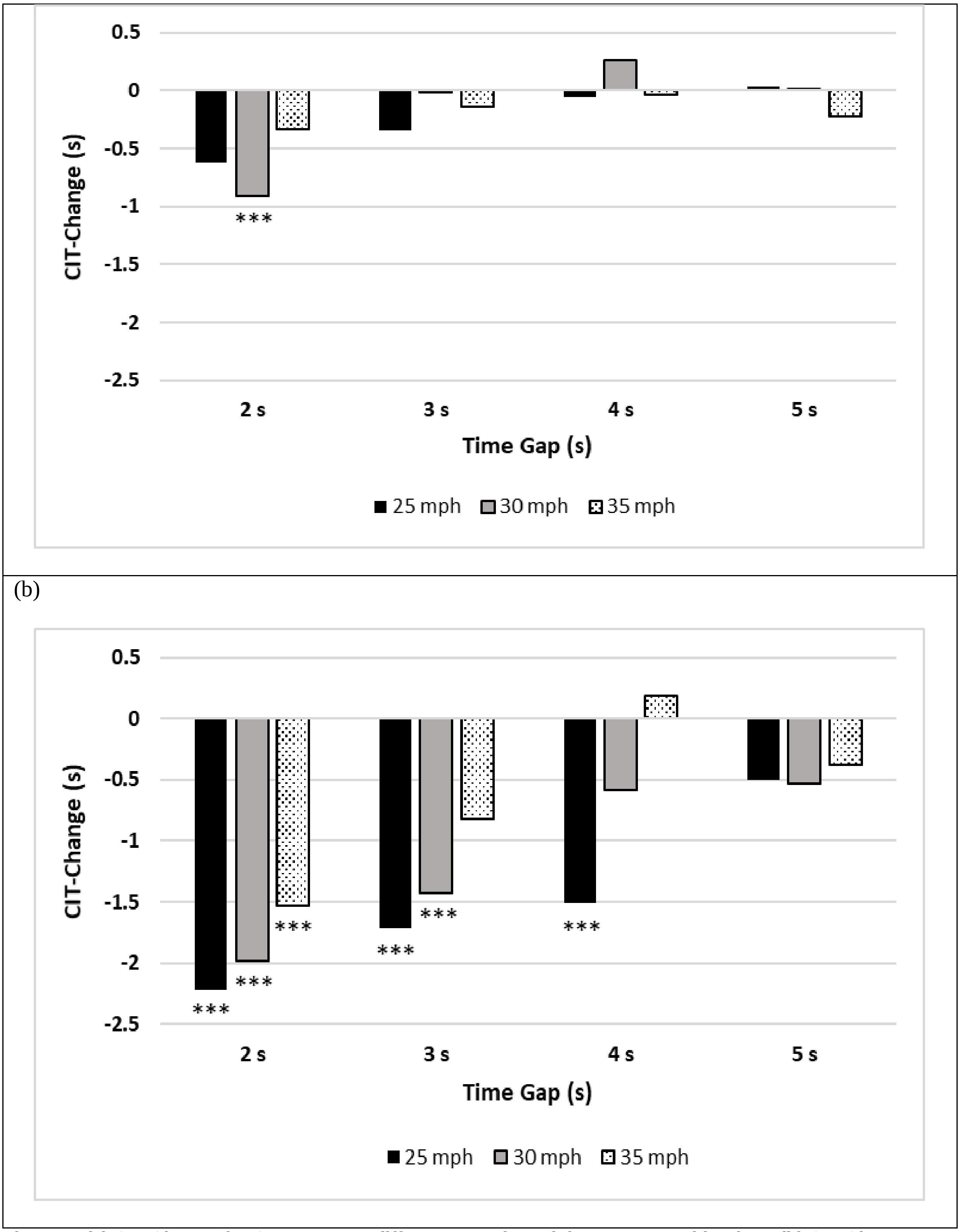

Figure 7. (a) CIT-Change for SPLB across different speeds and time gaps combinations (b) CIT-Change for FH across different speeds and time gaps. * depicted p ≤ 0.001 when CIT-Change was compared with zero, using one-sample t-tests.**

