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# Bio-inspired intent communication for automated vehicles

Max Oudshoorn, Joost de Winter, Pavlo Bazilinskyy, Dimitra Dodou *

*Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, the Netherlands*

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ABSTRACT

Various external human-machine interfaces (eHMIs) have been proposed that communicate the intent of automated vehicles (AVs) to vulnerable road users. However, there is no consensus on which eHMI concept is most suitable for intent communication. In nature, animals have evolved the ability to communicate intent via visual signals. Inspired by intent communication in nature, this paper investigated three novel and potentially intuitive eHMI designs that rely on posture, gesture, and colouration, respectively. In an online crowdsourcing study, 1141 participants viewed videos featuring a yielding or non-yielding AV with one of the three bio-inspired eHMIs, as well as a green/red lightbar eHMI, a walk/don't walk text-based eHMI, and a baseline condition (i.e., no eHMI). Participants were asked to press and hold a key when they felt safe to cross and to answer rating questions. Together, these measures were used to determine the intuitiveness of the tested eHMIs. Results showed that the lightbar eHMI and text-based eHMI were more intuitive than the three bio-inspired eHMIs, which, in turn, were more intuitive than the baseline condition. An exception was the bio-inspired colouration eHMI, which produced a performance score that was equivalent to the text-based eHMI when communicating 'non-yielding'. Further research is necessary to examine whether these observations hold in more complex traffic situations. Additionally, we recommend combining features from different eHMIs, such as the full-body communication of the bio-inspired colouration eHMI with the colours of the lightbar eHMI.



## 1. Introduction

Intent communication from a vehicle towards a pedestrian is currently achieved through implicit communication via vehicle kinematics, as well as explicit communication via gestures and eye contact with the driver (Haddington & Rauniomaa, 2014). The acceptance of automated vehicles (AVs) is influenced by their ability to interact with other road users (Domeyer et al., 2020; Schieben et al., 2019). However, traditional modes of explicit communication may be missing from AVs, as the AV occupant might be absent or distracted, leading to a gap in communication. To bridge this gap, various external human-machine interfaces (eHMIs) have been proposed to communicate the intent of AVs to pedestrians.

### 1.1. Existing eHMI-concepts

A wide range of eHMIs have been proposed by industry and academia, but there is no agreement on which eHMI is most suitable for intent communication (Bazilinskyy et al., 2019). In an analysis of 70 different visual eHMI concepts, Dey et al.

* Corresponding author.
*E-mail address:* d.dodou@tudelft.nl (D. Dodou).

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(2020a) found that most eHMIs rely on text, symbols, abstract elements, or anthropomorphic elements. Text-based eHMIs that instruct or advise the pedestrian (e.g., 'Don't walk') were found to be unambiguous (Ackermann et al., 2019; Bazilinskyy et al., 2019; De Clercq et al., 2019; Fridman et al., 2017), but may be difficult to read from a distance (Clamann et al., 2017) and are associated with language-related communication barriers (Bazilinskyy et al., 2019). Symbols (e.g., a walking silhouette) are not susceptible to these two disadvantages, but their performance depends on familiarity (Goonetilleke et al., 2001). Abstract eHMIs communicate through visual shapes and lights. Light-based eHMIs have the advantage that road users are already familiar with interpreting light signals in traffic (Faas & Baumann, 2019) and were found to be easy to distinguish from the environment, but required training to be fully understood (Bazilinskyy et al., 2019; Hensch et al., 2019).

Anthropomorphic eHMIs use human-like elements or human characteristics for communication (Dey et al., 2020a). Proposed anthropomorphic eHMIs communicate through the inclusion of eyes (Chang et al., 2017; Pennycooke, 2012), a smile (Deb et al., 2018; De Clercq et al. 2019), or an animated face or hand (Fridman et al., 2017; Mahadevan et al., 2018). Displaying eyes on the vehicle led to quicker decision-making and increased feelings of safety compared to not using such eyes (Chang et al., 2017). Similarly, an AV with a smiling eHMI led to improved crossing decisions compared to the baseline condition, but required some training in order to be understood by pedestrians (De Clercq et al., 2019). On the other hand, in a study that tested the vehicle-pedestrian interaction of four novel eHMI concepts, an animated face that established eye contact with the participant was found to be ambiguous (Mahadevan et al., 2018), and a survey study found that anthropomorphic eHMIs in general were not sufficiently clear or convincing (Bazilinskyy et al., 2019). Amongst academic experts, there appears to be no agreement on the usefulness of anthropomorphic eHMIs (Tabone et al., 2021).

### *1.2. Applicability of bio-inspired communication to eHMIs*

In nature, various ways of intent communication can be found, which have hardly been explored up to now in eHMI design. An exception is the Autonomous Electric Vehicle Interaction Testing Array (AEVITA), a concept inspired by cephalopods, which, through changes in posture and movement of the wheels, could communicate aggression or submission (Pennycooke, 2012). Another concept uses tiny 'feathers' on the hood of a vehicle that can lie down or deploy, thereby changing the size of the vehicle to communicate intent (Dey et al., 2018).

Deriving inspiration from nature could lead to novel eHMI concepts that apply previously unused communication principles. Communication is key for survival in nature, with organisms that have a competitive advantage (e.g., better communication capabilities) reproducing more, which in turn causes this competitive advantage to become more widely available. In an experiment with schoolchildren, Prokop and Fančovičová (2013) found that images of animals with aposematic colouration (i.e., colouration that communicates to predators that the animal has defensive mechanisms that make it not worthwhile to attack or eat) were perceived as more dangerous than similar animals with inconspicuous colouring. The correct interpretation of warning colouration suggests that other bio-inspired communication might be understood by humans as well and could therefore be suitable for intent communication.

In a literature study on visual intent communication in nature and its applicability to automated vehicles, we identified three channels that showed promise for use in eHMIs: posture, colouration, and gesture (Oudshoorn et al., 2020). Posture is used, for example, by octopi in agonistic interactions. The octopus raises its head to communicate threat, whereas lowering the head signals submission (Scheel et al., 2016). Another example of the use of posture is seen in rats, where an upright posture and lying on the back communicate aggression and submission, respectively (Koolhaas et al., 1980).

Next to posture, octopi use colouration in agonistic interactions (i.e., fighting-related interactions), where a dark colour signals threat and a light colour signals submission (Scheel et al., 2016). Other examples of communicating threat include the, often yellow, dewlap of the anole lizard (Nicholson et al., 2007) and the contrasting colouration used by poison dart frogs to warn predators of toxicity (Endler & Mappes, 2004; Santos et al., 2003).

