Bio-inspired intent communication for automated vehicles

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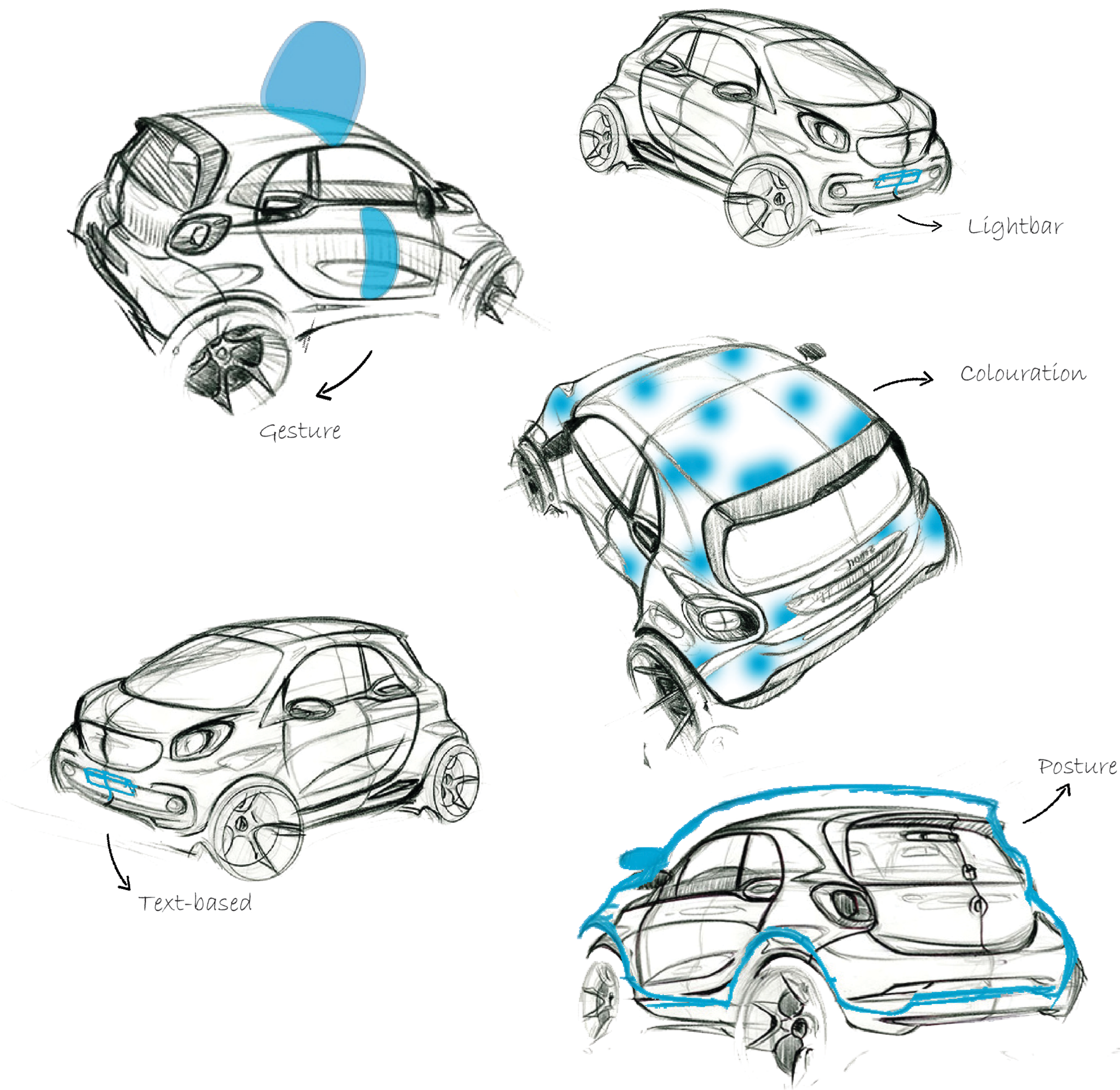

TU Delft

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by

Max Oudshoorn

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TU Delft

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Furthermore, I would like to thank my friends and family for their continuous support and interest. Special thanks to Sjors, Elvira, and Jill for their feedback and assistance. My thesis also marks the end of my time as a student. After almost 7.5 years spent studying and two master degrees, it is time to move on to the next challenge.

Max Oudshoorn
Rotterdam, December 2020

Contents

Paper
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Abstract

Various visual 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, or colouration, respectively. In an online crowdsourcing study, 1523 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 attained a higher performance score than the other eHMIs when communicating 'non-yielding' before driving away from a standstill. Further research is necessary to examine whether these observations hold in more complex traffic situations and other eHMI designs. 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.

Keywords: Automated Vehicles; External Human-Machine Interface; Bio-inspired; Intent communication; Crowdsourcing

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.

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. (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). The use of 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., 2020).

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. Prokop and Fančovičová (2013) found that 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) had a higher perceived fear by humans than a similar animal having inconspicuous colouring, indicating that humans understood the warning colouration of animals. The correct interpretation of warning colouration of animals suggests that other bio-inspired communication might be understood by humans as well and could therefore be suitable for intent communication.

In a previous 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. Rats use posture to communicate threat and submission, 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 inform 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, unrolling the ears 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).

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).

Method

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 of the poison dart frog. Moreover, the dewlap of the dewlap lizard is often yellow (Nicholson et al., 2007), indicating that this colour is conspicuous and able to attract attention.

The text-based eHMI communicated through a display installed on the bumper of the AV. This location was previously found to be a suitable place for eHMIs (Bazilinskyy et al., 2020a). 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 green and red were found to be suitable for communicating 'yielding' and 'non-yielding' (Bazilinskyy et al., 2020b). 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.

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., 2020b). 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 1280x720 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 and the non-yielding videos lasted 13 s.

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			

The timeline of the videos with respect to the vehicle trajectory is shown in Figure 1.

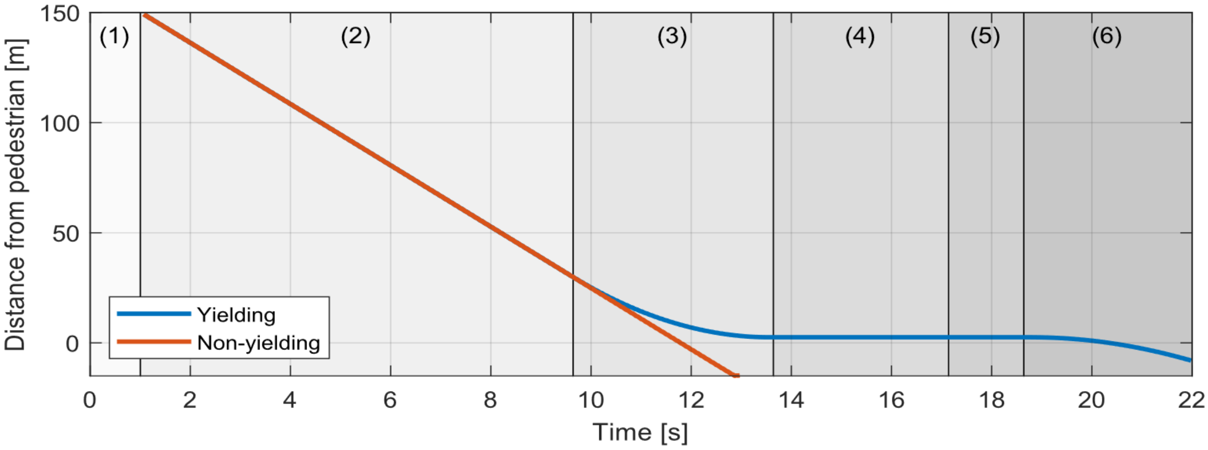

Figure 1. Vehicle trajectory and onsets of changes. Where (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents the period when the AV was standing 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.

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

Figure 2. The virtual street in which the experiment took place

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 questionnaire (provided in Supplement 1) and begin the experiment. The participant first 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 on a scale from 0 to 100 (0 = completely disagree, 100 = completely agree) twice, first for non-yielding and subsequently for yielding. Two images of the tested eHMI communicating ‘yielding’ and ‘non-yielding’ were provided and the following rating questions were asked:

- “*This concept was easy to understand*”
- “*I liked this concept as a way of communication*”
- “*This concept is intuitive for signalling ‘Please (do NOT) cross the road’*”

The experiment was designed to test all three components of intuitiveness: effectiveness, efficiency, and satisfaction. Effective interaction relates to accuracy and was measured in this experiment through the participant’s keypress behaviour, quantified through a performance score (see Section 2.3.2). 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 more 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. Additional information about the experimental procedure can be found in Supplement 1.

Data filtering

Each participant was assigned a worker ID which was used to relate the survey results with the keypress data. If the worker ID 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 to be 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.

Data analysis

For the yielding scenario, two distinct phases were analysed:

- YieldingApproach: The period between when the AV first communicated ‘yielding’ (9.7 s) until it started communicating ‘non-yielding’ (17.1 s).
- YieldingDrivingAway: The period between when the AV first communicated ‘non-yielding’ (17.1 s) until it started driving away (18.6 s).

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

- NonYielding: The period between when the AV first communicated ‘non-yielding’ (9.7 s) until the front of the AV passed the pedestrian (11.8 s).

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 every 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 to determine the correlation between the rating questions and the performance score for each phase.

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.

Results

Participants

Between May 28th 2020 and June 3rd 2020, 2000 participants completed the survey. After filtering, 1523 participants remained (mean age 36.7 years, *SD* = 11.4 years; 996 males, 523 females, and 4 participants indicated that they preferred not to respond). The mean survey time was 47 min (*SD* = 19.9 min). The three most represented countries were Venezuela (*N* = 737), the United States (*N* = 137), and Russia (*N* = 70). The survey was awarded an overall satisfaction score of 4.3 on a scale from 1 to 5 by 101 participants that completed the satisfaction survey.

Experiment results

Figure 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 Figure 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 Figure 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 experienced a steeper drop in the percentage of participants who felt safe to cross after communicating 'non-yielding' (beginning of (3) in Figure 3) than the baseline condition.

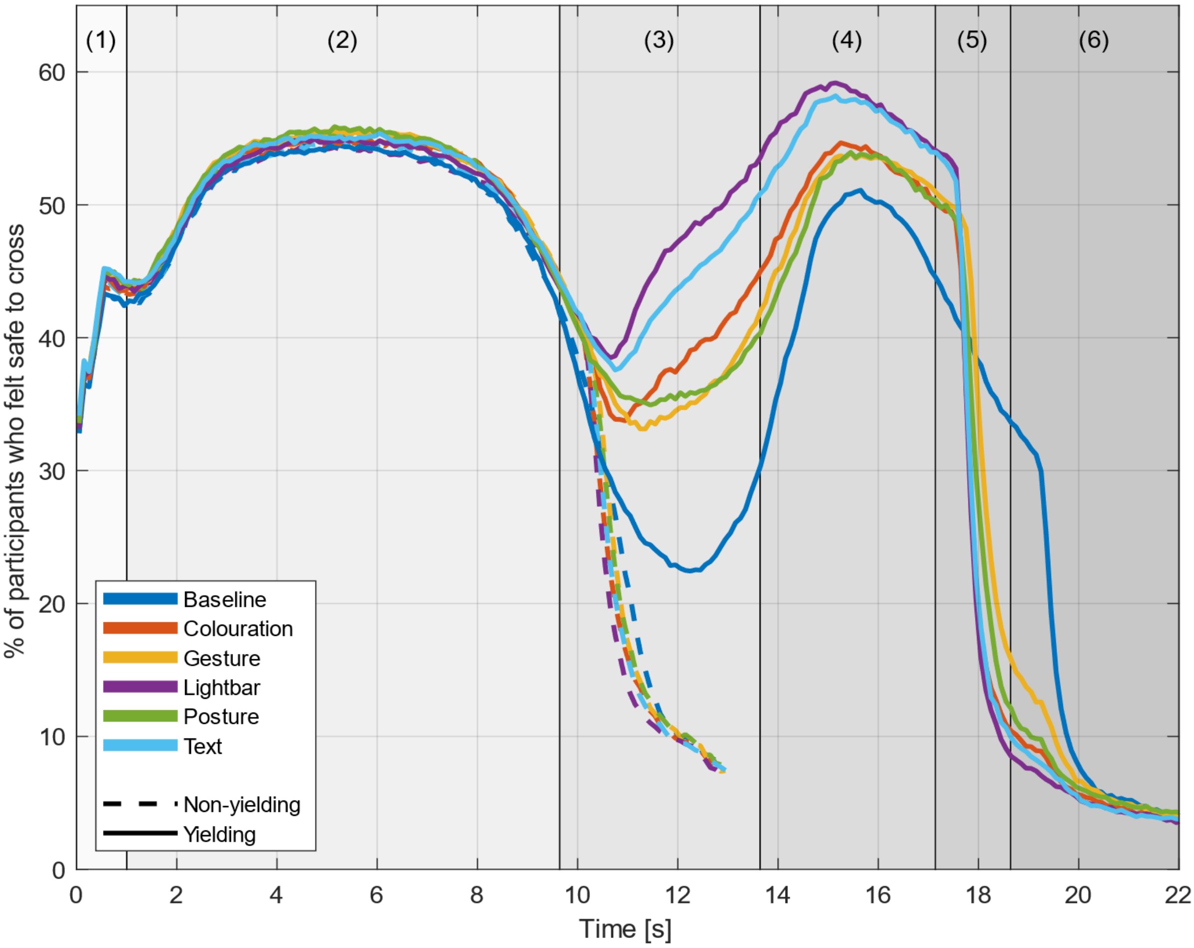

Figure 3. Keypress data for the yielding and non-yielding scenario. Where (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents the period when 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 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 ratings for the three rating questions were highly correlated, having Pearson correlation coefficients of $r > 0.97$ for yielding and $r > 0.89$ for non-yielding.

Table 2. *Mean scores (standard deviations in parentheses) for the three rating questions for each eHMI and 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* = 1456	42.6 (35.0)	39.3 (34.7)	39.3 (35.1)	43.1 (35.2)	39.7 (34.8)	38.8 (34.7)
Colouration	*N* = 1471	69.3 (29.0)	64.4 (31.5)	65.2 (31.6)	70.2 (28.8)	64.8 (31.5)	65.5 (31.3)
Gesture	*N* = 1465	57.8 (31.5)	48.8 (34.0)	52.0 (33.4)	59.6 (31.8)	49.6 (34.2)	54.1 (33.4)
Lightbar	*N* = 1454	89.6 (16.1)	88.7 (16.3)	88.9 (17.8)	89.2 (16.6)	88.1 (16.9)	88.2 (18.3)
Posture	*N* = 1448	62.6 (29.6)	56.1 (31.9)	58.1 (31.9)	64.1 (29.4)	56.8 (32.1)	58.8 (31.8)
Text	*N* = 1446	84.4 (19.4)	78.7 (23.8)	81.8 (21.8)	84.0 (19.8)	78.0 (24.0)	81.3 (21.8)

Figure 4 shows the mean of the corresponding three rating questions and the mean performance score in a scatter plot. The three rating questions were merged because they were highly correlated. The lightbar eHMI attained the highest mean performance score for YieldingApproach (50.7, *SD* = 34.6) and NonYielding (75.9, *SD* = 29.5), and the colouration eHMI attained the highest mean performance score for YieldingDrivingAway (66.9, *SD* = 29.6). 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, $r = 0.93$, $r = 0.82$, and $r = 0.90$, for YieldingApproach, YieldingDrivingAway, and NonYielding.

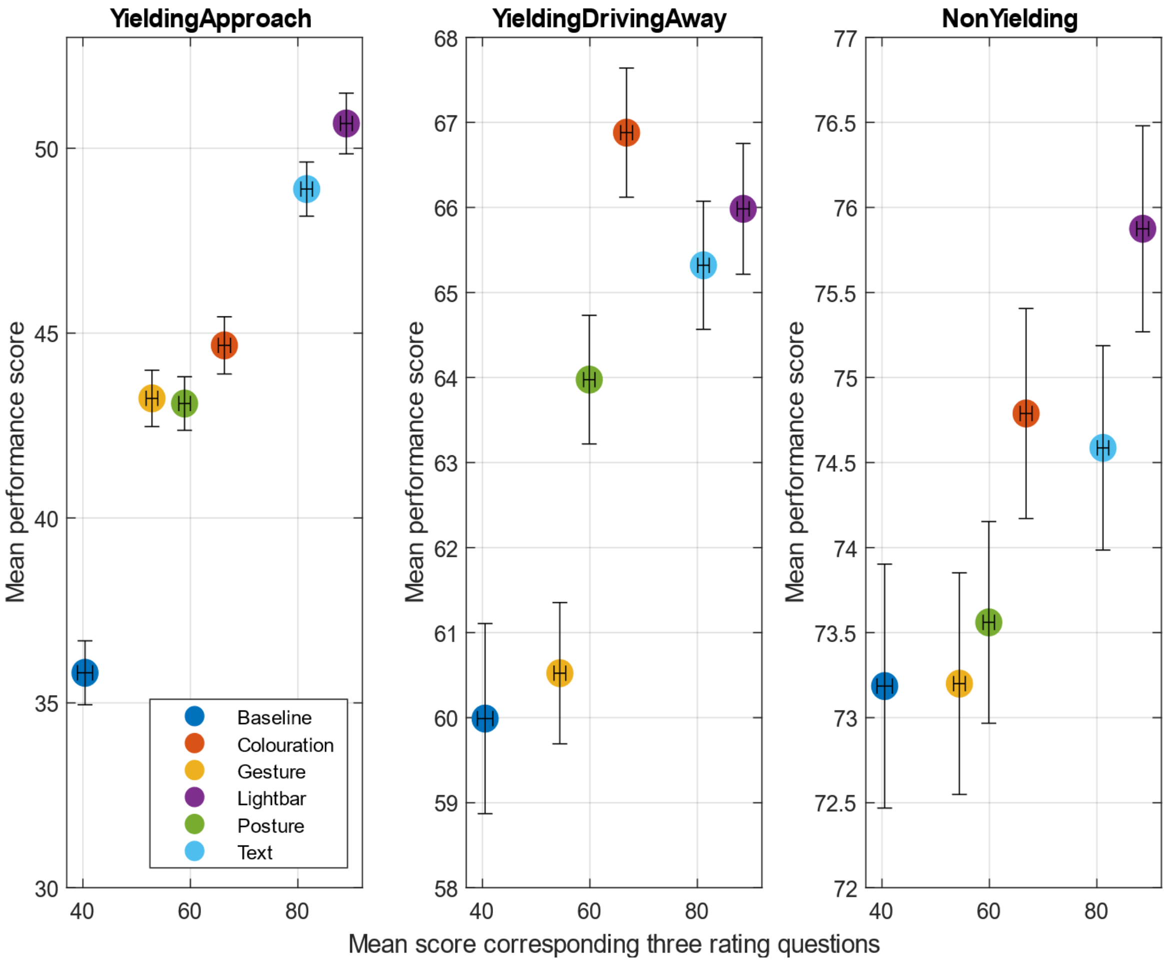

Figure 4. Scatter plot of the mean of the three rating questions (yielding for YieldingApproach and non-yielding for Yielding-DrivingAway and NonYielding) versus mean performance score. The black lines represent the 95% within-subjects confidence interval, computed using the approach specified in Cousineau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

Table 3 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.

Table 3. *Mean rank (standard deviations in parentheses) of the eHMIs on clarity and personal preferences (1 = best, 6 = worst) for N = 1130.*

eHMI condition	**Mean rank regarding clarity**	**Mean rank regarding personal preference**
Baseline	4.11 (1.87)	4.08 (1.81)
Colouration	3.09 (1.67)	3.23 (1.64)
Gesture	3.62 (1.37)	3.74 (1.44)
Lightbar	2.85 (1.84)	2.87 (1.90)
Posture	3.98 (1.36)	3.88 (1.41)
Text	3.36 (1.69)	3.21 (1.67)

The learning curves for the three distinct phases for the six eHMI conditions are shown in Figure 5. For YieldingApproach, the baseline condition showed a minimal improvement between the first and the fifth trial (from 34.3 to 36.2). All eHMIs showed comparable learning effects, with a significant improvement between the first and second trial and subsequently a more gradual improvement until the fifth trial. For YieldingDrivingAway, the colouration eHMI, lightbar eHMI, and posture eHMI experienced little to no improvement. The baseline condition exhibited the most improvement (from 57.8 to 61.0). For NonYielding, all performance scores improved between the first and fifth trial. The largest improvements were achieved with the baseline condition (from 71.7 to 75.5), the text-based eHMI (from 73.5 to 76.4), and the posture eHMI (72.6 to 74.8).