3.2 Comparison of subjective responses

At the end of each crossing trial, participants were asked to provide a rating from 1 to 4 to indicate their agreement with the following statement: '*I felt safe during this road crossing situation, both while standing and walking*', where 1 = 'Disagree' and 4 = 'Agree'. The mean of Perceived Safety (PS) rating for SPLB-present was 3.44 (S.D. = 0.32) and SPLB-absent was 3.30 (S.D. = 0.38); whereas the Perceived Safety rating for FH-present was 3.38 (S.D. = 0.38) and FH-absent 3.36 (S.D. = 0.40). Similar to CIT-Change (ΔCIT), PS-Change (ΔPS) was calculated by subtracting the PS ratings for the eHMI-absent conditions from those for the eHMI-present conditions. An average ΔPS in all conditions was calculated per participant. An independent-sample t-test showed no significant difference between SPLB (M = 0.13, S.D. = 0.24) and FH (M = 0.02, S.D. = 0.36) on ΔPS, $t(38) = 1.17$, $p = .25$. These findings suggest that there was no difference in how safe participants felt when crossing the road in front of the novel eHMI (SPLB), compared to the more conventional Flashing Headlights.

4. GENERAL DISCUSSION AND CONCLUSIONS

This study was designed with two main aims: firstly, to understand how the "give way" message conveyed by a novel eHMI (SPLB) was learnt across a set of crossing trials, compared to a more conventionally used Flashing Headlight, taking the visibility of each eHMI into account. The second aim of the study was to understand how crossing decisions were affected by each eHMI for the different approaching speeds and time gaps of the automated vehicle, in order to shed light on how kinematic information and explicit communication play a role in pedestrians' crossing decisions.

Results showed that the conventional Flashing Headlight led to earlier crossings when compared to the SPLB, especially when the vehicle was travelling at lower speeds, and with smaller time gaps. More crossings were observed immediately after the FH was perceivable, leading to a less obvious bimodal crossing pattern, which is often seen in pedestrian crossing studies (Giles et al., 2019; Lee et al., 2019, Markkula et al., 2018; Schneemann & Gohl., 2016). The CIT-Change values were also found to be significantly larger for FH than SPLB, demonstrating that it was a more effective external communication design than SPLB. Although the FH was visible earlier than SPLB, we believe the "give way" meaning conventionally associated with this type of message (e.g. Fitzsimons, 2019), had the power of initiating crossings, since the SPLB was also perceived at a relatively similar distance, but did not lead to any early crossings. The link between FH and "I am giving way" is also confirmed in a recent study by Lee et al. (2019c), who found that FH was ranked higher than SPLB, in terms of conveying this message. One caveat with these results is that the visibility of these messages in a Virtual Reality environment is not the same as that observed in the real world. When an image is rendered on a computer screen, the light sources, such as LEDs and headlights, do not have the same light emission as the light sources in the real world (e.g. Ghosh et al., 2005). Nevertheless, these results do illustrate that, regardless of the test environment, ensuring the visibility of eHMI is important in such studies, to ensure that the message it is intending to convey is perceived at the right time.

This study also illustrated that participants learnt the meaning conveyed from the FH immediately, within the first block of trials, but that experience with a block of 12 eHMI-present trials was required before the message conveyed by the SPLB was learnt. On average, the FH also accelerated crossings around 800ms earlier than SPLB. Therefore, it is likely to take road users some time to understand the meaning of novel eHMI concepts, which poses a challenge for AV manufacturers intending to provide the correct message to pedestrians by this form of communication. This study provided evidence that the visibility of eHMI is not the only important factor in this context, but that the comprehension, long-term exposure, and familiarity of novel messages must also be considered. Our results also indicate that using the correct eHMI can decrease Crossing Initiation Time by pedestrians, thus increasing traffic flow and efficiency (see also Pekkanen et al., in prep).

