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External human-machine interfaces: Effects of message perspective

Y.B. Eisma, A. Reiff, L. Kooijman, D. Dodou, J.C.F. de Winter *

Delft University of Technology, the Netherlands

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ABSTRACT

Future automated vehicles may be equipped with external Human-Machine Interfaces (eHMIs). Currently, little is known about the effect of the perspective of the eHMI message on crossing decisions of pedestrians. We performed an experiment to examine the effects of images depicting eHMI messages of different perspectives (egocentric from the pedestrian's point of view: WALK, DON'T WALK, allocentric: BRAKING, DRIVING, and ambiguous: GO, STOP) on participants' (N = 103) crossing decisions, response times, and eye movements. Considering that crossing the road can be cognitively demanding, we added a memory task in two-thirds of the trials. The results showed that egocentric messages yielded higher subjective clarity ratings than the other messages as well as higher objective clarity scores (i.e., more uniform crossing decisions) and faster response times than the allocentric BRAKING and the ambiguous STOP. When participants were subjected to the memory task, pupil diameter increased, and crossing decisions were reached faster as compared to trials without memory task. Regarding the ambiguous messages, most participants crossed for the GO message and did not cross for the STOP message, which points towards an egocentric perspective taken by the participant. More lengthy text messages (e.g., DON'T WALK) yielded a higher number of saccades but did not cause slower response times. We conclude that pedestrians find egocentric eHMI messages clearer than allocentric ones, and take an egocentric perspective if the message is ambiguous. Our results may have important implications, as the consensus among eHMI researchers appears to be that egocentric text-based eHMIs should not be used in traffic.

1. Introduction

With the increasing number of automated vehicles (AVs) on the road, an emerging challenge concerns the interaction between AVs and non-automated road users, such as pedestrians. Traditional ways of communication (e.g., gestures, eye contact) between drivers and pedestrians are likely to disappear, as the AV's 'driver' might be distracted or absent, raising the question as to how communication between AVs and pedestrians should take place (Ackermann, Beggiato, Schubert, & Krems, 2019; Habibovic et al., 2018; Joisten, Freund, & Abendroth, 2020; Stanciu, Eby, & Molnar, 2018; Sucha, Dostal, & Risser, 2017).

External Human-Machine Interfaces (eHMIs) have been proposed to compensate for the lack of communication between AVs and pedestrians (Lagström & Malmsten Lundgren, 2015). eHMIs appear in several shapes and forms, including text dis-

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* Corresponding author.
E-mail address: j.c.f.dewinter@tudelft.nl (J.C.F. de Winter).

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plays, symbolic messages, lights, and projections (Dey, Habibovic, Löcken, et al., 2020). The design of eHMIs raises concerns regarding the potential ambiguity of the eHMI message. For example, an eHMI in the form of a green braking light on the front of the car could be interpreted in different ways: pedestrians could either think that the meaning of the colour refers to themselves, giving them permission to cross the road (i.e., egocentric perspective) or that the colour refers to the vehicle, indicating its intention to continue driving (i.e., allocentric perspective).

Research in perspective-taking shows that people are inclined to make judgments from their own perspective, whereas adopting another agent's perspective is relatively demanding and error-prone, a phenomenon that has been called egocentric bias or egocentric interference (Ferguson, Apperly, & Cane, 2017; Martin et al., 2019; Surtees & Apperly, 2012). It has been found that the ability to take someone else's perspective decreases with cognitive load (Davis, Conklin, Smith, & Luce, 1996; Lin, Keysar, & Epley, 2010; Roxβnagel, 2000), decreases with time pressure (Epley, Keysar, Van Boven, & Gilovich, 2004; Todd, Cameron, & Simpson, 2017), and increases with accuracy incentive and accountability (Epley et al., 2004; Roxβnagel, 2000).

It is presently unknown whether an eHMI should feature an egocentric or allocentric message perspective. We define an egocentric message as a message that the pedestrian can interpret from his/her own perspective. An egocentric message communicates a call to action and addresses the pedestrian. We define an allocentric message as a message which the pedestrian has to interpret from the other agent's (i.e., the AV's) perspective. An allocentric message refers to the action or intention of the AV itself; this means that the pedestrian has to derive the consequences for his/her own actions.

A variety of egocentric and allocentric eHMIs have been proposed in the literature, including the following:

- *Egocentric text-based eHMIs*, such as eHMIs depicting WALK/DON'T WALK (Bazilinskyy, Dodou, & De Winter, 2019; De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Fridman, Mehler, Xia, Yang, Facusse, & Reimer, 2019), GO AHEAD (Ackermann et al., 2019; Daimler, 2017), or SAFE TO CROSS (Knight, 2016).
- *Egocentric symbolic eHMIs*, such as eHMIs with a walking pedestrian silhouette (Deb, Strawderman, & Carruth, 2018; Hudson, Deb, Carruth, McGinley, & Frey, 2019; Fridman et al., 2019), a stop sign (Hudson, Deb, Carruth, McGinley, & Frey, 2019; Urmson, Mahon, Dolgov, & Zhu, 2015), or a raised hand (Fridman et al., 2019; Weber, Chadowitz, Schmidt, Messerschmidt, & Fuest, 2019).
- *Allocentric text-based eHMIs*, including text messages such as AFTER YOU (Nissan, 2015), BRAKING (Deb et al., 2018) and STOPPING (Nissan, 2015).
- *Allocentric symbolic eHMIs*, such as eyes on the car (Chang, Toda, Sakamoto, & Igarashi, 2017), a car with a giving way icon (Weber, Chadowitz, Schmidt, Messerschmidt, & Fuest, 2019), or a car depicting it is in automated mode (Joisten, Alexandi, Drews, Klassen, Petersohn, Pick, & Abendroth, 2019).
- *Allocentric light-based eHMIs* depicting the state of the vehicle or of the automated driving system, without specifically addressing pedestrians (Cefkin, Zhang, Stayton, & Vinkhuyzen, 2019; Faas, Kao, & Baumann, 2020a; Habibovic et al., 2018; Kaß et al., 2020). It should be noted that some light-based eHMIs use the colour red or green, which the pedestrian should interpret from his/own perspective (e.g., a front brake light in green). In these cases, it can be argued that the light-based eHMIs messages are egocentric rather than allocentric (De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Petzoldt, Schleinitz, & Banse, 2018; Zhang, Vinkhuyzen, & Cefkin, 2017).