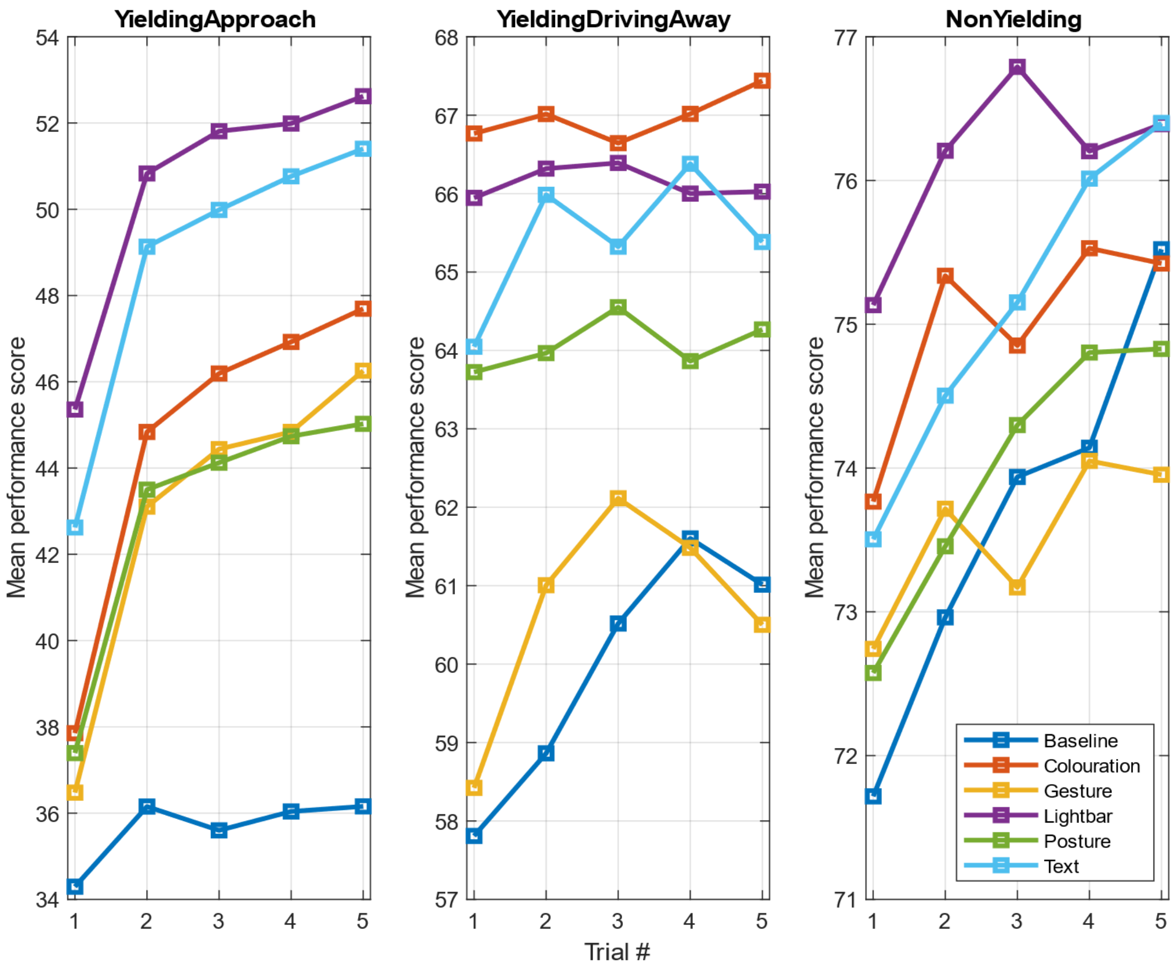

Figure 5. Learning curves for YieldingApproach, YieldingDrivingAway, and NonYielding, for the different eHMIs.

Discussion

The aim of this paper was to determine the intuitiveness of three bio-inspired eHMIs and compare them with two existing eHMI concepts and a baseline condition with no eHMI. By means of a crowdsourcing study, participants' crossing intentions and self-reported ratings were acquired for yielding and non-yielding AVs, providing a measure of intuitive interaction with each of the eHMIs. 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-reported ratings. Additionally, the participants were asked to rate the intuitiveness of each eHMI and rank them on clarity and personal preference to obtain further insight in how the eHMIs compared with each other.

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 attained the lowest performance scores, self-reported ratings, and the worst rankings (i.e., a high ranking) of the tested conditions. These results are consistent with previous research, which found that having an eHMI is preferred by participants over no eHMI (Bazilinskyy et al.,2020a; 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 attained higher performance scores, received higher ratings, and the concepts were mostly ranked better (i.e., a lower ranking) than the bio-inspired eHMIs. An exception was the colouration eHMI, which attained a higher performance score for YieldingDrivingAway than the text-based eHMI and the lightbar eHMI, scored slightly better for NonYielding than the text-based eHMI, and received a higher ranking for clarity than the text-based eHMI.

The colouration eHMI attained the highest performance scores and self-reported ratings, and was ranked best of the bio-inspired eHMI. The posture eHMI generally obtained higher performance scores and self-reported ratings than the gesture eHMI. Surprisingly, the gesture eHMI was ranked better for both 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 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 on 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, thereby lowering the ambiguity of the lightbar eHMI compared to the previous studies, 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 higher performance score than the other tested bio-inspired eHMIs: In the colouration eHMI, the colour change occurred instantaneously, whereas the change in the other two eHMIs was more gradual. Sudden changes are capable of grabbing attention (Von Mühlenen & Conci, 2016), benefitting the colouration eHMI in terms of detectability over the other bio-inspired eHMIs. Furthermore, a change in colour is known to receive attentional priority (Von Mühlenen & Conci, 2016), giving the colouration eHMI an advantage over the other bio-inspired eHMIs for discriminability. Last, the colouration eHMI also benefitted from memorability, because colour is already commonly used in traffic.

The learning curves in Figure 5 show that all eHMIs benefitted similarly from training. An analysis of the learning effect throughout the experiment (see Supplement 2) showed that the YieldingApproach performance score kept on improving until the end of the experiment. It is likely that more trials (i.e., training) would have increased the performance score even more. Several academic experts have expressed the need for training in interactions with AVs (Tabone et al., 2020), and the results from this study support the need for training.

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 study was completed by 2000 participants, but 477 participants (23.9%) were removed. In a previous crowdsourcing study testing eHMIs, 304 of the 1770 participants (17.2%) and 681 of the 2000 participants (34.1%) were removed using comparable exclusion criteria (Bazilinskyy et al., 2019). In a crowdsourcing study by Dey et al. (2020b) testing light-based eHMIs, only 25 of the 400 participants (6.3%) 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. In a third crowdsourcing study testing various eHMI designs, 797 of the 2231 participants (35.7%) were removed (Bazilinskyy et al., 2020a), but the exclusion criteria were stricter with no missing data allowed. The number of excluded participants in this study therefore appears in line with previous research, considering the exclusion criteria used.

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 a supplementary analysis, we studied the impact that the participants' age and country had on the results (see Supplement 2). We found that age had little impact on the findings, with the overall results being similar for older and younger participants. The impact of country was also minimal, consistent with previous 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). Interestingly, the differences between the various countries analysed were more profound for the three bio-inspired eHMIs than for the lightbar eHMI and text-based eHMI (e.g., a difference of 18.4 in the mean rating assigned to the posture eHMI communicating non-yielding between participants from India and Turkey). It might be possible that novel eHMI concepts (e.g., the bio-inspired eHMIs) that are not well-established are more susceptible to cultural differences.

Limitations and recommendations

For the design of the bio-inspired eHMIs, various limitations are in place. In the design process, the technical and practical feasibility of the bio-inspired eHMIs was not considered. Especially the gesture eHMI needs to be carefully designed, as the flaps might pose harm to other road users or could unintentionally act as an air brake. Another approach is implementing the eHMIs via augmented reality, although this introduces many challenges that need to be addressed, including privacy, technological feasibility, and user-friendliness (Tabone et al., 2020).

A second limitation is that only visual communication was considered. Also, the design of the bio-inspired eHMIs solely focused on a single visual channel (i.e., colouration, posture, or gesture), whereas in nature it is common to communicate through multiple channels (Oudshoorn et al., 2020). It is therefore 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 of 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 simultaneously pressed the F key was 55.6%, whereas approximately 10% of the participants pressed the F key the moment the AV passed them. Both observations suggest that not all participants were actively participating in the experiment, thereby adding noise to this study. However, we believe 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 in research that crowdsourcing is suitable for acquiring participants in behavioural science experiments and is equally valid as other approaches of acquiring data (Behrend et al., 2011; Horton et al., 2011; Mason & Suri, 2012).

Another 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 (i.e., able of communicating intent with any number of AVs or pedestrians present). Scalability was previously mentioned as a design consideration for an effective eHMI (Dey et al., 2020a).

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 best of the colouration eHMI and the lightbar eHMI, for example, the full-body communication of the bio-inspired colouration eHMI, but using the colours of the lightbar eHMI instead.

Supplementary material

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 resultant data and the MATLAB scripts used to process the data can be accessed through the following link: https://www.dropbox.com/sh/cg6neqjnhieelkf/AADjot0EIU5CLtQbDIlZhnxJa.

References

Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

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

Bazilinskyy, P., Dodou, D., & De Winter, J. C. F. (2020b). External Human-Machine Interfaces: Which of 729 colors is best for signaling 'Please (do not) cross'? *IEEE International Conference on Systems, Man and Cybernetics (SMC).*

Bazilinskyy, P., Kooijman, L., Dodou, D., & De Winter, J. C. F. (2020a). How should external Human-Machine Interfaces behave? Examining the effects of colour, position, message, activation distance, vehicle yielding, and visual distraction among 1,434 participants. *Manuscript submitted for publication*.

Behrend, T. S., Sharek, D. J., Meade, A. W., & Wiebe, E. N. (2011). The viability of crowdsourcing for survey research. *Behavior Research Methods*, *43*, 800. https://doi.org/10.3758/s13428-011-0081-0

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. *9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*. Oldenburg, Germany. https://doi.org/10.1145/3131726.3131765

Brattstrom, B. H. (1971). Social and thermoregulatory behavior of the bearded dragon, *Amphibolurus barbatus*. *Copeia*, *1971*, 484–497. https://doi.org/10.2307/1442446

Cefkin, M., Zhang, J., Stayton, E., & Vinkhuyzen, E. (2019). Multi-methods research to examine external HMI for highly automated vehicles. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems.*

HCII 2019. Lecture Notes in Computer Science (vol. 11596) (pp. 46–64). Cham: Springer. https://doi.org/10.1007/978-3-030-22666-4_4

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. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 65–73). Oldenburg. Germany. https://doi.org/10.1145/3122986.3122989

Clamann, M., Aubert, M., & Cummings, M. L. (2017). Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. *Transportation Research Board 96th Annual Meeting*, 17-02119.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology*, *1*, 42–45. https://doi.org/10.20982/tqmp.01.1.p042

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

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. https://doi.org/10.1016/j.trf.2018.08.016

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

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

Dey, D., Habibovic, A., Pfleging, B., Martens, M., & Terken, J. (2020b). Color and animation preferences for a light band eHMI in interactions between automated vehicles and pedestrians. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3313831.3376325

Dey, D., Martens, M., Wang, C., Ros, F., & Terken, J. (2018). Interface concepts for intent communication from autonomous vehicles to vulnerable road users. *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (pp. 82–86). Toronto, ON. https://doi.org/10.1145/3239092.3265946

Domeyer, J. E., Lee, J. D., & Toyoda, H. (2020). Vehicle automation–Other road user communication and coordination: Theory and mechanisms. *IEEE Access*, *8*, 19860–19872. https://doi.org/10.1109/ACCESS.2020.2969233

Endler, J. A., & Mappes, J. (2004). Predator mixes and the conspicuousness of aposematic signals. *The American Naturalist*, *163*, 532–547. https://doi.org/10.1086/382662

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*, 1232–1236. https://doi.org/10.1177/1071181319631049

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

Girard, M. B., Kasumovic, M. M., & Elias, D. O. (2011). Multi-modal courtship in the peacock spider, *Maratus volans* (OP-Cambridge, 1874). *PLOS ONE*, *6*, e25390. https://doi.org/10.1371/journal.pone.0025390

Goonetilleke, R. S., Shih, H. M., & Fritsch, J. (2001). Effects of training and representational characteristics in icon design. *International Journal of Human-Computer Studies*, *55*, 741–760. https://doi.org/10.1006/ijhc.2001.0501

Guilford, T., & Dawkins, M. S. (1991). Receiver psychology and the evolution of animal signals. *Animal Behaviour*, *42*, 1–14. https://doi.org/10.1016/S0003-3472(05)80600-1

Haddington, P., & Rauniomaa, M. (2014). Interaction between road users: Offering space in traffic. *Space and Culture*, *17*, 176–190. https://doi.org/10.1177/1206331213508498

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 N. Stanton (Ed.), *Advances in Human Factors of Transportation. AHFE 2019. Advances in Intelligent Systems and Computing, vol 964* (pp. 79–91). Cham: Springer. https://doi.org/10.1007/978-3-030-20503-4_8

Horton, J. J., Rand, D. G., & Zeckhauser, R. J. (2011). The online laboratory: Conducting experiments in a real labor market. *Experimental Economics*, *14*, 399–425. https://doi.org/10.1007/s10683-011-9273-9

Hurtienne, J., & Blessing, L. (2007). Design for intuitive use-testing image schema theory for user interface design. *Proceedings of the 16th International Conference on Engineering Design* (pp. 829–830). Paris, France.

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*, *10*, 386. https://doi.org/10.3390/info10120386

Koolhaas, J. M., Schuurman, T., & Wiepkema, P. R. (1980). The organization of intraspecific agonistic behaviour in the rat. *Progress in Neurobiology*, *15*, 247–268. https://doi.org/10.1016/0301-0082(80)90024-6

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*, paper 429. https://doi.org/10.1145/3173574.3174003

Mason, W., & Suri, S. (2012). Conducting behavioral research on Amazon's Mechanical Turk. *Behavior Research Methods*, *44*, 1–23. https://doi.org/10.3758/s13428-011-0124-6

Mitoyen, C., Quigley, C., & Fusani, L. (2019). Evolution and function of multimodal courtship displays. *Ethology*, *125*, 503–515. https://doi.org/10.1111/eth.12882

Moore, D., Currano, R., Strack, G. E., & Sirkin, D. (2019). The case for implicit external human-machine interfaces for autonomous vehicles. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (pp. 295–307). https://doi.org/10.1145/3342197.3345320

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorial in Quantitative Methods for Psychology*, *4*, 61–64. https://doi.org/10.20982/tqmp.04.2.p061

Nicholson, K. E., Harmon, L. J., & Losos, J. B. (2007). Evolution of Anolis lizard dewlap diversity. *PLOS ONE*, *2*, e274. https://doi.org/10.1371/journal.pone.0000274

Oudshoorn, M. P. J., De Winter, J. C. F., Bazilinskyy, P., & Dodou, D. (2020). Intent communication in nature: an overview of biological paradigms and their applicability to automated vehicles. Manuscript in preparation.

Pennycooke, N. (2012). *AEVITA: designing biomimetic vehicle-to-pedestrian communication protocols for autonomously operating & parking on-road electric vehicles* (Doctoral dissertation). Massachusetts Institute of Technology.

Poole, J., & Granli, P. (2011). Signals, gestures, and behavior of African elephants. In C. J. Moss, H. Croze, & P. C. Lee (Eds.), *The Amboseli Elephants: A long-term perspective on a long-lived mammal*. University of Chicago Press. https://doi.org/10.7208/chicago/9780226542263.003.0008

Prokop, P., & Fančovičová, J. (2013). Does colour matter? The influence of animal warning coloration on human emotions and willingness to protect them. *Animal Conservation*, *16*, 458–466. https://doi.org/10.1111/acv.12014

Robert, L. P., Jr. (2019). The future of pedestrian-automated vehicle interactions. *XRDS: Crossroads, The ACM Magazine for Students*, *25*, 30–33. https://doi.org/10.1145/3313115

Rothenbücher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *Proceedings of the 25th IEEE international symposium on robot and human interactive communication (RO-MAN)* (pp. 795–802). New York. https://doi.org/10.1109/ROMAN.2016.7745210

Rowe, C. (1999). Receiver psychology and the evolution of multicomponent signals. *Animal Behaviour*, *58*, 921–931. https://doi.org/10.1006/anbe.1999.1242

Santos, J. C., Coloma, L. A., & Cannatella, D. C. (2003). Multiple, recurring origins of aposematism and diet specialization in poison frogs. *Proceedings of the National Academy of Sciences*, *100*, 12792–12797. https://doi.org/10.1073/pnas.2133521100

Scheel, D., Godfrey-Smith, P., & Lawrence, M. (2016). Signal use by octopuses in agonistic interactions. *Current Biology*, *26*, 377–382. https://doi.org/10.1016/j.cub.2015.12.033

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology & Work*, *21*, 69–85. https://doi.org/10.1007/s10111-018-0521-z

Shine, R. (1990). Function and evolution of the frill of the frillneck lizard, *Chlamydosaurus kingii* (Sauria: Agamidae). *Biological Journal of the Linnean Society*, *40*, 11–20. https://doi.org/10.1111/j.1095-8312.1990.tb00531.x

Singer, T., Kobbert, J., Zandi, B., & Khanh, T. Q. (2020). Displaying the driving state of automated vehicles to other road users: An international, virtual reality-based study as a first step for the harmonized regulations of novel signaling devices. IEEE Transactions on Intelligent Transportation Systems. https://doi.org/10.1109/TITS.2020.3032777

Tabone, W., De Winter, J. C. F., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock. P. A., Happee, R., Krems, J., Lee, J. D., Martens, M., Merat, N., Norman, D. A., Sheridan, T. B., & Stanton, N. (2020). Vulnerable road users and the coming wave of automated vehicles: expert perspectives. Manuscript submitted for publication.

Von Mühlenen, A., & Conci, M. (2016). The role of unique color changes and singletons in attention capture. *Attention, Perception, & Psychophysics*, *78*, 1926–1934. https://doi.org/10.3758/s13414-016-1139-y

Supplement 1
Additional information for the experiment

1.1. Process of development of the experiment

In developing the eHMIs and videos, multiple iterations were made to improve the designs. Through discussing the designs and renderings, modifications were made until all involved parties were satisfied with the result.

From the initial designs for the bio-inspired eHMIs, various changes were made. Initially, the flaps for the gesture eHMI had a rectangular shape. It was decided to make the flaps more rounded to make the eHMI feel more natural. Furthermore, various frequencies and angles were tried until a suitable combination was found. The main considerations in selecting the combination of frequencies and angles were that the signal needed to be sufficiently clear and that the combinations seemed mechanically plausible. For the colouration eHMI, the initial design was changed to make the pattern appear more natural, closely mimicking the pattern of the poison dart frog. Furthermore, various shades of yellow were tried, until the right shade was found which was well distinguishable from the environment. For the gesture eHMI, various heights were tested. It was decided to go for a height change of 15 cm because it appeared physically realistic and was perceivable from a distance. Last, the colour of the Smart ForTwo was changed. Initially, the Smart ForTwo was red, but this could conflict with the colour-based eHMIs (i.e., the lightbar eHMI and the colouration eHMI). It was therefore decided to change the colour to blue.

On deciding on the approach speed, the moment of deceleration, the onset of communication, and the appropriate deceleration and subsequent acceleration, three main criteria were used. First, it needed to feel realistic to enhance the effectiveness of the videos. Second, there should be some doubt as to the behaviour of the AV, to ensure the added value of communicating its intention. Third, it should be based on findings from academic literature.

Last, small changes were made to the virtual environment to ensure that the rendered videos looked realistic and were appropriate for use in the experiment. Minor elements of the environment were removed, whereas the location of the light source was also changed. The height of the camera was changed to ensure the video was rendered from a realistic height. Anti-aliasing was turned on to make the videos appear smoother. The resolution of the videos was 1280x720 pixels at 30 frames per second to ensure a small file size, making it easier for participants with a slow internet connection to participate in this study.

1.2. Detailed description of the experiment

To provide a detailed description of the experiment, all information provided to the participant is supplied in order of appearance in the study. Section 1.2.1 details the information and questionnaire that the participant received and filled in before the start of the experiment. Section 1.2.2 specifies the exact instructions the participant received prior to the experiment. Section 1.2.3 shows two screenshots of the anthropomorphic smile eHMI that was used to demonstrate the concept of the AV communicating. Next, section 1.2.4 details the instructions the participant received throughout the experiment. Section 1.2.5 shows the rating screens the participant saw after each block of 10 trials. In section 1.2.6, the ranking screen shown to the participants after having interacted with all six eHMIs is displayed and section 1.2.7 details the questions asked to the participant after having finished the experiment.

1.2.1. Pre-experiment procedure

You are invited to participate in a research study entitled “Measuring pedestrian’s willingness to cross in front of an automated vehicle with a bio-inspired eHMI ”. The study is being conducted by Max Oudshoorn, Dr. Pavlo Bazilinskyy, Dr. Dimitra Dodou and Dr. Joost de Winter, Department of Cognitive Robotics, Delft University of Technology, The Netherlands, p.bazilinskyy@tudelft.nl.

The purpose of this research is to determine willingness to cross the road in front of a car with an external Human Machine Interface (eHMI). Such an interface may be used in future cars to communicate with pedestrians or cyclists. Your participation in the study will contribute to a better understanding of visual interfaces for automated vehicles.

You are free to contact the investigators at the above email address to ask questions about the study. You must be at least 18 years old to participate. The survey will take approximately 30 minutes of your time. In case you participated in a previous survey of one of the present investigators, your responses may be combined with the previous survey.

The information collected in the survey is anonymous. Participants will not be personally identifiable in any research papers arising from this study. If you agree to participate and understand that your participation is voluntary, then continue. If you would not like to participate, then please close this page. Before the study starts, the videos will be preloaded. This may take a few minutes depending on your Internet connection.

Please maximise your browser window before the start of the experiment. Do not switch tabs during the experiment. Please do use Internet Explorer for this study.

Have you read and understood the above instructions? (required)

☐ Yes

☐ No

What is your gender? (required)

☐ Male

☐ Female

☐ I prefer not to respond

What is your age? (required)

...

In which type of place are you located now? (required)

☐ Indoor, dark

☐ Indoor, dim light

☐ Indoor, bright light

☐ Outdoor, dark

☐ Outdoor, dim light

☐ Outdoor, bright light

☐ Other

☐ I prefer not to respond

If you answered ’Other’ in the previous question, please describe the place where you located now below.

...

Which input device are you using now? (required)

☐ Laptop keyboard
☐ Desktop keyboard
☐ Tablet on-screen keyboard
☐ Mobile phone on-screen keyboard
☐ Other
☐ I prefer not to respond

If you answered 'Other' in the previous question, please describe your input device below.

...

At what age did you obtain your first license for driving a car or motorcycle?

...

What is your primary mode of transportation?