Finally, it is acknowledged that our conclusions are based on a simple, well controlled, laboratory-based, road-crossing scenario. Since real-world traffic involves many more interactions within a complex, mixed-actor, environment, much more needs to be understood about the effect of different eHMI messages, and their role in providing information for more complex scenarios, such as intersections, and, for example, how response from one pedestrian is affected by the presence of other pedestrians, since research shows that groups of pedestrians can also affect each-others' road crossing behaviour (e.g. Rosenbloom, 2009; Faria et al., 2010).

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5. REFERENCES

Ackermann, C., Beggiato, M., Bluhm, L., Löw, A., & Krems, J. F. (2019a). Deceleration parameters and their applicability as informal communication signal between pedestrians and automated vehicles. Transportation Research Part F: Psychology and Behaviour, 62, 757–768.

Ackermann, C., Beggiato, M., Schubert, S., Krems, J.F. (2019b). An experimental study to investigate design and assessment criteria: what is important for communication between pedestrians and automated vehicles? Applied Ergonomics, 75, 272–282

Anne Treisman. 1985. Preattentive processing in vision. Computer vision, graphics, and image processing 31, 2 (1985), 156–177. https://doi.org/10.1016/S0734-189X(85)80004-9

Bazilinskyy, P., Dodou, D., & 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.

Böckle, M.-P., Brenden, A.P., Klingegård, M., Habibovic, A., Bout, M., 2017. SAV2P – Exploring the Impact of an Interface for Shared Automated Vehicles on Pedestrians' Experience, in: Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct - AutomotiveUI '17. Oldenburg, Germany, pp. 136–140

Cavallo, V., & Laurent, M. (1988). Visual information and skill level in time-to-collision estimation. Perception, 17, 623-632.

Chang, C.-M., Toda,K., Sakamoto,D., Igarashi,T., 2017. Eyes on a Car:an Interface Design for Communication between an Autonomous Car and a Pedestrian, in: Proceedings of the 9th ACM International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17), pp. 65–73

Clamann, M., Aubert, M., & Cummings, M. L. (2017). Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles(No. 17-02119).

Daimler, A.G., 2015. The Mercedes-Benz F 015 luxury in motion. https://www.mercedes-benz.com/en/mercedes-benz/innovation/research-vehicle-f-015-luxury-in-motion/.

Daimler, A.G., 2017. Autonomous concept car smart vision EQ fortwo: welcome to the future ofcar sharing - Daimler global media site. http://media.daimler.com/marsMediaSite/en/ instance/ko/Autonomous-concept-car-smart-vision-EQ-fortwo-Welcome-to-the-future-of-car-sharing.xhtml?oid=29042725.

de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. (2019). External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. Human factors, 0018720819836343.

Deb, S., Strawderman, L. J., & 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.

DeLucia, P. R. (2008). Critical roles for distance, task, and motion in space perception: Initial conceptual framework and practical implications. Human Factors, 50, 811-820.

Department for Transport. (2019, August 20). General rules, techniques and advice for all drivers and riders (103 to 158). Retrieved December 03, 2020, from https://www.gov.uk/guidance/the-highway-code/general-rules-techniques-and-advice-for-all- drivers-and-riders-103-to-158

Dey D, & Terken, J. (2017) Pedestrian interaction with vehicles: roles of explicit and implicit communication. In: International conference on automotive user interfaces and interactive vehicular applications, pp 109–113

Dey, D., Holländer, K., Berger, M., Eggen, B., Martens, M., Pfleging, B., & Terken, J. (2020a). Distance-Dependent eHMIs for the Interaction Between Automated Vehicles and Pedestrians, 192–204.

Dey, D., Matviienko, A., Berger, M., Pfleging, B., Martens, M., & Terken, J (2020). Communicating the intention of an automated vehicle to pedestrians: The contributions of eHMI and vehicle behaviour. Information Technology.

Drive.ai, The self-driving car with screens to warn pedestrians: drive.ai launches its stand- out cars in Texas (2018). URL http://www.dailymail.co.uk/sciencetech/article- 6008793/The-self-driving-car-screens-warn-pedestrians-Drive-ai-launches-standout-cars- Texas.html.

