My Eyes Speak: Improving Perceived Sociability of Autonomous Vehicles in Shared Spaces Through Emotional Robotic Eyes

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The ability of autonomous vehicles (AVs) to interact socially with pedestrians poses a significant impact on their integration with urban traffic. This is particularly important for vehicle-pedestrian shared spaces due to increased social requirements in comparison to vehicular roads. Current pedestrian experience in shared spaces suffers from negative attitudes towards AVs and the consequently low acceptability of AVs in these spaces. HRI work shows that the acceptability of robots in public spaces can be positively impacted by their perceived sociability (i.e., possessing social skills), which can be enhanced by their ability to express emotions. Inspired by this approach, we follow a systematic process to design emotional expressions for AVs using the headlight ("eye") area and investigate their impact on perceived sociability of AVs in shared spaces, by conducting expert focus groups (N=12) and an online video-based user study (N=106). Our findings confirm that the perceived sociability of AVs can be enhanced by emotional expressions indicated through emotional eyes. We further discuss implications of our findings for improving pedestrian experience and attitude in shared spaces and highlight opportunities to use AVs' emotional expressions as a new external communication strategy for future research.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; **Empirical studies in interaction design**.

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1 INTRODUCTION

The last decade witnessed significant growth in autonomous mobility services, from delivery vehicles in local campuses to autonomous shuttles in city centres [25, 66, 85, 92]. These autonomous vehicles (AVs) show promise to operate safely on roads but are still faced with challenges around their social acceptability [76, 81, 92]. Part of the public scepticism stems from AVs' inability to interact socially with nearby pedestrians, such as exchanging social cues (e.g., gestures, eye contact) and following road etiquette [25, 63, 84]. Such challenges are even more critical for urban areas like shared spaces, where pedestrians and vehicles share the same public space with equal rights [51, 68] and interactions are controlled primarily by informal social norms rather than strict traffic rules [82, 104]. While the objective of shared spaces is to enhance pedestrian priority and well-being [51, 68], field studies reveal that current pedestrian experience in shared spaces are marred by negative attitudes during vehicle encounters, such as feelings of insecurity in close proximity to AVs and irritation towards vehicles intruding on "their spaces" [34, 35, 50, 82]. Therefore, developing interaction approaches for AVs that can improve current pedestrian experience and attitude is necessary for their smooth integration into shared spaces.

As AVs share similar technical features and appearances with mobile robots [82], human-robot interaction (HRI) paradigms offer valuable inspirations for improving AV-pedestrian communication [33, 67]. The integration of robots into human spaces has been shown to be facilitated by their sociability [31, 58], i.e., possessing social skills, such as praise and rudeness [58, 91], which has been largely indicated by their ability to express emotions to users [24, 29]. Emotionally expressive robots are perceived to have higher likeability and social acceptability [28, 37], and interactions with them are considered to be more pleasant and empathy-fostering [28, 37, 61]. This strategy has been indeed applied to many autonomous mobile robots seen in public spaces, such as delivery robots[1] and restaurant service robots[2]. In the context of AV-pedestrian communication, external human-machine interfaces (eHMIs) have gained considerable research attention in recent years [19, 100]. They are designed to restore driver cues in pedestrian communication and have emerged as a new category of mobile interfaces and human-computer interaction (HCI) [13, 43, 44, 59]. However, limited attention has been given to social challenges related to pedestrian experience and attitude in shared spaces, and there is a lack of eHMIs that specifically aim to improve the perceived sociability of AVs for such environments.

In this work, we design emotional expressions for AVs and evaluate its influence on AVs' perceived sociability in a series of traffic situations in shared spaces. Inspired by social robots, we design emotions through the AV's headlight position, which functions analogously to the AV's "eyes". We refer to this concept as **emotional eyes** for the rest of the paper. We chose eye representation because (1) anthropomorphism is found to foster the sociability of robots [29, 62, 109]; (2) robotic eyes are a pervasive element in the emotional expression of commercial-grade social robots [49, 109] and can affect the perception of robots' personal and emotional traits [62]; and (3) eye gaze on

[1]https://www.kiwibot.com/blog-posts/kiwibot-announces-rebranding-we-deliver-emotions
[2]https://www.robotlab.com/restaurant-robots/store/bellabot

AVs as eHMIs to indicate intent and awareness has shown to enhance pedestrian trust and safety [9, 10, 33]. Building on prior work, we aim to investigate the potential of AVs' emotional expressions as a new external communication strategy that addresses inherent social challenges in shared space situations, diverging from the prevalent focus on crossing situations on vehicular roads. To this end, we first generate three emotional eye designs from existing commercial-grade social robots and evaluate them with 12 domain experts to select one design most associated with emotion conveyance. Combining the design with shared space scenarios identified from real-world evidence, we then investigate effects of AVs' emotional expressions on their perceived sociability through an online video-based user study with 106 participants.

Our contribution is twofold. First, to our best knowledge, this is the first work that systematically designs and evaluates AVs' emotional expressions (in particular, emotional eyes equipped on AVs) to support AV-pedestrian interaction. Second, we investigate the role of emotional eyes in improving AVs' perceived sociability (i.e., possession of social skills) in shared spaces with prompts of specific user scenarios that extend beyond the conventional road crossing context. We further discuss the potential of our findings to address challenges around current pedestrian experience and attitude towards AVs in shared spaces. Therefore, we answer two research questions: (**RQ1**) *How can we design emotional expressions for AVs through robotic eyes inspired by social robots?* (**RQ2**) *How do emotional expressions of AVs influence their perceived sociability in shared space scenarios?*

2 RELATED WORK

2.1 Pedestrian Experience in Shared Spaces

Shared space approach aims to increase pedestrian priority and comfort in urban environment by minimising the segregation between pedestrians and vehicles, such as removing curbs, road markings, traffic signs and signals [50, 51, 68]. However, currently pedestrians still tend to feel uneasy around cars in shared spaces [50, 68] and have demonstrated various negative emotions around AVs. Shared space deployments in the UK found that pedestrians showed anxiety during peak hours and around high-speed vehicles [50, 68]. In the SionSmart shuttle project, pedestrians felt stressed in close proximity to the unmanned AV [25]. Even when AVs ensure the physical safety of pedestrians, i.e., collision-free, pedestrians can still find AVs intimidating and feel threatened [82, 95]. Additionally, pedestrians can have a higher sense of space ownership over vehicles in shared spaces, which can lead to feelings of intruding on their spaces [35] and even irritation when priority is compromised [35, 82]. For example, pedestrians in the CityMobil2 project considered themselves to have higher priority than the AV when road markings were absent [66]. In the WEpods project, over three-fourths of pedestrians expected the AV to always stop even when the pedestrian was breaking rules [85].

Current negative pedestrian experiences can lead to disincentives to use shared spaces [35, 68] and low acceptability for AV technology in this environment [38, 106]. In motion planning research, AVs are increasingly trained to drive not only safely but also in a socially-aware manner in shared spaces [47, 56], while more explicit communication forms (e.g., eHMIs) that address such an issue are still lacking. In the context of designing eHMIs for shared spaces, Li et al. [57] suggested windshield displays to replicate drivers' gestures (e.g., waving, thumbs) to help AVs reach passage agreements with pedestrians. Hoggenmueller et al. [42] investigated LED light patterns to signal pick-up manoeuvres for passengers. We add to the work on shared space eHMIs by proposing emotional expressions for AVs that portray them as sociable agents, seeking to positively affect perceptions of AVs and consequently pedestrian experience in shared spaces.