☐ Private vehicle
☐ Public transportation
☐ Motorcycle
☐ Walking/Cycling
☐ Other
☐ I prefer not to respond

On average, how often did you drive a vehicle in the last 12 months? (required)

☐ Every day
☐ 4 to 6 days a week
☐ 1 to 3 days a week
☐ Once a month to once a week
☐ Less than once a month
☐ Never
☐ I prefer not to respond

About how many kilometres (miles) did you drive in the last 12 months? (required)

☐ 0 km/mi
☐ 1 - 1,000 km (1 - 621 mi)
☐ 1,001 – 5,000 km (622 – 3,107 mi)
☐ 5,001 – 15,000 km (3,108 – 9,321 mi)
☐ 15,001 – 20,000 km (9,322 – 12,427 mi)
☐ 20,001 – 25,000 km (12,428 – 15,534 mi)
☐ 25,001 – 35,000 km (15,535 – 21,748 mi)
☐ 35,001 – 50,000 km (21,749 – 31,069 mi)
☐ 50,001 – 100,000 km (31,070 – 62,137 mi)
☐ More than 100,000 km (more than 62,137 mi)
☐ I prefer not to respond

How many accidents were you involved in when driving a car in the last 3 years? (please include all accidents, regardless of how they were caused, how slight they were, or where they happened) (required)

☐ 0
☐ 1
☐ 2
☐ 3
☐ 4
☐ 5
☐ More than 5
☐ I prefer not to respond

How often do you do the following?: Becoming angered by a particular type of driver, and indicate your hostility by whatever means you can. (required)

☐ 0 times per month
☐ 1 to 3 times per month
☐ 4 to 6 times per month
☐ 7 to 9 times per month
☐ 10 or more times per month
☐ I prefer not to respond

How often do you do the following?: Disregarding the speed limit on a motorway. (required)

☐ 0 times per month
☐ 1 to 3 times per month
☐ 4 to 6 times per month
☐ 7 to 9 times per month
☐ 10 or more times per month
☐ I prefer not to respond

How often do you do the following?: Driving so close to the car in front that it would be difficult to stop in an emergency. (required)

☐ 0 times per month
☐ 1 to 3 times per month
☐ 4 to 6 times per month
☐ 7 to 9 times per month
☐ 10 or more times per month
☐ I prefer not to respond

How often do you do the following?: Racing away from traffic lights with the intention of beating the driver next to you. (required)

☐ 0 times per month
☐ 1 to 3 times per month
☐ 4 to 6 times per month
☐ 7 to 9 times per month
☐ 10 or more times per month
☐ I prefer not to respond

How often do you do the following?: Sounding your horn to indicate your annoyance with another road user. (required)

- ☐ 0 times per month
- ☐ 1 to 3 times per month
- ☐ 4 to 6 times per month
- ☐ 7 to 9 times per month
- ☐ 10 or more times per month
- ☐ I prefer not to respond

How often do you do the following?: Using a mobile phone without a hands free kit. (required)

- ☐ 0 times per month
- ☐ 1 to 3 times per month
- ☐ 4 to 6 times per month
- ☐ 7 to 9 times per month
- ☐ 10 or more times per month
- ☐ I prefer not to respond

Experiment to measure willingness to cross in front of an automated vehicle
In this experiment you will see multiple videos of a vehicle approaching you. Your task is to press and hold a specific key when you feel safe to cross the road. You will be asked to leave Appen to participate in the experiment. You will need to open the link below. Do not close this tab. At the end of the experiment you will be given a code to input in the next question on this tab. Please take a note of the code. Without the code, you will not be able to receive money for your participation. All videos will be preloaded before the start of the experiment. It may take a few minutes. Please do not close your browser during that time.

Open this link to start experiment.

1.2.2. Instructions start experiment

You will watch 60 videos of approaching cars. Some cars will stop, and other cars will continue driving. Some cars have a special feature. This feature is informative about whether the car stops or continues driving.

Each video starts with a black screen. As soon as you see the black screen, press and HOLD the key 'F'.

1. Hold the key as long as you feel safe to cross.
2. Release the key if you do not feel safe to cross anymore.
3. You can press and release the key as many items as you want per video.

1.2.3. Demonstration of the interaction

The participant was subsequently shown two videos of an AV approaching that yielded in the first video and continued driving in the second video. The AV communicated through an anthropomorphic smile eHMI, as shown in Figure 1.1 and 1.2. A message was included below the videos, stating 'Watch this video with an example of a communication feature'.

Watch this video with an example of a communication feature.

Figure 1.1: An image of the yielding video shown to the participant, demonstrating the anthropomorphic smile eHMI. The video was accompanied by text specifying this was an example

Watch this video with an example of a communication feature.

Figure 1.2: An image of the non-yielding video shown to the participant, demonstrating the anthropomorphic smile eHMI. The video was accompanied by text specifying this was an example

1.2.4. Instructions throughout the experiment

After each video, a white screen was shown with the text 'Press 'C' to continue to the next video.' Below each video, the text 'Press and HOLD 'F' when you feel safe to cross' was shown.

1.2.5. Rating of the eHMI

After each block of 10 videos, the participant was asked to rate the tested eHMI for both the non-yielding and yielding state. This happened through the questions and sliders shown in Figure 1.3 and Figure 1.4.

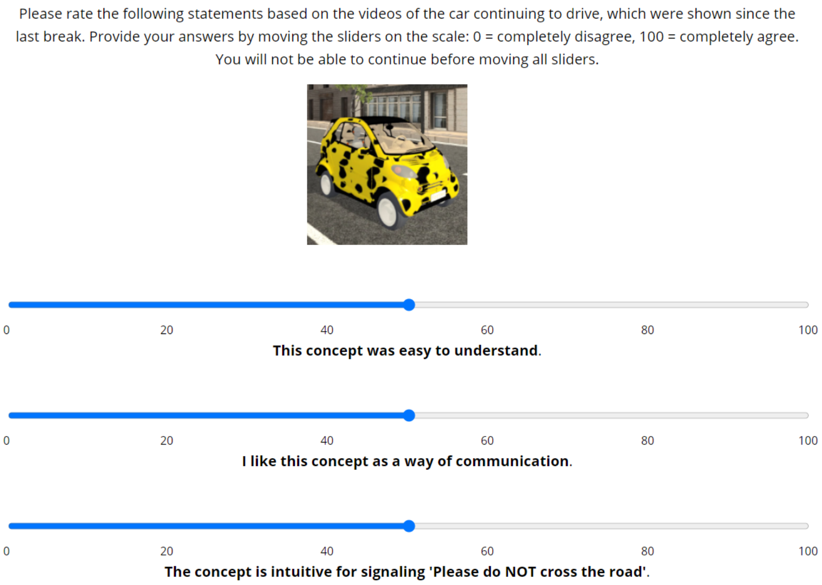

Figure 1.3: The rating screen that was shown to the participant after each block, showing an image of the tested eHMI communicating non-yielding behaviour

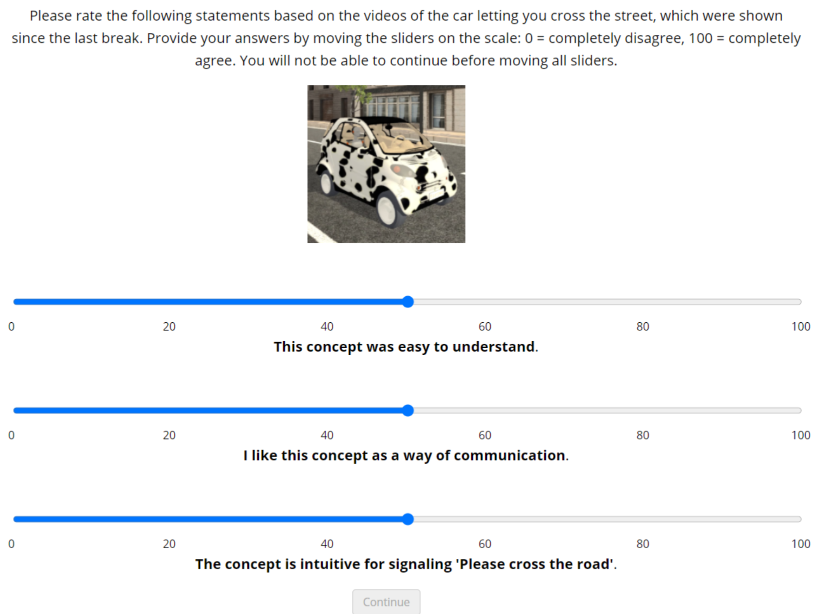

Figure 1.4: The rating screen that was shown to the participant after each block, showing an image of the tested eHMI communicating yielding behaviour

1.2.6. Ranking of the eHMIs

Figure 1.5 shows the screen that was shown to the participants after all 60 trials, asking them to rank the eHMIs on clarity and personal preference.

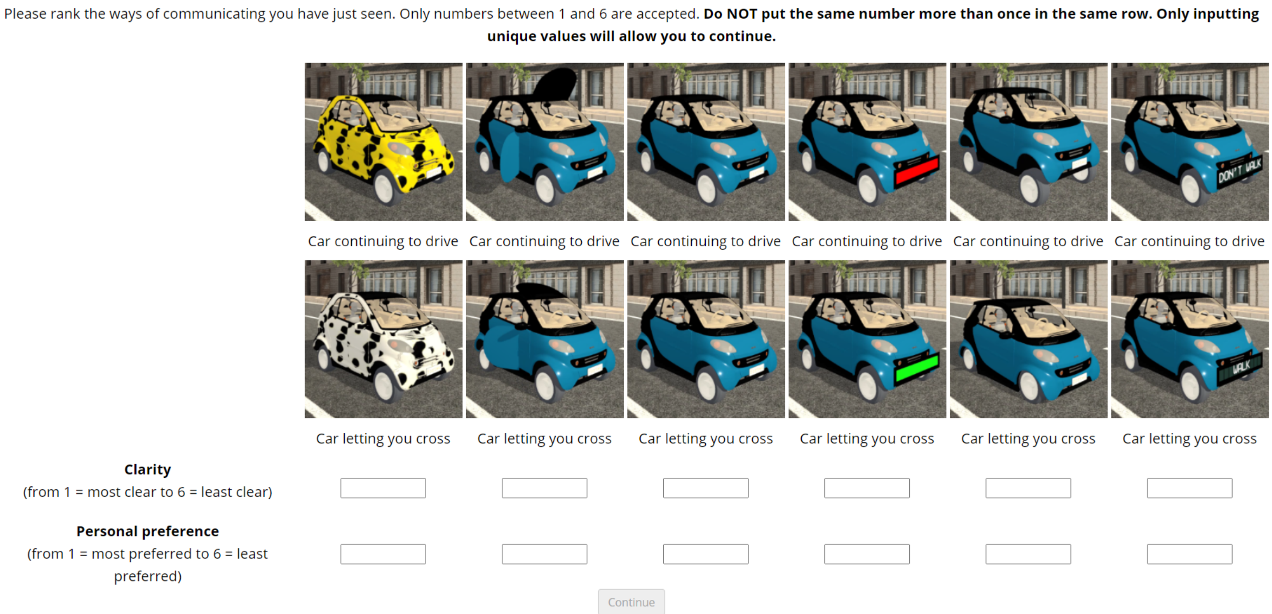

Figure 1.5: The ranking screen that was shown to the participant at the end of the experiment

1.2.7. Post-experiment questionnaire

Type the code that you received at the end of the experiment. (required)

...

Miscellaneous questions

In which year do you think that most cars will be able to drive fully automatically in your country of residence? (required)

...

Please provide any suggestions that could help engineers to build safe and enjoyable automated cars

...

Supplement 2
Additional analysis data

This chapter explores the impact the learning effect throughout the experiment, age, and country, had on the findings of the study.

2.1. Impact of learning effect throughout the experiment

Figure 2.1 shows the development of the mean performance score throughout the experiment. Only participants of whom data for all 60 trials were available were included.

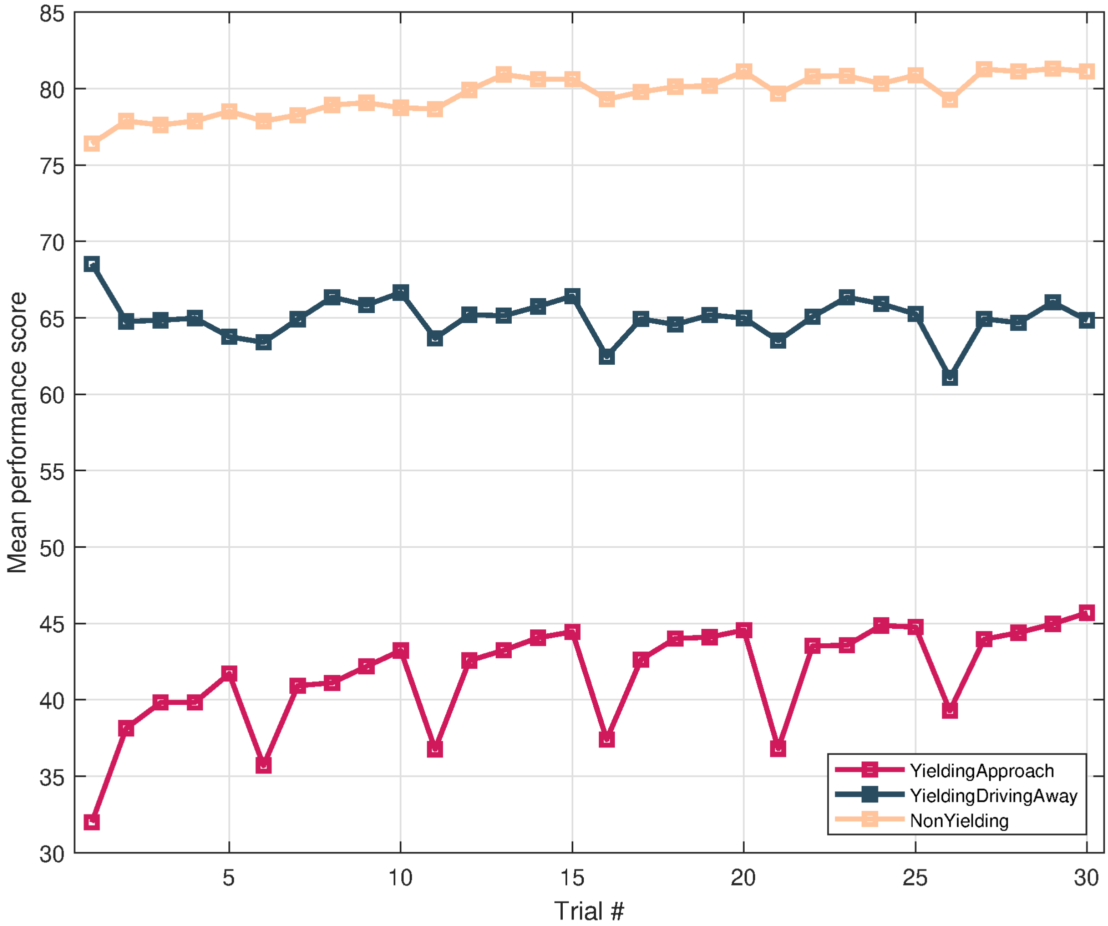

Figure 2.1: Learning curve throughout the experiment for the three distinct phases

There was a clear learning effect noticeable for YieldingApproach. The mean performance score for the 1st trial was 32.0, whereas the performance score for the 26th trial (i.e., the first trial of the last block) was 39.3. Similarly, the mean performance score for the 5th trial was 41.7, and for the 30th and last trial it was 45.7. Interesting about the performance score is that a dip occurred for every first trial of a new eHMI, indicating the participants were hesitant to cross with an unfamiliar eHMI. Another observation is that the performance score for YieldingApproach kept on increasing until the end, indicating that near the end of the experiment there was still a learning effect taking place.

In contrast to YieldingApproach, YieldingDrivingAway had a relatively constant performance score. The 1st trial had a mean performance score of 68.5 and the 26th trial had a performance score of 61.1. This appears to indicate a noteworthy deterioration, but it is believed that both trials were outliers. For the 1st trial, participants were probably unsure on what to expect and where therefore reluctant to press the F key, leading to a higher performance score for YieldingDrivingAway. This hypothesis was strengthened by the subsequent first trials of new eHMIs attaining a lower mean performance score than the subsequent trials of the eHMI. For the 26th trial, participants were more familiar with the task and might have become more confident with the virtual environment, explaining the relatively high performance score for YieldingApproach (i.e., pressing the F key more), as well as the relatively low performance score for YieldingDrivingAway. The 5th trial had a performance score of 63.8 and the 30th trial a performance score of 64.8. There was therefore barely a learning effect perceivable for YieldingDrivingAway throughout the experiment.

NonYielding had a slight upward trend in mean performance score throughout the experiment. The mean performance score of the 1st trial was 76.4 and for the 26th trial it was 79.3. Similarly, the mean performance score of the fifth trial was 78.5, and for the 30th and last trial it was 81.1.

To determine the impact of how active participants participated in the experiment on the learning curve throughout the experiment, the maximum keypress rate of participants per trial was analysed. Only participants of whom data for all 60 trials were available were included. This was done for each phase, as well as the complete yielding and non-yielding trial, and is shown in Figure 2.2.

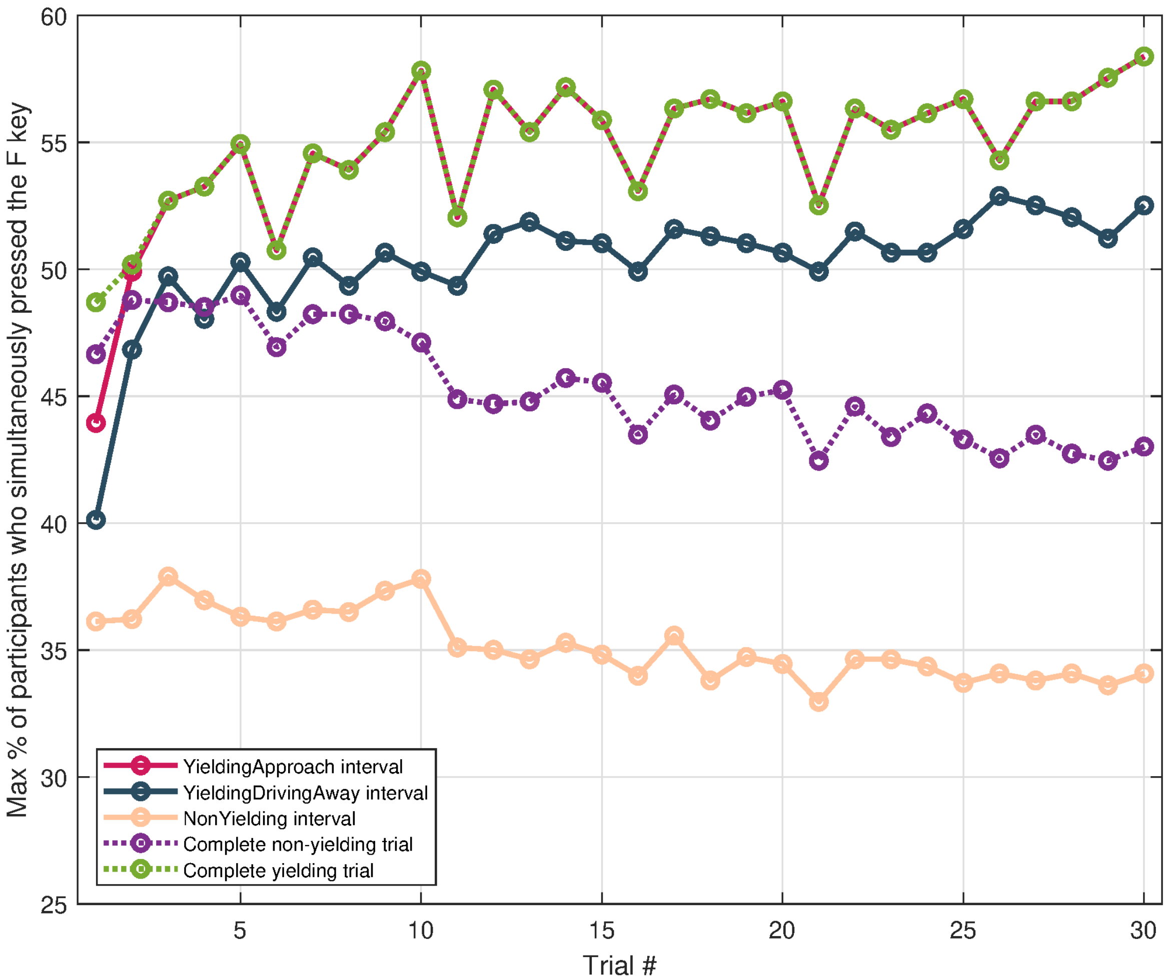

Figure 2.2: Maximum % of participants who simultaneously pressed the F key for the specified interval per trial. The dashed lines indicate the entire trial, while the other lines indicate the specific intervals of the three phases

For the first trial, the maximum keypress rate was far apart for YieldingApproach (44.0%) and the Complete yielding trial (48.7%), whereas starting from the 3rd trial, the maximum keypress rates were similar, indicating that participants became more familiar with the behaviour of the AVs and the experiment. It also means that the peak occurred in the YieldingApproach interval, most likely when the AV stopped. Subsequently, the maximum keypress rate kept on increasing throughout the experiment, starting at 54.9% for the 5th trial and ending at 58.4% for the 30th trial. This continuous increase also explains the increase in performance score and indicates that participants became more confident in the virtual environment and the eHMIs and were therefore more willing to cross. Similar to the performance score throughout, the first new trial of a new eHMI had a lower maximum keypress rate, strengthening the aforementioned hesitance of participants to cross with an unfamiliar eHMI.

Analysis of the maximum keypress rate for YieldingDrivingAway led to various interesting insights. It is important to note that YieldingDrivingAway began the moment YieldingApproach ended. The maximum keypress rate was consistently lower for YieldingDrivingAway than YieldingApproach, indicating that various participants already anticipated that the AV would start driving away and released the F key. The maximum keypress rate also clarified both outliers for YieldingDrivingAway. For the 1st trial, fewer participants pressed the F key than in the subsequent trial, benefitting the performance score because the participants were not supposed to cross. For the 26th trial, the maximum keypress rate was the highest of all YieldingDrivingAway intervals (52.9%), thereby negatively impacting the performance score for the 26th trial.

There was an average difference of 10.2% between the maximum keypress rate for NonYielding and the Complete non-yielding trial, suggesting that numerous participants already made the decision not to cross before the eHMI started communicating. It is surprising that the maximum keypress rate for the Complete non-yielding trial went down throughout the experiment, dropping from 49.0% for the fifth trial to 42.5% for the 29th trial. This seems to indicate that participants became less active throughout the experiment. Surprisingly, this drop was not perceived for the Complete yielding trial.

Though various changes in keypress rate occurred throughout the experiment, the impact of these on the results was minimal, because block randomisation was used. The analysis showed that a long experiment length could lower the involvement of participants throughout the experiment. Furthermore, it appears that for YieldingApproach there was still a learning effect until the end of the experiment.

2.2. Impact of age

To determine the impact of age on the results, the participants were divided in two groups. The first group consisted of participants aged younger than or equal to the mean age of the experiment (36.7 years) and the second group consisted of participants aged older than the mean age. First, the keypress rate of the participants was averaged over the yielding and non-yielding trials to determine the impact of age on the overall keypress rate. This has been visualised in Figure 2.3.