Faas, S. M., & Baumann, M. (2019). Light-Based External Human Machine Interface: Color Evaluation for Self-Driving Vehicle and Pedestrian Interaction. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 63(1), 1232–1236.

Faria, J.J., Krause, S., & Krause, J. (2010). Collective behaviour in road crossing pedestrians: the role of social information. Behavioral Ecology, 21(6), 1236-1242.

Feldstein, I.T., Lehsing, C., Dietrich, A., Bengler, K., 2018. Pedestrian simulators for traffic research: state of the art and future of a motion lab. Int. J. Hum. Factors Model. Simul. 6 (4), 250–265.

Feldstein, I.T., Dietrich, A., Milinkovic, S., Bengler, K., 2016. A pedestrian simulator for urban crossing scenarios. IFAC-Papers OnLine 49 (19), 239–244.

Fitzsimons, J. (2019) Flashing your lights and 5 other driving 'mistakes' you can be fined for https://www.mirror.co.uk/money/flashing-your-lights-5-driving-14974894

Fridman L, Mehler B, Xia L, Yang Y, Facusse LY, Reimer B (2017) To walk or not to walk: crowdsourced assessment of external vehicle-to-pedestrian displays. Retrieved from http://arxiv .org/ abs/1707.02698

Giles, O. T., Markkula, G., Pekkanen, J., Yokota, N., Matsunaga, N., Merat, N., & Daimon, T. (2019). At the Zebra Crossing: Modelling Complex Decision Processes with Variable-Drift Diffusion Models. In A. Goel, C. Seifert, & C. Freksa (Eds.), *Proceedings of the 41st Annual Conference of the Cognitive Science Society* (pp. 366–372).

Habibovic, A., Lundgren, V.M., Andersson, J., Klingegard, M., Lagström, T., Sirkka, A., Fagerlonn, J., Edgren, C., Fredriksson, R. Krupenia, S., Saluäär, D., Larsson, P. (2018). Communicating Intent of Automated Vehicles to Pedestrians. Frontiers in Psychology, 9(August).

Hensch, A. C., Neumann, I., Beggiato, M., Halama, J., & Krems, J. F. (2019). How Should Automated Vehicles Communicate?–Effects of a Light-Based Communication Approach in a Wizard-of-Oz Study. In International Conference on Applied Human Factors and Ergonomics (pp. 79-91). Springer, Cham.

Hillis, W. D., Williams, K. I., Tombrello, T. A., Sarrett, J. W., Khanlian, L. W., Kaehler, A. L., & Howe, R. (2016). *U.S. Patent No. 9,475,422*. Washington, DC: U.S. Patent and Trademark Office.

Holländer, K., Wintersberger, P., Butz, A., 2019a. Overtrust in External Cues of Automated Vehicles: An Experimental Investigation, in: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications. pp. 211–221.

Holländer, K., Colley, A., Mai, C., Häkkilä, J., Alt, F., Pfleging, B., 2019b. Investigating the Influence of External Car Displays on Pedestrians' Crossing Behavior in Virtual Reality, in: International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '19), pp. 1–11.

Jaguar Land Rover, The virtual eyes have it (2018). URL https://www.jaguarlandrover.com/ 2018/virtual-eyes-have- it.

Jander, H., Borgvall, J., & Ramberg, R (2012). Towards a Methodological Framework for HMI Readiness Evaluation. Conference: Human Factors and Ergonomics Society (HFES) Volume: In proceedings of HFES 2013, vol. 56(1), pp. 2349-2353. DOI: 10.1177/1071181312561436

John, Honest (23 March 2004). "Honest John's agony column". The Daily Telegraph. Retrieved 28 July 2009.