Gestures are used in nature to communicate threat and submission. African elephants, for example, communicate threat via ear-spreading to increase their size, whereas ear-flattening (i.e., hiding the ears) communicates submission (Poole & Granli, 2011). Other examples of intent communication via gestures include expandable structures that are repeatedly erected and collapsed as used by the frillneck lizard and peacock spider (Girard et al., 2011; Shine, 1990), and rapid versus slow head bobs used by the bearded dragon to communicate, respectively, threat and submission (Brattstrom, 1971).

### *1.3. Aim of the study*

The aim of the present study was to determine the intuitiveness of bio-inspired eHMIs as compared to currently proposed concepts. Three bio-inspired eHMIs were created that rely on the aforementioned visual channels. The bio-inspired eHMIs were compared in terms of intuitive interaction with three control conditions: a lightbar eHMI, a text-based eHMI, and a baseline condition without an eHMI. Intuitive interaction was defined as the unwitting application of prior knowledge to a new situation, consisting of three components: effectiveness, efficiency, and satisfaction (Hurtienne & Blessing, 2007). Intuitive interaction is important for eHMIs, because it could make the interaction between AV and pedestrian more pleasant, thereby stimulating the acceptance of AVs (Haddington & Rauniomaa, 2014; Schieben et al., 2019).

## 2. Method

### 2.1. Bio-inspired eHMIs and control group

Bio-inspired eHMIs were developed that used posture, gesture, and colouration, respectively, to communicate 'yielding' and 'non-yielding' to a pedestrian in a crossing situation. Technical and practical feasibility were not considered during the design process. The three bio-inspired concepts were compared with a control group consisting of a text-based eHMI, a lightbar eHMI, and a baseline condition with no eHMI.

Inspired by the use of posture by the octopus and the rat to communicate threat or submission, the posture eHMI communicated 'non-yielding' and 'yielding' through, respectively, raising and lowering the body of the AV with 15 cm with respect to its base position. The transition from one position to another took 0.5 s to complete. Various heights and transition times were pilot-tested and the aforementioned settings were judged to be physically most realistic.

The gesture eHMI was primarily inspired by the African elephants, with learnings from the frillneck lizard, peacock spider, and bearded dragon to communicate intent. Specifically, the eHMI consisted of flaps on the left, right, and top of the AV. 'Non-yielding' was communicated through repeatedly moving the flaps between 5° and 125° at a frequency of 1 Hz. 'Yielding' was communicated through repeatedly moving the flaps between 5° and 25° at 0.8 Hz. The angles and frequencies were iteratively refined until they were deemed mechanically plausible.

The colouration eHMI communicated 'non-yielding' through changing the colour of the entire AV to yellow with black spots. 'Yielding', on the other hand, was communicated by changing the colour of the entire AV to white with black spots. The colour change occurred instantaneously. The principle underlying the colouration eHMI was similar to the use of colouration by octopi in agonistic interactions, communicating threat or submission through assuming a different colour. The colour yellow served as an aposematic warning, similar to the use of colour by the poison dart frog. Moreover, the dewlap of the anole lizard is often yellow (Nicholson et al., 2007), indicating that this colour is conspicuous and able to attract attention.

The text-based eHMI consisted of a display installed on the bumper of the AV. This location was previously found to be a suitable place for eHMIs (Bazilinskyy et al., in press). The text-based eHMI showed 'WALK' and 'DON'T WALK' in white text to communicate 'yielding' and 'non-yielding', respectively. In research amongst eHMI concepts proposed by the automotive industry, concepts that used text were regarded as clearer than concepts that did not use text. Furthermore, egocentric text messages (e.g., 'Walk', 'Don't walk') received higher clarity ratings than allocentric text messages ('Will stop', 'Won't stop') (Bazilinskyy et al., 2019). The lightbar eHMI also consisted of a display installed on the bumper, turning green and red to communicate, respectively, 'yielding' and 'non-yielding'. Earlier research showed that, compared to other colours, green and red were judged to be the most suitable for communicating 'yielding' and 'non-yielding' (Bazilinskyy et al., 2020). For the baseline condition, no communication mechanism was in place, so the intent was solely implicitly communicated through the speed and distance of the AV.

Table 1 provides an overview of the six tested eHMIs and the manner in which intent was communicated.

### 2.2. Experimental design

To test the intuitiveness of the eHMIs, a survey was made using the crowdsourcing platform Appen (www.appen.com). Participants were offered a payment of USD 0.40 for completing the survey. Participants were first asked to complete a questionnaire and subsequently watched 60 videos of a self-driving blue Smart ForTwo approaching from 150 m at a speed of 50 km/h. There was no person in the driver's seat, but a passenger was present. The colour blue was chosen for the vehicle because this colour was previously identified to carry no connotation for communicating either 'yielding' or 'non-yielding' to pedestrians (Bazilinskyy et al., 2020). Two scenarios were tested:

- Yielding: The AV communicated 'yielding' at a distance of 30 m from the pedestrian. The AV simultaneously started decelerating with 3.5 $m/s^2$ and stopped 2.5 m in front of the pedestrian. After standing still for 3.5 s, the AV communicated 'non-yielding' and started driving 1.5 s later.
- Non-yielding: The AV communicated 'non-yielding' at a distance of 30 m from the pedestrian and maintained a speed of 50 km/h.

The videos were rendered in the simulator previously used by De Clercq et al. (2019) and Kooijman et al. (2019). The videos were rendered from a camera height of 1.63 m with a resolution of 1280 × 720 pixels and 30 frames per second. The first second for both the yielding and non-yielding videos was a black screen, after which the street was shown with the AV approaching. The yielding videos lasted 22 s, whereas the non-yielding videos lasted 13 s. The distance of the approaching vehicle from the pedestrian is shown in Fig. 1.

Throughout each video, the participants were tasked with pressing and holding the F key whenever they felt safe to cross the street shown in Fig. 2.