Ackermann et al. (2019) showed that participants prefer instructions/advice about what the pedestrian should do (egocentric messages) over information about the vehicle's status or intention (allocentric messages). Furthermore, Bazilinskyy et al. (2019) found that participants were more inclined to cross in front of an eHMI displaying WALK as compared to an eHMI depicting WILL STOP, again suggesting that egocentric messages are most effective. Of note, egocentric messages are already common in traffic to resolve ambiguities (e.g., a hand gesture to give right of way or traffic signs with a green walking pedestrian). On the other hand, it has been broadly recommended that eHMIs should not offer egocentric messages (i.e., instructions), but should only give information about the state of the vehicle (Faas, Mathis, & Baumann, 2020b; International Organization for Standardization, 2018; Zhang, Vinkhuyzen, & Cefkin, 2017). More specifically, it has been argued that egocentric messages can confuse pedestrians if there are multiple pedestrians in the vicinity of the car (Dietrich, Willrodt, Wagner, & Bengler, 2018) and that egocentric messages may have legal implications in case a pedestrian gets involved in an accident because he/she complied with the eHMI instructions (Dey et al., 2020a; Tabone et al., 2021).

2. Study aim, approach, and hypotheses

This study aimed to investigate the effect of cognitive load and the perspective of the eHMI message on pedestrians' crossing decisions. The experiment was conducted using still images, an approach that resembles previous image-based eHMI experiments (Bazilinskyy et al., 2019; Fridman et al., 2019; Hagenzieker et al., 2020).

We opted for text because, although text requires the participants' visual attention, it appears to be more easily understood than symbolic displays and LED lights (Ackermann et al., 2019; Bazilinskyy et al., 2019; De Clercq et al., 2019). To investigate the effect of message perspective, we selected WALK and DON'T WALK (Bazilinskyy, Dodou, & De Winter, 2019; De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Hudson, Deb, Carruth, McGinley, & Frey, 2019; Fridman et al., 2019) for egocentric messages, and BRAKING (Deb et al., 2018) and DRIVING (Eisma et al., 2020) for allocentric messages. In addition, we selected GO (Fridman et al., 2019; Song, Lehsing, Fuest, & Bengler, 2018) and STOP (Fridman et al., 2019; Mercedes-Benz, 2015; Strickland, Yuan, Bai, Weber, & Miucic, 2016; Urmson, Mahon, Dolgov, & Zhu, 2015) as ambiguous messages, defined as messages that can be interpreted either as egocentric or allocentric from a pedestrian's perspective. The ambiguous eHMIs were included to investigate which perspective the participants adopt when the eHMI is not explicit about the perspective to be taken. For example, if most participants indicate not to cross for the message STOP then this would represent an overall egocentric perspective taken by the participants, and if most participants indicate they can cross for the message STOP (as was found by Fridman et al., 2019) this points to an allocentric perspective (i.e., the participants generally assume that the vehicle stops).

2.1. Hypotheses

As mentioned above, taking another agent's perspective is cognitively demanding (e.g., Lin et al., 2010). In the context of pedestrian crossing decisions, if the eHMI provides an allocentric message, the pedestrian first needs to interpret what the other agent (i.e., the AV) is going to do, before being able to decide whether he or she can cross the road. In comparison, if the eHMI depicts an egocentric message, the pedestrian could comply with the message directly. Accordingly, we expected that egocentric messages would be regarded as clearer than allocentric messages, where clarity is expressed objectively in terms of the uniformity of crossing decisions (i.e., the extent to which different participants provide the same crossing responses) and subjectively as high clarity ratings. This hypothesis is in line with the works of Ackermann, Beggiato, Schubert, & Krems, 2019; Bazilinskyy, Dodou, & De Winter, 2019; De Clercq, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Clamann, Aubert, & Cummings, 2017, and Fridman et al. (2019), who found that the text messages providing advice to the pedestrian were more preferred, clear, or persuasive than text messages describing the vehicle's state or intent.

For ambiguous message perspectives, the crossing decisions of pedestrians were expected to be less uniform, and response times longer, as compared to the unambiguous (i.e., ego- or allocentric) message perspectives. As people tend to be egocentrically biased, we expected that participants take an egocentric perspective when interpreting ambiguous messages.

In real traffic, pedestrians are likely to integrate information from multiple sources (e.g., vehicles, cyclists, intersection, traffic signs). Furthermore, factors such as visual clutter (Tapiro, Oron-Gilad, & Parmet, 2020), mobile phone use (Bungum, Day, & Henry, 2005; Jiang et al., 2018; Thompson, Rivara, Ayyagari, & Ebel, 2013), or time pressure (Walker, Lanthier, Risko, & Kingstone, 2012) could contribute to additional cognitive load. We added a memory task to the experiment to mimic the cognitive demands that may occur in real traffic. It was expected that with increasing cognitive load, participants would have more difficulty interpreting the meaning of the egocentric and allocentric messages when making a crossing decision, manifested by less uniform decisions and slower response times. Moreover, we expected that for ambiguous messages, participants would make slower and more egocentric decisions (e.g., cross for the message GO, not cross for the message STOP) when cognitive load increases, in line with previous research that suggests that the ability to take someone else's perspective decreases with cognitive load.