2.2 Emotional Expressions of Social Robots

Emotional expression is one of the key indicators of socially interactive robots [29]. Prior HRI research found that emotional expressions can ascribe mind and intentionality to robots [28, 37], foster feelings of social connection and empathy in the interaction [37, 52], and increase the likeability and sociability of robots [24, 28]. Besides, humans have the innate tendency to attribute liveliness and intelligence to moving objects [36, 103], and various autonomous mobile robots, from ground robots to drones, are designed with emotional expressions to improve interactions with users [37, 40]. While emotional expressions in non-humanoid robots often adopt abstract representations (e.g., lights and motions) [40, 61, 96, 103], commercial-grade social robots are usually equipped with a display showing animated facial expressions that are easily understandable to users [49], such as restaurant servers[2] and airport guides[3]. Additionally, it is found that people map car front features to human facial features, with headlights predominately frequent associated with eyes [107]. Besides matching users' mental model, headlights are a readily available car feature, which can avoid excessive information sources and allow adaptation for a multi-functional use. As such, we seek design representations from emotional robotic eyes and equip them at the AVs' headlight position, to evoke familiarity and immediate emotion recognition from users.

2.3 AV-to-Pedestrian Interaction

Vehicle movements can implicitly communicate intentions to pedestrians [22, 71], such as using vehicle stopping behaviours [23] and speed profiles [93]. However, pedestrians may require additional driver cues (e.g., gestures, facial expressions) to facilitate decision-making, particularly when vehicles are travelling at lower speeds [93] or when misunderstanding happens [74]. This poses challenges for unmanned AVs due to the lack of direction interaction with pedestrians, which can lead to pedestrian confusion and even vandalism, such as jaywalking with impunity [46, 69, 85]. External human-machine interfaces (eHMIs) address this gap by externalising AVs' decision-making to nearby pedestrians, such as communicating (non-)yielding intent, awareness of pedestrian, and information about current or future maneuvers [19, 81, 84]. They are designed through various modalities (e.g., lights, sounds, haptics) and loci (e.g., vehicle-mounted displays [20, 43], on-road projections [75, 81], mobile devices [44, 101]). Representing high intuitiveness and familiarity, several anthropomorphic eHMIs have been proposed for increasing perceived safety of AVs and efficiency of pedestrian crossing, including eyes around headlights [9, 10, 33, 80], smile on the grille [8, 81, 94], and a printed hand [63]. Moreover, several studies used virtual drivers as proxy to communicate on behalf of AVs [32, 43, 86]. In particular, Rouchitsas and Alm [86] designed emotional facial expressions on realistic virtual drivers to convey pedestrian awareness and (non-)yielding intentions, which were shown to be intuitive and efficient [86, 87].

Current eHMIs are still mostly akin to operational street signage and are designed for collision avoidance between AVs and pedestrians on vehicular roads [92, 100]. Shared spaces present distinct social challenges due to their flexible road type and prevalent social interactions among road users. Pedestrian behavior is typically more diverse and unstructured in these environments [82, 104]. However, current eHMIs lack sufficient social connotations to address the social layer of pedestrian communication in shared spaces. Several studies started to address the social aspect of eHMIs for pedestrian crossing on vehicular roads, such as displaying "thank you" as feedback to yielding pedestrians [11] and conveying prosociality by providing additional lights for more vulnerable pedestrians like children [90]. Based on previous work, we contribute to the following gaps: firstly, we systematically design eHMIs mimicking "eyes" that express AVs' emotions, in contrast to previous work using any third party for emotional expression, e.g., virtual drivers [86, 87]; secondly,

[3]https://www.lgcorp.com/media/release/7871

existing eHMIs using eyes or emotional expressions are limited to signalling awareness or (non-) yielding intentions for crossing situations on vehicular roads. Our concept seeks to support social interactions with pedestrians in shared spaces and address social challenges unique to this context.

3 METHODOLOGY

This research has two main stages as demonstrated in Figure 1. In the first stage, we address RQ1 – *how can we design emotional expressions for AVs through robotic eyes inspired by social robots?* We first reviewed eye designs from 30 commercially available social robots to identify representation styles and developed three emotional eye designs for AVs using a suitable emotion model. We then performed an evaluation with 12 domain experts to select one design that was most effective in establishing an association with emotion conveyance and encoding specific emotions. In the second stage, we address RQ2 – *how do emotional expressions of AVs influence their perceived sociability in shared space scenarios?* We coupled the emotional eye design selected from the first stage with four user scenarios developed for shared spaces. Then, we conducted a video-based evaluation with 106 participants recruited via Amazon Mechanical Turk (MTurk) to assess the effects of the emotional eyes on the perceived sociability of AVs in shared spaces. We discuss the two stages in detail in the following sections.

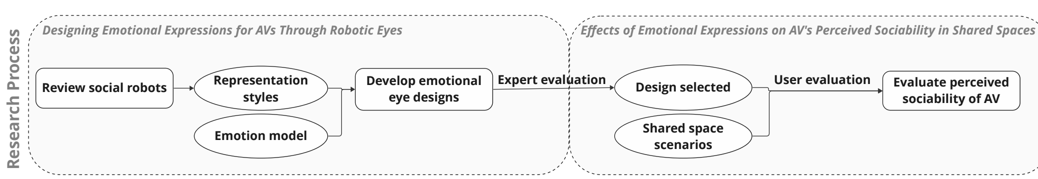

Fig. 1. The overall process of this research.

4 DESIGNING EMOTIONAL EXPRESSIONS FOR AVS THROUGH ROBOTIC EYES

Robotic eyes vary in abstraction and analogy to human eyes, as depicted from prior research using paper-based robot probes [62] to mechanics or display-based ones in well-received animated feature films (e.g., *WALL-E*, *The Mitchells vs. the Machines*). To design emotional eyes that are familiar to and easily recognised by users (RQ1), we initially reviewed 30 current commercially available social robots (Appendix Figure A.1). We retrieved the robots from the top results of an informal online search on Google using keywords "emotional" or "emotion", "social", and "robot", following the approach in literature selecting modalities to encode emotions for mobile robots [61]. We excluded highly humanoid robots as they convey emotions via fine-grained facial features, which would be difficult to translate into eye designs for AVs. In the following, we discuss the emotional model used for selecting emotions, representation styles derived from the social robots retrieved, and the expert evaluation of how well the emotions were conveyed and encoded.