Before starting the experiment, the participant was informed that the purpose of the experiment was to determine the willingness to cross in front of a car with an eHMI. Furthermore, the participant was informed of the method used and was subsequently asked to complete a short demographic questionnaire and begin the experiment. The participant first

**Table 1**
Overview of the tested eHMIs and the manner in which their intent was communicated.

| eHMI condition | Base state | Yielding | Non-yielding |
|---|---|---|---|
| *Posture* |  |  |  |
| *Gesture* |  |  |  |
| *Colouration* |  |  |  |
| *Text* |  |   |   |
| *Lightbar* |  |  |  |
| *Baseline* |  |  |  |

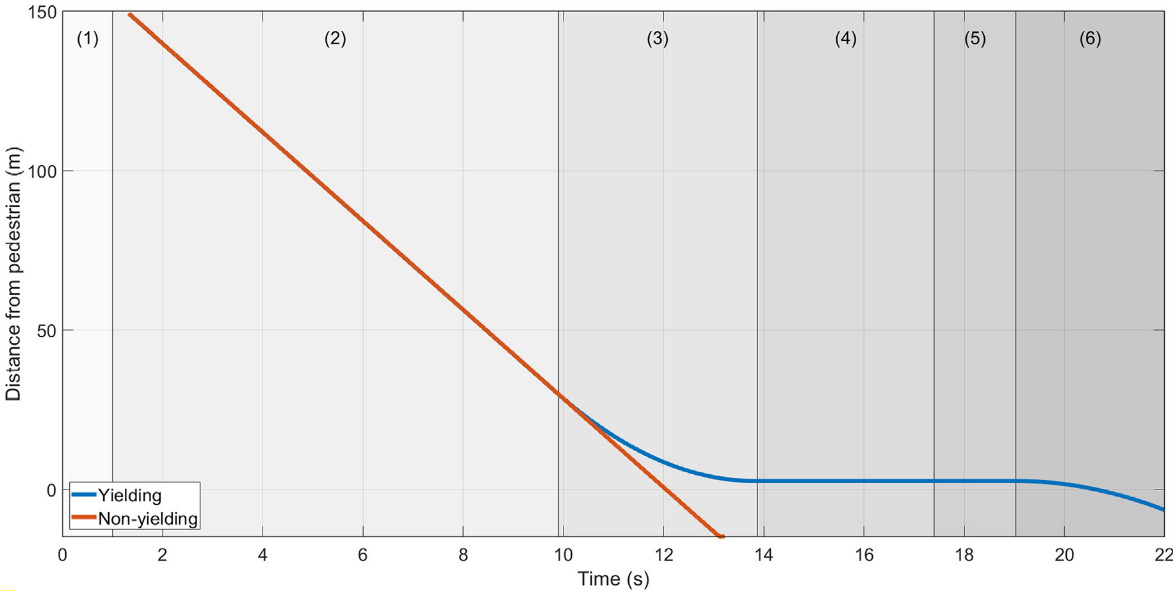


**Fig. 1.** Distance of the vehicle from the pedestrian, and onsets of changes. (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents the period when the AV was standing still, (5) is the period the AV signalled 'non-yielding', and (6) is the period the AV started driving again. The non-yielding trials ended after 13 s.

**Fig. 2.** The virtual street in which the experiment took place.

watched two videos to familiarise themselves with the surrounding. In these two videos, an AV approached that communicated 'yielding' and 'non-yielding', respectively, via an eHMI that used smiling and which was not further used in the study.

Next, the participant viewed 60 videos in six blocks of ten videos each. Each block randomly featured one of the six eHMIs, with five yielding videos and five non-yielding videos in random order. Before the next video was shown, the participant was asked to press the C key and subsequently press and hold the F key, to ensure that all participants started a trial with the F key pressed. After each block of ten videos, the participant was asked to rate the featured eHMI twice, first for non-yielding vehicles and subsequently for yielding vehicles. More specifically, images of the tested eHMI communicating 'non-yielding' and 'yielding' were provided, and the following questions were asked, representing self-reported efficiency, self-reported satisfaction, and self-reported intuitiveness, respectively:

- *"This concept was easy to understand*"
- *"I like this concept as a way of communication*"
- *"This concept is intuitive for signaling 'Please do NOT cross the road'*" (for the non-yielding vehicle) or *"This concept is intuitive for signaling 'Please cross the road'*" (for the yielding vehicle)

Participants entered their responses using a slider bar on a scale of 0 (completely disagree) to 100 (completely agree).

In summary, the experiment was designed to test all three components of intuitiveness: effectiveness, efficiency, and satisfaction. Effective interaction was measured in this experiment through the participant's keypress behaviour, quantified through a performance score. Efficiency refers to the mental effort required and was quantified through the first rating question. Satisfaction represents the participant's attitude towards the system and was quantified through the second rating question. The third rating question provided an indication of self-reported intuitiveness.

After having interacted with all six eHMIs, the participant was asked to rank the six eHMIs on clarity and personal preference, in order to obtain insight in how the eHMIs compared with each other. Furthermore, a unique code was shown that the participant had to enter into the Appen platform to finish the experiment and receive the reimbursement.

### *2.3. Data filtering*

Each participant was assigned a code that was used to relate the survey results with the keypress data. If the code was not present in both the survey results and the keypress data, or was used multiple times, the corresponding participant was excluded. Participants (1) who reported they did not read the instructions, (2) who reported being younger than 18 years, (3) whose data from less than 50 trials were available (i.e., due to an issue affecting the storage of data, segments of data from various participants for the final part of the experiment were lost), or (4) who completed the study in less than 1050 s (i.e., the minimum time someone would need to complete the study, based on video length) were removed. If the survey was executed multiple times from the same IP address, all but the first attempt were removed.

### *2.4. Data analysis*

For the yielding scenario, two distinct phases were analysed:

- YieldingApproach: The period between 0.3 s after the AV first communicated 'yielding' until it came to a stop (10.2–13.9 s).
- YieldingDrivingAway: The period between 0.3 s after the AV first communicated 'non-yielding' until 1 s after it started driving away (17.7–20.0 s).

For the non-yielding scenario, one phase was analysed:

- NonYielding: The period between 0.3 s after the AV first communicated 'non-yielding' until the front of the AV passed the pedestrian (10.2–12.1 s).

The 0.3 s margin was included to account for human reaction time and minimise carry-over effects from one phase to the other. To quantify the effectiveness of each eHMI, a performance score was computed per participant and was subsequently averaged over all participants. The performance score was computed for the three identified phases, and for each eHMI, with 0 being the worst and 100 the best:

- YieldingApproach: The performance score per participant was computed by averaging the keypress percentage over the YieldingApproach period and thereafter computing the mean over the five trials.
- YieldingDrivingAway: The performance score per participant was computed by averaging the keypress percentage over the YieldingDrivingAway period, computing the mean over the five trials, and subsequently subtracting the mean from 100.
- NonYielding: The performance score per participant was computed by averaging the keypress percentage over the NonYielding period, computing the mean over the five trials, and subsequently subtracting the mean from 100.

The mean score of the three rating questions was plotted against the mean performance score for each eHMI and for the three different phases, and the corresponding Pearson correlation coefficient was computed.

The performance score was also computed per trial of the various eHMI and was subsequently used to construct learning curves for the three distinct phases and six conditions.