For the first 9.7 seconds ((1) and (2)) the older group felt safer to cross than the younger group, with a maximum of 61.3% versus 50.4% participants simultaneously pressing the F key. This could indicate that the older group participated more actively in the experiment. Subsequently, for yielding, the differences levelled out and both age categories had comparable keypress data. Surprisingly, an increase occurred in the participants that pressed and held the F key for the younger group, with a maximum of 54.6% of the participants simultaneously pressing the F key during (4). For the older group, there was a decrease, with a maximum of 55.4% of the participants simultaneously pressing the F key during (4). This could indicate a certain distrust of the older participants towards the AV once it had stopped and therefore a reluctance to cross.

For non-yielding, the differences almost levelled out during (3). A small difference between the two age categories remained, as a larger percentage of older participants were willing to cross during (3) than younger participants.

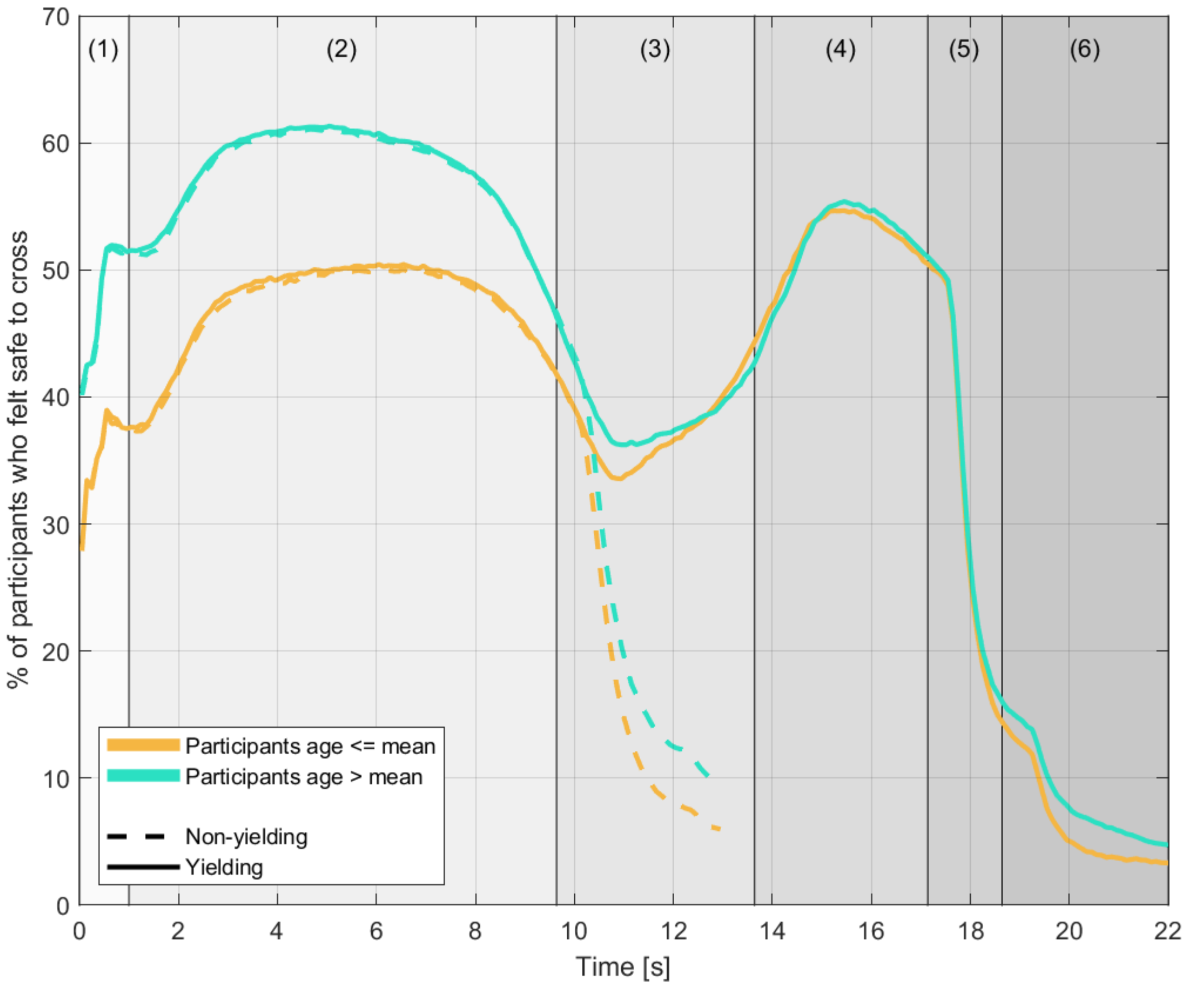

Figure 2.3: Keypress data for the yielding and non-yielding scenario for participants aged younger or equal to the mean age and participants aged older than the mean age. Where (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period 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.

To further study the impact of age, a scatter plot was made, relating the mean ratings with the mean performance score for the three phases and for the two age groups, shown in Figure 2.4.

As visible in Figure 2.4, the two age groups assigned a similar mean rating to the eHMIs for both yielding and non-yielding, meaning the ratings were independent of age. A similar trend can be seen for YieldingApproach, where the differences in mean performance scores for the eHMIs were small. The most significant difference introduced through age was that the older participants attained a higher performance score for the gesture eHMI than the posture eHMI, whereas for younger participants this was vice versa.

The differences for YieldingDrivingAway were more noticeable. The colouration eHMI (66.0) and the lightbar eHMI (66.0) both attained the highest mean performance score for the older group. For the younger participants, the colouration eHMI earned the highest performance score (67.5), followed by the text-based eHMI (66.1) and the lightbar eHMI (65.9). Surprising is that the text-based eHMI attained a noticeably lower mean performance score for the older participants (64.3) than for the younger participants. Also remarkable is that the gesture eHMI attained a slightly lower mean performance score than the baseline condition for the older participant group.

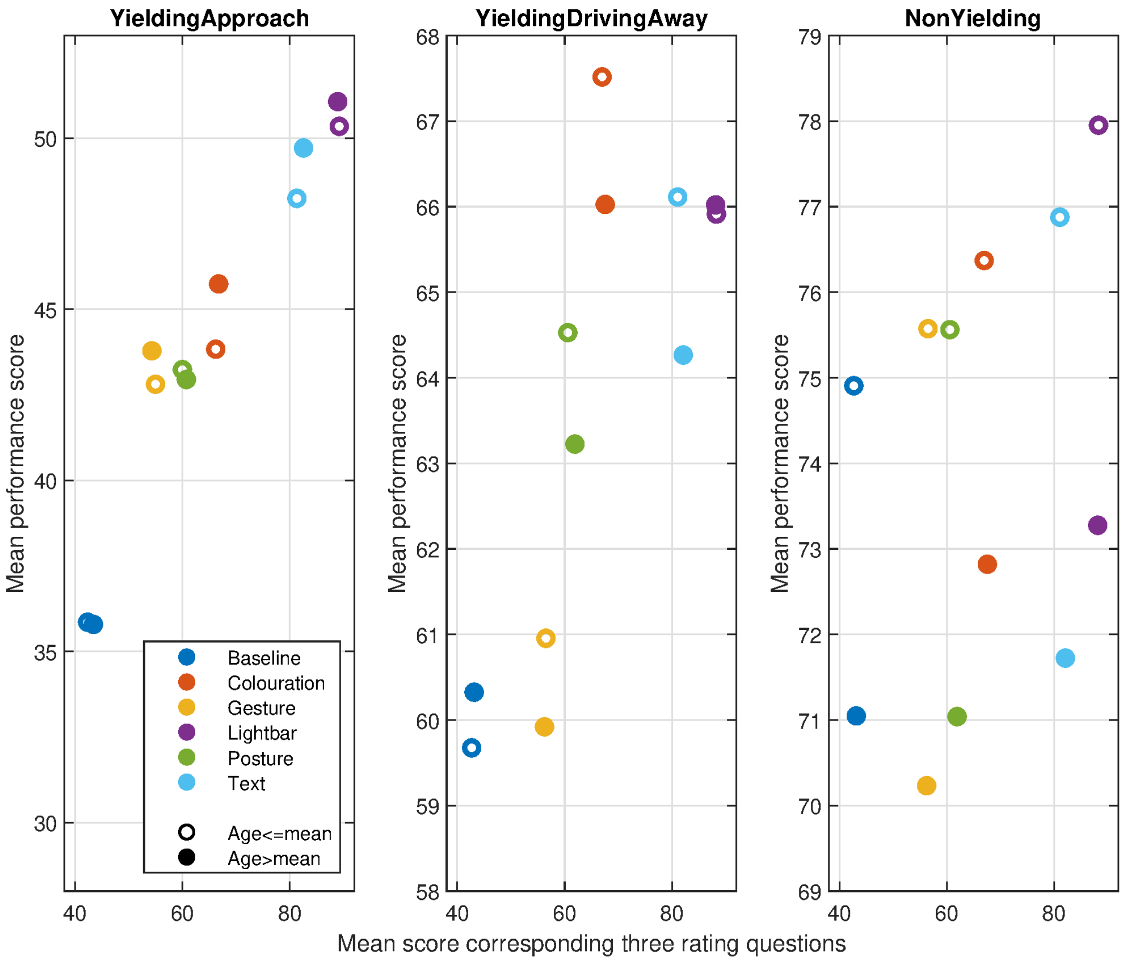

Figure 2.4: Scatter plot of the mean score of the three corresponding rating questions (about yielding for YieldingApproach and about non-yielding for YieldingDrivingAway and NonYielding) versus the mean performance score for the eHMIs for all three phases. Each colour represents a different eHMI condition and whether the shape is filled represents the age category.

For NonYielding, numerous differences were to be found between the two age groups. First, there was a consistent gap of approximately 4 between the performance score of the younger and older group. The probable cause was that more participants from the older group pressed the F key during (3) than participants from the younger group. Second, the eHMIs increased the performance score for younger participants, whereas for the older participants the gesture eHMI (70.3) and posture eHMI (71.0) scored respectively lower and equal to the baseline condition (71.0), even though they were rated higher than the baseline condition. Third, for younger participants the text-based eHMI (76.9) attained a performance score in between the colouration eHMI (76.4) and lightbar eHMI (78.0), whereas for older participants the colouration eHMI scored higher than the text-based eHMI (72.8 for the colouration eHMI and 71.7 for the text-based eHMI) and slightly below the lightbar eHMI (73.3). Surprisingly, both the text-based and lightbar eHMI were rated significantly higher than the colouration eHMI.

Analysis of the keypress data, performance scores, and ratings led to the conclusion that age influenced the findings for YieldingDrivingAway and NonYielding, though the impact was small. The most substantial difference was introduced in the performance score for the colouration eHMI and the text-based eHMI, with the older participants scoring higher for the colouration eHMI than the text-based eHMI when communicating 'non-yielding', even though the text-based eHMI was rated better. Another noticeable difference is that the gesture eHMI failed to communicate 'non-yielding' to older participants and actually lowered the score with respect to the baseline condition, whereas the posture eHMI had no impact on the performance score with respect to the baseline condition for NonYielding.

2.3. Impact of country

Another factor that could have influenced the findings was the impact of country of the participants. To determine the impact of country on the findings, the data of the five countries most prevalent in this study were analysed, being Venezuela (*N*=737), the United States (*N*=137), Russia (*N*=70), Egypt (*N*=56), and India (*N*=56).

2.3.1. Impact of country on keypress data

First, the keypress data were sorted for these five countries to identify differences between the keypress data of the participants from various countries, as shown in Figure 2.5.

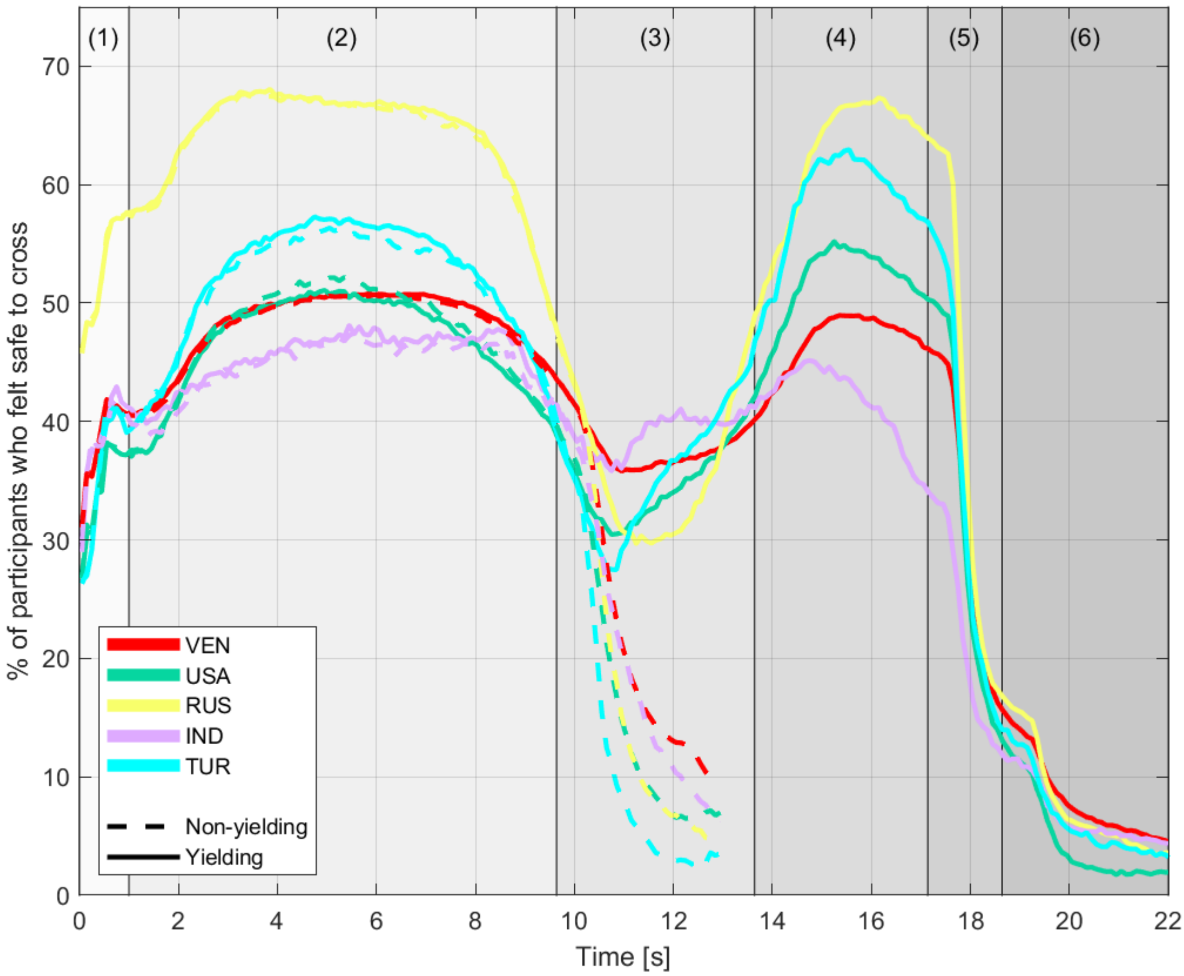

Figure 2.5: Keypress data for the yielding and non-yielding scenario filtered per country. Where (1) represents the period in which the black screen was shown, (2) is the period the AV approached, (3) represents the period the AV started signalling and decelerating for the yielding scenario, (4) represents 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.

There were some clear differences for the various countries. Russian participants were the most active participants, with on average a maximum of 68.1% of the participants pressing the F key simultaneously. This was notably higher than the maximum percentage of Indians that simultaneously pressed the F key on average (48.1%). A reason could be that the participants from India did not participate in the experiment as actively as participants from Russia, or were in general less inclined to cross in front of an AV, even when the AV was still quite far away.

Another interesting observation is that a steep drop occurred in participants feeling safe to cross once the AV started decelerating and communicating yielding ((3) in Figure 2.5), with a low of 29.9% of the participants from Russia feeling safe to cross. This decrease was less noticeable for Indian participants, with a low of 35.8% of the participants from India feeling safe to cross. This could indicate that Indian participants were quicker to understand the signal of the eHMI and its implications, thereby feeling safer to cross. However, the increase once the AV was standing still ((4) in Figure 2.5) was limited, again indicating that Indian participants were less active in the experiment than participants from other countries.

To further study the impact of country differences, three scatter plots were made that related the mean score for the rating questions with the mean performance score per country and eHMI.

2.3.2. Impact of country for YieldingApproach

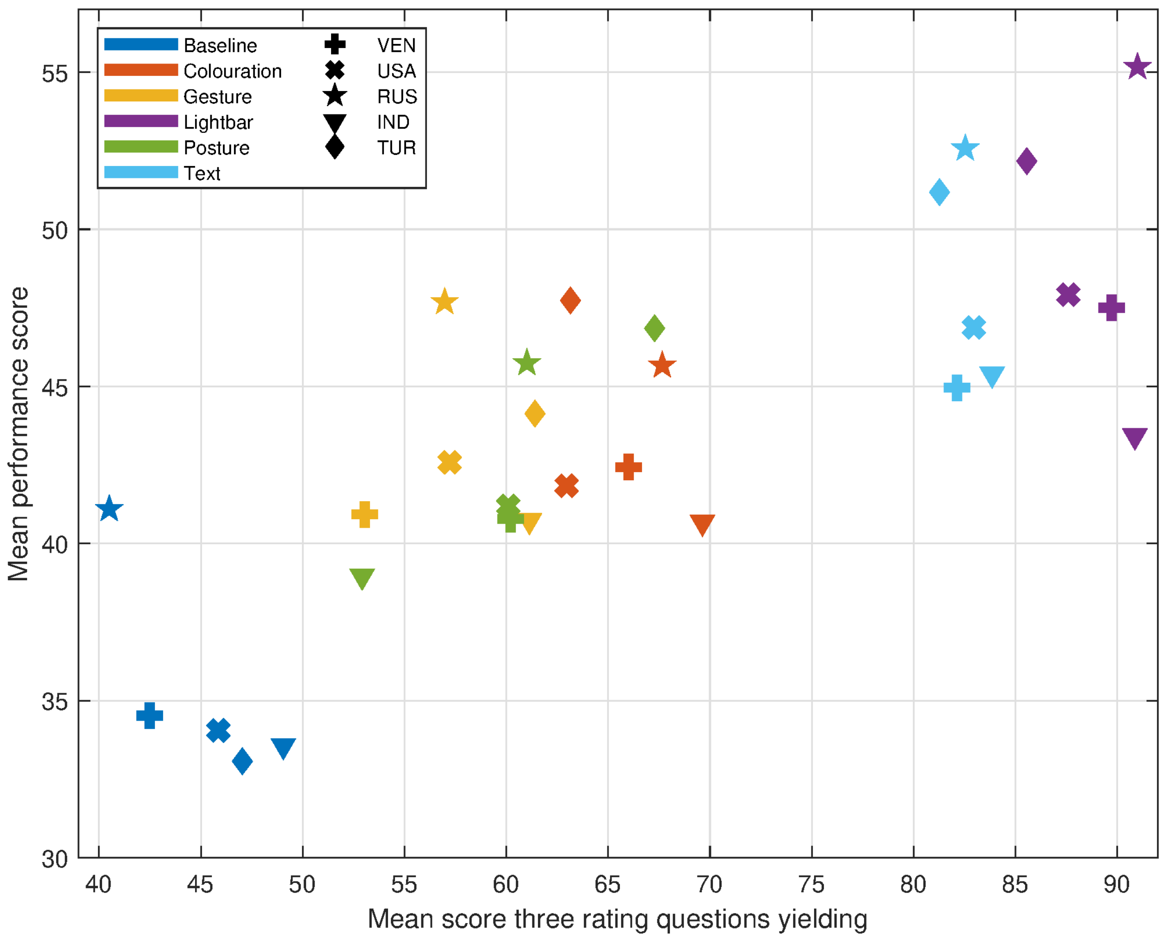

Figure 2.6: Scatter plot of the mean score of the three rating questions for yielding versus the mean performance score for YieldingApproach with country distinction. The colours indicate the various eHMIs and the shapes indicate the country.

Figure 2.6 shows a scatter plot of the mean rating for the three rating questions on yielding versus the mean performance score for YieldingApproach. Overall, the various eHMIs were grouped together, indicating that the participants from the various countries rated the eHMIs similar and that the eHMIs attained comparable performance scores for each country. Furthermore, the baseline condition clearly received the lowest mean ratings and attained the lowest mean performance scores, whereas the lightbar eHMI and text-based eHMI attained the highest mean performance scores and received the highest mean ratings.

The ratings and performance scores of the six eHMIs for the participants from Venezuela showed a similar trend as the complete study, favouring the lightbar eHMI and the text-based eHMI over the bio-inspired eHMIs and the baseline condition. The highest rated and best performing bio-inspired eHMI was the colouration eHMI, similarly in line with the general findings of this study.

The data of the participants from the United States were generally in line with the findings from the complete study, though there was a discrepancy for the bio-inspired eHMIs. The gesture eHMI scored a better mean performance score (42.6) than the posture eHMI (41.2) and the colouration eHMI (41.8), but received the lowest mean rating of the three bio-inspired eHMIs. The text-based eHMI attained the highest mean performance score and received the highest ratings, followed by the lightbar eHMI.

Analysis of the results from Russian participants led to some interesting observations. First, the mean performance scores were significantly higher than the mean performance scores of other countries, especially for the baseline condition. The cause for this phenomenon was the high keypress rate of the Russians. With respect to the eHMIs, Russians favoured the lightbar eHMI and the text-based eHMI over the bio-inspired eHMIs. Within the bio-inspired eHMIs, the gesture eHMI attained the highest mean performance score (47.7), but received the lowest ratings of the three eHMIs (57.0).

The mean performance scores of the Indian participants were consistently lower in comparison with the other countries, probably due to the relatively low keypress rate of the Indian participants. Surprisingly, the mean performance score for the text-based eHMI (45.4) was higher than the mean performance score for the lightbar eHMI (43.4), whilst the lightbar eHMI received a higher rating (90.9) than the text-based eHMI (83.9). For the bio-inspired eHMIs, the colouration eHMI (40.7) and the gesture eHMI (40.7) had a similar mean performance score, even though the colouration eHMI (69.6) received a higher mean rating than the gesture eHMI (61.1).