4.1 Emotion Model

Two emotion models are widely adopted for designing emotional expressions for robots: Ekman's six basic emotions [26], including anger, disgust, fear, happiness, sadness, and surprise; and Russell's circumplex model [88], which positions emotions on a two-dimensional space, namely, valence (i.e., the positive or negative connotation of the emotion) and arousal (i.e., the intensity of the emotion). A later extension by Russell and Mehrabian [89] includes another dimension of dominance (i.e., the controlling or submissive nature of the emotion), resulting in a three-dimensional space of valence-arousal-dominance (VAD), commonly measured by the Self-Assessment Manikin (SAM)

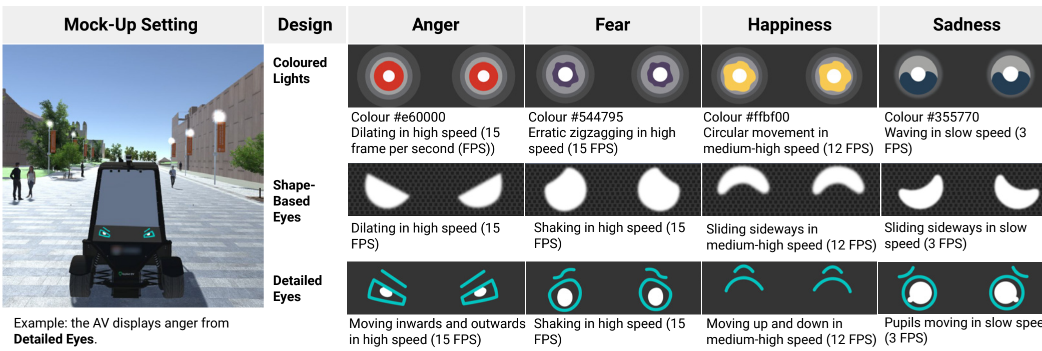

Fig. 2. The AV and the shared space used in mock-ups (left) and three design representations of AV's emotional eyes (right).

questionnaire [6]. As a first step into designing emotional expressions for AVs, we chose anger, fear, happiness, and sadness since they are universal emotions easily recognised across cultures and are more frequently selected for designing robot emotions in contrast to disgust and surprise which are inherently more complex and need more context-based information to interpret [40, 61, 103].

4.2 Representation Styles

Two researchers discussed the 30 robotic eyes retrieved from the online search and noticed three main trends for design: (1) physical, fixed eyes emitting coloured lights around the eye areas (n=9); (2) display-rendered eyes using simple geometric shapes that change shape to express emotions (n=10); and (3) display-rendered eyes with more anthropomorphic details, such as pupils and eyebrows (n=11). We then generated three designs based on these three trends, as illustrated in Figure 2 and detailed in the following sections.

4.2.1 Design 1: Coloured Lights. To mimic the first trend described above, we based the arrangement of coloured lights on the typical "halo headlights" seen on cars, which refers to adding a luminous ring around the headlamps. Since colour and dynamic are two commonly used parameters for emotion encoding via lights in HRI [40, 61, 96, 103], we chose to employ these two parameters suggested in previous studies (see Figure 2) designing emotional expressions for ground mobile robots [40, 61, 96].

4.2.2 Design 2: Shape-Based Eyes. Following the second trend, we utilised basic geometric shapes and employed a shape-changing technique for emotion encoding. We first adapted the static, shape-based emotional eyes developed by Peng et al. [78] and designed the shape-changing patterns referencing the Facial Action Coding System (FACS) [27]. FACS taxonomises human facial movements and is widely used for designing facial expressions for robots [37, 78, 103]. The design also follows an LED pixel art style used in traffic lights [30] and recent headlights for electric AVs[4].

4.2.3 Design 3: Detailed Eyes. Based on the third trend, we adapted the eyes of Omate's Yumi robot[5] because its face was rated as most friendly and likeable in a survey of over 150 animated robotic faces [49] and has been used to design facial expressions for drones [37]. In comparison to the other two designs, the additional eye details included pupils and eyebrows. Since the eyes in the

[4]https://insideevs.com/news/522417/vw-idbuzz-offer-three-variants/
[5]https://newatlas.com/omate-yumi-robot/46226/

original design were not animated and remained with a neutral expression, we further developed animated emotional expressions based on FACS [27].

4.3 Expert Evaluation

We conducted an expert evaluation to determine the design that most effectively conveys emotion, evaluate how well the expressions encode four emotions, and identify contributing factors to such perceptions. We created animated mock-ups[6] to support the demonstration of the eye animations, with the shared space background and the AV rendered in Unity (Figure 2). The AV was a representative vehicle type commonly observed in urban shared spaces, e.g., for short-distance passenger transport [18, 104]. In the mock-ups, the AV faced the viewers, stayed still, and showed the expressions in its headlight areas.

4.3.1 Procedure. The evaluation was conducted through online focus groups using a collaborative digital whiteboard [7] and video conferencing (video/audio-recorded). Participants were divided into four sessions (three per session) following the focus group size suggested in literature [54]. Prior to the sessions, participants gave written consent and completed a demographic questionnaire (gender, age, profession). Each session lasted for approximately 45 minutes. Each participant was reimbursed with a $50 gift voucher. This study was approved by the Ethics Committee of our university.

Participants were presented with the three designs one after another, randomised with a balanced Latin Square (LS) to minimise carryover effects. For each design, participants answered a free-form question (*What aspects did you notice about the autonomous vehicle (AV)?*) and rated how well they could associate the design with emotion conveyance (*On scale 1 to 7, how well could you tell the AV was conveying emotions?*). They were also asked to rate the humanlikeness and the novelty of the design with two semantic differential scales (*machinelike-humanlike* and *traditional-novel*, both from 1 to 7), followed by indicating their preferences (*What did you like and/or dislike about the interface?*). To confirm how well the four emotions were encoded, participants were asked to write down any categorical emotion label in one word as well as provide ratings on the valence, arousal, and dominance (VAD) using 9-point SAM scales [6]. Participants provided answers and ratings on digital sticky notes and elaborated on their thoughts. We observed little group effect during the expert discussions, and the facilitator (lead author) controlled the speaking time and frequency of each expert by cueing those that were less vocal.

4.3.2 Participants. Twelve experts (6 male, 6 female; age range of 18-35 years) were recruited via social media advertisement. They came from academic or professional backgrounds relevant to HCI and intelligent transport, including five UI/UX design researchers, three engineering researchers in autonomous mobility systems, two product/service designers, one HCI ethics researcher, and one software engineer specialising in VR. We recruited experts as they could transfer their experience and knowledge from existing interfaces into assessing the proposed designs.

4.3.3 Results. We derived the following results based on both quantitative and qualitative analyses of the data.

Detailed eyes established the most association with emotion conveyance: we calculated descriptive statistics and created side-by-side box plots for *association with emotion*, *humanlikeness*, and *novelty* (Figure 3). Friedman tests revealed a statistically significant difference in *association with emotion* (χ^2=20.364, p<0.001), *humanlikeness* (χ^2=21.143, p<0.001), and *novelty* (χ^2=13.471, p=0.001) respectively. Post-hoc analysis with Wilcoxon signed-rank tests and a Bonferroni correction found

[6]https://www.cateater.com/
[7]https://miro.com/

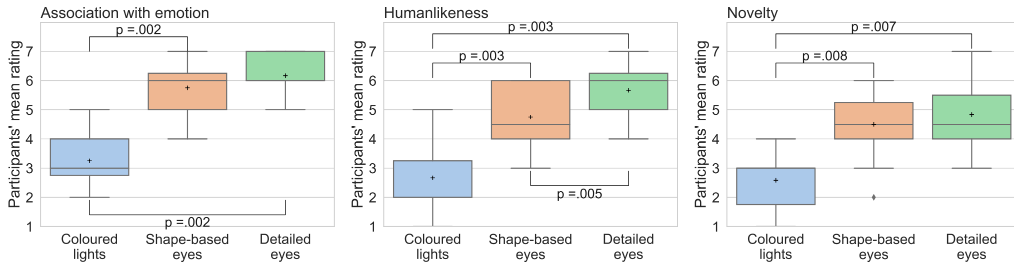

Fig. 3. Participants' mean rating for *association with emotion*, *humanlikeness*, and *novelty*. Significance level is adjusted at p<0.017. Means are denoted with + inside the box plots.