## 3. Results

### 3.1. Participants

Between 28 May 2020 and 2 June 2020, 2000 participants completed the survey. Most participants were excluded based on the repeated use of codes/non-matching codes or repeated use of IP addresses ($n$ = 324 and $n$ = 596, respectively), or by completing the study in less than 1050 s ($n$ = 251), or because they viewed less than 50 of the 60 videos ($n$ = 100). A relatively small number of participants were excluded because they indicated they did not read the instructions ($n$ = 11) or were younger than 18 years ($n$ = 9). After exclusion, 1141 participants from 63 countries remained (mean age = 37.4 years, $SD$ = 11.5; 762 males, 375 females, and 4 participants indicated that they preferred not to respond).

The mean study completion time was 45.0 min ($SD$ = 17.9). The three most represented countries were Venezuela ($n$ = 471), the United States ($n$ = 69), Russia ($n$ = 65), India ($n$ = 54), and Turkey ($n$ = 53). The study yielded an average satisfaction score of 4.3 on a scale from 1 to 5 by 101 participants who completed the optional satisfaction survey offered by Appen.

### 3.2. Experiment results

Fig. 3 shows the keypress data for yielding and non-yielding AVs. Analysis of the three distinct phases provided insight into the impact of eHMIs.

- For YieldingApproach, a sharp increase occurred in the percentage of participants who felt safe to cross after 'yielding' was communicated ((3) in Fig. 3) by the eHMIs. Such an increase also occurred for the baseline condition, but at a later stage and with a lower peak.
- For YieldingDrivingAway, a steep drop in the percentage of participants who felt safe to cross occurred after the eHMIs communicated 'non-yielding' ((5) in Fig. 3). For the baseline condition, the drop in the percentage of participants who felt safe to cross occurred only after the AV started driving away.
- For NonYielding, the eHMIs showed a steeper drop in the percentage of participants who felt safe to cross after communicating 'non-yielding' (beginning of (3) in Fig. 3) than the baseline condition.

Table 2 shows the mean scores for the three rating questions. The lightbar eHMI received the highest ratings on all three questions for both yielding and non-yielding, followed by the text-based eHMI, whereas the baseline condition scored the lowest for all questions. Among the three bio-inspired eHMIs, the colouration eHMI received the highest ratings for all three questions. The means of the three rating questions were highly correlated, $r$ > 0.988 ($n$ = 6) for yielding scenarios and $r$ > 0.985 ($n$ = 6) for non-yielding scenarios.

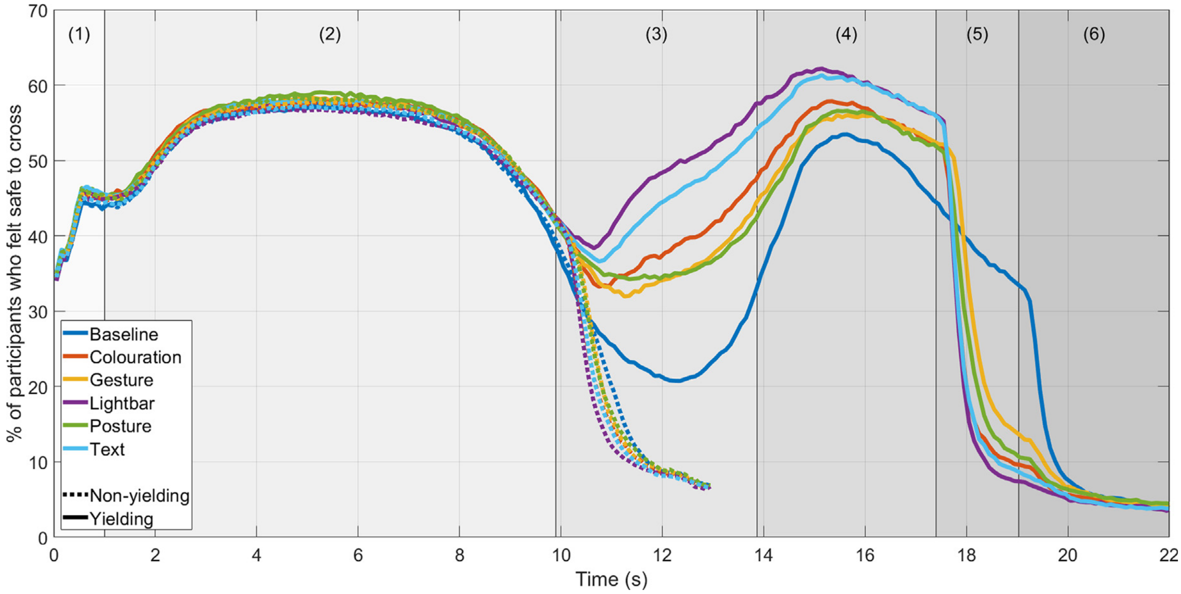


**Fig. 3.** Keypress data for the yielding and non-yielding scenario. (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents the period when the AV was standing still, (5) is the period the AV signalled 'non-yielding', and (6) is the period the AV started driving again. The non-yielding trials ended after 13 s.

**Table 2**
Mean scores (standard deviations in parentheses) for the three rating questions for each eHMI condition for yielding and non-yielding scenarios. The scores are expressed on a scale from 0 (completely disagree) to 100 (completely agree).

| | | Yielding | | | Non-yielding | | |
|---|---|---|---|---|---|---|---|
| eHMI condition | Sample size | Self-reported efficiency | Self-reported satisfaction | Self-reported intuitiveness | Self-reported efficiency | Self-reported satisfaction | Self-reported intuitiveness |
| Baseline | $n$ = 1091 | 40.9 (34.7) | 37.5 (34.2) | 37.1 (34.4) | 41.4 (34.9) | 37.9 (34.5) | 36.7 (34.1) |
| Colouration | $n$ = 1105 | 67.6 (30.0) | 62.2 (32.5) | 63.1 (32.4) | 68.7 (29.8) | 62.7 (32.5) | 63.4 (32.1) |
| Gesture | $n$ = 1093 | 56.3 (32.0) | 46.3 (34.4) | 49.9 (33.7) | 58.2 (32.3) | 47.1 (34.8) | 51.8 (33.9) |
| Lightbar | $n$ = 1092 | 89.7 (15.5) | 88.5 (16.2) | 88.8 (17.5) | 89.5 (15.9) | 87.8 (16.9) | 88.2 (18.1) |
| Posture | $n$ = 1087 | 60.9 (30.5) | 54.1 (32.5) | 56.0 (32.4) | 62.6 (30.1) | 55.0 (32.9) | 56.8 (32.5) |
| Text | $n$ = 1089 | 84.4 (19.3) | 77.5 (24.9) | 81.1 (22.6) | 84.0 (19.8) | 76.9 (25.0) | 80.8 (22.3) |

Fig. 4 shows the mean of the three rating questions and the mean performance score in a scatter plot. The three rating questions were averaged because they were nearly perfectly correlated. The lightbar eHMI attained the highest mean performance score for YieldingApproach (47.4, $SD$ = 37.8), YieldingDrivingAway (87.7, $SD$ = 19.0), and NonYielding (84.1, $SD$ = 25.2). For all three phases, the baseline condition attained the lowest mean performance score. The mean rating and the mean performance score were found to be strongly correlated, with Pearson correlation coefficients of, respectively, $r$ = 0.97, $r$ = 0.89, and $r$ = 0.95, for YieldingApproach, YieldingDrivingAway, and NonYielding.