During the experiment, we measured eye saccades and pupil diameter using an eye tracker, to make inferences about participants' visual effort and cognitive load, respectively. These measures served as a validation check of the effects of the memory task and allowed us to interpret our findings further.

3. Methods

3.1. Participants

Hundred and sixty-five MSc students from the Delft University of Technology participated as part of a course. We removed the responses that occurred before the onset of the image (too early) and response times longer than 5000 ms (too late). Participants who responded too early or too late in five or more trials were excluded ($N = 62$). Accordingly, our final sample consisted of 103 participants (68 males and 35 females), aged between 21 and 29 years ($M = 23.3$, $SD = 2.0$). Informed consent was obtained from all participants, and the experiment was approved by the TU Delft Human Research Ethics Committee. All participants were tested individually.

3.2. Materials and equipment

Eye movements were recorded binocularly at a sampling rate of 2000 HZ using an SR-Research EyeLink 1000 Plus eye tracker (Fig. 1). The stimuli were shown on a 24.5-inch BENQ XL2420Z monitor with a resolution of 1920 × 1080 pixels (display area 531 × 298 mm). The distance between the monitor and the table edge was 94 cm. Luminescent lamps on the ceiling lit the room. The participants wore closed-back headphones (Beyerdynamic DT-770 Pro 32 Ohm) to suppress external sounds.

Fig. 1. The experimental setup.

3.3. Independent variables

Six eHMIs (Fig. 3) were presented. The eHMIs were generated with the online tool LCD Display Screenshot Generator (Avtanski, 2020). We opted for white letters instead of coloured ones to prevent associations with colours that are already used in traffic, such as red and green. Even though the colour cyan is recommended for eHMIs because of its good visibility and for the fact that it is not yet used in traffic (Dey, Habibovic, Pfleging, Martens, & Terken, 2020; Faas & Baumann, 2019; Werner, 2018), we did not use cyan because it could be misinterpreted as green (Bazilinskyy, Dodou, & De Winter, 2020).

The eHMI concepts were placed on the bumper of a vehicle that contained a driver and a passenger (Fig. 2; photo taken from Rodríguez Palmeiro et al., 2018). We included a driver because AVs of SAE levels 1–4 still require human presence (Society of Automotive Engineers, 2019).

Three independent variables were used. The first independent variable was the perspective of the eHMI message: (1) egocentric (WALK, DON'T WALK), i.e., providing an instruction to the pedestrian, (2) allocentric (DRIVING, BRAKING), i.e., providing information about the state of the vehicle, or (3) ambiguous (STOP, GO), in which case the message perspective could be interpreted either egocentrically or allocentrically. The second independent variable was the yielding intention of the vehicle as conveyed by the eHMI message, that is, whether the vehicle is yielding (WALK, BRAKING) or non-yielding (DON'T WALK, DRIVING). The ambiguous messages STOP and GO were again open to interpretation. The third independent variable was the memory task: we used a forward digit span task, with three levels: 0 digits (baseline), 2 digits (low cognitive load), and 5 digits (high cognitive load). We opted for a maximum of 5 digits based on Miller's law, according to which the number of objects humans can hold in short-term memory is 7 ± 2 (Miller, 1956). After responding to the eHMI stimulus, participants had to type in the digits they remembered. In the baseline condition, participants had to type "0".

3.4. Procedure

The experiment consisted of 18 trials (6 eHMIs × 3 memory task levels) that were presented in a random order that was different for each participant. Each of the 18 trials featured a sequence of digits that was the same for all participants. For example, the message BRAKING in the high load condition featured the digits 02809 for all participants. After finishing all trials, participants were asked to rate the clarity of the six eHMI concepts.

Fig. 2. One of the six eHMIs used in the experiment. The person in the driver seat provided written consent for the publication of this photograph.

Fig. 3. The eHMI concepts used in the experiment. Left column: Egocentric messages, Middle column: Allocentric messages, Right column: Ambiguous messages.

In case no memory task was shown, the trial began with a fixation cross at the centre of the screen shown for 5750 ms, followed by a blank screen for 1000 ms. When a memory task was included, the fixation cross was shown for 3750 ms for the low load memory task and 750 ms for the high load memory task, followed by a blank screen for 250 ms and a digit for 750 ms. The blank screen and digit presentation sequence was repeated twice for the low load memory task and five times for the high load memory task. Next, a blank screen appeared for 1000 ms, followed by the statement 'I can cross' shown for 2000 ms, which served to remind the participant about the task. This was followed by a blank screen for 250 ms, a fixation cross for 750 ms, and another blank screen for 250 ms, after which the image with the eHMI was shown until the spacebar is pressed, with a maximum of 5000 ms. Finally, on the last screen of each trial, participants typed in the digits from the memory task. Fig. 4 illustrates the presentation sequence of one trial. Note that the time between the onset of the first fixation cross and the onset of the image was identical (10 s) for all trials. A grey background (greyscale level 50% or 127 on a scale from 0 to 255) was used in all cases, except for the eHMI images. The digits and the statement 'I can cross' were presented in a black outline Arial font of 2-pt thickness.

3.5. Participants' task

The participants first read and signed the informed consent form. Participants faced the monitor and adjusted the seat height so that they could comfortably position their head in the head support. They were then presented with an introductory text on the screen that informed them about the contents of the experiment. Note that the experiment described in this paper was the first part of a larger study that included two subsequent unrelated experiments (Eisma & De Winter, 2020). Next, participants completed a standard nine-dot calibration. After the calibration was completed, instructions on the screen informed the participants that they would view images of an AV with textual messages on the bumper and that they had to respond to the statement 'I can cross' by using the L-shift key for 'no' and the R-shift key for 'yes'. These keys were covered with stickers stating 'NO' and 'YES', respectively. Furthermore, they were informed that, for two-thirds of the images, 2 or 5 digits would be shown before the 'I can cross' statement and were explained that they had to remember the digits until after they had responded to the eHMI image. The participants were asked to respond as quickly as possible. One practice trial was performed with a 2-digit memory task and a different eHMI message (WILL STOP) to avoid familiarization.