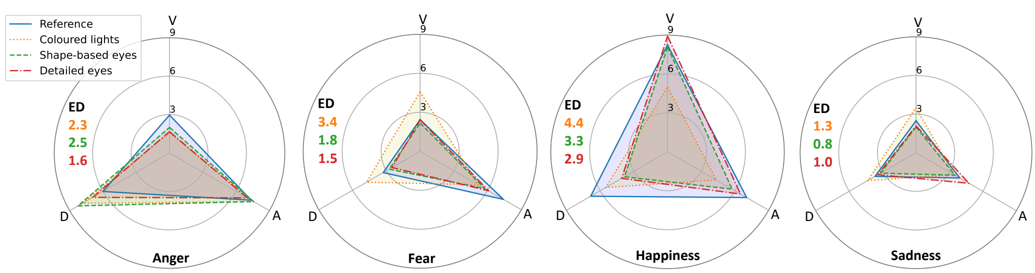

Fig. 4. Mean ratings of valence (V), arousal (A), and dominance (D) for the four emotions, along with referential ratings [89]. Euclidean distances (ED) between ratings of our expressions and the referential ratings are provided.

that both *detailed eyes* and *shape-based eyes* were rated significantly higher than *coloured lights* for the three measures. *Detailed eyes* was also rated significantly higher than *shape-based eyes* for *humanlikeness* but not for the other two measures. Nevertheless, *detailed eyes* yielded a higher mean rating for *association with emotion* (mean=6.17, SD=0.72) than *shape-based eyes* (mean=5.75, SD=0.97).

Detailed eyes could most effectively encode the four emotions: from the categorical emotion labels provided by participants, we found the four emotions can be most correctly recognised for *detailed eyes* (*anger*: 12/12 (i.e., 12 out of 12 participants recognised anger from the expression), *fear*: 9/12, *happiness*: 12/12, *sadness*: 10/12), closely followed by *shape-based eyes* (*anger*: 11/12, *fear*: 5/12, *happiness*: 11/12, *sadness*: 10/12), both much better than *coloured lights* (*anger*: 9/12, *fear*: 1/12, *happiness*: 2/12, *sadness*: 9/12). We also calculated participants' VAD ratings, with comparisons to referential ratings validated by Russell and Mehrabian [89] (Figure 4). To measure the differences, we calculated the Euclidean distance between the rating of an expression and its corresponding referential rating, following the same approach in the literature that designed emotional expressions for mobile robots [96]. The results showed that *detailed eyes* yielded the smallest distance to the referential rating for *anger*, *fear*, and *happiness* and ranked second for *sadness* where, however, the three designs were close.

Clarity of emotional expressions was influenced by eye shapes and the level of eye details: we identified factors affecting participants' ratings from the two open-ended questions: *what aspects did you notice about the autonomous vehicle (AV)?* and *what did you like and/or dislike about the interface?*. The lead author who was also the facilitator of the sessions conducted an inductive coding by grouping keywords directly extracted from the sticky notes. Results showed

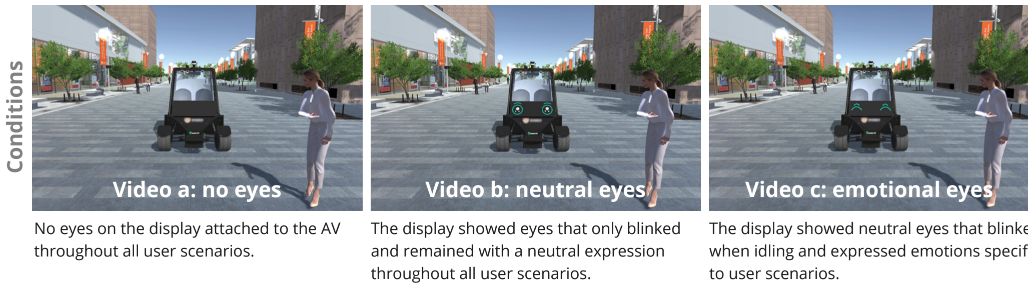

Fig. 5. Three experimental conditions of the online video-based study: (1) video a, no eyes; (2) video b, neutral eyes; (3) video c, emotional eyes.

that *detailed eyes* was perceived as high in clarity due to the eyebrows and pupils (E1-5,8,11), which made AVs seem more expressive and interactive (E2,3,7,9). These additional eye features also allowed room for designing a wider range of emotions (E8,12). Nonetheless, a higher level of eye detail could induce a higher cognitive workload (E3,6). *Shape-based eyes* was considered intuitive (E2,7-10). Participants appreciated the simplicity of this design (E5,6,8,12) in which the shape-changing technique seemed sufficient to encode emotions (E1,5,6,8). Nevertheless, some participants still found it difficult to differentiate between *fear* and *sadness* (E5,6). As for *coloured lights*, though E6 appreciated the familiar light element commonly seen in traffic and a quicker receipt of information than reading the other eyes, most participants could not find clear associations with the signals (E1,2,4-7,9,12).

5 EFFECTS OF EMOTIONAL EXPRESSIONS ON AV'S PERCEIVED SOCIABILITY IN SHARED SPACES

Based on the expert evaluation, we chose *detailed eyes* as the representation for the AV's emotional expressions, as it was found to have the strongest association with emotion conveyance and the most effective encoding of emotions. Next, we conducted an online video-based study to investigate the impact of AVs' emotional expressions on their perceived sociability in a set of shared space scenarios (RQ2).

5.1 Experimental Conditions and Hypotheses

Prior work suggests that pedestrians can still discriminate against AVs [25, 34, 46, 69] even when AVs ensure the physical safety of pedestrians (e.g., maintain good distance and speed) in shared spaces [47, 56, 82, 95]. For smooth integration into shared spaces, AVs should also be perceived as socially-capable while moving safely [47, 56, 57, 104]. To this end, we aimed to use emotional eyes to increase the perceived sociability of AVs and formulated the following hypotheses:

- (H1) An AV that expresses emotions to pedestrians will be perceived higher in sociability than an AV without emotional expressions, regardless of the presence of eyes.
- (H2) An AV with eyes will be perceived higher in sociability than an AV without eyes.