Table 3 shows the ranking of the participants of the six eHMIs on clarity and personal preference. The lightbar eHMI was ranked highest for both criteria. The colouration eHMI was ranked higher than the text-based eHMI for clarity, while the baseline condition was ranked lowest for both questions.

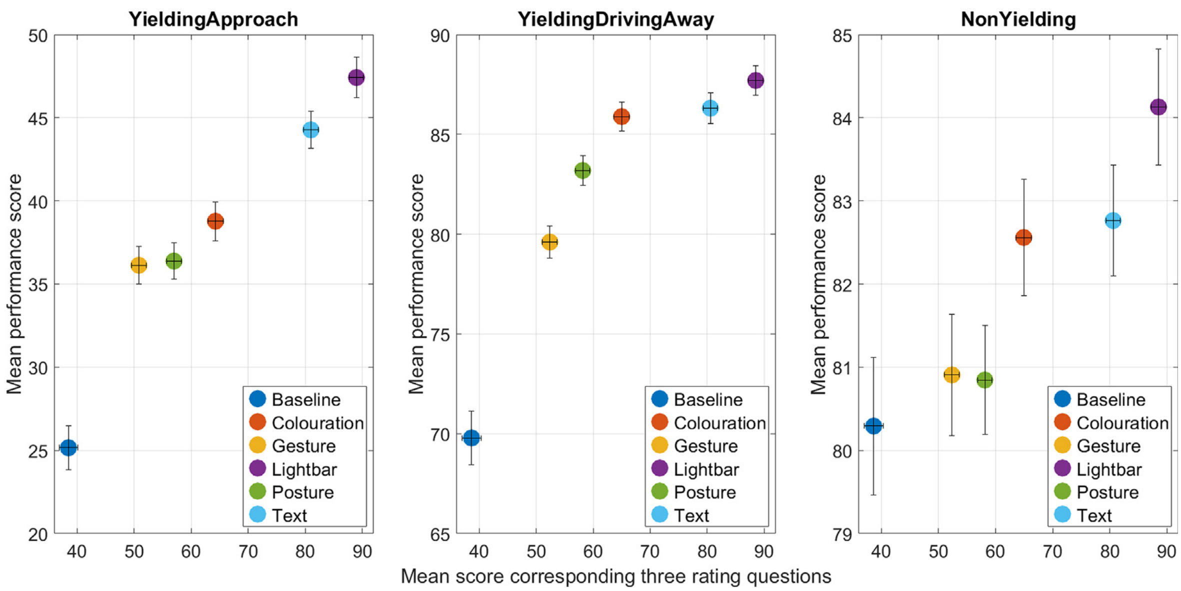


**Fig. 4.** Scatter plot of the mean of the three rating questions (yielding for YieldingApproach and non-yielding for Yielding- DrivingAway and NonYielding) versus the mean performance score. The black lines represent the 95% within-subjects confidence interval, computed using the approach specified in Cousineau (2005) and corrected in accordance with Morey (2008).

**Table 3**
Mean ranks (standard deviations in parentheses) of the eHMI conditions regarding clarity and personal preference ($n$ = 855).

| eHMI condition | Mean rank regarding clarity (1 = most clear, 6 = least clear) | Mean rank regarding personal preference (1 = most preferred, 6 = least preferred) |
|---|---|---|
| Baseline | 4.16 (1.86) | 4.13 (1.80) |
| Colouration | 3.13 (1.65) | 3.27 (1.63) |
| Gesture | 3.65 (1.35) | 3.78 (1.42) |
| Lightbar | 2.76 (1.84) | 2.78 (1.89) |
| Posture | 4.00 (1.36) | 3.89 (1.40) |
| Text | 3.30 (1.68) | 3.14 (1.66) |

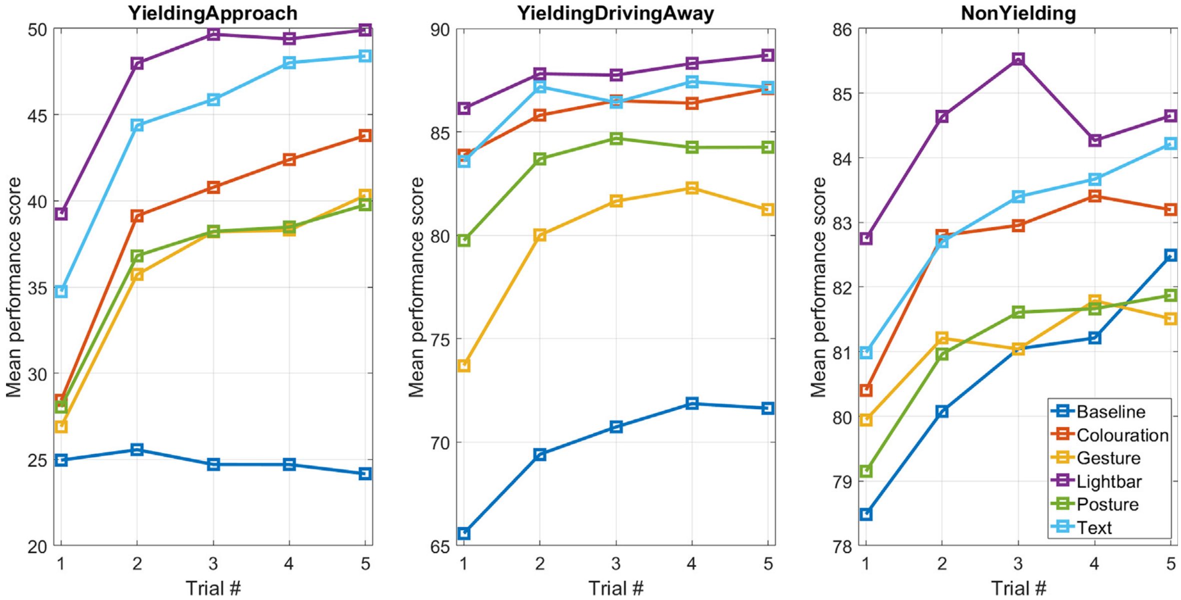


**Fig. 5.** Learning curves for YieldingApproach, YieldingDrivingAway, and NonYielding, for the different eHMIs.

The learning curves for the three distinct phases for the six eHMI conditions are shown in Fig. 5. For YieldingApproach, the baseline condition showed a small decline in performance. All five eHMIs showed strong learning effects, with a substantial improvement between the first and second trial and a more gradual improvement until the fifth trial. For YieldingDrivingAway and NonYielding, all six conditions showed improvement with trial number.