After the participants had completed all 18 trials, the six images were shown one by one, and the participants rated the clarity of the eHMI message on the vehicle on a scale from 0 (completely disagree) to 10 (completely agree).

3.6. Dependent variables

The following variables were computed:

- *Self-reported clarity.* The participants' response to the statement 'The message on the vehicle is clear' on a scale of 0 (completely disagree) to 10 (completely agree).
- *Objective clarity.* For the messages WALK and BRAKING, the participants were expected to press 'yes' (R-shift), and for DON'T WALK and DRIVING, the participants were expected to press 'no' (L-shift). For the ambiguous eHMI messages, however, it is undefined whether 'yes' or 'no' constitutes good performance. We have determined a so-called clarity score that allows us to compare the six different conditions in a meaningful way. More specifically, the clarity score was calculated as follows: Objective clarity (%) = 2 × (|percentage of participants pressing 'yes' – 50%|). A score of 100% resembles 'very clear'; that is, participants interpreted the message in a uniform manner. A score of 0% resembles 'very unclear', meaning that 50% of the participants interpreted the message as they could cross the street and 50% as they could not cross the street. Non-responses were excluded from the calculation of objective clarity.
- *Response time.* The response time was measured from the moment when the eHMI image appeared on the screen until the participant pressed the L- or R-shift key.
- *Pupil diameter.* We extracted the participants' pupil diameter from the eye-tracker data. We used pupil diameter as an index of cognitive load, with pupil dilation indicating increased task difficulty (Kahneman & Beatty, 1966). The EyeLink records pupil diameter in arbitrary units. The pupil diameter in millimetres was obtained through a multiplication factor which was based on printed circles of known size.
- *Number of saccades.* Saccades were extracted using a fixation filter previously used by Eisma, Cabrall, and De Winter (2018). The number of saccades during a trial reflects how many eye movements the participants made to reach a decision.

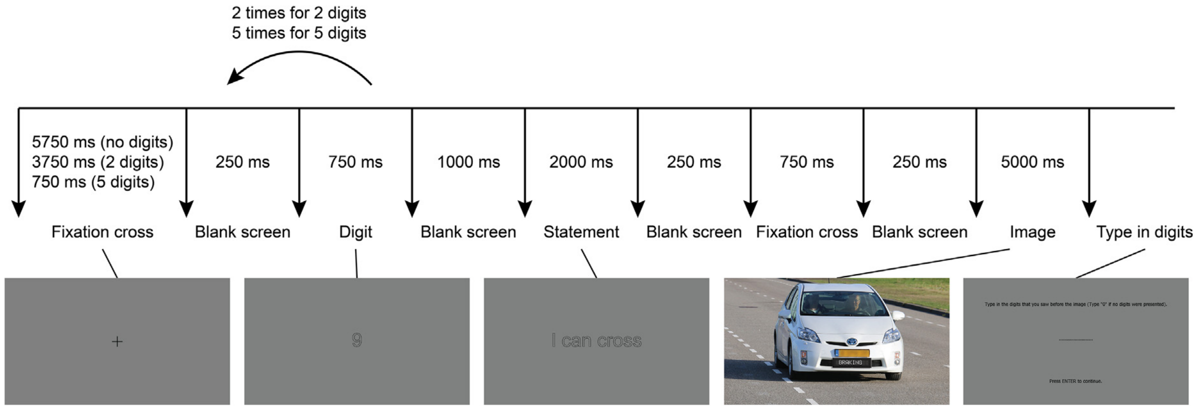

Fig. 4. The presentation sequence of one trial.

3.7. Statistical analyses

In the literature, there is a growing concern about the use of null hypothesis significance testing, with some voices arguing that *p*-values should be abandoned altogether (Amrhein, Greenland, & McShane, 2019). Consistent with this philosophy, we mostly interpret the data based on point estimates (e.g., means and standard deviations) rather than via *p*-values. However, to assist the reader in identifying which mean values differ significantly from each other, we depict 95% confidence intervals in the figures. For the variables that showed positive correlations between conditions (pupil diameter, response time, self-reported clarity rating, number of saccades), within-subject confidence intervals were computed by first subtracting the participant mean score (for details of this method, see Morey, 2008).

4. Results

Fig. 5 shows the pupil diameter for the three memory task conditions as a function of time. Initially, the pupil diameter declined, which can be explained by the recovery from the previous trial. At $t = 10$ s, the pupil diameter was higher for the high-load condition (5 digits; $M = 4.02$ mm, $SD = 0.45$ mm) as compared to the low-load (2 digits; $M = 3.92$ mm, $SD = 0.45$ mm) and baseline conditions (0 digits; $M = 3.90$ mm, $SD = 0.43$ mm). The differences between the high-load