To test our hypotheses, we designed three experimental conditions: no eyes, neutral eyes, and emotional eyes (see Figure 5). *Video a, no eyes* served as the baseline condition where the AV simply ensured the physical safety of pedestrians with good distance and speed. This also allowed us to assess the emotional eyes as a standalone modality, following the convention in eHMI literature [9]. We added *video b, neutral eyes* to make sure that any effect from emotional expressions would not be confounded with the presence of eyes. Pedestrian behaviours and movements of the AV were

Scenarios	The AV expresses happiness to a pedestrian who kindly gives way.	The AV expresses sadness when being ignored and blocked by two conversing pedestrians on a narrow corridor.	The AV expresses anger to a pedestrian who deliberately teases it and blocks its way.	The AV expresses fear when a skateboarding pedestrian suddenly appears in front without watching out for traffic.
Literature	Pedestrians can use road etiquette with vehicles, e.g. gesturing to give way and smiling (Rasouli et al., 2017; Wang et al., 2022).	Pedestrians can engage in social activities and fail to clear the path for a long period of time (Petrak et al., 2021; Wang et al., 2022).	Pedestrians can intentionally block the AV's path to test or delay it (Currano et al., 2018; de Miguel et al., 2019; Moore et al., 2020).	Pedestrians can lose vigilance of their surroundings and demonstrate risky behaviours around vehicles (Wang et al., 2022).

Fig. 6. User scenarios derived based on literature [17, 18, 69, 79, 83, 104]. Note that each video (video a, b, or c) comprised these four scenarios, and the only difference was what was shown on the AV's display (no eyes, neutral eyes, or emotional eyes).

the same across the three conditions, i.e., the only difference was what was shown on the AV's display. The AV drove at a slow speed of 2 m/s and decelerated to a complete stop at a distance of 2 m from the pedestrians' location, demonstrating appropriate and safe movements.

5.2 User Scenarios in Shared Space

We derived four user scenarios based on previous real-world observations of AV-pedestrian interactions in shared spaces. These scenarios connoted social challenges for which increasing AVs' perceived sociability can be required (see Figure 6 for detailed descriptions). We created computer-generated (CG) scenarios in Unity, with the shared space environment and the AV modelled in Autodesk 3ds Max. Based on suggestions from the expert evaluation, we made the windshield transparent to show clearly that no human was on-board or in control. For creating pedestrian behaviours, we used high-fidelity models of people from a 3D library[8] and customised their movements for the scenarios. As the videos were designed to replicate the predetermined scenarios, participants were then situated outside the interactions and the viewing perspective was adjusted for a clear view of the interface to support evaluation. Each video (video a, b, or c) comprised the four scenarios, however, in video a, no eyes were displayed at all times; in video b, the AV always displayed neutral eyes; and in video c, the AV displayed emotional eyes, i.e., the eyes changed expressions according to the scenarios.

5.3 Measures

Sociability is complex in definition but can generally refer to the possession of social capabilities, such as empathy, praise, rudeness, etc. [58, 91]. The sociability of robots can be captured through a series of attributes related to designing socially interactive robots, such as anthropomorphism, likeability, perceived intelligence, etc. [28, 29, 39, 53]. The Godspeed questionnaire developed by Bartneck et al. [3] is widely used for measuring the sociability of robots [39, 53, 103]. Using this questionnaire, we measured the AV's anthropomorphism (i.e., attribution of a human form,

[8] https://renderpeople.com/

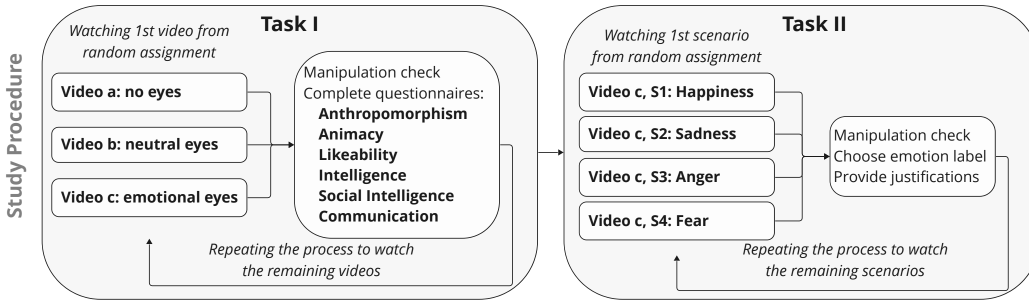

Fig. 7. The procedure of the online study. Participants first completed Task I and then Task II.

characteristics, or behaviour), animacy (i.e., perception of being "alive"), likeability (i.e., positive impression), and perceived intelligence (i.e., behaviours comparable to results of human intelligence) on 7-point semantic differentials. Furthermore, we measured the AV's perceived social intelligence on 7-point Likert scales (strongly disagree to strongly agree) using the PSI questionnaire developed by Barchard et al. [2]. The PSI scales contain two sub-scales: social information processing (i.e., the abilities to recognise, adapt to, and predict human emotions, desires, behaviours, cognitions, and beliefs) and social presentation (i.e., the ability to present oneself as a desirable social partner), while a total score can be calculated as perceived social intelligence. Lastly, We measured the perception of communication on 7-point Likert scales (strongly disagree to strongly agree) adapted from Matthews et al. [65] and used in an eHMI study by Sadeghian et al. [90] investigating AVs' prosocial communication. Items in the above questionnaires can be found in Appendix Table 1.

5.4 Procedure

We deployed the study as an online survey via MTurk, hosted by the Qualtrics software. Participants read the study information, gave their consent, and completed two tasks as depicted in Figure 7 and detailed in the following sections.

5.4.1 Task I. The objective of Task I was to assess the impact of the emotional eyes on the variables capturing perceived sociability, by comparing the three conditions (video a, b, or c). Participants experienced all three conditions one after another, randomised with a balanced LS (within-subject). For each condition, they first watched the corresponding video (video a, b, or c), answered a free-form question (*What can you notice about this vehicle in the video?*) (manipulation-check), and then rated their perceptions of the AV using the scales. Participants were encouraged to revisit the video, which was provided throughout the condition.

5.4.2 Task II. The objective of Task II was to examine the recognition and interpretation of the emotional expressions within the specific user scenarios as well as to corroborate the findings from the expert focus group with the general public. Hence, we used the four scenarios from video c only, i.e., video a or b were not used for this task. We broke down *video c, emotional eyes* into four snippets so that each snippet was one scenario. Participants were presented with the four scenarios/snippets one after another, randomised with a balanced LS. For each scenario, participants were asked to describe the scenario (free-form, manipulation check), choose an emotion label (from six basic emotions), and provide justifications for the choice (free-form). They also rated their level of confidence (1 to 7) in choosing the emotion label and had the opportunity to provide a second emotion label that could apply.

5.5 Participants

We recruited 106 participants (52% male, 44% female, 4% others; M=39.2 years, SD=12.1 years) using the MTurk platform, with all participants located in the US. Participants had completed more than 1000 human intelligence tasks (HITs) with an approval rate above 95%, commonly used recruitment criteria for MTurk studies [77, 105]. They were also required to be at least 18 years old and speak fluent English (professional working proficiency). The study took an average of 35 minutes (SD=12.4) to complete, which was estimated at 30 minutes based on a pilot study with 20 people. Participants were remunerated $4 plus a bonus between $0.5 to $2 for elaborating answers to the open-ended questions. This value was based on the highest minimum wage rate and prior HRI studies on MTurk [37, 105]. Participants were required to pass three attention-check questions in the survey, which allowed us to ascertain the validity of their responses. We discarded 7 from the initially collected 113 responses as they either contained qualitative answers irrelevant to the videos (n=5) or were not completed in a reasonable time (n=2). This study was approved by the Ethics Committee of our university.