## 4. Discussion

This paper aimed to determine the intuitiveness of three bio-inspired eHMIs and compare them with two existing eHMI concepts and a baseline condition with no eHMI. Through a crowdsourcing study, participants' crossing intentions and self-reported ratings were acquired for yielding and non-yielding AVs, providing a measure of intuitive interaction. Intuitive interaction was defined based on three components: effectiveness, efficiency, and satisfaction (Hurtienne & Blessing, 2007). Effectiveness was determined by converting the participant's crossing intentions for each phase (i.e., YieldingApproach, YieldingDrivingAway, and NonYielding) into a performance score. Efficiency and satisfaction were determined through self-reports. Additionally, the participants were asked to rate the intuitiveness of each eHMI and also rank them on clarity and personal preference.

Whether an eHMI is needed to inform the pedestrian or whether implicit communication (i.e., vehicle kinematics) alone suffices has been debated in the literature (Dey & Terken, 2017; Moore et al., 2019; Rothenbücher et al., 2016). The baseline condition yielded the lowest performance scores and self-reported ratings, and the worst rankings of the tested conditions. These results are consistent with previous research, which found that having an eHMI is preferred by participants (Bazilinskyy et al., in press; Cefkin et al., 2019) and that the presence of an eHMI improves crossing behaviour compared to no eHMI (Böckle et al., 2017; Chang et al., 2017; De Clercq et al., 2019).

The lightbar eHMI and the text-based eHMI generally yielded higher performance scores, higher ratings, and better rankings than the bio-inspired eHMIs. An exception was the colouration eHMI, which for YieldingDrivingAway and NonYielding performed on par with the text-based eHMI. Furthermore, among the three bio-inspired eHMIs, the colouration eHMI attained the highest performance scores and self-reported ratings. The posture eHMI generally obtained higher self-reported ratings than the gesture eHMI, whereas the gesture eHMI was ranked better for clarity and personal preference than the posture eHMI. It is possible that the images that accompanied the ranking questions were clearer for the gesture eHMI than for the posture eHMI, whereas for the videos, this was vice versa.

The differences in the performance scores of the various eHMIs could be explained if we consider the three factors that contribute to successful communication of a signal in nature: detectability (i.e., the degree to which the signal is different from the environment and easy to perceive), discriminability (i.e., the degree to which the signal can be distinguished from other signals), and memorability (i.e., the degree to which the signal is memorable and can be associated with a certain action) (Guilford & Dawkins, 1991). More specifically, the lightbar eHMI and the text-based eHMI rely on principles already established in traffic (i.e., communication through colour and text), giving them an advantage with respect to memorability compared to the bio-inspired eHMIs.

In previous research, text-based eHMIs were found to be clearer than light-based eHMIs (Bazilinskyy et al., 2019). In the present study, we found that the lightbar eHMI was more effective (i.e., higher performance score) than the text-based eHMI. An important difference between the aforementioned study and this study is that we used a moving AV. The movement of the AV might have made it easier to relate the kinematics of the AV to the signal, benefitting the memorability of the signal.

The three aforementioned factors of successful communication of a signal could also explain why the bio-inspired colouration eHMI had a relatively high performance score: In the colouration eHMI, the colour change occurred instantaneously, whereas the changes in the other two bio-inspired eHMIs were more gradual. Sudden changes grab attention (Von Mühlenen & Conci, 2016), benefitting the colouration eHMI in terms of detectability over the other bio-inspired eHMIs. Furthermore, a colour change is known to receive attentional priority (Von Mühlenen & Conci, 2016), giving the colouration eHMI an advantage regarding discriminability. Lastly, the colouration eHMI benefitted from memorability, because the use of colour is already commonly used in traffic.

The learning curves in Fig. 5 show that the five eHMIs benefitted similarly from experience. Several academic experts have expressed the need for training in interactions with AVs (Tabone et al., 2021), and the results from the present study are consistent with this recommendation. It should be noted that participants may have learned to understand not only the eHMIs but also the preprogrammed behaviour of the vehicle. Inspection of Fig. 3 shows that some participants released the response key before the eHMI drove off and before the eHMI switched back to its non-yielding state. This suggests that participants had formed expectations that the vehicle would drive off after standing still.

A noteworthy aspect of the experiment is that crowdsourcing was used. One of the strengths of crowdsourcing is that the experiment was conducted with a large sample of participants. A consequence of crowdsourcing is that the data needed to be filtered to remove unsuitable participants. The current study was completed by 2000 participants, but 859 participants (43%) were removed. In previous crowdsourcing studies testing eHMIs, 304 of 1770 participants (17%), 681 of 2000 participants (34%), and 797 of 2231 participants (36%) were removed using comparable exclusion criteria (Bazilinskyy et al., 2019, in press). In a crowdsourcing study by Dey et al. (2020b) testing light-based eHMIs, only 25 of the 400 participants (6%) were removed. However, Dey et al. used a different platform and solely allowed 'Master Workers' (i.e., workers who have received a qualification by having participated successfully in previous experiments), which could explain the difference in participants excluded.

The use of crowdsourcing allows for attracting a more geographically diverse and typically older group of participants than the traditional university participant pool (Behrend et al., 2011). As an additional analysis, we studied the impact of the participants' country on the performance scores and self-reports (see Fig. S1 in the Supplementary Material). The results revealed differences in performance scores and self-report ratings between the different countries, but the rank-ordering of the eHMI conditions was consistent between countries, with baseline scoring the lowest and the text-based and lightbar eHMI scoring the highest. Our findings are consistent with previous cross-national research in which various icon-based eHMIs were tested (Singer et al., 2020), and a study in which the effect of text, colour, and perspective on eHMI concepts was investigated (Bazilinskyy et al., 2019).