The participants from Turkey appeared to benefit more from the presence of an eHMI than the participants from other countries. The Turkish participants generally attained high mean performance scores for the various eHMIs, whereas the mean performance score for the baseline condition was low in comparison (33.1). The lightbar eHMI (52.2) and the text-based eHMI (51.2) were close together for mean performance score, as well as the mean ratings (85.6 for the lightbar eHMI and 81.3 for the text-based eHMI). For the bio-inspired eHMIs, the posture eHMI (67.3) received a higher mean rating than the colouration eHMI (63.2) and the gesture eHMI (61.4), though this was not reflected in the mean performance score.

The results indicate that small country differences were present for YieldingApproach. The ratings for the various eHMIs showed overlap most of the time, with the posture eHMI being an exception. Furthermore, the mean performance score showed an upward trend as the rating increased, with almost all countries favouring the lightbar eHMI over the other concepts. An exception was the mean performance score for the text-based eHMI for the participants from India, which was higher than the mean performance score of the lightbar eHMI. Furthermore, it appears that the bio-inspired eHMIs were susceptible to cultural differences, as indicated by the differences in mean ratings and mean performance scores for the bio-inspired eHMIs for the different countries.

2.3.3. Impact of country for YieldingDrivingAway

Figure 2.7 shows the scatter plot of mean rating versus the mean performance score for YieldingDrivingAway. Overall, the eHMIs were still grouped together, but there were some interesting outliers, especially for the bio-inspired eHMIs.

The data from Venezuela showed that most eHMIs increased the mean performance score and ratings with respect to the baseline condition. Interestingly, the gesture eHMI received a higher mean rating than the baseline condition (54.9 for the gesture eHMI and 42.4 for the baseline condition), but the performance score was marginally lower for the gesture eHMI. The lightbar eHMI (66.8) and the text-based eHMI (67.0) received the highest ratings, but their performance score was slightly lower than the mean performance score of the colouration eHMI (68.5). The colouration eHMI did receive a higher mean rating than the other two bio-inspired eHMIs.

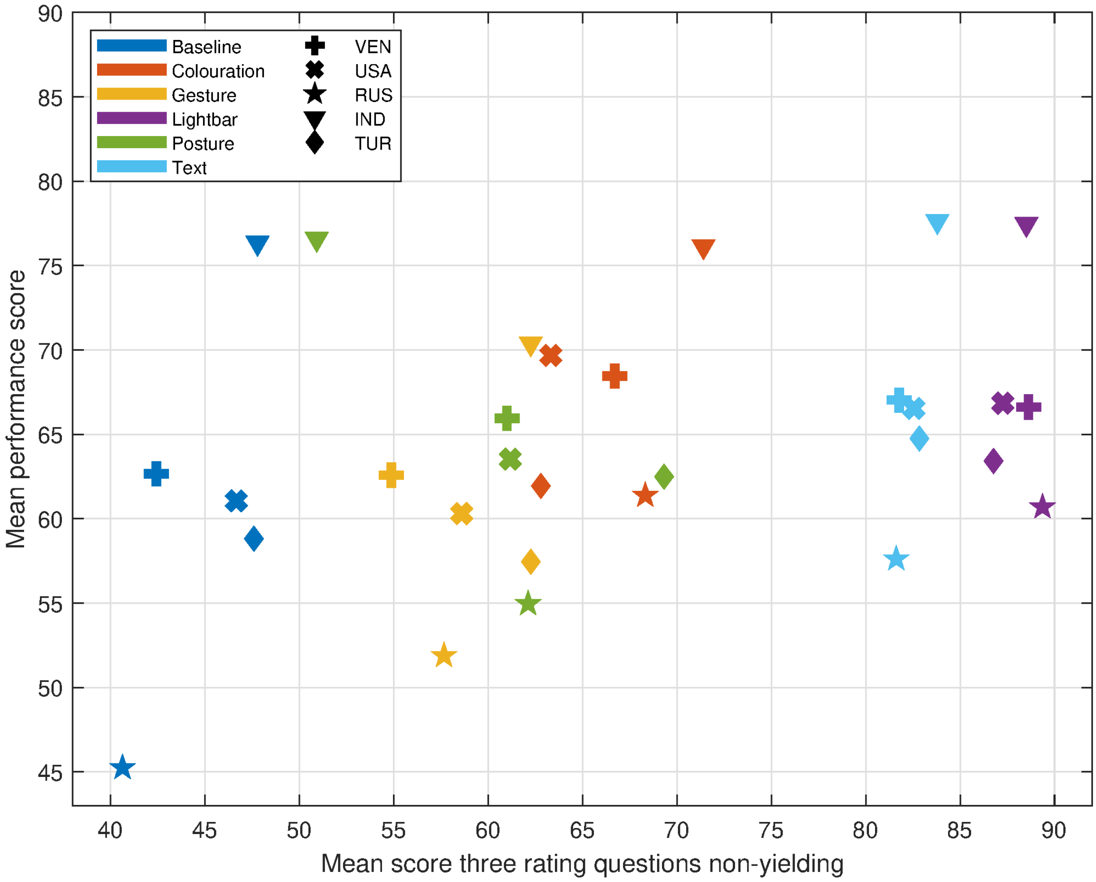

Figure 2.7: Scatter plot of the mean score of the three rating questions for non-yielding versus the mean performance score for YieldingDrivingAway with country distinction. The colours indicate the various eHMIs and the shapes indicate the country.

These findings also applied to the participants from the United States. The gesture eHMI (58.6) received a higher rating than the baseline condition (46.7), but attained a lower mean performance score (60.3 for the gesture eHMI and 61.1 for the baseline condition). The colouration eHMI attained the highest mean performance score, though there still was a significant gap between the colouration eHMI (63.3), the lightbar eHMI (87.3), and the text-based eHMI (82.6), for the rating questions.

For Russian participants, the gesture eHMI (51.9) attained a higher mean performance score than the baseline condition (45.2) and received a higher rating (57.7 for the gesture eHMI and 40.6 for the baseline condition). The colouration eHMI (68.3) achieved the highest mean performance score, but received a lower mean rating than the lightbar eHMI (89.4) and the text-based eHMI (81.6). The lightbar eHMI (60.7) also attained a higher mean performance score than the text-based eHMI (57.6), indicating Russians participants had a clear preference for the lightbar eHMI over the text-based eHMI.

The results from Indian participants showed some surprising differences with the other countries. The mean performance scores of five of the six eHMIs were above 75 and higher than the mean performance scores from other countries. The probable cause is that Indians had relatively low key-press rates, which positively impacted their score for the phases when one should not cross. Another interesting insight is that all eHMIs, except for the gesture eHMI, attained an almost similar mean performance score in the range of 76.1 to 77.6. Surprisingly, there was a large spread on the ratings assigned from 47.8 to 88.5, which was not reflected in the mean performance score. Furthermore, the gesture eHMI (62.3) received a higher rating than the baseline condition (47.8), but attained a lower mean performance score (70.4 for the gesture eHMI and 76.3 for the baseline condition). Also surprising is that the posture eHMI (50.9) barely received a better rating than the baseline condition.

The participants from Turkey rated the lightbar eHMI best, even though the text-based eHMI attained the highest mean performance score. With respect to the bio-inspired eHMIs, the posture eHMI received the highest mean rating of the three and attained the highest mean performance score. Interesting to note is that the colouration eHMI (62.8) received an almost similar mean rating as the gesture eHMI (62.3), but attained a higher mean performance score (61.9 for the colouration eHMI and 57.5 for the gesture eHMI). When comparing the gesture eHMI with the baseline condition, the performance score was lower, even though the gesture eHMI received a higher rating. The other eHMIs attained higher performance scores and received higher ratings than the baseline condition.

The results for YieldingDrivingAway indicate that there were some overall trends to be found, though this phase was more prone to differences per country than YieldingApproach. The lightbar eHMI and the text-based eHMI received the highest ratings and attained high mean performance scores. The impact of cultural differences was most noticeable for the bio-inspired eHMIs, which received very different ratings and attained varying mean performances scores for the participants from the different countries. Remarkable is that the gesture eHMI had a lower mean performance score than the baseline condition for all countries except Russia, even though the gesture eHMI received higher mean ratings. Another interesting find is that the presence of an eHMI had little impact on the mean performance score for the Indian participants, except for the gesture eHMI, which led to a lower mean performance score than the baseline condition.

2.3.4. Impact of country for NonYielding

Figure 2.8 shows the scatter plot between mean rating and mean performance score for NonYielding. Noteworthy differences existed for each eHMI, but there were also some patterns to be found.

For the Venezuelan participants, the gesture eHMI (70.3) attained a lower mean performance score than the baseline condition (71.2), as was also the case for YieldingDrivingAway. Another observation is that there was a large spread for the ratings assigned (between 42.4 for the baseline condition and 88.6 for the lightbar eHMI), whereas the performance score increased from 71.2 for the baseline condition to 72.9 for the lightbar eHMI. This seems to indicate that the eHMIs had little impact on the crossing behaviour of Venezuelans. The colouration eHMI received the best rating of the bio-inspired eHMIs and attained the highest mean performance score of the bio-inspired eHMIs, though both were lower than the mean ratings assigned to the lightbar eHMI and the text-based eHMI.

The results for NonYielding for the participants from the United States illustrated the benefit of having an eHMI, because all eHMIs received a higher mean ratings and attained a higher mean performance score than the baseline condition. The highest mean performance score was achieved by the lightbar eHMI (79.0), closely followed by the colouration eHMI (78.7), and the text-based eHMI (78.0). The three bio-inspired eHMIs were quite close together both for mean rating (58.6 for the gesture eHMI to 63.3 for the colouration eHMI) and mean performance score (76.7 for the gesture eHMI to 78.7 for the colouration eHMI).

Interesting about the results of participants from Russia was that the colouration eHMI (77.1) attained a mean performance score that was marginally worse than the lightbar eHMI (77.5), but better than the text-based eHMI (75.0). The posture eHMI (72.9) and gesture eHMI (73.1) achieved a mean performance score that was slightly better than the baseline condition (72.3).

The data obtained from Indian participants showed one interesting outlier. The text-based eHMI had the lowest mean performance score of all eHMIs (72.1), excluding the baseline condition (70.0), even though the mean rating was the second-highest of the eHMIs (83.8). Only the lightbar eHMI received a higher mean rating (88.5). The colouration eHMI attained the second-highest mean performance score (75.4) and was only outperformed by the lightbar eHMI (76.5).

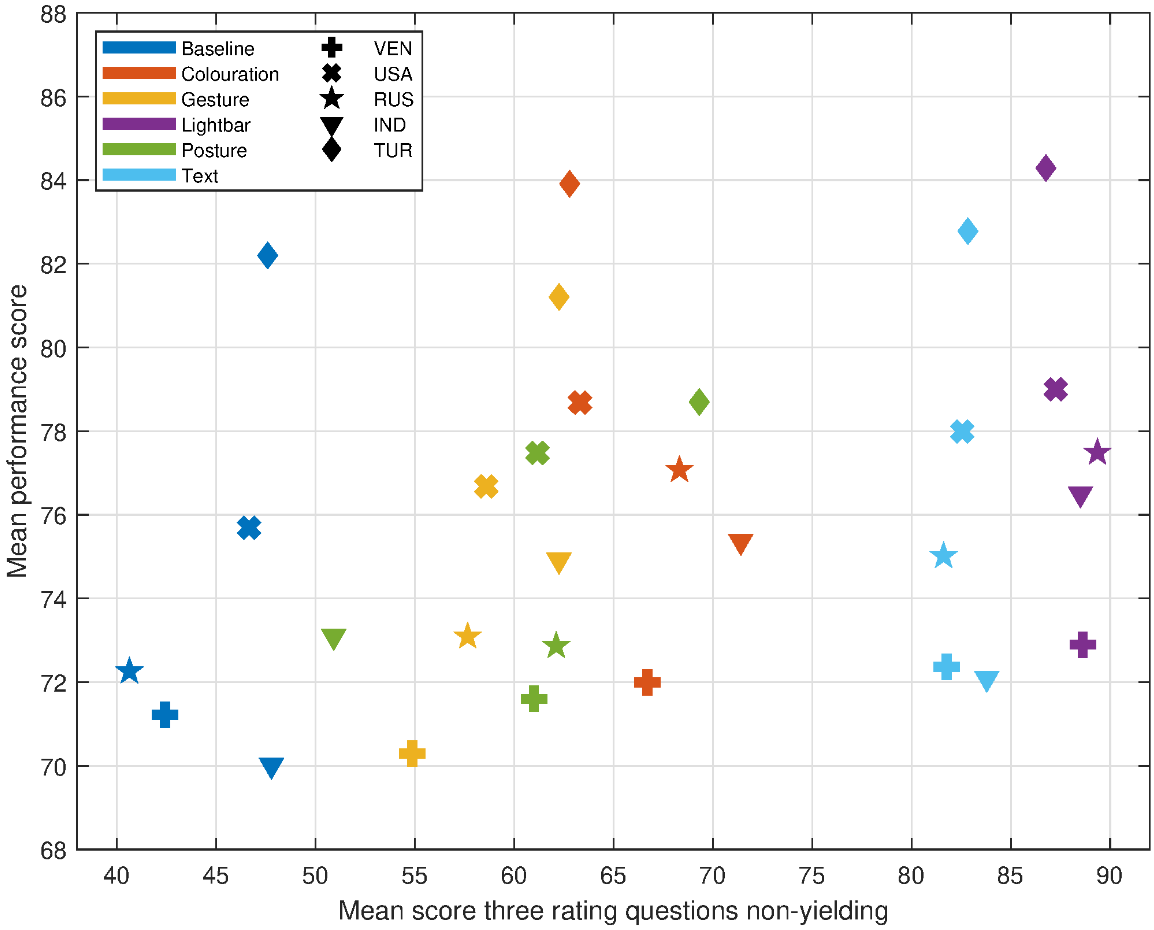

Figure 2.8: Scatter plot of the mean score of the three rating questions for non-yielding versus the mean performance score for NonYielding with country distinction. The colours indicate the various eHMIs and the shapes indicate the country.

The results from Turkish participants showed an interesting discrepancy between the mean rating and mean performance score for the three bio-inspired eHMIs. The posture eHMI received a higher mean rating than the colouration eHMI and the gesture eHMI, but achieved the lowest mean performance score of the bio-inspired eHMIs (78.7 for the posture eHMI, 81.2 for the gesture eHMI, and 83.9 for the colouration eHMI). Furthermore, the baseline condition attained a mean performance score that was higher (82.2) than both the gesture eHMI and posture eHMI and was close to the performance score of the text-based eHMI (82.8). The mean performance score of the colouration eHMI was close to that of the lightbar eHMI (83.9 for the lightbar eHMI and 84.3 for the colouration eHMI), though the lightbar eHMI received a significantly higher mean rating (86.8 for the lightbar eHMI and 72.8 for the colouration eHMI).

The results for NonYielding were interesting for numerous reasons. Overall, the lightbar eHMI and the text-based eHMI received the highest mean ratings, but this was not always reflected in the performance score. Similarly, the bio-inspired eHMIs at times received a mean rating that was higher than the baseline condition, even when the mean performance score was lower. This was surprising, because the eHMI provided additional information on top of the baseline condition and was expected to increase the performance score.

2.3.5. Conclusion on the impact of country

In general, the mean ratings assigned to the control group were close together, indicating that between the participants from the various countries there was consensus to their ratings. The mean ratings for the bio-inspired eHMIs were further apart, most noticeable in the spread between the ratings participants from India and Turkey assigned to the posture eHMI for both yielding and non-yielding. The ratings and performance scores for the colouration eHMI were comparable for most countries, indicating that the colouration eHMI would be most suitable of the bio-inspired eHMIs for most countries. An interesting observation is that the mean ratings were not always related to the mean performance score, especially when communicating non-yielding.

The mean performance scores of the eHMIs also differed per country. In most scenarios, the lightbar eHMI and the text-based eHMI attained the highest performance scores, whereas the mean performance scores of the bio-inspired eHMIs were more susceptible to cultural differences, even potentially leading to a lower mean performance score than the baseline condition. It therefore appeared that the bio-inspired eHMIs were more susceptible to cultural differences than the lightbar eHMI and the text-based eHMI.

Appendix

Bio-inspired intent-communication for automated vehicles with human road users

Bio-Inspired Intent-Communication for Automated Vehicles with Human Road Users

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***Abstract*—With the development of automated vehicles (AV), multiple means of communication currently used in interactions between a driver and a human road user (HRU) will no longer be available. The use of an external human-machine interface (eHMI) can serve to communicate intention from the AV to the HRU. This paper systematically studied visual intent-communication methods in nature and their applicability for eHMI. We found that posture, gesture, facial expression, colouration and bioluminescence are often used in nature for communication. The applicability of each of these communication channels for use in eHMI has been discussed, as well as possible ways in which these can be implemented.**

***Index Terms*—Automated vehicles; External Human-Machine Interface; Intent-communication; Biomimicry; Bio-inspired**

I. Introduction

The introduction of Automated Vehicles (AVs) to traffic holds numerous advantages. AVs are expected to improve traffic capacity and efficiency by eliminating driver involvement [1]. This elimination leads to an expected decrease of 93.5% in traffic accidents by removing the majority of human errors, under the assumption that the AV does not cause new types of accidents [2].

AVs are vehicles that typically use sensors, big data and artificial intelligence to perceive the environment and make decisions without human intervention [3]. SAE defined six levels of automation, ranging from no automation (level 0) to full automation (level 5). SAE level 3 vehicles are conditionally automated, still requiring a human driver for backup. This is not necessary for levels 4 or 5. SAE level 4 vehicles are highly automated, able of driving independently at certain places and under specific conditions, whereas SAE level 5 vehicles are fully automated and capable of driving at all times and under all conditions [4]. This elimination of human driver involvement has significant consequences for communication in traffic.

Current interaction between Human Road Users (HRUs) relies on multiple channels that may not be available for communication between AVs and HRUs. Communication currently occurs through spatial copresence, transmitting information through velocity changes and trajectory, as well as interactions through eye contact and gestures. Communication also occurs through the car's technology, e.g. flashing lights and honking [5]. Communication between HRUs can be divided in formal communication established through traffic rules and informal communication, e.g. gestures, eye contact and braking. Informal communication is especially important when there are few or unclear regulations, e.g. pedestrian crossings and parking areas. However, it will lose its functionality in interactions with AVs, due to consisting of aspects that are difficult to understand for AVs [6].

Several researchers have highlighted the importance of communication of AVs with HRUs. According to Müller, Risto, and Emmenegger, "the AV is acting in an environment that is loaded with expectations and habits" [7]. An essential part of communication is that both parties need to comprehend the intentions of the other party [8]. It is believed that a pedestrian attempting and failing to establish eye contact with an AV experiences mistrust and uncertainty [9]. Additionally, behaviour from current AVs is often non-human-like and primarily aimed at collision avoidance. These actions sometimes appear nonsensical to human drivers, e.g. by not comprehending creeping and gap communication, thereby leading to a decrease in safety and traffic flow [10]. It has been suggested to include an external human-machine interface (eHMI) that can communicate appropriate information to the surrounding HRUs. In a survey study it was found that 23% of the participants had a negative attitude towards fully automated driving [11]. According to Schieben, Wilbrink, Kettwich, *et al.*, the acceptance of AVs will depend on their capacity to interact with HRUs [12], thereby stressing the need for well-established communication channels between AVs and HRUs.

A. Existing eHMI-concepts

A wide variety of concepts for eHMIs have been proposed in the literature. In an extensive search on eHMI-concepts proposed by companies, 22 different eHMI-concepts have been identified. These concepts typically communicate through text, icons and light, displaying the message either on the car or projecting it on the road [13]. No consensus has been reached about the impact of eHMIs. Textual eHMI has been reported by pedestrians to facilitate their decision to cross, though only 4% of the participants stated the eHMI would be their primary source of information [14]. In other research, it has

Figure 1. The smiling car concept is an example of an anthropomorphic eHMI [23]

been found that many eHMI are often misunderstood [6], experience issues with quick comprehension of the signals and have shortcomings in the visibility [15]. It has also been proposed to use a wristband to send a warning message to elderly people [16], or sending a signal to a mobile phone [17]. However, sending signals through mobile phones or wearables was found to be invasive and annoying [18]. Other eHMI rely on anthropomorphism, attributing human characteristics to the car. Examples are the use of an animated face on top of the AV [19], placing eyes on a car [20], or displaying the current state of the AV in the form of a smile (see fig. 1) [21]. However, the impact of anthropomorphic eHMIs is still unclear: displaying eyes led to quicker decision making and increased feeling of safety [20]; the smiling car led to an increased feeling of safety, but required instructions [21]; whereas the face was not received well [19]. Furthermore, in a survey study it was found that anthropomorphic eHMI in general are not sufficiently clear and convincing [13]. Overall, according to Rasouli and Tsotsos, most research fails to address what modality of communication is most suited for eHMIs [22].

B. *Bio-inspired eHMI*

Applying the principle of biomimicry to derive inspiration from nature and develop a bio-inspired eHMI could be promising in discovering new suitable modalities for eHMIs. Biomimicry stems from the Greek words *bio* and *mimesis*, which together mean *to copy life*. The main principle of biomimicry is to understand a biological process and use the knowledge to solve a technical challenge [24]. A bio-inspired eHMI has the advantage that it introduces a new way of thinking in the design of eHMI that has barely been explored. It is possible that bio-inspired communication is more effective than current means used for eHMIs: according to natural selection, organisms with a competitive advantage, e.g. through better being able to communicate, should be able to reproduce more, thereby leading to a spread of this competitive advantage. Additionally, because these strategies are employed in nature, it could be that bio-inspired eHMIs are more intuitive than current eHMIs.

Biomimicry has scarcely been used in the development of eHMIs. An example of a bio-inspired eHMI is the Autonomous Electric Vehicle Interaction Testing Array (AEVITA) concept. The headlights of AEVITA act as eyes and are able of following HRUs and dilate when needed. Furthermore, the vehicle can change its posture, thereby taking a more or less threatening stance, while also communicating through the movement of its wheels. Additionally, inspired by cephalopods, the wheels can change colour, based on the perceived threat level [25]. Another bio-inspired eHMI is the hedgehog-concept. This concept uses tiny ‘feathers’ on the hood of the AV that can lie flat or pop out. This changes the shape of the car to intuitively communicate the intention of the AV, similar to how animals make themselves bigger when threatened [26].