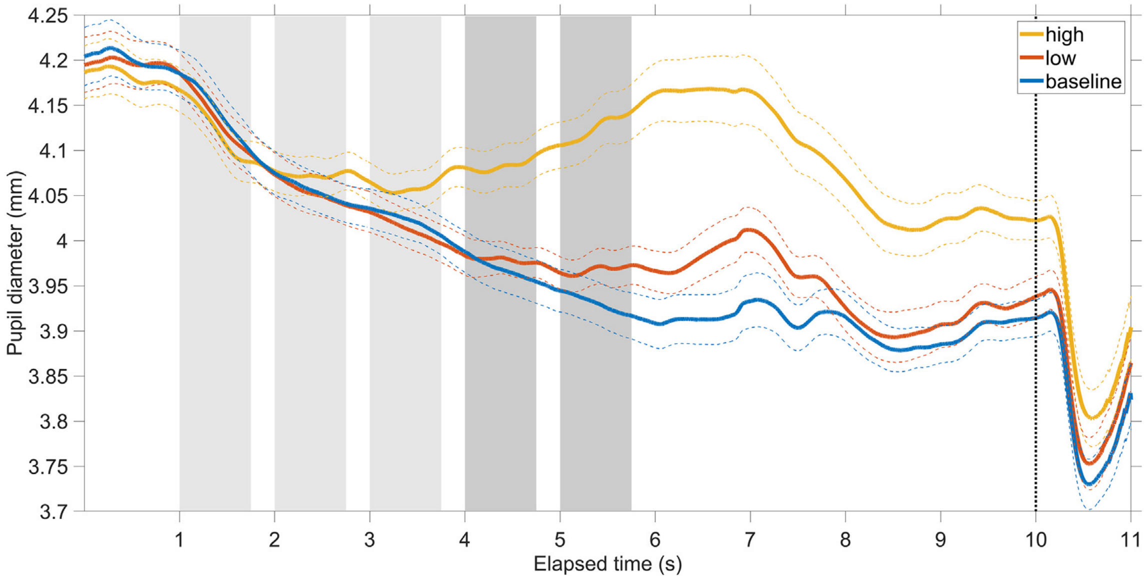

Fig. 5. Mean pupil diameter for each memory task condition as a function of time. The grey vertical bands represent the periods when the digits were visible (only the two last darker grey bands for the 2-digit condition and all five grey bands for the 5-digit condition). The black dotted vertical line represents the onset of the stimulus. The dashed lines surrounding the mean pupil diameter are 95% confidence intervals, calculated for each sample point separately.

and baseline condition were statistically significant, as indicated by the nonoverlapping confidence intervals. In other words, the participants experienced cognitive load, as intended. After the presentation of the eHMI at t = 10 s, the pupil diameter showed a sharp decline, which can be explained by the pupillary light reflex in response to the increased brightness of the eHMI stimulus as compared to the previous screens.

Fig. 6 shows the distribution of responses and the corresponding objective clarity scores per condition. Most participants indicated they could cross for the messages WALK and BRAKING and indicated they could not cross for the messages DON'T WALK and DRIVING, consistent with the intended design. It can also be seen from Fig. 6 that the egocentric messages WALK and DON'T WALK yielded the highest objective clarity scores, with the ratio of the number of 'yes' and 'no' responses relative to the total number of responses ('yes' and 'no' combined) being closer to the extremes of the scale (100% and 0%) as compared to the other four conditions. The allocentric BRAKING and the ambiguous STOP yielded the lowest objective clarity scores. For the ambiguous GO, the majority pressed 'yes', and for the ambiguous STOP, the majority pressed 'no', which suggests that the participants took an egocentric perspective.

It was expected that the objective clarity scores would decrease with increasing cognitive load. However, Fig. 6 shows that the memory task hardly affected the crossing decisions. For the messages DON'T WALK, clarity scores indeed decreased with cognitive load, with 99% of participants indicating that they could cross in the baseline condition, compared to 95% for the high-load condition. However, this effect was not large enough to be statistically significant (p = 0.125 according to a two-tailed McNemar test, with n = 97, 4, 0, 1 for no/no, no/yes, yes/no, yes/yes, respectively).

Fig. 7 shows the corresponding mean response times, with 95% confidence intervals. For the baseline condition (0 digits), the fastest response times were found for egocentric messages, whereas the slowest responses were found for the allocentric BRAKING and the ambiguous STOP. Contrary to our expectations, the memory task reduced the response time compared to the baseline.

Fig. 8 shows the cumulative number of saccades, after an offset correction so that the cumulative number of saccades equalled 0 when the stimulus was presented. It can be seen that the message DON'T WALK yielded the largest number of saccades, followed by BRAKING and DRIVING.

Fig. 9 shows that there was a negative correlation between objective clarity and response time, with the ambiguous STOP and the allocentric BRAKING yielding lower objective clarity and slower responses times than the other conditions (r = -0.92, n = 6 conditions). The subjective clarity values were highest for the egocentric messages WALK (M = 8.74, SD = 2.07) and DON'T WALK (M = 9.05, SD = 2.00), followed by the allocentric messages BRAKING (M = 7.19, SD = 2.46) and DRIVING (M = 7.60, SD = 2.43) while the lowest values were obtained for the allocentric GO (M = 6.66, SD = 3.09) and STOP (M = 5.75, SD = 3.52), as illustrated in Fig. 9 (middle). Fig. 9 (middle) further shows that the mean subjective clarity and objective clarity were strongly positively correlated (r = 0.87, n = 6 conditions). Fig. 9 (right) illustrates that the mean number of saccades at t = 11 s (as shown in Fig. 8) correlated positively (r = 0.92, n = 6 conditions) with the horizontal length of the eHMI message in degrees. Of note, the correlation between the number of saccades and mean response time was near zero (r = -0.13, n = 6 conditions), with the lengthy message DON'T WALK yielding a high number of saccades while being amongst the messages that yielded the fastest response times (Fig. 9, left).