## 5. Limitations and recommendations

For the design of the bio-inspired eHMIs, various limitations are in place. The designs were based on visual intent communication in nature, and were discussed among the authors, but were not modified based on pilot testing. Technological feasibility and plausibility of the bio-inspired eHMIs were not considered either. Schlackl et al. (2020) presented a prototype of an eHMI visualisation on the entire car body, suggesting that our colouration eHMI may be technologically viable. The posture eHMI may function via ride height adjustments, and relates to other research which has proposed to use vehicle pitch as communication cue (Cramer et al., 2017; Dietrich et al., 2019). However, the gesture eHMI needs to be designed carefully, as the flaps might pose harm to other road users or could unintentionally function as an air brake (and therefore be associated with yielding rather than non-yielding). Another approach is implementing the eHMIs via augmented reality, although this introduces several challenges that need to be addressed, including availability for all, privacy, and user-friendliness (Tabone et al., 2021).

A second limitation is that only visual communication was considered, whereas in nature, it is common to communicate through multiple channels (see Oudshoorn et al., 2020). It would be interesting to consider a bio-inspired eHMI that combines multiple channels and appeals to multiple senses (e.g., vision and hearing). In nature, multi-modal signals were found to lead to better detectability (Rowe, 1999) and increase the accuracy of the signal interpretation (Mitoyen et al., 2019). Furthermore, the multi-modal signal could help make the eHMI inclusive to the visually impaired. Inclusivity of eHMIs was reported as an understudied area of eHMI research (Robert, 2019), whereas it was also mentioned numerous times in the remarks from participants to "add sound effects so that visually impaired people can understand".

The bio-inspired eHMIs communicated 'yielding' and 'non-yielding' using most of the body of the AV, whereas the lightbar eHMI and the text-based eHMI communicated using a small part of the AV body. However, the performance scores of the bio-inspired eHMIs were lower than the lightbar eHMI and text-based eHMI. A factor that could have caused the difference in performance scores is the lack of familiarity with the bio-inspired eHMIs. To increase the familiarity of these concepts and thereby increase their effectiveness, it could be interesting to create concepts that combine the best of the bio-inspired eHMIs with the best of the non-bio-inspired eHMIs. Especially the colouration eHMI showed promise and could be combined with the lightbar eHMI, e.g., having the full-body colouration of the colouration eHMI, but use green and red to communicate, respectively, 'yielding' and 'non-yielding' to increase familiarity.

There were some limitations in the experimental design and the use of crowdsourcing. It is recommended to repeat this study in a lab-based environment to validate the findings from the crowdsourcing study. The lab-based environment makes it possible to immerse the participant in the virtual environment, introducing the possibility of moving and looking around to make the crossing situation feel more realistic. Also, it introduces the option of measuring more variables, e.g., eye-tracking, than what was possible through crowdsourcing.

Another possible limitation introduced through the use of crowdsourcing is that participants did not take the task seriously. In this study, the maximum mean percentage of participants who pressed the F key was about 60%, whereas approximately 10% of the participants pressed the F key the moment the AV passed them. These observations suggest that not all participants understood the task or were actively participating in the experiment. An analysis of learning trends shows that participants became less engaged as the experiment progressed (as evidenced by the reduction of key press rates with trial number while the vehicle was approaching) but became better at recognising that the vehicle was yielding (as evidenced by the increase of key press rates when the vehicle was stopping), see Figs. S2 and S3 in the Supplementary Materials. We believe that the non-serious workers did not impair the relative comparisons between eHMIs, due to the large number of participants in this study. Furthermore, it was previously shown that crowdsourcing is suitable for acquiring participants in behavioural science experiments (e.g., Behrend et al., 2011; Horton et al., 2011; Mason & Suri, 2012).

A final limitation is that the participant was not distracted through a secondary task or distractions in the environment, which could have led to behaviour that is not realistic. It is therefore recommended to use a secondary task to quantify mental workload and/or distractions in the environment e.g., other road users. It could also be interesting to have multiple AVs communicate with the same eHMI in the same environment, or have multiple pedestrians in the same environment, to determine whether the eHMI is scalable. Scalability was previously mentioned as a design consideration for an effective eHMI (Dey et al., 2020a).

## 6. Conclusions

Current communication between a driver and a pedestrian consists of various cues, including gestures and eye contact. However, these communication methods will not be possible for communication with AVs, which could negatively impact the acceptance of AVs. To encourage acceptance, AVs need to be able to communicate their intention, possibly through the use of an eHMI. In this study, the intuitiveness of three newly designed bio-inspired eHMIs using posture, gesture, and colouration was compared with a lightbar eHMI, a text-based eHMI, and a baseline condition with no eHMI. The three bio-inspired eHMIs were found to be more intuitive than the baseline condition, whereas the lightbar eHMI and the text-based eHMI were more intuitive than the bio-inspired eHMIs. An exception was the colouration eHMI, which was effective in communicating 'non-yielding' and thus warrants further investigation. An interesting approach to consider is combining the colouration eHMI and the lightbar eHMI, by using full-body communication with the colours of the lightbar eHMI.

## CRediT authorship contribution statement

**Max Oudshoorn:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Joost de Winter:** Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Pavlo Bazilinskyy:** Conceptualization, Methodology, Software, Investigation, Resources, Data curation, Writing - review & editing, Supervision. **Dimitra Dodou:** Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration.

## Data Availability

The virtual environment used for rendering the videos and the videos used in the experiment can be accessed through the following link: https://github.com/bazilinskyy/coupled-sim. The raw data and the MATLAB scripts used to process the data are available here: https://doi.org/10.4121/14096067.