Kaleefathullah, A., Merat, N., Lee, Y.M., Eisma, Y.B., Madigan, R., Garcia, J., & Winter, J. (2020) External Human-Machine Interfaces can be Misleading: An examination of trust development and misuse in a CAVE-based pedestrian simulation environment. Human Factors : The Journal of the Human Factors and Ergonomics Society. DOI: 10.1177/0018720820970751

Kooijman, L., Happee, R., & de Winter, J. C. F. (2019). How do eHMIs affect pedestrians' crossing behavior? A study using a head-mounted display combined with a motion suit. Information (Switzerland), 10(12), 1–18. https://doi.org/10.3390/info10120386

Lagström T, Lundgren VM (2015) AVIP-Autonomous vehicles' ínter- action with pedestrians. Retrieved from http://publi catio ns.lib. chalm ers.se/recor ds/fullt ext/23840 1/23840 1.pdf

Lee, Y.M., Madigan, R., Giles, O., Garach-Morcillo, L., Markkula, G., Fox, C., Camara, F., Rothmueller, M., Vendelbo-Larsen, S.A., Rasmussen, P.H., Dietrich, A., Nathanael, D., Portouli, V., Schieben, A., & Merat, N. (2020) Road users rarely use explicit communication techniques when interacting in today's traffic: Implication for Automated Vehicles. Cognition, Technology and Work, 1-14. DOI: 10.1007/s10111-020-00635-y

Lee, Y.M., Madigan, R., Markkula, G., Pekkanen, J., Merat, N., Avsar, H., Utesch, F., Schieben, A., Schießl, C., Dietrich, A., Boos, A., Boehm, M., Weber, F., Tango, F., & Portouli, E. (2019a) interACT D6.1 Methodologies for the evaluation and impact assessment of the interACT solutions

Lee, Y.M., Uttley, J., Solernou, A., Giles, O., Markkula, G., Romano, R., & Merat, N. (2019b) Investigating pedestrians' crossing behaviour during car deceleration using wireless head mounted display: an application towards the evaluation of eHMI of automated vehicles. Proceedings of the Tenth International Driving Symposium on Human Factors in Driving Assessment, Training and Vehicle Design, 252-258, New Mexico, Driving Assessment, 2019.

Lee, Y.M., Uttley, J., Madigan, R., Garcia, J., Tomlinson, A., Solernou, A., Romano, R., Markkula, G., & Merat, N. (2019c). Understanding the messages conveyed by automated vehicles. 2019 the 11th International Conference Automotive User Interfaces, Utrecht, Netherlands. DOI: 10.1145/3342197.3344546.

Lex Fridman, Bruce Mehler, Lei Xia, Yangyang Yang, Laura Yvonne, Facusse, and Bryan Reimer. (2017). To Walk or Not to Walk: Crowdsourced Assessment of External Vehicle-to-Pedestrian Displays. CoRRabs/1707.02698 (2017), 7. arXiv:1707.02698

Lobjois, R., & Cavallo, V. (2007). Age-related differences in street-crossing decisions: The effects of vehicle speed and time constraints on gap selection in an estimation task. Accident Analysis and Prevention, 39(5), 934–943.

Lobjois, R., & Cavallo, V. (2009). The effects of aging on street-crossing behavior: From estimation to actual crossing. Accident Analysis and Prevention, 41(2), 259–267.

Löcken, A., Golling, C., Riener, A., 2019. How Should Automated Vehicles Interact with Pedestrians? A Comparative Analysis of Interaction Concepts in Virtual Reality, in: 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '19). pp. 262–274.

Mahadevan, K., Somanath, S., Sharlin, E., (2018). Communicating awareness and intent in autonomous vehicle-pedestrian interaction. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18, University of Calgary , pp. 1–12

Markkula, G., Madigan, R., Nathanael, D., Portouli, E., Lee, Y.M., Dietrich, A., Billington, J., Schieben, A., and Merat, N. (2020) Defining interactions: A conceptual framework for understanding interactive behaviour in human and automated road traffic. Theoretical Issues in Ergonomics Science (TTIE).

Matthews, M., Chowdhary, G., & Kieson, E. (2017). Intent communication between autonomous vehicles and pedestrians. arXiv preprint arXiv:1708.07123

Merat N, Louw T, Madigan R, Wilbrink M, Schieben A (2018) What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space? Accident Analysis and Prevention, 118(April):244–252.