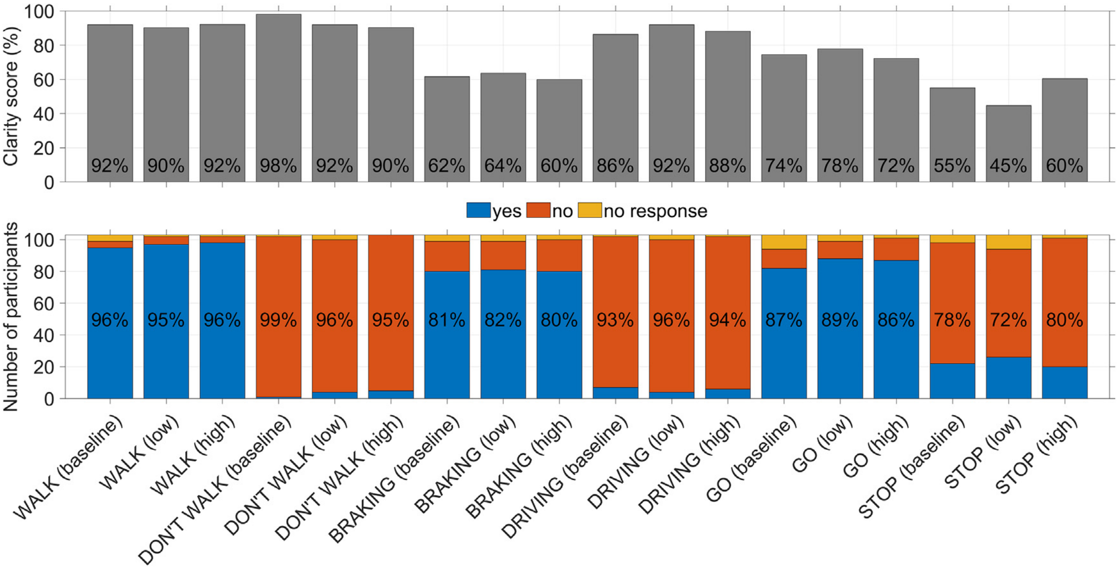

Fig. 6. Top: The clarity scores per eHMI condition. Bottom: The corresponding distribution of responses to the statement 'I can cross'. The percentage of 'yes' and 'no' responses is calculated relative to the number of participants who provided a response ('yes' and 'no' combined), excluding non-responses.

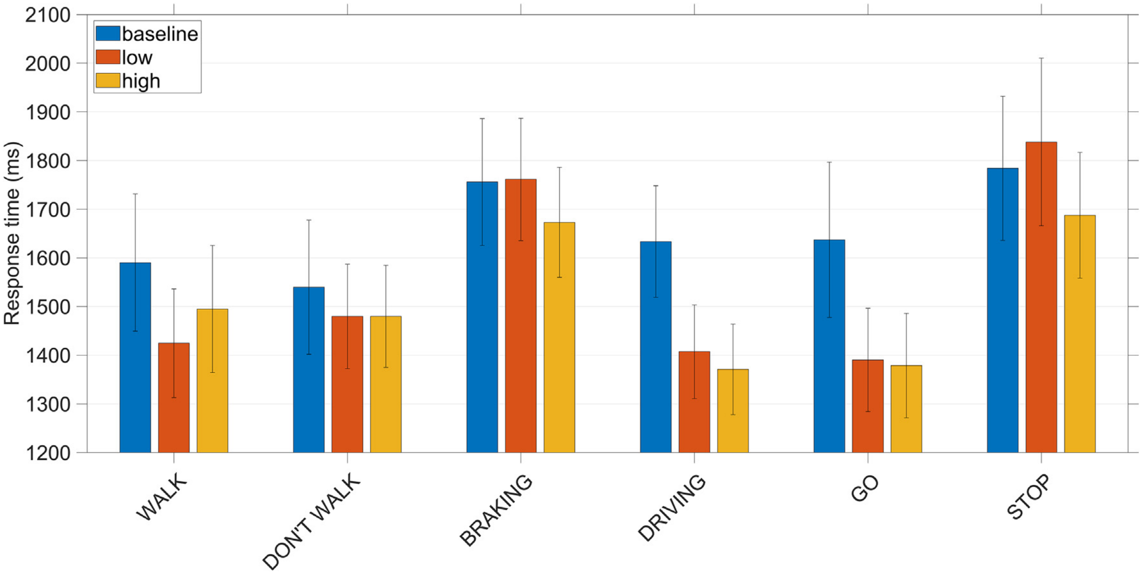

Fig. 7. Mean response time. Error bars represent 95% confidence intervals.

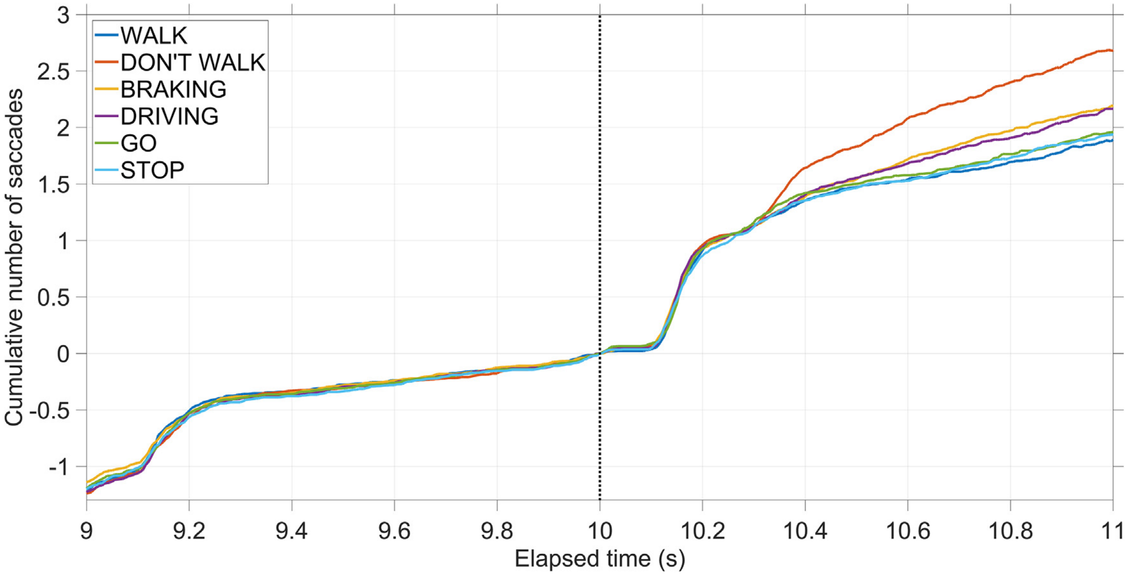

Fig. 8. Cumulative number of saccades, after an offset correction so that the value equals zero during the onset of the stimulus. The black dotted vertical line represents the onset of the stimulus.