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## Supplementary material

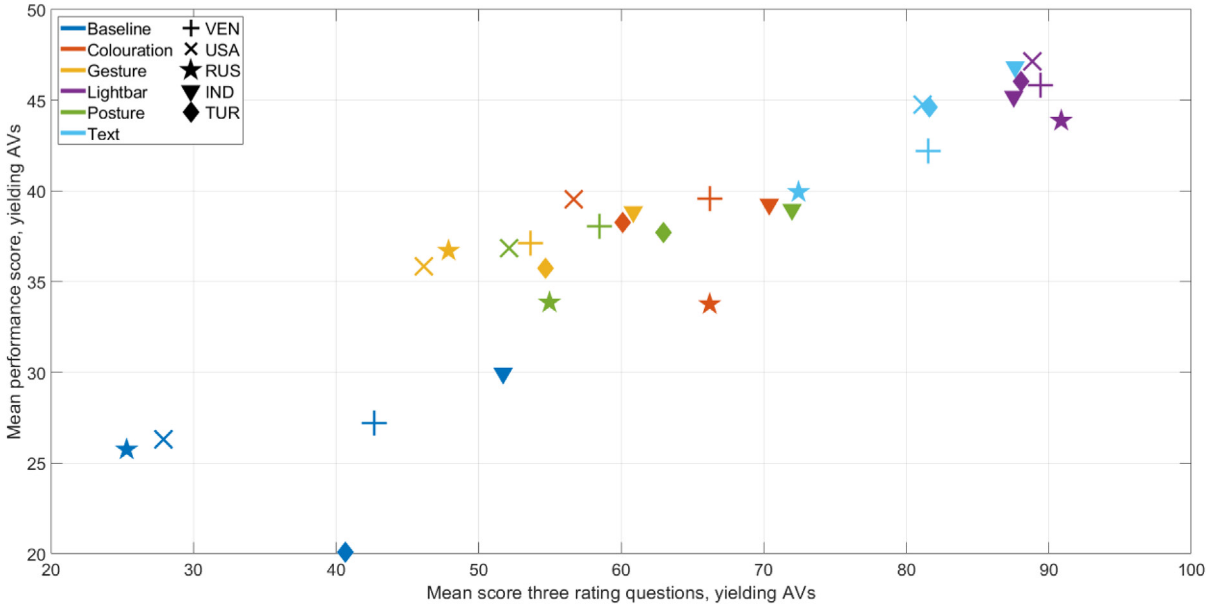


**Fig. S1.** Scatter plot of the mean score of the three rating questions versus the mean performance score for YieldingApproach, with country distinction.

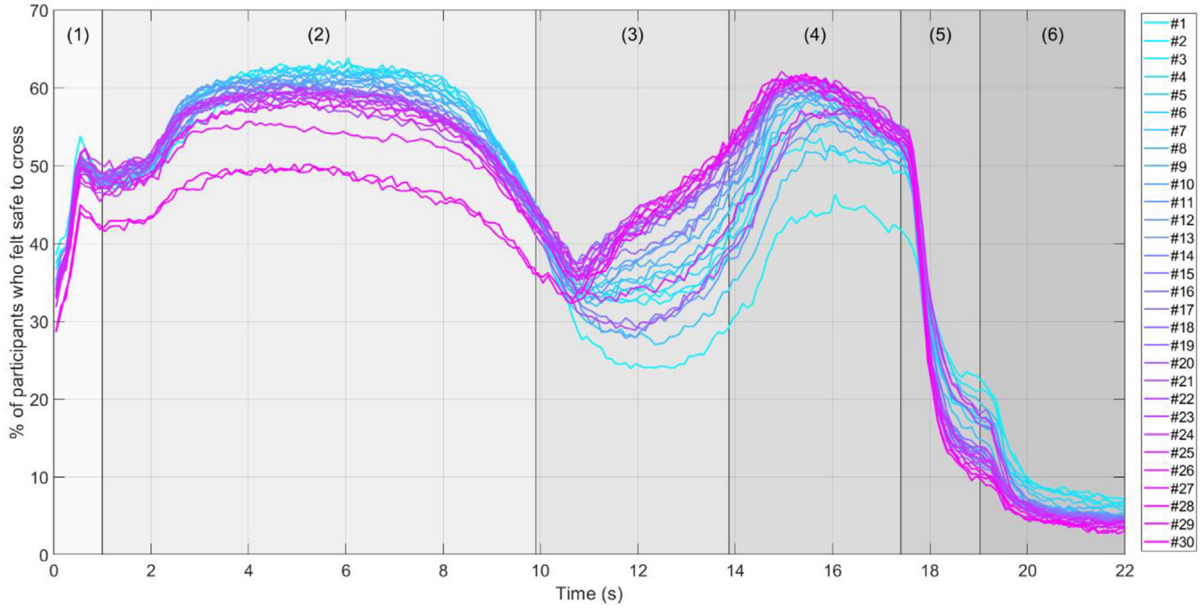


**Fig. S2.** Keypress data as a function of trial number for the yielding scenarios (1 to 30), for all six eHMI conditions combined. (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents the period when the AV was standing still, (5) is the period the AV signalled 'non-yielding', and (6) is the period the AV started driving again.

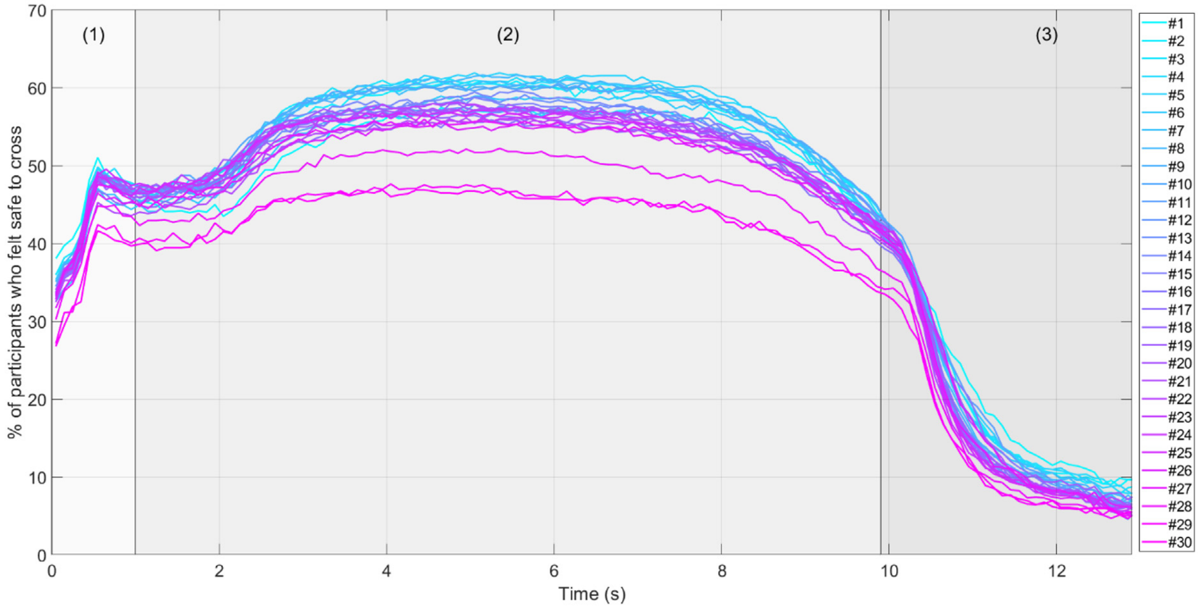


**Fig. S3.** Keypress data as a function of trial number for non-yielding scenarios (1 to 30), for all six eHMI conditions combined. (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling.

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