5.6 Data Analysis

5.6.1 Quantitative Analysis. We first assessed the internal reliability of the scales using Cronbach's alpha. Using descriptors and thresholds suggested by literature [99], the overall internal reliability was strong for *anthropomorphism* (α=0.919), *animacy* (α=0.920), *perception of communication* (α=0.922), *perceived social intelligence* (α=0.940) and *social information processing* (α=0.947); reliable for *likeability* (α=0.899) and *perceived intelligence* (α=0.894); and robust for *social presentation* (α=0.801). Since Cronbach's alpha yielded good results, we generated a single score for each variable for each participant. This was done by averaging the items in each of *anthropomorphism*, *animacy*, *likeability*, *perceived intelligence*, *perception of communication*, and summing the items in each of *perceived social intelligence*, *social information processing* and *social presentation*, as instructed by the corresponding questionnaires [2, 3] and previous papers using these scales [65, 90]. Normality of the above data was confirmed by conducting Kolmogorov-Smirnov tests and a visual inspection of their Q-Q plots. Consequently, we opted for Repeated Measures ANOVA with Greenhouse-Geisser corrections to test the effects of the conditions (video a, b, or c) on each of the variables and to answer our hypotheses (Section 5.1). In case of significant differences, we further performed pairwise comparisons with Bonferroni post-hoc tests to understand the differences between each pair of conditions.

5.6.2 Qualitative Analysis. In Task I, before providing ratings to the questionnaires, participants were asked to describe what they could notice from the vehicle. This provided us with insights into their thoughts and added further evidence to the statistical effects. Particularly, we were interested to understand how social qualities of the AV were perceived differently across conditions. Since the answers to this question were typically short (1-2 sentences), the initial codes were developed by the lead author through a deductive coding and were further discussed and refined with two senior researchers. Task II required participants to recognise the emotions within the scenarios and provide justifications. This allowed us to understand whether the emotional expressions were interpreted as intended and how the scenarios had influenced the perception of these emotions. Hence, in addition to calculating the recognition rate of the emotions (i.e., ratio that the emotion was correctly labelled), we coded participants' justifications to see whether they referred to the expression on the AV, the situation (the pedestrian behaviour), or both. The lead and the third authors each conducted a deductive coding to half of the dataset individually, reviewed each other's codes, and resolved any disagreements through discussions. The coding was conducted in an online spreadsheet to aid the discussions. This analysis helped us to understand the interplay between the

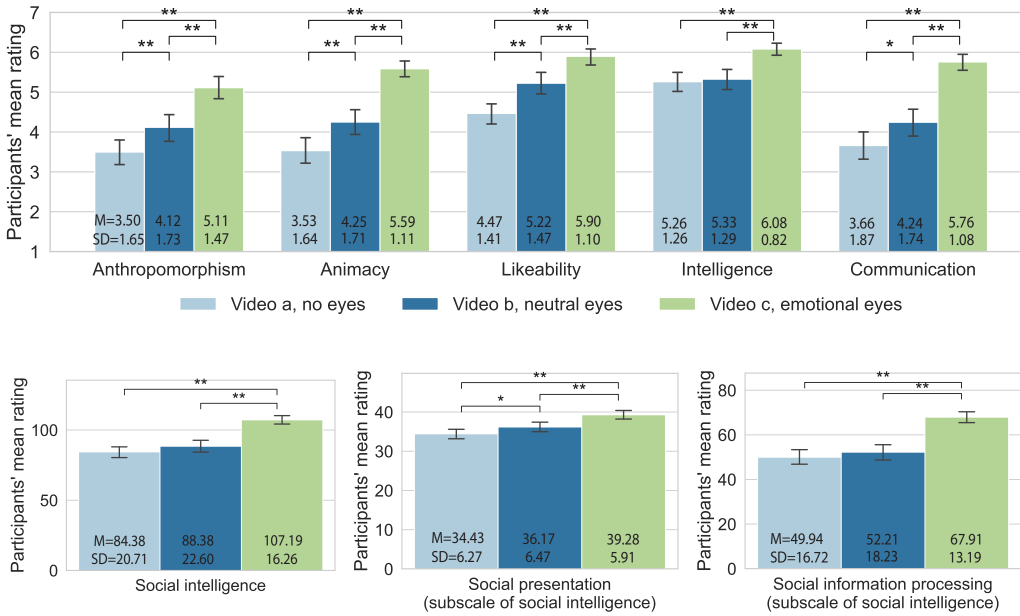

Fig. 8. Participants' mean ratings for the measures in Godspeed questionnaire and for *perception of communication* (top), and for the PSI questionnaire (bottom). Error bars denote 95% confidence intervals. **p<0.001, *p<0.05.

expressions designed and the user scenarios proposed (i.e., how suitable the expressions might be for the scenarios?) and would have implications for using emotional expressions as scenario-oriented solutions to support AV-pedestrian interactions in shared spaces.

5.7 Results

5.7.1 Effects of the AV's Emotional Expressions. From the quantitative analyses, we found a significant effect of the conditions (video a, b, and c) on all variables measured (Figure 8). The ANOVA tests revealed significant differences in *anthropomorphism* (F(2, 210) = 50.753, p<0.001), *animacy* (F(2, 210) = 85.121, p<0.001), *likeability* (F(2, 210) = 39.991, p<0.001), *perceived intelligence* (F(2, 210) = 23.333, p<0.001), *perceived social intelligence* (F(1.874, 196.817) = 68.572, p<0.001), *social presentation* (F(2, 210) = 23.395, p<0.001), *social information processing* (F(1.825, 191.650) = 76.737, p<0.001), and *perception of communication* (F(2, 210) = 73.804, p<0.001). Pair-wise comparisons revealed specific differences between the conditions (Figure 8). Firstly, *emotional eyes* was rated significantly higher than the other two conditions for all variables. Secondly, though *neutral eyes* was rated significantly higher than *no eyes* for most of the variables, it did not show significant differences for *perceived intelligence*, *perceived social intelligence* and its subscale *social information processing*. Hence, in answer to our hypotheses, the results supported H1 but only partially supported H2 due to the negligible differences in the aforementioned variables between *neutral eyes* and *no eyes*.