5. Discussion

This study aimed to investigate the effect of eHMI message perspective (egocentric, allocentric, ambiguous) as well as cognitive load (baseline, 2 digits, 5 digits) on pedestrians' objective (as computed from their crossing decisions) and subjective (based on their self-reports) clarity levels. The results showed that egocentric messages (WALK and DON'T WALK) yielded higher subjective clarity scores than the allocentric (BRAKING and DRIVING) messages, whereas the egocentric messages yielded higher objective clarity scores than the allocentric BRAKING and the ambiguous STOP. These findings are consistent with our hypotheses, and with previous eHMI studies showing strong pedestrian compliance with egocentric messages (Ackermann et al., 2019; Bazilinskyy et al., 2019; De Clercq et al., 2019; Fridman et al., 2019). A possible explanation for these findings is egocentric bias (e.g., Lin et al., 2010; Todd et al., 2017). That is, participants may naturally be better able to interpret messages that pertain to themselves as compared to messages that pertain to the other (i.e., the AV). Besides egocentric bias, another explanation for the high clarity scores of egocentric messages is that these messages leave little

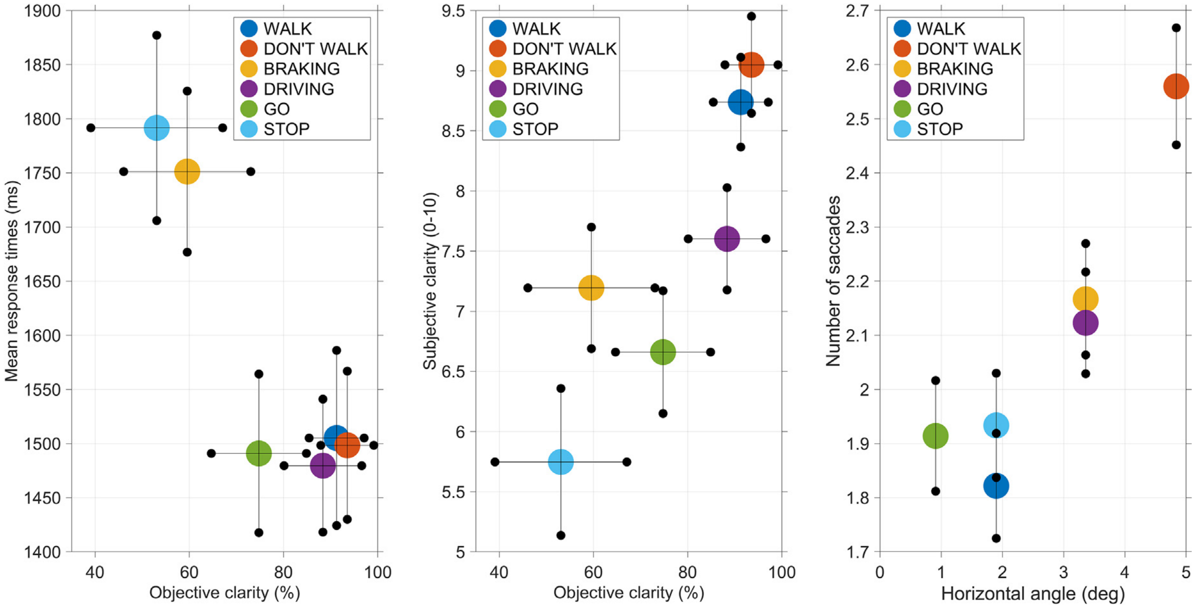

Fig. 9. Left: Scatter plot of mean response time and mean objective clarity, averaged across the three cognitive load conditions. Middle: Scatter plot of mean self-reported clarity and mean objective clarity, averaged across the three cognitive load conditions. Right: Scatter plot of the mean number of saccades at 11.0 s and the horizontal viewing angle from the leftmost to the rightmost part of the eHMI text message. The error bars represent 95% confidence intervals after averaging the results across the three cognitive load levels per participant.

room for misinterpretation (Ackermann et al., 2019; Fridman et al., 2019). In comparison, the allocentric BRAKING might be open to interpretation, as it is unknown whether a braking AV is actually going to a stop for the participant; it can brake for whatever reason. In summary, the effectiveness of egocentric messages may be due to the fact that pedestrians do not have to shift their mental perspective from themselves to the vehicle, but also due to the low ambiguity of these messages.

At the aggregate level, there was a strong positive correlation between objective and subjective clarity ($r = 0.87$), a finding which replicates previous research using animated videos that showed a strong correlation between objective performance and subjective clarity for six eHMI conditions ($r = 0.99$; Eisma et al., 2020). Of note, the allocentric DRIVING and ambiguous GO resulted in faster responses and higher objective clarity than the allocentric BRAKING and ambiguous STOP. These findings suggest that the time needed to interpret the meaning of the message depends on features that affect perceived clarity, and that, consistent with our argument above, message perspective is not the only factor that affects pedestrian's decision making. We also found that lengthy messages involved a higher number of saccades, presumably reflecting the process of reading the text. However, the negative correlation between the horizontal viewing angle of the text message and the response time suggests that text length was not a contributor to slower responding. In particular, DON'T WALK was the longest text but yielded a fast response.