Nissan Motor Corporation, 2015. Nissan IDS Concept: Nissan's vision for the future of EVs and autonomous driving. https://europe.nissannews.com/en-GB/releases/release-139047 https://www.youtube.com/watch?v=9zZ2h2MRCe0.

Nunnally, J. C. 1978. Psychometric Theory. New York: McGraw-Hill.

Otherson, I.; Conti-Kufner, A.S.; Dietrich, A.; Maruhn, P.; Bengler, K. Designing for Automated Vehicle and Pedestrian Communication: Perspectives on eHMIs from Older and Younger Persons. In Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference, Berlin, Germany, 8–10 October 2018; pp. 135–148.

Pekkanen, J. et al. (in prep). Variable-drift diffusion models of pedestrian road-crossing decisions.

Petzoldt, T., Schleinitz, K., Banse, R. (2018). Potential safety effects of a frontal brake light for motor vehicles. IET Intelligent Transport Systems, 12, 449–453.

Rasouli A, Kotseruba I, Tsotsos JK (2018) Understanding pedestrian behavior in complex traffic scenes. IEEE Trans Intell Veh 3(1):61– 70. https ://doi.org/10.1109/tiv.2017.27881 93

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2017, June). Agreeing to cross: How drivers and pedestrians communicate. In Intelligent Vehicles Symposium (IV), 2017 IEEE (pp. 264-269).

Rasouli, A., Tsotsos, J.K., (2019). Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice, IEEE Transactions on Intelligent Transportation Systems (May), pp. 1–19 arXiv:1805.11773

Rosenbloom, T. (2009). Crossing at a red light: Behaviour of individuals and groups. Transport Research Part F, 12, 389-394.

Sadraei, E., Romano, R., Merat, N., de Pedro, J.G., Lee, Y.M., Madigan, R., Uzondu, C., Lyu, W., & Tomlinson, A. (2020). Vehicle-Pedestrian Interaction: A Distributed Simulation Study. DSC 2020. 19th Driving Simulation and Virtual Reality Conference and Exhibition, Antibes, France, Palais des Congrès.

Schieben, A., Wilbrink, M., Kettwich, C., Dodiya, J., Weber, F., Sorokin, L., Lee, Y.M., Madigan, R., Markkula, G., Merat, N., Dietrich, A., Kaup, M. (2019). Testing external HMI designs for automated vehicles – An overview on user study results from the EU project interACT. Automatisiertes Fahren, 2019, Munich

Schieben A, Wilbrink M, Kettwich C, Madigan R, Louw T, Merat N (2018) Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. Cognit Technol Work. ISSN 1435-5558

Scialfa, C.T., Guzy, L.T., Leibowitz, H.W., Garvey, P.M., & Tyrrell, R.A. (1991). Age Differences in Estimating Vehicle Velocity. Psychology and Aging, 6(1), 60-66.

Semcon, 2016. The smiling car. http://semcon.com/smilingcar/.

Smeets, J. B. J., Brenner, E., Trébuchet, S., & Mestre, D. R. (1996). Is judging time-to-contact based on 'tau'? Perception, 25, 583-590.

Sucha M, Dostal D, Risser R (2017) Pedestrian-driver communica- tion and decision strategies at marked crossings. Accident Analysis and Prevention, 102:41–50.

Uttley, J., Lee, Y.M., Madigan, R., & Merat, N. (2020) Road user interactions in a shared space setting: understanding what means of communication are needed for future automated vehicles. Transportation Research Part F, 72, 32-46.

Van der Laan, J.D., Heino, A., 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.

Várhelyi A (1998) Drivers' speed behaviour at a zebra crossing: a case study. Accident Analysis and Prevention, 30(6):731–743.

Volvo Cars, 2018. Concept 360c. https://www.volvocars.com/us/cars/concepts/360c.

Wang C, Gu J, Terken J, Hu J (2014) Driver-to-driver communica- tion on the highway: what drivers want. Ambient intelligence. In: Aarts E, de Ruyter B, Markopoulos P, van Loenen E, Schouten R, Wichert B, Terken J, Van Kranenburg R, Den Ouden E, O'Hare G, (eds) Springer International, Amsterdam, pp 315–327.