5.7.2 Perceptions of the AV's Qualities. For the *no eyes* condition, the AV remained in the realm of mechanics: *"it seems like a regular car programmed to stop at pedestrians."* (P96), *"it looks a little more boring and almost lifeless as if a ghost was driving the vehicle"* (P86). While most participants praised that the movement of the AV was effective and appropriate, some of them expressed difficulties in understanding what the AV was "thinking": *"this vehicle is hard to gauge because it doesn't show any sign of what it's doing or feeling or how it's reacting."* (P66). By comparison to the other

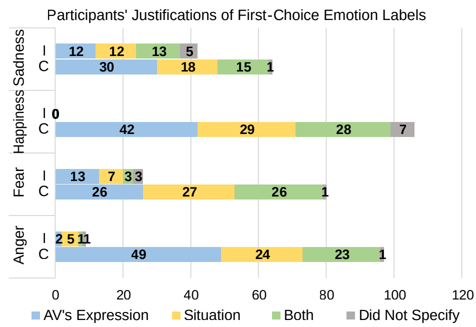

Fig. 9. The number of correct (C) and incorrect (I) labelling of emotions with distribution of justifications.

conditions, this AV seemed to evoke negative feelings in some participants despite driving properly: *"its reactions were the same and entirely appropriate but I found it a bit more nerve-wracking despite the relatively slow speed of operation."* (P25), *"that it does not have eyes like the other one, this one seems more sinister and imposing to me."* (P23), *"it appears to some degree to be a rogue vehicle until it stops for humans."* (P44).

For the *neutral eyes* condition, the eyes added a layer of liveliness to the AV and made it seem conscious: *"[the eyes] give an impression that it is lively and can see things in front of it."* (P30), *"the blinking effect really humanizes the vehicle and it makes it seem as if it is thinking."* (P18). Despite that, the unchanging expression still did not show indications of the AV's internal states and was even further associated with incompetency, which might explain the insignificant difference for perceived intelligence and perceived social intelligence compared to *no eyes*: *"it has digital eyes that blink which makes it seem more friendly than the vehicle without any eyes but the eyes don't change expression at all so it makes it hard to know what it is 'thinking' or going to do."* (P52), *"[it is] making for ineffective communication."* (P58), *"this one seems to have no actual expression, but it is still patient and polite. The eyes stay the same, which makes it appear rather dumb."* (P99). Interestingly, we found some participants imagined pragmatic functionalities for the eyes; for example, showing awareness – *"the vehicle blinked to indicate it recognized human presence"* (P14), detection – *" when it 'blinks' its headlights, it seems to be scanning the area in front of it"* (P79), and sending requests – *"[it] blinks its LED lights to signal the person to step aside."* (P81).

For the *emotional eyes* condition, the emotional expressions gave the impression that the AV could "think" and "feel": *"the autonomous vehicle acts like a sentient being."* (P34), *"this vehicle had very expressive robot eyes that conveyed various feelings to the pedestrians...it had personality!"* (P31). Meanwhile, some participants found the emotional expressions relatable to human emotions and contextually appropriate: *"[the expressions are] based on what is going on and what a human might feel in those cases."* (P17), *"it behaves like when a cyclist riding a cycle."* (P74), *"the vehicle displays contextually appropriate emotions using its 'eyes'."* (P4), *"[it] shows reaction emotions to situations it is experiencing."* (P61). As the AV responded to human behaviours, some participants perceived it as an interactive agent conversing with pedestrians: *"it picks up conversations."* (P47), *"it seems to ask questions and make comments with its 'eyes'/headlights."* (P101). Furthermore, some participants interpreted social meanings carried by the expressions; for example, *"it was saying 'thank you' [in the happiness scenario]."* (P15), *"it seemed to be pleading through its LED display for them to move [in the sadness scenario]."* (P44).

5.7.3 Emotion Interpretation within Scenarios. For the emotion recognition rate, we found excellent accuracy for *Happiness* (100%) and *Anger* (91.51%). The accuracy for *Fear* was 75.47%, with the emotion of surprise being the second most selected label (17.92%). *Sadness* was the least recognised (60.38%), as disgust (12.26%), surprise (10.38%), and anger (9.43%) were frequently selected. Regarding participants' justifications (Figure 9): (1) for correct recognition, *Happiness*, *Sadness*, and *Anger* were more frequently recognised from the AV's expressions, and *Fear* was attributed almost evenly to the expression and the situation; (2) for incorrect recognition, the ratio of situations increased for *Sadness* and *Anger* while decreased for *Fear*. There was no incorrect recognition for *Happiness*.

From participants' descriptions of the scenarios, we found the modelling of the situations was successful, as they could not only describe the pedestrians' behaviours but also infer a motivation or even a personality behind these pedestrians. For *Happiness*, the pedestrian was *"nice"* and *"treat the vehicle in a good manner"*, and in return, the vehicle conveyed appreciation, e.g., *"the eyes move up and down as if saying 'thank you'"* (P6). For scenarios where the vehicle expressed negative emotions (i.e., *Anger*, *Fear*, *Sadness*), we found that participants could empathise with the vehicle, for example, by criticising the pedestrian in *Angry* as *"obnoxious"*, *"menacing"* and the skateboarder in *Fear* as *"careless"*, *"irresponsible"*. P9 sympathised with vehicle in *Sadness*: *"the vehicle wanted to move forward on the path...Unfortunately for the vehicle, these people were too self-absorbed to even notice."*. P5 resonated with the fear expression: *"I'd be pretty scared if some skateboarding kid went in front of me out of nowhere"*. Consequently, the expressions seemed justifiable, as participants could infer an intention behind the expressions: *"the automated vehicle wants the pedestrian to stop [being] annoying and make a way (Anger)"* (P12), and even ascribe prosociality to the vehicle : *"the vehicle expresses concern for the kids' safety (Fear)"* (P48).

6 DISCUSSION

Our study aimed to examine the effects of AVs' emotional expressions on their perceived sociability in shared space scenarios. Particularly, we investigated whether an emotional eye design equipped on an AV could influence the AV's perceived sociability on a series of measures (anthropomorphism, animacy, likeability, perceived intelligence, communication, and perceived social intelligence). In the following sections, we discuss how the emotional eyes positively affected the AV's perceived sociability and its potential to improve pedestrian experience and attitude towards AVs in shared spaces, which are inherent social challenges in contrast to vehicular roads. Finally, we set forth a set of design and methodological recommendations for future research.

6.1 Improved Perceived Sociability through Emotional Eyes

Revisiting our hypotheses (Section 5.1), the quantitative analysis revealed a significant increase in perceived sociability of the AV with *emotional eyes* compared to eyes without emotions. Not only did the *emotional eyes* imbued liveliness into the AV, as indicated by the higher anthropomorphism and animacy, but they also increased the positive impression of the AV (higher likeability) and made the AV seem more like an intelligent, sociable agent (higher perceived intelligence and social intelligence). Our findings are in line with research in human-robot interaction showing that robots' perceived sociability can be positively impacted by their emotional expressions [39, 53, 78] and a higher level of anthropomorphic resemblance [28, 29, 62]. Through this research, we further provided that AVs' perceived sociability can be improved by their emotional expressions, and the emotional eye design can serve as a viable solution to this goal.

In relation to applying these emotional eyes to shared spaces, we further discuss in the following sections potential positive effects on pedestrian experience and attitude towards AVs, and social functions carried by emotional expressions for resolving current interaction challenges.