For the ambiguous messages GO and STOP, most participants were inclined to cross and not cross, respectively. In other words, the majority of the participants interpreted the ambiguous messages from their own point of view. These findings point to an egocentric bias, as in principle, the messages GO and STOP could just as well refer to the AV (i.e., the AV could indicate: 'I stop' or 'I go') or to the pedestrian (i.e., the pedestrian may think: 'I should stop' or 'I can go'). Our findings are consistent with an online study by Vlakveld, Van der Kint, and Hagenzieker (2020), which found that cyclists were more likely to cross when an AV depicted GO as compared to a baseline without eHMI. In an online study by Fridman et al. (2019), on the other hand, most participants interpreted the message STOP allocentrically; that is, participants thought they could cross. The difference with our study was that in Fridman et al., the word STOP was depicted in red, which participants may have associated with a brake light. Because of their inherent ambiguity, we recommend avoiding the words STOP and GO in eHMIs. It is noted that the word STOP is already used in traffic without apparent problems, for example in STOP signs or as a warning not to cross (e.g., a parent may shout STOP to a child when they should not cross the road). The low clarity scores for the message STOP in the present experiment (Fig. 9) are likely due to the ambiguity of the perspective to be taken, which arises when this message is attached to an approaching vehicle.

It was expected that the memory task would cause a reduction of objective clarity scores and a slowing of response times. Furthermore, it was expected that for ambiguous messages, cognitive load would contribute to an increase of egocentric crossing decisions (i.e., cross for GO, not cross for STOP). However, contrary to our expectations, crossing decisions were hardly affected by the memory task and participants made *faster* decisions when performing a memory task as compared to not performing the task. An explanation for the faster response times with increasing mental demands is that participants tried to shed tasks quickly: the faster participants responded, the earlier they could enter their response and the shorter the memory decay (Burke, Allen, & Gonzalez, 2012).

6. Limitations

This study has a number of limitations. First, we used images to ensure that each participant responded to the same stimulus, without introducing variance in eye movements and decision making caused by vehicle speed and distance. However, the use of images may limit the generalisability of our findings because participants could not make use of vehicle speed to disambiguate the meaning of the eHMI. For example, in reality, a message such as BRAKING may be easier to understand if the vehicle is slowing down at the same time. Previous research suggests that vehicle behaviours are more important than eHMI messages when trying to understand an approaching vehicle's intentions (Clamann, Aubert, & Cummings, 2017; Lee et al., 2020; Li, Dikmen, Hussein, Wang, & Burns, 2018; Moore, Currano, Strack, & Sirkin, 2019). A second limitation is that participants needed to imagine whether they would cross while sitting behind the computer and not having an actual incentive to cross, and not being at risk, which might contribute to response bias. Third, we used a memory task to increase cognitive load, whereas, in real traffic, task load is also determined by visual load and sounds, such as determined by the number of road users. A fourth limitation is that data from about one-third of the participants had to be excluded. Many of these participants misunderstood the task and pressed 'yes' (R-shift) immediately after the statement 'I can cross' was shown.

7. Conclusion and recommendations

It is concluded that pedestrians find egocentric messages (WALK, DON'T WALK) clearer than allocentric (BRAKING, DRIVING) and ambiguous (STOP, GO) messages. These findings may be caused by the perspective of the message and associated mental perspective-taking by participants, but may have other causes as well, such as the fact that certain allocentric messages (e.g., BRAKING) are open to multiple interpretations, whereas the messages WALK and DON'T WALK are not. Moreover, it was found that pedestrians take an egocentric perspective if the eHMI message is ambiguous, a finding that provides support for the hypothesis of egocentric bias. Finally, it is concluded that cognitive load in the form of a concurrent memory task reduces response times and that longer messages take longer to read, but do not increase response times. The lengthy message DON'T WALK, for example, yielded a relatively fast response.

Our findings can be placed in the context of recommendations made by experts in eHMI research and design, stating that instructive text-based eHMI messages should not be used in traffic as they could be hard to read from a distance and difficult to understand by people who speak a different language, and might be misleading when multiple pedestrians have to be addressed at the same time (e.g., Tabone et al., 2021). Our results, however, indicate that egocentric text messages, even two-worded ones, such as DON'T WALK, are responded to quickly and effectively. The present study was conducted in a lab environment with engineering students as participants, and should not be used to make direct inferences about how eHMIs should be deployed in real traffic. In particular, the use of the egocentric message WALK can have negative consequences if a pedestrian decides to cross while this message from the AV was intended for another pedestrian, or when a second vehicle approaches from the opposite direction. Accordingly, the message WALK should perhaps not be used on an eHMI, especially if further research indicates that pedestrians blindly follow up such an instruction even when other indicators indicate that it is not safe to cross. Alternatively, the message SAFE TO CROSS (Bazilinskyy et al., 2019; Knight, 2016) could be used instead of WALK, if the AV (based on its omnidirectional sensor inputs) is confident that it is indeed safe for the pedestrian to cross. In line with the above, we recommend further research into pedestrian compliance and misuse of eHMIs (see also Holländer, Wintersberger, & Butz, 2019; Kaleefathullah et al.). Furthermore, it is recommended that future research examines the topic of message perspective for text-based eHMIs versus symbol-based eHMIs, especially in cluttered environments where multiple vehicles are present.

CRediT authorship contribution statement

Y.B. Eisma: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Software, Data curation, Project administration, Validation. **A. Reiff:** Conceptualization, Methodology, Resources, Formal analysis, Visualization, Investigation, Writing - original draft, Project administration. **L. Kooijman:** Writing - review & editing, Investigation, Project administration. **D. Dodou:** Methodology, Writing - review & editing, Investigation, Project administration, Resources, Validation. **J.C.F. de Winter:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Visualization, Validation, Supervision, Project administration, Funding acquisition.

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