Weber, F., Sorokin, L., Schmidt, E., Schieben, A., Wilbrink, M., Kettwich, C., Dodiya, J., Oehl, M., Kaup, M., Willrodt, J., Lee, Y.M., Madigan, R., Markkula, G., Romano, R., & Merat, N. (2019) interACT D4.2 Final human-vehicle interaction strategies for the interACT AVs.

Appendix 1. Mean and Standard Deviations of Crossing Initiation Time (CIT) for all conditions in yielding trials (Speed, Time Gap, eHMI Design, eHMI-status) across Blocks

		25mph								30mph								35mph							
		2 sec		3 sec		4 sec		5 sec		2 sec		3 sec		4 sec		5 sec		2 sec		3 sec		4 sec		5 sec	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Block 1	SPLB_Absent	3.81	1.51	3.47	2.73	2.79	3.30	1.05	3.04	4.01	1.27	2.96	2.83	1.49	3.14	1.42	3.21	3.93	1.21	2.88	2.78	2.31	3.25	1.31	3.09
	SPLB_Present	3.42	2.11	3.07	2.75	2.49	3.48	1.76	3.47	3.35	1.53	3.48	2.66	2.30	3.33	1.38	3.26	3.71	1.48	3.24	2.71	1.43	2.94	1.33	2.98
	FH_Absent	3.77	1.55	3.64	2.37	3.81	3.33	1.70	3.62	4.02	1.22	4.12	2.49	3.30	3.46	2.79	4.00	3.82	1.31	4.04	2.25	2.73	3.43	1.75	3.58
	FH_Present	1.25	2.11	1.54	2.32	2.06	2.48	1.40	2.72	1.75	1.86	2.38	2.40	2.23	2.89	1.29	2.94	2.36	1.81	2.72	2.18	2.42	2.62	0.95	2.90
Block 2	SPLB_Absent	3.80	1.41	3.58	2.59	2.21	3.17	2.03	3.78	4.15	0.84	3.25	2.77	1.70	3.22	1.60	3.44	3.46	1.52	2.76	2.94	1.32	3.01	1.32	3.26
	SPLB_Present	2.66	1.70	2.91	2.51	3.07	3.26	1.99	3.73	2.84	2.08	2.68	2.82	2.11	3.35	1.36	3.14	3.67	1.03	2.75	2.79	1.57	2.93	0.42	1.96
	FH_Absent	3.51	1.55	3.18	2.55	3.54	3.13	2.49	3.87	3.37	1.73	3.19	2.70	2.58	3.14	1.52	3.30	3.45	1.38	3.05	2.63	1.43	2.89	1.49	3.18
	FH_Present	1.26	1.96	1.52	2.42	2.29	2.95	1.64	3.05	1.69	1.97	1.93	2.35	2.52	2.99	1.61	3.10	1.73	1.84	2.67	2.23	2.45	2.88	0.79	2.60
Block 3	SPLB_Absent	3.58	1.69	2.26	2.68	2.15	3.38	1.60	3.47	3.74	1.24	2.74	2.94	1.57	3.16	1.08	3.14	3.97	0.59	3.55	2.49	1.30	2.87	0.48	2.43
	SPLB_Present	3.23	1.51	2.31	2.61	1.78	2.83	1.11	2.90	2.87	1.67	2.66	2.59	1.59	3.08	1.20	3.20	3.15	1.53	2.69	2.60	1.55	3.00	0.68	2.51
	FH_Absent	2.82	1.65	2.94	2.56	3.51	3.05	1.36	3.00	3.50	1.34	3.17	2.51	2.93	3.38	1.01	3.18	3.19	1.38	2.74	2.63	1.81	3.12	0.53	2.43
	FH_Present	0.94	1.87	1.54	2.19	1.92	2.55	0.87	2.55	1.53	1.75	1.74	2.11	2.31	2.81	0.93	2.64	1.70	1.79	2.06	2.25	1.77	2.87	0.82	2.55