C. *Scope*

This study provides an overview of signal transmission in nature and the applicability for interaction between AVs and HRUs. Signal design can be divided into strategic design and tactical design. Strategic design focuses on the information that is communicated and the relevance to the receiver, whereas tactical design focuses on the manner in which the signal is transmitted and how this affects the efficacy [27].

1) *Strategic design:*

There are four distinct signal categories that an eHMI can communicate information about [12]:

- Current state
- Future intentions
- Perception of the environment
- Cooperation capabilities

No unambiguous answer has yet been found for the information that needs to be communicated by the AV. Several studies found that pedestrians would like to be informed about the state of the AV [10][28][29], while in other research it is argued that such information is not relevant [30][31] or could even lead to misuse [32]. There is agreement about the added value of informing HRUs about the intended manoeuvres of AVs [28][30]. Receiving information about intended manoeuvres was found to have little impact on crossing decisions made by pedestrians, but was reported as helpful [14]. Pedestrians also appreciate receiving information about AV perception [12]. Pedestrians have been reported to be hesitant about crossing in front of a vehicle when the driver appeared distracted, highlighting the need for informing pedestrians of detection [28]. There are situations that need coordinated action from both AV and HRU, requiring information to be communicated to establish unison in the executed action by both parties. In a literature review conducted by Schieben, Wilbrink, Kettwich, *et al.*, only a single study was identified on communicating cooperation capabilities. It was found that the communication of cooperation capabilities through an additional display showing continuous speed information had no influence on participants, because gap size was leading [12].

This study aims to investigate different channels to communicate future intent. It is believed that through intent-communication the most relevant information is conveyed, while also preventing communicating too much information, which could lead to a complex signal that could be difficult to decipher.

2) Tactical design:
For the transmission of the signal, it is important that the signal is sent by the AV in a way that can be perceived by the HRU. Various modes exist for sending signals in nature [33], but these need to match with the exteroceptive senses humans possess to perceive these signals [34], which eliminates electrical signals [35] and magnetic signals [36]. Of the remaining modes, tactile signals might not be preferred, because physical proximity to the AV is required, making it impossible to send signals from a distance, except through the use of an external device, which was found to be invasive and annoying [18]. Nor is the use of olfaction an option, because this is a slow means of communication that cannot be directed [37]. Both visual and auditory signals allow for swift communication with multiple channels available. However, auditory signals mix easily with background noise [37]. Additionally, it has been found that visual signals are preferred over auditory signals [19]. Last, human eyesight is elite in comparison to other animals, suggesting that a visual eHMI could be more effective on humans than the use of another mode [38].

The following research question was addressed in this study:

How can bio-inspired visual communication be used for communicating intent from Automated Vehicles to Human Road Users?

II. Method

A. Approach

To organise this study, the functions of communication in nature have been reviewed. A selection has been made of fitting functions and purposes for intent-communication, leading to a framework that served to structure the search of intent-communication in nature.

Information about intent-communication in nature has been derived from multiple sources. The AskNature database provides information on communication strategies used in nature by various creatures [33]. Additional targeted searches for each of the purposes using various key words led to further information. The aim of this research was not to systemically categorise all communication that occurs in nature, but to explore the possibilities of communication in nature for AVs.

Subsequently, the various means of communication have been categorised to identify recurring patterns of communication in nature. Last, based on certain design considerations for eHMIs, the opportunities and shortcomings of the various channels have been discussed, along with potential manners in which these channels can be used in an eHMI.

B. Framework

The following functions for animal communication, both inter- and intraspecies, have been identified [39]:

- Agonistic interactions
  Signals for contests and aggression between individuals
- Courtship rituals
  Signals to attract members of the other sex
- Food-related signals
  Communicate the presence of food
- Alarm calls
  Communicate the presence of a threat
- Meta-communication
  Signals that change the meaning of following signals
- Ownership or territorial signals
  Signals that show dominance

Not all functions are relevant for communicating intent between AVs and HRUs. It has therefore been decided to solely focus on agonistic interactions, courtship rituals and alarm calls, because the other functions are not related to intent communication, whereas territorial signals often rely on vocalisations, scent markings and displays to inform a potential rival of their presence [40].

1) Agonistic interactions:
Agonistic behaviour has three communication purposes [41]:

- Communicating threat
- Communicating aggression
- Communicating submission

All three purposes are relevant for intent communication and have thus been explored, albeit for communicating aggression has solely been on hunting, which is a special form of aggression [41].

2) Courtship rituals:
Courtship rituals entail attracting and reproducing with individuals of the opposite sex. Though this does not directly apply to AVs, courtship rituals serve to attract attention and could therefore be useful in obtaining the attention of HRUs. Courtship rituals can have five purposes [42]:

- Highlighting male quality
- Sex and species recognition
- Sexual stimulation
- Female choice process
- Moderation of female aggression

Only highlighting male quality serves the purpose of attracting attention and has therefore been studied in more detail. The other purposes were deemed irrelevant for intent-communication.

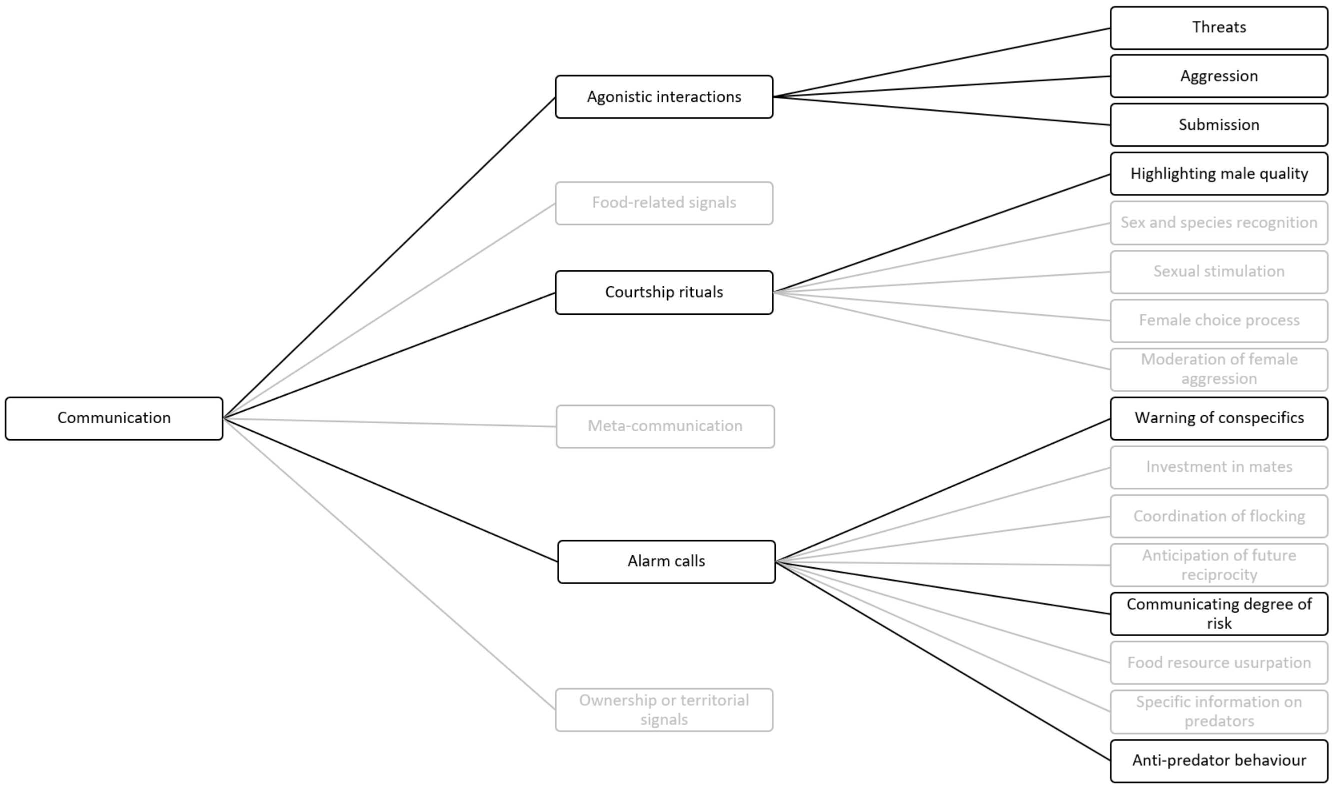

Figure 2. Framework used for structuring the search for intent-communication, based on functions and purpose of communication in nature. The boxes in grey have not been reviewed.

3) Alarm calls:
The following possible functions of alarm calls have been identified for mammals and birds [43]:

- Warning of conspecifics
- Investment in mates
- Coordination of flocking
- Anticipation of future reciprocity
- Communicating degree of risk
- Food resource usurpation
- Specific information on predators
- Anti-predator behaviour

Only warning of conspecifics, communicating degree of risk and anti-predator behaviour are applicable for intent-communication. The other functions either do not convey information appropriate for intent-communication, whereas communicating specific information on predators typically relies on the use of sound [44].

4) Overview:
Combining the previously identified purposes and functions results in the framework that has been used for structuring the search into intent-communication in nature. A visual representation of the framework can be seen in fig. 2. Only the black segments of the framework have been studied.

C. Design considerations

Three features influence the tactical design and therefore the efficacy of a signal [27]:

- Detectability
  Degree to which the signal is different from the environment and easy to perceive
- Discriminability
  Degree to which signal can be distinguished from other signals
- Memorability
  Degree to which the signal is memorable and can be associated with a certain action

Important factors that influence the detectability and discriminability are the environment and salience. The memorability is influenced by contrast, specific colours and patterns, novelty and potentiating display [27].

Numerous criteria have been mentioned in academic literature. During the 2016 Grand Cooperative Driving Challenge, a contest was held in the best HMI design for an AV. The various concepts were judged on transparency, innovation, aesthetic & minimalism, coherence & consistency and vision [45]. In a study executed by Ackermann, Beggiato, Schubert, *et al.* it was found that the most important evaluation criteria for an eHMI are unambiguousness, recognisability, interaction comfort and intuitive understanding [6]. Several studies stress the need for the eHMI to present information that is not easily misinterpreted to prevent potentially unsafe situations [46][47]. Stadler, Cornet, Theoto, *et al.* also introduce multiple factors that influence the usability of the eHMI and the implications for eHMI. Usefulness, efficiency, effectiveness, learnability, satisfaction and accessibility are labelled as components of usability [47]. Last, thoughtful of individual and cultural differences, adaptive to the environment, scalable and non-obstructive have also been named as important considerations for the design of a communication system [48].

Based on the criteria used in academic literature and the features that influence the efficacy of a signal, the following design considerations have been used in discussing the findings:

- Detectability
  The signal needs to be recognisable in a wide range of environments
- Discriminability
  The signal needs to be distinguishable from other signals
- Ambiguity
  The signal needs to be quickly and unambiguously interpreted
- Memorability
  The signal needs to be memorable to ensure that a display leads to a quick action
- Scalability
  The signal needs to be able of being used on many AVs without losings its efficacy or cluttering the environment

III. Results

A. Agonistic interactions

1) Threats:

a) Cephalopod: Cephalopods possess the ability of dynamic camouflage. This enables them to change colour at will, as demonstrated in fig. 3, and camouflage themselves in almost any environment [49]. This is achieved through the chromatophores that cephalopods have; pigment sacs that can be made visible or invisible through the use of muscles. Cuttlefish also have the ability to change the texture of their skin through papillae, while also possessing leucophores and iridophores that can reflect light [50]. These visual **cues** are important in camouflage, but also in agonistic interactions. During agonistic interactions with other octopuses, the octopuses take on a dark body colour. If both octopuses have a similar shade of darkness, this often leads to conflict. These interactions are paired with the use of posture. During agonistic interactions, octopuses make themselves big by raising their head and mantle and spreading their arms, while also taking the high ground if possible [51]. Similar behaviour can be seen in cuttlefish. During agonistic interactions, a male cuttlefish displays the intense zebra display, assuming a contrasting striped pattern and extending their fourth arm towards the opponent. Depending on the reaction of the opponent, this could escalate to a conflict [52].

Figure 3. Caribbean reef squid changing colour [53]

Figure 4. The frillneck lizard displaying agonistic behaviour through its erected neck frill [60]

b) Rat: Upon the introduction of a new rat in the territory of a dominant male rat, the dominant male rat starts displaying agonistic behaviour. In the beginning, the dominant male rat starts investigating the male rat through genital sniffing, whereas the intruder explores the environment. Next, the dominant rat moves towards the other rat and grooming occurs. Subsequently, the dominant male takes an upright posture, standing on its hind legs with an arched back. Additionally, the dominant male moves towards the intruder and exhibits lateral threatening behaviour, consisting of moving sideways around the opponent. It depends on the response of the intruder whether this will escalate in a fight. If the new rat also assumes an upright posture, this meeting will result in a fight [54].

c) Frillneck lizard: The frillneck lizard (see fig. 4) lives in the wet-dry tropical woodlands of Australia [55]. The frillneck lizard has a deimatic display that is intended to startle the predator and scare them off [56], while also serving a role in male-male interactions [57]. When threatened, it erects its frill, a collar of up to 25cm in diameter. This procedure is executed in close proximity to predators and rivals and is repeated multiple times, in combination with tail-whipping, head-bobbing, waving of the forelimbs and mouth gaping [58]. Additionally, the frill consists of conspicuous colours [59].

d) Anole: Anoles (see fig. 5) are a genus of lizards that possess a dewlap, a retractable piece of skin that serve an important role in intraspecies agonistic interactions. It has

Figure 5. A male striped anole displaying the coloured dewlap [65]

been found that there is a relationship between the size of the dewlap and the bite force for dimorpic lizards, meaning for species in which only the male has these signals [61]. This makes it a way of communicating fighting prowess and settling disputes without fighting when there is an asymmetry in ability [62]. The visual signal of the dewlap can be divided in three components: size, colour and pattern. Most dewlaps have a solid yellow or orange colour, whereas a marginal pattern also occurred relatively often, having one colour covering the majority of the dewlap with a second colour along the outer margin of the dewlap. Overall, the selected colour and pattern are dependent on the habitat of the lizard and have the purpose of maximising visibility [63]. The dewlap is retractable, thereby giving the lizards the advantage of possessing a distinctive colour pattern, while still being able to camouflage against predators [59]. Last, it has been mentioned that the dewlap serves a function in sexual selection [63], while it was discovered that this is not the case [64].

2) Aggression:

a) Anglerfish: Living in the deep sea where no surface light can reach, the anglerfish (see fig. 6) have adopted a special technique for hunting. The first dorsal fin of the anglerfish, known as the illicium, extends to the mouth. Through moving the illicium back and forth, the anglerfish mimics the movements of a small fish, using it to lure prey to its mouth [66]. Special about the illicium is the presence of the luciferase enzyme, making the illicium bioluminescent [67]. The bioluminescence, similar to the gestures made with the illicium, serves to attract prey [68].

b) Glowworm: Glowworm larvae (see fig. 7) use bioluminescence to hunt. Their habitat are often caves where little or no light can reach, or forests. The larvae live in a nest constructed of mucous tube from which it vertically suspends multiple snares with evenly-spaced adhesive droplets. Through the enzyme luciferase, the larvae create a bluish light that attracts insects that get stuck in the snare and can be consumed [70]. The effectiveness of bioluminescence in luring prey for the New Zealand glowworm larvae has been demonstrated in an experiment, in which it was shown that bioluminescent snares catch more insects than regular snares [71].

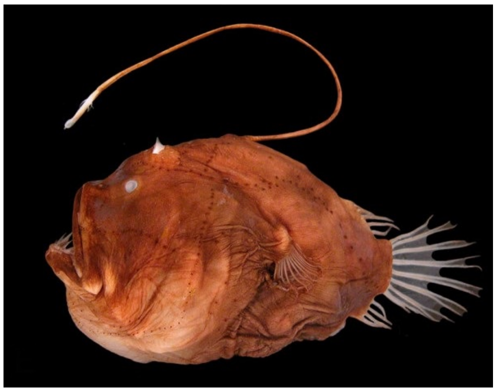

Figure 6. The anglerfish, using the first dorsal fin to mimic the movements of a small fish and thus attract prey [69]

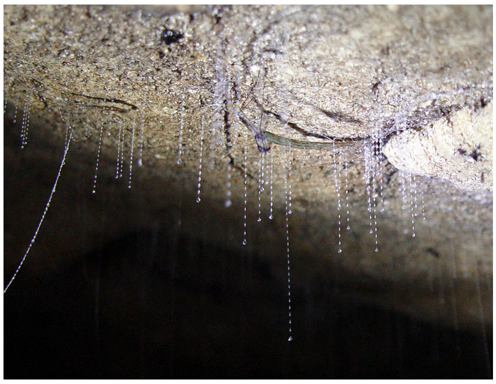

Figure 7. The snares of two New Zealand glowworm larvae that attract prey through bioluminescence [72]

c) Cuttlefish: Cuttlefish use their ability to change colour during hunting. The common cuttlefish uses a dynamic visual signal known as the passing cloud while hunting. The passing cloud consists of a wave-pattern, moving from the body of the cuttlefish towards its arms. It is thought to attract the attention of the prey and make them stop their current actions [73]. Similar behaviour has also been found in the broadclub cuttlefish, that display a unidirectional wave in the final steps of approaching its prey [74].

3) Submission:

a) Cephalopod: In response to an octopus displaying threatening behaviour, the octopus can display submission through assuming a lighter body colour and not reciprocating the change in posture, as well as fleeing [51]. Likewise, the cuttlefish can communicate submission through displaying a lighter face [52].

b) Rat: Once a rat has conceded defeat in a fight, signals are emitted to communicate submission. If possible, the rat will flee. Another option is that the defeated rat will assume a submissive posture, consisting of lying on the back. This also marks the end of the threatening behaviour displayed by the rat that won the conflict [54]. Another submissive posture is moving forward with the neck and tail outstretched and the feet bent [75].

Figure 8. A chimpanzee displaying the fear grin [78]

c) Chimpanzee: Chimpanzees use a variety of ways of visually communicating submission, which could either relate to fear or appeasement. One of the most important fear related response is the fear grin (see fig. 8) [76]. The fear grin consists of animals displaying bared-teeth and holds various meanings for different animals. For chimpanzees, the fear grin serves to communicate that the chimpanzee is not aggressive and does not wish to harm [77].

B. Courtship rituals

1) Highlighting male quality:

a) Frigatebird: The frigatebird is a type of sea-bird where the males have adopted two sexual traits to highlight their quality. First, the male frigatebirds have iridescent plumage that serves to highlight long-term male quality. Second, the frigatebird have an inflatable red gular pouch (see fig. 9) that is used to attract attention. This pouch serves to communicate current condition, as indicated through the colour and saturation. Once the males have found a suitable location to display their qualities, they will inflate the gular pouch and attempt to attract the attention of nearby females [79]. This is often done in groups, whereas the males flutter the wings, do bill-clattering and whinnying to attract attention [80]. If the females indicate interest through hovering, the male will start a display. This display includes drumming, the frequency of which is inversely related to the gular pouch size. However, it was found that the mate selection of the female was unrelated to the presence of these sexual traits, leaving the impact of these sexual traits unclear [79][81].

Figure 9. A male greater frigate bird displaying the red gular pouch [82]

b) Peacock spider: Peacock spiders are minute spiders whose size is 2-6 mm and are native to Australia. The peacock spider can be found in many different environments, ranging from sand dunes to grasslands. Furthermore, most species of peacock spiders are ground-dwelling. There are clear differences between the males and females, with the males possessing a colourful abdomen, lateral flaps in a fan-like structure and elongated third legs that are tipped with white brushes. To identify potential mates, the Maratus Volans (see fig. 10), a species of peacock spider, will periodically find a high spot and wave his third pair of legs to charm any nearby female peacock spiders [83]. Subsequently, a more complicated courtship routine begins, which predominantly consists of a fan dance in which the fan is laterally moved in synchronisation with the leg wave. Additionally, fan-flapping occurs during the fan dance, which entails extending and retracting the fan flaps repeatedly [84].

Figure 10. A male Maratus Volans, a species of peacock spider, displaying its colourful fan to attract females whilst raising its third legs [85]

c) Baboon: Female baboons have a way of signalling their reproductive status to male baboons through swelling of the perineal skin (see fig. 11). It has been found that female olive baboons with greater swellings receive more interest from males [86]. Two hypotheses exist as to the functional relevance of the swellings. It is thought that the size of the swelling either serves to communicate female fitness to attract high-quality males, or that the size of the swelling indicates the likelihood of ovulation and thereby indicate when chances of conception are highest [87][88].

C. Alarm calls

1) Warning of conspecifics:

a) Beaver: Warning signals intended to alert conspecifics are typically an auditory signal, at times accompanied by a certain alarm movement [90]. The beaver uses a combination of an alarm movement and an auditory signal in warning its conspecifics. When a disturbance in the territory occurs, the beaver slaps its tail on water [91] and elicits a response of other beavers, typically diving to deep water [92]. Interesting

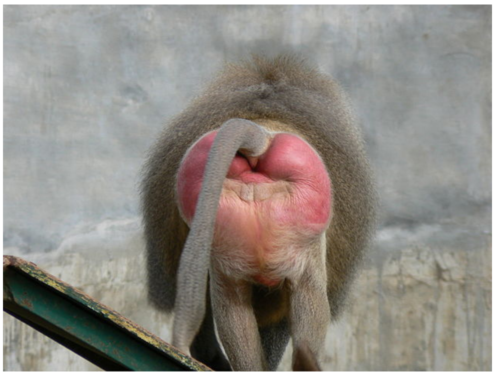

Figure 11. Swelling of the perineal skin of a female baboon, used to signal reproductive status [89]

Figure 12. The black-tailed prairie dog assuming an alert posture [96]

Figure 13. The California ground squirrel displaying its large tale that is used in warning conspecifics [98]

Figure 14. A springbok stotting [102]

about this communication is the inherent relation between the alarm movement and the auditory signal, where the visually perceivable movement generates the sound.

b) Prairie dog: Prairie dogs are herbivorous rodents that live in the North American grasslands. Prairie dogs live in colonies with an extensive underground burrow system, where the entrance to the burrow is kept free from vegetation [93]. Prairie dogs have the ability to distinguish various predators and each elicit different vocal responses that serve to inform the other prairie dogs of the identity of the predator. When a coyote is detected by a prairie dog, the prairie dog will make a sound to warn conspecifics, run towards the burrow and, depending on the proximity of the predator, either takes up a posting stand (see fig fig. 12) or enter the burrow [94]. The posting stand is not intended to warn other prairie dogs of danger, but to protect itself by obtaining awareness of the surrounding. Prairie dogs are constantly watching their neighbours for visual cues about a predator, making it an unintended warning signal for conspecifics [95].

2) Communicating degree of risk:

a) California ground squirrel: The California ground squirrel (see fig. 13) uses tail flagging, moving the tail from side-to-side, in agonistic interactions, male-female interactions and encounters with predators. Upon encountering a snake, the squirrel starts tail flagging. This serves as a means of attracting other squirrels, which is followed by collectively harassing the snake. In encounters with bobcats and similar predators, the squirrel moves the tail in large, lateral sweeps and barks, followed by running away. Thus, the squirrels have various types of tail movements that serve to communicate the degree of risk [97].

3) Anti-predator behaviour:

a) Gazelle: Stotting is a movement that is known to occur in all species of gazelles. Stotting entails the gazelle jumping with stiffly outstretched front- and hind-legs (see fig. 14). Stotting primarily occurs at the beginning or near the end of fleeing for a predator [99]. It is believed that stotting in Thomson's gazelles is intended to inform the predator of the ability of the gazelle to outrun them [100]. It therefore acts as a pursuit-deterrent signal in an attempt to convince the predator to stop pursuing, because it is not worth the effort [101].

Figure 15. The yellow-banded poison dart frog with clearly noticeable distinctive colouring and pattern [107]

b) Poison dart frog: The poison dart frog (see fig. 15) belongs to a family of frogs that live in the tropics in South- and Central-America. Multiple species of this family use aposematic signals to warn predators of their toxicity through bright colourations. [103]. More generalised, aposematic visual signals serve to communicate toxicity or distastefulness through conspicuous colourations and patterns and scare off potential predators. It is therefore important that visual aposematic signals are highly visible, so that the message of toxicity can be communicated. Typical colours to be used are red, yellow and orange, often in combination with black. An advantage of these colours is that they contrast with brown and green backgrounds, creating a signal that is easy to discriminate from the surrounding. Aposematic signals work through creating an association in predators between the bright colouration and unprofitability [104]. Interestingly, it was discovered that the learning of unpalatability in wild-caught great tits is not affected by any specific colour [105]. It is therefore relevant to also consider the achromatic aspect of the aposematic colouration, because there are different roles for both. Colour information is used for distinguishing large targets, whereas achromatic contrast is used for distinguishing smaller targets [106].

c) Dinoflagellate: Dinoflagellates (see fig. 16), a subspecies of plankton, use bioluminescence as a means of anti-predator behaviour. Dinoflagellates live in the water and during the night, upon mechanical stimulation, light up. This bioluminescent reaction of the dinoflagellates is found to significantly reduce consumption by predators [108]. Two dominant reasons for this reduction in consumption have been identified. If a concentration threshold has been reached, meaning enough dinoflagellates are together, it acts as a ’burglar alarm’. By lighting up, it draws attention to the predator that is trying to consume the dinoflagellates, thereby potentially attracting another predator that can consume the first predator. If the concentration threshold is not reached, it serves as an aposematic warning, warning potential predators of toxicity [109]. The bioluminescence also serves to startle predators [68].

d) Green bomber worm: Another form of anti-predator behaviour is distracting the predator. Green bomber worms are a species of worm living in the Pacific ocean at a depth of circa 3000 metres [111]. When threatened or attacked, the green bomber worm release bioluminescent capsules that glow brightly for many seconds after which the glow subsides. These capsules serve to distract the predator and give the worm time to escape [112].

Figure 16. Many dinoflagellates together showing their bioluminescence upon mechanical stimulation [110]

D. Overview

Upon analysis of the various methods of visual communication in nature, five different channels of communication have been identified: posture, gesture, facial expression, colouration and bioluminescence. Because posture and gesture partially overlap, the distinction has been made that a signal sent through posture is done via assuming a certain stance with the body, whereas a gesture is sent via a bodily action with only part of the body. A categorisation has been made of the various examples of visual communication found and the channels used, which can be seen in table I.

E. Patterns

Certain patterns can be found within the various functions of communication. All four examples of threat communication used either posture or gesture, or both, often in combination with colouration. An example of this is the frillneck lizard that creates a startling display through repeated erection of the frill, mouth gaping, tail-lashing and conspicuous colouring. Communicating aggression, or hunting, primarily consists of attracting the attention of the prey, either through bioluminescence or conspicuous colouration. On signalling submission, posture is typically used, whereas the chimpanzee uses facial expression. For the cephalopod, the use of posture is combined with colouration.

For the courtship rituals, all three examples combine a gesture with colouration. Important for highlighting male quality is obtaining the attention of the other sex. It is therefore of paramount importance that the signal is able to attract the attention of the opposite sex, requiring conspicuous colouration and noticeable gestures.

Table I
OVERVIEW OF THE VARIOUS PURPOSES OF COMMUNICATION AND THE CHANNELS USED FOR COMMUNICATING THIS PURPOSE

Function	**Purpose**	**Animal**	**Posture**	**Gesture**	**Facial expression**	**Colouration**	**Bioluminescence**
Agonistic interactions	*Threats*	Cephalopod	✓			✓	
		Rat	✓	✓			
		Frillneck lizard		✓	✓	✓	
		Anole		✓		✓	
	Aggression	Anglerfish		✓			✓
		Glowworm					✓
		Cuttlefish				✓	
	Submission	Cephalopod	✓			✓	
		Rat	✓				
		Chimpanzee			✓		
Courtship rituals	*Highlighting male quality*	Frigatebird		✓		✓	
		Peacock spider		✓		✓	
		Baboon		✓		✓	
Alarm calls	*Warning of conspecifics*	Beaver		✓			
		Prairie dog	✓				
	Communicating degree of risk	California ground squirrel		✓			
	Anti-predator behaviour	Gazelle		✓			
		Poison dart frog				✓	
		Dinoflagellate					✓
		Green bomber worm					✓

The communication of alarm calls occurs in various manners. Warning of conspecifics occurs through a visual action, either through posture or a gesture. The tail-slap of the beaver also leads to the generation of a sound, thereby warning conspecifics with two different modes. For visual communication of degree of risk, only a single suitable example has been found of the California ground squirrel, who has various distinct tail movements for different predators. Last, anti-predator behaviour occurs in various ways that significantly differ. Both the gazelle and poison dart frog communicate with the predator that they are not worthwhile to be eaten, either through stotting to communicate fitness or bright colouring to communicate toxicity. An important aspect to consider for the distinct colouring of the poison dart frog is that it needs to send out an aposematic signal to all potential predators, suggesting that the colouration acts as a universal warning signal. The bioluminescence of dinoflagellates serves as an aposematic warning, while also, upon reaching a concentration threshold, acting as a burglar alarm, attracting attention to the predator and thereby luring more predators. Last, the green bomber worm uses bioluminescence to startle and distract the predator through the release of a bioluminescent capsule.

Certain patterns can be found in the function of a specific channel. Posture is used for communicating mental state, signalling either threat, submission or alertness for the prairie dog. Gestures were found to attract attention. This is often done through specialised morphological adaptations that increase the size of the animal, e.g. the swelling of the perineal skin of the female baboon and the dewlap of the anole. Special about these adaptations is that most of them are collapsible, e.g. the gular pouch of the male greater frigate bird and the frill of the frillneck lizard. The use of facial expressions has barely been encountered in this study, with only the chimpanzee and frillneck lizard using facial expression for communication. Facial expressions are therefore important in agonistic interactions, probably due to the proximity of the receiver, making it possible to distinguish facial features. Interesting, both use their mouth for communication. Colouration serves a role in communication for all functions. The use of colouration can be divided in permanent colouration, e.g. the poison dart frog, and temporary colouration. The temporary colouration can be done either through changing colour, as is done by the cephalopods, or hiding the conspicuous colouring, as is done by the anole and the frigatebird. Last, bioluminescence is solely used in dark places, because the light produced is not sufficiently intense to create a clearly visible signal in sunlight. Bioluminescence is used to attract the attention of either prey or predator. By releasing a bioluminescent capsule, it is also possible to focus the attention of the predator elsewhere and escape.

Upon analysing the results, two overarching trends are noticeable. First, multi-channel signals occur often; nine of the twenty cases studied combine multiple visual channels. Five cases combine a gesture and colouration, with the frillneck lizard combining colouration, multiple gestures and facial expression. Two examples have been found of combining posture with colouration; the cephalopod for communicating threat and submission. The rat uses a combination of threat and gesture in displaying threat, whereas the anglerfish comines a gesture and bioluminescence in hunting. Second, many signals are dynamic, e.g. the flapping of the fan by the peacock spider and the repeated erection of the frill by the frillneck lizard.

IV. Applicability to AVs

Based on the identified patterns and the previously established design considerations, the applicability of the various channels is discussed, as well as potential ways in which the channel can be used in an eHMI.

A. Posture

The use of posture to communicate intent is independent of the surrounding, though two important aspects need to be considered for the detectability. First, there needs to be sufficient ambient light to ensure that a change in posture can be seen. Second, it is important that the outline of the body is clearly perceivable in any environment. An important advantage of posture is that it is not yet used in existing communication with vehicles, thereby leading to a signal that is unique and distinguishable from other signals. This uniqueness will probably also positively impact the memorability. Furthermore, posture is predominantly used in threat and submission communication, thereby making it a suitable channel for intent communication. Additionally, the use of posture to communicate intent is scalable with no risk of saturating the environment. A potential manner in which this signal can be implemented in an AV is through modifying the suspension system, allowing the AV to change height, pitch and roll to communicate intent. It has been found that larger vehicles are perceived as less safe [21][113], suggesting it is possible to communicate intent through posture and appear more or less threatening.

B. Gesture

Gestures are widely used in nature in various manners. Gestures are often a dynamic signal, thereby enabling them to attract attention through initiating movement [114], or through the appearance of a new object [115]. Another advantage of the use of gestures is that it is similar to how informal communication currently occurs, thereby leading to a signal that is memorable and distinguishable from other signals. A potential way in which communication via gestures can occur is through a collapsible structure than can fold and unfold, thereby creating a dynamic signal. Other advantages of an eHMI using a collapsible structure is that this will have little impact on the appearance of the AV, except when sending a signal. Furthermore, collapsible structures are used in nature during courtship rituals, strengthening the hypothesis that these signals are suitable for attracting attention. A potential shortcoming is that excessive use of gestures to communicate could clutter the environment, negatively impacting scalability.

C. Facial expression

In nature, facial expressions are only marginally used in communication. An explanation for this could be that communication via facial expression only has a relatively small area for communication, thereby leading to a signal that requires proximity to detect. In the identified examples, facial expressions were used in communicating either threat, or submission, indicating that the use of facial expressions is suitable for intent communication. Both the frillneck lizard and chimpanzee use their mouth in agonistic interactions, suggesting that the mouth is most suitable for communicating intent. Various eHMI-concepts using facial expressions have been proposed, e.g. the placement of eyes on an AV [20] or an AV that can smile [21].

D. Colouration

Colour can be well suited for use in AVs. By changing colour depending on the environment, it is possible to create a signal that is conspicuous, independent of the environment as long as there is sufficient ambient light. An added benefit of changing colour is that this is an effective manner of attracting attention [116]. A good colour to include in the colour scheme is turquoise. Turquoise has been identified as the best colour for identification of AVs, based on visibility, discriminability, uniqueness and attractivity [117]. Colouration has already been used in various proposed eHMI-concepts that communicate through a light strip or light bar [13]. In order to make this signal more conspicuous, lessons can be learned from nature. The visual signal sent out by anoles through their dewlap is influenced by size, colour and pattern, whereas a poison dart frog combines bright colouring with contrast. eHMIs using colouration to communicate can therefore play with size of the colour signal, as well as combining multiple colours to create patterns and increase contrast.

E. Bioluminescence

In contrast to the previous channels, bioluminescent signals are best detectable in environments with little ambient light, limiting the diversity of environments it works in. Another important consideration is that the distinguishability and discriminability of the signal are affected by ambient light, e.g. light emitted by vehicles and lamp posts. This also affects the scalability of the channel. Another deliberation is that bioluminescence serves to attract attention. It could therefore be difficult to use it to communicate intent on its own. In existing eHMI-concepts that use light, this gap is compensated for by projecting additional cues that provide the HRU with more information, e.g. through projecting a zebra crossing, or projecting motion [13].

F. Multi-channel

In nature, a significant amount of communication occurs through multiple channels. It could therefore be interesting to not limit the eHMI to a single channel, but combine various channels to create a more distinctive signal. A channel that must be included to ensure visibility in all environments is the emission of light. Two channels that could provide a good combination are the use of colouration and posture. Through a change in colour, the outline of the body can be made to stand out in any environment, thereby increasing the visibility. It is also possible to integrate the use of colouration in a gesture. This could lead to an eHMI similar to the frill of the frillneck lizard that can fold, unfold and change colour to create a conspicuous signal that can communicate intent.

V. Discussion

The purpose of this paper was to research different means of visual communication in nature and determine their applicability to AVs. It was found that five different channels are often used for communication in nature: posture, gesture, facial expression, colouration and bioluminescence. Various potential ways in which these channels can be used in eHMIs have been discussed, as well as certain aspects to consider upon using this channel in an eHMI. A combination of various channels could lead to an eHMI where the channels used complement each other. However, an important consideration mentioned in literature is that there should not be an overflow of visual cues [19], which is a risk of combining multiple channels.

Interesting about the findings is that the channels used in nature are different from many of the proposed eHMIs, with only facial expressions and light being used in current concepts. The impact of the eHMI using facial characteristics is still unclear. The use of eyes on a car led to an increased feeling of safety by pedestrians [20], whereas the smiling car also led to an increased feeling of safety, though requiring instructions [21]. In another study, anthropomorphic eHMI received medium ratings, indicating that these are not clear and convincing enough in communication [13].

This relates to an important assumption of biomimicry: that it introduces a novel way of thinking that can lead to an eHMI that is more efficient and intuitive. These findings about anthropomorphic eHMI do not support this statement, whereas the anthropomorphic eHMI not being clear enough and the smiling car requiring instructions actually conflict with the statement that bio-inspired eHMI are more intuitive. Furthermore, no direct proof has been found in academic literature to support or reject this statement.

A. *Limitations*

In determining the scope of this research, various assumptions were made. The most important assumption was that an eHMI is needed to facilitate communication between AV and HRU. It was found that leading in the decision of pedestrians to cross is the gap between them and the vehicle, thus possibly negating the need for an eHMI [14]. Moore, Currano, Strack, *et al.* found that the presence of an eHMI may not be needed, because implicit communication is sufficient [118]. The effectiveness of other methods that could fill this communication gap, e.g. communication through infrastructure or vehicle manoeuvres, have not been studied and could serve as an alternative to eHMI. Additionally, it is also possible that the eHMI predominantly serves a role in the early phase of adoption, but will no longer be needed once HRUs are sufficiently used to AVs, acting as training wheels for interaction between AVs and HRUs. This was mentioned by a participant in a study by Mahadevan, Somanath, and Sharlin [19].

The design of a signal consists of two components, strategic and tactical design. In determining the strategic design, a restriction was made to solely focus on intent communication, neglecting other information that can be communicated. For the tactical design, it was decided to only study visual communication. The decision to focus on visual communication has two consequences. First, inclusivity of eHMI has been reported as an understudied area, with little focus on visually impaired road users [119], thereby limiting the inclusivity to visually impaired HRUs. Second, multi-modal signals are common in nature, which could mean that such signals are more effective in conveying information. An important benefit of multi-modal signals is that these improve signal efficiency through increasing detectability in various environments, as well as creating a redundant signal to increase accuracy of the signal interpretation [42]. Moreover, it has been found that multi-modal signals lead to better signal reception in receivers [120].

Additionally, due to the sheer abundance, a selection has been made of various ways in which visual communication occurs in nature. This makes the sample susceptible to selectivity bias, leading to certain manners of visual communication not being studied, whereas other groups might be overpresented in the sample. Nevertheless, it is believed that the patterns identified will be generalisable to a majority of visual communication in nature.

B. *Future research*

There are only a few studies on bio-inspired eHMI, making it relevant to do more research in this field. First, it will be insightful to develop and test multiple eHMIs based on the findings in this study, using one or multiple channels in the eHMI. This could give insight in which channel or combination of channels is most suitable for use in an eHMI. Furthermore, the findings can be compared with existing eHMIs to see which eHMI performs best. It will be especially interesting to see whether the bio-inspired eHMI is indeed more intuitive to understand, as this was a potential benefit of bio-inspired eHMI.

Furthermore, the application of other modes of communication, including multi-modal signals, warrants further research. Multi-modal signals are prevalent in nature, while also being more inclusive. A good starting point could be the use of sound, because it works from a distance, allows for fast communication and introduces the possibility of conveying specific information.

Finally, an unexpected area where the bio-inspired eHMI can have an impact is in interactions with wildlife. Because the bio-inspired eHMI incorporates principles from communication in nature, it could be possible to successfully send signals to wildlife and scare them away from the road when the AV is approaching, thereby leading to a reduction of vehicle-wildlife collisions. These collisions are the cause of death of an estimated one million vertebrates per day on the American roads, and also lead to substantial vehicle damage and human fatalities: collisions with deer in America lead to damages to vehicles in excess of one billion dollar, as well as more than 200 human fatalities per year [121]. This is hence an important issue to address, requiring research on the role bio-inspired eHMIs can have in vehicle-animal communication and the impact this has on wildlife-vehicle collisions.

VI. Conclusion

The introduction of AVs to traffic has many benefits, but the inability to have informal communication between AVs and HRUs could influence the acceptance of AVs. Numerous concepts have been proposed for eHMIs, but these are at times difficult to comprehend unambiguously. The design of a signal consists of two components, strategic design and tactical design. In order to introduce a different way of thinking to eHMI design, this paper studied communication in nature and the role this could play in interactions between AVs and HRUs. It was decided to only focus on intent communication for strategic design, whereas for tactical design only visual signals were to be studied. Five different channels were identified that were used for agonistic interactions, courtship rituals and alarm calls. These channels are posture, gesture, facial expression, colouration and bioluminescence. Additionally, certain patterns were identified in how these channels were used. The various channels and their applicability to AVs has been discussed, based on five design considerations: detectability, discriminability, ambiguity, memorability and scalability. Furthermore, certain manners of implementing one or multiple of these channels were proposed, including a foldable structure that combines gesture, colouration and light. Another option is using the suspension system of the AV to change the height, pitch and roll of the AV, in combination with colouration and light. These are novel designs that lead to a different line of thinking than is currently used for the design of eHMIs. Subsequent steps will be the development of an eHMI based on these findings and testing it, to discover whether a bio-inspired eHMI is more intuitive and performs better than current eHMI-concepts.

References

[1] Q. Lu, T. Tettamanti, D. Hörcher, and I. Varga, "The impact of autonomous vehicles on urban traffic network capacity: An experimental analysis by microscopic traffic simulation," *Transportation Letters*, pp. 1–10, 2019.

[2] T. Winkle, "Safety benefits of automated vehicles: Extended findings from accident research for development, validation and testing," in *Autonomous driving*, Springer, 2016, pp. 335–364.

[3] A. Taeihagh and H. S. M. Lim, "Governing autonomous vehicles: Emerging responses for safety, liability, privacy, cybersecurity, and industry risks," *Transport reviews*, vol. 39, no. 1, pp. 103–128, 2019.

[4] SAE, *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*, Jun. 2018. DOI: https://doi.org/10.4271/J3016_201806.

[5] P. Haddington and M. Rauniomaa, "Interaction between road users: Offering space in traffic," *Space and Culture*, vol. 17, no. 2, pp. 176–190, 2014.

[6] C. Ackermann, M. Beggiato, S. Schubert, and J. F. Krems, "An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles?" *Applied ergonomics*, vol. 75, pp. 272–282, 2019.

[7] L. Müller, M. Risto, and C. Emmenegger, "The social behavior of autonomous vehicles," in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, ACM, 2016, pp. 686–689.

[8] A. Rasouli and J. K. Tsotsos, "Joint attention in driver-pedestrian interaction: From theory to practice," *arXiv preprint arXiv:1802.02522*, 2018.

[9] L. K. Vissers, S. van der Schagen, and M. INLG van & Hagenzieker, "Safe interaction between cyclists, pedestrians and automated vehicles: What do we know and what do we need to know?," 2017.

[10] B. Brown and E. Laurier, "The trouble with autopilots: Assisted and autonomous driving on the social road," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, ACM, 2017, pp. 416–429.

[11] P. Bazilinskyy, M. Kyriakidis, and J. de Winter, "An international crowdsourcing study into people's statements on fully automated driving," *Procedia Manufacturing*, vol. 3, pp. 2534–2542, 2015.

[12] A. Schieben, M. Wilbrink, C. Kettwich, R. Madigan, T. Louw, and N. Merat, "Designing the interaction of automated vehicles with other traffic participants: Design considerations based on human needs and expectations," *Cognition, Technology & Work*, vol. 21, no. 1, pp. 69–85, 2019.

[13] P. Bazilinskyy, D. Dodou, and J. De Winter, "Survey on ehmi concepts: The effect of text, color, and perspective," *Transportation research part F: traffic psychology and behaviour*, vol. 67, pp. 175–194, 2019.

[14] M. Clamann, M. Aubert, and M. L. Cummings, "Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles," in *Transportation Research Board 96th Annual Meeting*, 2017, 13p.

[15] M. Risto, C. Emmenegger, E. Vinkhuyzen, M. Cefkin, and J. Hollan, "Human-vehicle interfaces: The power of vehicle movement gestures in human road user coordination," *Proceedings of the 9th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design: driving assessment 2017*, Jun. 2017. DOI: 10.17077/drivingassessment.1633.

[16] S. Cœugnet, A. Dommes, S. Panëels, A. Chevalier, F. Vienne, N.-T. Dang, and M. Anastassova, "A vibrotactile wristband to help older pedestrians make safer street-crossing decisions," *Accident Analysis & Prevention*, vol. 109, pp. 1–9, 2017.

[17] P. Rahimian, E. E. O'Neal, S. Zhou, J. M. Plumert, and J. K. Kearney, "Harnessing vehicle-to-pedestrian (v2p) communication technology: Sending traffic warnings to texting pedestrians," *Human factors*, vol. 60, no. 6, pp. 833–843, 2018.

[18] H. Verma, G. Pythoud, G. Eden, D. Lalanne, and F. Evéquoz, "Pedestrians and visual signs of intent: Towards expressive autonomous passenger shuttles," *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 3, no. 3, p. 107, 2019.

[19] K. Mahadevan, S. Somanath, and E. Sharlin, "Communicating awareness and intent in autonomous vehicle-pedestrian interaction," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, ser. CHI '18, Mon-

treal QC, Canada: Association for Computing Machinery, 2018. DOI: 10.1145/3173574.3174003.
[20] C. M. Chang, K. Toda, D. Sakamoto, and T. Igarashi, "Eyes on a car: An interface design for communication between an autonomous car and a pedestrian," in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ACM, 2017, pp. 65–73.
[21] K. de Clercq, A. Dietrich, J. P. Núñez Velasco, J. de Winter, and R. Happee, "External human-machine interfaces on automated vehicles: Effects on pedestrian crossing decisions," *Human factors*, pp. 1353–1370, 2019.
[22] A. Rasouli and J. K. Tsotsos, "Autonomous vehicles that interact with pedestrians: A survey of theory and practice," *IEEE Transactions on Intelligent Transportation Systems*, 2019.
[23] R. Aron, *Semcon - smiling car / f&b*, 2016. [Online]. Available: http://robinaron.com/?post_type=portfolio&p=5028 (visited on 01/15/2020).
[24] E. Lurie-Luke, "Product and technology innovation: What can biomimicry inspire?" *Biotechnology advances*, vol. 32, no. 8, pp. 1494–1505, 2014.
[25] N. Pennycooke, "AEVITA: Designing biomimetic vehicle-to-pedestrian communication protocols for autonomously operating & parking on-road electric vehicles," Ph.D. dissertation, Massachusetts Institute of Technology, 2012.
[26] D. Dey, M. Martens, C. Wang, F. Ros, and J. Terken, "Interface concepts for intent communication from autonomous vehicles to vulnerable road users," English, in *AutomotiveUI '18*, United States: Association for Computing Machinery, Inc, Sep. 2018, pp. 82–86, ISBN: 978-1-4503-5947-4. DOI: 10.1145/3239092.3265946.
[27] T. Guilford and M. S. Dawkins, "Receiver psychology and the evolution of animal signals," *Animal behaviour*, vol. 42, no. 1, pp. 1–14, 1991.
[28] V. M. Lundgren, A. Habibovic, J. Andersson, T. Lagström, M. Nilsson, A. Sirkka, J. Fagerlönn, R. Fredriksson, C. Edgren, S. Krupenia, *et al.*, "Will there be new communication needs when introducing automated vehicles to the urban context?" In *Advances in human aspects of transportation*, Springer, 2017, pp. 485–497.
[29] A. Habibovic, J. Andersson, M. Nilsson, V. M. Lundgren, and J. Nilsson, "Evaluating interactions with non-existing automated vehicles: Three wizard of oz approaches," in *2016 IEEE Intelligent Vehicles Symposium (IV)*, IEEE, 2016, pp. 32–37.
[30] D. Rothenbücher, J. Li, D. Sirkin, B. Mok, and W. Ju, "Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles," in *2016 25th IEEE international symposium on robot and human interactive communication (RO-MAN)*, IEEE, 2016, pp. 795–802.
[31] D. Dey, M. Martens, B. Eggen, and J. Terken, "Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour," *Transportation research part F: traffic psychology and behaviour*, vol. 65, pp. 191–205, 2019.
[32] A. Millard-Ball, "Pedestrians, autonomous vehicles, and cities," *Journal of Planning Education and Research*, vol. 38, no. 1, pp. 6–12, 2018.
[33] J. M. Deldin and M. Schuknecht, "The asknature database: Enabling solutions in biomimetic design," in *Biologically inspired design*, Springer, 2014, pp. 17–27.
[34] N. Damann, T. Voets, and B. Nilius, "TRPs in our senses," *Current Biology*, vol. 18, no. 18, R880–R889, 2008.
[35] B. Kramer, *Electroreception and communication in fishes*. Gustav Fischer, 1996, vol. 42.
[36] L. E. Foley, R. J. Gegear, and S. M. Reppert, "Human cryptochrome exhibits light-dependent magnetosensitivity," *Nature communications*, vol. 2, p. 356, 2011.
[37] J. A. Endler, "Some general comments on the evolution and design of animal communication systems," *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, vol. 340, no. 1292, pp. 215–225, 1993.
[38] E. M. Caves, N. C. Brandley, and S. Johnsen, "Visual acuity and the evolution of signals," *Trends in ecology & evolution*, vol. 33, no. 5, pp. 358–372, 2018.
[39] N. S. Dash and A. Bhattacharyya, "The animal communication system (anicoms): Some interesting observations," *International Journal of Communication*, vol. 27, no. 2, 2017.
[40] J. L. Brown and G. H. Orians, "Spacing patterns in mobile animals," *Annual review of ecology and systematics*, vol. 1, no. 1, pp. 239–262, 1970.
[41] J. J. McGlone, "Agonistic behavior in food animals: Review of research and techniques," *Journal of Animal Science*, vol. 62, no. 4, pp. 1130–1139, 1986.
[42] C. Mitoyen, C. Quigley, and L. Fusani, "Evolution and function of multimodal courtship displays," *Ethology*, vol. 125, no. 8, pp. 503–515, 2019. DOI: 10.1111/eth.12882.
[43] S. Haftorn, "Contexts and possible functions of alarm calling in the willow tit, parus montanus; the principle of'better safe than sorry'," *Behaviour*, vol. 137, no. 4, pp. 437–449, 2000.
[44] C. S. Evans, L. Evans, and P. Marler, "On the meaning of alarm calls: Functional reference in an avian vocal system," *Animal Behaviour*, vol. 46, no. 1, pp. 23–38, 1993.
[45] O. Benderius, C. Berger, and V. M. Lundgren, "The best rated human–machine interface design for autonomous vehicles in the 2016 grand cooperative driving challenge," *IEEE Transactions on intelligent transportation systems*, vol. 19, no. 4, pp. 1302–1307, 2017.
[46] Y. M. Lee, R. Madigan, J. Garcia, A. Tomlinson, A. Solernou, R. Romano, G. Markkula, N. Merat, and J. Uttley, "Understanding the messages conveyed by automated vehicles," in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2019, pp. 134–143.
[47] S. Stadler, H. Cornet, T. N. Theoto, and F. Frenkler, "A tool, not a toy: Using virtual reality to evaluate the communication between autonomous vehicles and pedestrians," in *Augmented Reality and Virtual Reality*, Springer, 2019, pp. 203–216.
[48] A. Löcken, P. Wintersberger, A.-K. Frison, and A. Riener, "Investigating user requirements for communication between automated vehicles and vulnerable road users," in *2019 IEEE Intelligent Vehicles Symposium (IV)*, IEEE, 2019, pp. 879–884.
[49] R. Hanlon, "Cephalopod dynamic camouflage," *Current Biology*, vol. 17, no. 11, R400–R404, 2007.
[50] M. Brooks, "Do you speak cuttlefish?" *New Scientist*, vol. 198, no. 2653, pp. 28–31, 2008.
[51] D. Scheel, P. Godfrey-Smith, and M. Lawrence, "Signal use by octopuses in agonistic interactions," *Current Biology*, vol. 26, no. 3, pp. 377–382, 2016.
[52] S. A. Adamo and R. Hanlon, "Do cuttlefish (cephalopoda) signal their intentions to conspecifics during agonistic encounters?" *Animal Behaviour*, vol. 52, no. 1, pp. 73–81, 1996.
[53] B. Wills, *File: Bufoceratias.jpg*, 2006. [Online]. Available: https://commons.wikimedia.org/wiki/File:Squid_colors_2.tif (visited on 11/26/2019).
[54] J. Koolhaas, T. Schuurman, and P. Wiepkema, "The organization of intraspecific agonistic behaviour in the rat," *Progress in neurobiology*, vol. 15, no. 3, pp. 247–268, 1980.

[55] G. S. Bedford, K. A. Christian, and A. D. Griffiths, "Preliminary investigations on the reproduction of the frillneck lizard chlamydosaurus kingii in the northern territory," *Herpetology in Australia: A Diverse Discipline*, pp. 127–131, 1993.

[56] T. M. Caro and G. Ruxton, "Aposematism: Unpacking the defences," *Trends in ecology & evolution*, 2019.

[57] G. G. Watkins, "Function of a secondary sexual ornament: The crest in the south american iguanian lizard microlophus occipitalis (peters, tropiduridae)," *Herpetologica*, pp. 161–169, 1998.

[58] R. Shine, "Function and evolution of the frill of the frillneck lizard, chlamydosaurus kingii (sauria: Agamidae)," *Biological Journal of the Linnean Society*, vol. 40, no. 1, pp. 11–20, 1990.

[59] D. G. Hamilton, M. J. Whiting, and S. R. Pryke, "Fiery frills: Carotenoid-based coloration predicts contest success in frillneck lizards," *Behavioral Ecology*, vol. 24, no. 5, pp. 1138–1149, 2013.

[60] M. Clancy, *File:frill-necked lizard (chlamydosaurus kingii) (8692607976).jpg*, 2013. [Online]. Available: https://commons.wikimedia.org/wiki/File:Frill-necked_Lizard_(Chlamydosaurus_kingii)_(8692607976).jpg (visited on 12/09/2019).

[61] S. P. Lailvaux and D. J. Irschick, "The evolution of performance-based male fighting ability in caribbean anolis lizards," *The American Naturalist*, vol. 170, no. 4, pp. 573–586, 2007.

[62] P. Taylor and R. W. Elwood, "The mismeasure of animal contests," *Animal Behaviour*, vol. 65, no. 6, pp. 1195–1202, 2003.

[63] K. E. Nicholson, L. J. Harmon, and J. B. Losos, "Evolution of anolis lizard dewlap diversity," *PLoS one*, vol. 2, no. 3, e274, 2007.

[64] R. R. Tokarz, A. V. Paterson, and S. McMann, "Importance of dewlap display in male mating success in free-ranging brown anoles (anolis sagrei)," *Journal of Herpetology*, vol. 39, no. 1, pp. 174–178, 2005.

[65] W. Kreijkes, *File:male striped anole (anolis lineatus) displaying dewlap.jpg*, 2016. [Online]. Available: https://commons.wikimedia.org/wiki/File:Male_striped_anole_(Anolis_lineatus)_displaying_dewlap.jpg (visited on 12/10/2019).

[66] M. Yasugi and M. Hori, "Predominance of parallel-and cross-predation in anglerfish," *Marine Ecology*, vol. 37, no. 3, pp. 576–587, 2016.

[67] G. Leisman, D. H. Cohn, and K. H. Nealson, "Bacterial origin of luminescence in marine animals," *Science*, vol. 208, no. 4449, pp. 1271–1273, 1980.

[68] S. H. Haddock, M. A. Moline, and J. F. Case, "Bioluminescence in the sea," *Annual Review of Marine Science*, vol. 2, no. 1, pp. 443–493, 2010. DOI: 10.1146/annurev-marine-120308-081028.

[69] *File: Bufoceratias.jpg*, 2010. [Online]. Available: https://commons.wikimedia.org/wiki/File:Bufoceratias.jpg (visited on 11/26/2019).

[70] J. Von Byern, V. Dorrer, D. J. Merritt, P. Chandler, I. Stringer, M. Marchetti-Deschmann, A. McNaughton, N. Cyran, K. Thiel, M. Noeske, *et al.*, "Characterization of the fishing lines in titiwai (= arachnocampa luminosa skuse, 1890) from new zealand and australia," *PloS one*, vol. 11, no. 12, 2016.

[71] R. A. Broadley and I. A. Stringer, "Prey attraction by larvae of the new zealand glowworm, arachnocampa luminosa (diptera: Mycetophilidae)," *Invertebrate Biology*, vol. 120, no. 2, pp. 170–177, 2001.

[72] M. Nolf, *File:arachnocampa luminosa larvae.jpg*, 2005. [Online]. Available: https://commons.wikimedia.org/wiki/File:Arachnocampa_luminosa_larvae.jpg (visited on 11/26/2019).

[73] R. T. Hanlon and J. B. Messenger, *Cephalopod behaviour*. Cambridge University Press, 2018, pp. 80–81.

[74] M. J. How, M. D. Norman, J. Finn, W.-S. Chung, and N. J. Marshall, "Dynamic skin patterns in cephalopods," *Frontiers in physiology*, vol. 8, p. 393, 2017.

[75] J. P. Scott, "Agonistic behavior of mice and rats: A review," *American Zoologist*, vol. 6, no. 4, pp. 683–701, 1966.

[76] L. Brent, A. Kessel, and H. Barrera, "Evaluation of introduction procedures in captive chimpanzees," *Zoo Biology: Published in affiliation with the American Zoo and Aquarium Association*, vol. 16, no. 4, pp. 335–342, 1997.

[77] L. A. Parr and B. M. Waller, "Understanding chimpanzee facial expression: Insights into the evolution of communication," *Social Cognitive and Affective Neuroscience*, vol. 1, no. 3, pp. 221–228, 2006.

[78] F. de Waal, *Human and chimp: Can our genes tell the story of our divergence?* 2005. [Online]. Available: https://journals.plos.org/plosbiology/article/figure?id=10.1371/journal.pbio.0030202.g001 (visited on 12/16/2019).

[79] V. Madsen, T. Dabelsteen, D. Osorio, and J. L. Osorno, "Morphology and ornamentation in male magnificent frigatebirds: Variation with age class and mating status," *the american naturalist*, vol. 169, no. S1, S93–S111, 2007.

[80] D. R. Khanna, *Biology of birds*. Discovery Publishing House, 2005, p. 318.

[81] D. Dearborn and M. Ryan, "A test of the darwin–fisher theory for the evolution of male secondary sexual traits in monogamous birds," *Journal of Evolutionary Biology*, vol. 15, no. 2, pp. 307–313, 2002.

[82] C. J. Sharp, *File:male greater frigate bird displaying.jpg*, 2012. [Online]. Available: https://commons.wikimedia.org/wiki/File:Male_greater_frigate_bird_displaying.jpg (visited on 12/17/2019).

[83] M. B. Girard and J. A. Endler, "Peacock spiders," *Current Biology*, vol. 24, no. 13, R588–R590, 2014.

[84] M. B. Girard, M. M. Kasumovic, and D. O. Elias, "Multimodal courtship in the peacock spider, maratus volans (op-cambridge, 1874)," *PLoS One*, vol. 6, no. 9, e25390, 2011.

[85] J. Otto, *Img_2945 (7) peacock spider maratus volans for wikipedia*, 2009. [Online]. Available: https://www.flickr.com/photos/59431731@N05/12584670244/ (visited on 12/17/2019).

[86] L. G. Domb and M. Pagel, "Sexual swellings advertise female quality in wild baboons," *Nature*, vol. 410, no. 6825, p. 204, 2001.

[87] T. Deschner, M. Heistermann, K. Hodges, and C. Boesch, "Female sexual swelling size, timing of ovulation, and male behavior in wild west african chimpanzees," *Hormones and behavior*, vol. 46, no. 2, pp. 204–215, 2004.

[88] D. P. Zinner, C. L. Nunn, C. P. van Schaik, and P. M. Kappeler, "Sexual selection and exaggerated sexual swellings of female primates," *Sexual selection in primates: New and comparative perspectives*, pp. 71–89, 2004.

[89] P. Amba, *Fili: Baboon buttocks.jpg*, 2007. [Online]. Available: https://commons.wikimedia.org/wiki/File:Baboon_buttocks.jpg (visited on 01/02/2020).

[90] T. M. Caro, *Antipredator defenses in birds and mammals*. University of Chicago Press, 2005, p. 182.

[91] J. O. Wolff and P. W. Sherman, *Rodent societies: an ecological and evolutionary perspective*. University of Chicago Press, 2008, p. 286.

[92] H. E. Hodgdon and J. S. Larson, "Some sexual differences in behaviour within a colony of marked beavers (castor canadensis)," *Animal Behaviour*, vol. 21, no. 1, pp. 147–152, 1973.

[93] A. D. Whicker and J. K. Detling, “Ecological consequences of prairie dog disturbances.,” *BioScience*, vol. 38, no. 11, pp. 778–785, 1988.
[94] C. N. Slobodchikoff, “Cognition and communication in prairie dogs,” *The cognitive animal: empirical and theoretical perspectives on animal cognition*, pp. 257–264, 2002.
[95] J. L. Hoogland, “The evolution of coloniality in white-tailed and black-tailed prairie dogs (sciuridae: Cynomys leucurus and c. ludovicianus),” *Ecology*, vol. 62, no. 1, pp. 252–272, 1981.
[96] C. J. Carley, *File:cynomys ludovicianus 2.jpg*, 2002. [Online]. Available: https://commons.wikimedia.org/wiki/File:Cynomys_ludovicianus_2.jpg (visited on 12/11/2019).
[97] D. F. Hennessy, M. P. Rowe, R. G. Coss, D. W. Leger, and D. H. Owings, “The information afforded by a variable signal: Constraints on snake-elicited tail flagging by california ground squirrels,” *Behaviour*, vol. 78, no. 3-4, pp. 188–224, 1981.
[98] T. O’Brien, *File:california ground squirrel dana point harbor 2007 2.jpg*, 2007. [Online]. Available: https://commons.wikimedia.org/wiki/File:California_Ground_Squirrel_Dana_Point_Harbor_2007_2.jpg (visited on 12/11/2019).
[99] F. R. Walther, “Flight behaviour and avoidance of predators in thomson’s gazelle (gazella thomsoni guenther 1884),” *Behaviour*, pp. 184–221, 1969.
[100] C. D. FitzGibbon and J. H. Fanshawe, “Stotting in thomson’s gazelles: An honest signal of condition,” *Behavioral Ecology and Sociobiology*, vol. 23, no. 2, pp. 69–74, 1988.
[101] O. Hasson, “Pursuit-deterrent signals: Communication between prey and predator.,” *Trends in Ecology & Evolution*, vol. 6, no. 10, pp. 325–329, 1991.
[102] Y. Krishnappa, *File:springbok pronk.jpg*, 2012. [Online]. Available: https://en.wikipedia.org/wiki/File:Springbok_pronk.jpg (visited on 12/11/2019).
[103] J. C. Santos, L. A. Coloma, and D. C. Cannatella, “Multiple, recurring origins of aposematism and diet specialization in poison frogs,” *Proceedings of the National Academy of Sciences*, vol. 100, no. 22, pp. 12 792–12 797, 2003.
[104] J. A. Endler and J. Mappes, “Predator mixes and the conspicuousness of aposematic signals,” *The American Naturalist*, vol. 163, no. 4, pp. 532–547, 2004.
[105] A. Ham, E. Ihalainen, L. Lindström, and J. Mappes, “Does colour matter? the importance of colour in avoidance learning, memorability and generalisation,” *Behavioral Ecology and Sociobiology*, vol. 60, no. 4, pp. 482–491, 2006.
[106] M. Stevens, “Predator perception and the interrelation between different forms of protective coloration,” *Proceedings of the Royal Society B: Biological Sciences*, vol. 274, no. 1617, pp. 1457–1464, 2007.
[107] T. Shears, *File:poison dart frog by trisha 5.jpg*, 2012. [Online]. Available: https://commons.wikimedia.org/wiki/File:Poison_Dart_Frog_By_Trisha_5.jpg (visited on 02/10/2020).
[108] W. E. Esaias and H. C. Curl Jr, “Effect of dinoflagellate bioluminescence on copepod ingestion rates,” *Limnology and Oceanography*, vol. 17, no. 6, pp. 901–906, 1972.
[109] K. A. Hanley and E. A. Widder, “Bioluminescence in dinoflagellates: Evidence that the adaptive value of bioluminescence in dinoflagellates is concentration dependent,” *Photochemistry and photobiology*, vol. 93, no. 2, pp. 519–530, 2017.
[110] H. Hillewaert, *File:noctiluca scintillans.jpg*, 2010. [Online]. Available: https://commons.wikimedia.org/wiki/File:Noctiluca_scintillans.jpg (visited on 11/26/2019).
[111] K. J. Osborn and G. W. Rouse, “Phylogenetics of acrocirridae and flabelligeridae (cirratuliformia, annelida),” *Zoologica Scripta*, vol. 40, no. 2, pp. 204–219, 2011.
[112] K. J. Osborn, S. H. Haddock, F. Pleijel, L. P. Madin, and G. W. Rouse, “Deep-sea, swimming worms with luminescent “bombs”,” *Science*, vol. 325, no. 5943, pp. 964–964, 2009.
[113] B. R. Kadali and P. Vedagiri, “Proactive pedestrian safety evaluation at unprotected mid-block crosswalk locations under mixed traffic conditions,” *Safety science*, vol. 89, pp. 94–105, 2016.
[114] R. A. Abrams and S. E. Christ, “Motion onset captures attention,” *Psychological Science*, vol. 14, no. 5, pp. 427–432, 2003.
[115] C. J. Howard and A. O. Holcombe, “Unexpected changes in direction of motion attract attention,” *Attention, Perception, & Psychophysics*, vol. 72, no. 8, pp. 2087–2095, 2010.
[116] A. von Mühlenen, M. I. Rempel, and J. T. Enns, “Unique temporal change is the key to attentional capture,” *Psychological Science*, vol. 16, no. 12, pp. 979–986, 2005.
[117] A. Werner, “New colours for autonomous driving: An evaluation of chromaticities for the external lighting equipment of autonomous vehicles,” *Colour Turn*, no. 1, 2018.
[118] D. Moore, R. Currano, G. E. Strack, and D. Sirkin, “The case for implicit external human-machine interfaces for autonomous vehicles,” in *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2019, pp. 295–307.
[119] L. Robert, “The future of pedestrian–automated vehicle interactions,” *Robert, LP (2019). The Future of Pedestrian-Automated Vehicle Interactions, XRDS: Crossroads, ACM*, vol. 25, no. 3, 2019.
[120] C. Rowe, “Receiver psychology and the evolution of multicomponent signals,” *Animal behaviour*, vol. 58, no. 5, pp. 921–931, 1999.
[121] J. A. Litvaitis and J. P. Tash, “An approach toward understanding wildlife-vehicle collisions,” *Environmental Management*, vol. 42, no. 4, pp. 688–697, 2008.