6.1.1 Positive Effect on AV's Perceived Safety. We found that *emotional eyes* could positively affect the **perceived** safety of the AV's movements. This outcome is particularly important because prior motion planning research suggests that AV's physical safety (i.e., collision-free) is not equivalent to their perceived safety [47, 95]. For instance, although our AV demonstrated physically safe movements (slow speed and appropriate distance to pedestrians [47, 82, 95]) and were the same across the conditions, some participants sensed negative energy from the AV with *no eyes*, describing it as *"nerve-wracking"*, *"imposing"* or *"sinister"*. This even altered the perception of the movements, with some thinking that the vehicle *"did much faster and without hesitation"* or *"could suddenly drive right into them (the pedestrians)"*. With *emotional eyes*, participants envisioned the benefits of relieving pedestrians' negative emotions (e.g., anxiety, distrust) and improving the overall pedestrian experience in shared spaces. P92 stated: *"it's meant to make motorists and/or pedestrians alike feel a bit more at ease about the autonomous vehicle's presence"*. P25 reflected on their personal experience: *"I'm very leery of cars on normal streets, but I really loved the expressions the one vehicle could make and that seemed to help me"*. Therefore, the emotional eyes can be an effective alternative to improve the perceived safety of AVs, which can be valuable for interests in the community around pedestrian safety and trust [13, 43, 44].

6.1.2 Positive Effect on AV's Perceived Capability. Perceived intelligence and perceived social intelligence were not significantly different between *no eyes* and *neutral eyes*, while *emotional eyes* was significantly higher for these two measures than the other two conditions. From the qualitative answers, participants attributed the reason to the "unchanging" expression that seemed to portray the AV as rather unintelligent. Recalling on its definition, perceived intelligence is associated with the extent to which robot behaviours are comparable to that of human intelligence [3]. Correspondingly, the AV with *emotional eyes* was considered to manifest *"what a human might feel in those cases"*, meaning that the AV demonstrated the ability to sense and respond to the situations and the pedestrian behaviours, thereby presenting itself as a sentient agent. Additionally, we found that the animated fidelity of expression could alleviate the aggressiveness of negative emotions; for example, the anger expression could brush off the tension in the situation and add a sense of humour – *"I had to laugh when it came to the third scenario where the vehicle encountered a pedestrian who chose to be a nuisance and the LEDs changed to annoyance/frustration. I would even venture as far as to say the vehicle was rather cute"* (P92).

6.1.3 Empathy and Legitimising the Expressions. From qualitative descriptions of the scenarios, we found an elicitation of empathy in participants as they provided critical remarks towards the pedestrian behaviours in scenarios connoting negative emotions (*Anger*, *Fear*, and *Sadness*). Participants associated the expressions with plausible reactions of a human in those situations, further suggesting their empathetic inferences of the AV's responses. Furthermore, we found that the stories told by the scenarios were also important in helping participants to justify the expressions, in line with the concept of "affective grounding" coined by Jung [48] indicating a shared understanding between humans and robots of what emotional responses should be communicated in a given situation. In previous studies, participants had the tendency to believe that robots should always be happy [37, 40] and that AVs should always give way or be submissive on the road [46, 85] - potentially due to the asymmetrical superiority that humans have with robots [1, 45]. Hence, findings of this study further suggests an opportunity to use emotional expressions as eHMIs for empathy-evoking and increasing agreements in intentions or behaviours that "conventionally" would not be appreciated by passersby.

6.1.4 Social and Communicative Functions of Emotional Expressions. Participants interpreted social messages from the emotional expressions, though the designs simply followed the four basic emotions. The happiness expression was often associated with conveying gratitude for the pedestrian's kind gesture; the sadness expression was interpreted to request the pedestrians to clear path; the anger expression established *"an aggression profile"* that seemed to be confronting the hostile behaviour of the pedestrian, similar to the approach of equipping AVs with aggressive or assertive driving behaviours to achieve successful right-of-way negotiation with pedestrians [4, 46, 108]; in the "near-accident" situation depicted by the *Fear* scenario, most participants were blaming the skateboarder and could relate to the fear expression, which might provide implications for AVs to avert blame when they are not at fault. Behavioural research has long identified the social and communicative functions of emotional expressions to resolve relational problems [7, 55, 73] and to initiate and maintain reciprocity in social interactions [7, 73]. Designed as a response strategy to pedestrian behaviours, the AV's emotional expressions maintained the reciprocity of the interactions and communicated attitudes through nonverbal means, e.g., *"it used its 'eyes' to let people know what it wanted."* (P40), *"it is making an emotional connection with the pedestrian[s]."* (P83). This builds a foundation for using emotional expressions as a communication approach in social traffic scenarios like shared spaces and tackling social challenges in similar use cases.

6.2 AV's Emotional Expression as eHMI

6.2.1 Categorising Emotional Expression. We categorise the emotional eyes into existing eHMIs based on a design space proposed by Colley and Rukzio [14] which contains three dimensions: *Message Type*, *Modality*, and *Locus*. The emotional eyes of AVs should be classified as *affective* message type, i.e., messages related to emotions [14], *vehicle* locus, and *visual* modality. Colley and Rukzio [14] also proposed a situation design space focusing on urban vehicular roads (i.e., number of lanes). We suggest shared space as an additional road type to be considered by future research, given its rising popularity in urban planning and challenges related to pedestrian interaction.

6.2.2 Emotional Expression on AV, When to Use? As our study showed, emotional expressions on AVs can be designed to support the social aspects of AV-pedestrian interaction. With the same goal of "living in harmony with pedestrians", delivery robots [9] roaming pavements and shared spaces are increasingly equipped with expressive eyes on their LED screens, e.g., to "wink" or flash heart eyes at passersby, to stimulate the perception of life and agency and foster empathy. Different from operational cues (e.g., turn indicators) that are essential to coordinate day-to-day actions, the emotional eyes have the potential to serve "corner cases" stemmed from various social challenges, from making anxious pedestrians comfortable to intervening malicious pedestrian actions. As suggested by our focus group experts researching in AV motion planning, such "corner cases" can be much less common but also much more complex to tackle. To that end, the emotional eyes can be integrated as a secondary (social) layer of communication and support the primary function of AVs [40, 103], and the activation of emotional expressions is more likely to be situation-based than to every signal casual encounter.

Furthermore, we used an AV type that resembles many lightweight, utilitarian vehicles seen in urban shared spaces (e.g., transporting people for short local distances, patrolling, etc.) and lies between mobile robots and regular passenger cars. Thus, our findings are benefited from and have implications for research in both communities. Nevertheless, vehicle form and size could elicit different expectations from pedestrians [12, 21]. As heavier vehicles enter shared spaces, it should be further explored the desired level of sociability and emotional expressions to demonstrate on different vehicles.

[9]https://thebolditalic.com/why-do-i-want-to-kick-those-cute-little-food-delivery-robots-ba0555a144d9

6.3 Design and Methodological Recommendations

To provide operational insights for future research, we developed design recommendations (DRs) for designing emotional eyes on AVs and methodological recommendations (MRs) for using video prototypes to evaluate AVs' emotional expressions.

DR1. Use shape, movement, and additional eye details: Participants suggested that shape and movement of the eyes were important in signifying emotions; for example, we found descriptors related to eye shapes (e.g., *"trapezoid"*, *"slanted"*, *"crinkled up"*) and movements (e.g., *"wiggling"*, *"shaking"*, *"scrunching up"*). These two factors facilitated the association with overall facial expression (e.g., *"you could easily picture a smile going along with the eyes"*) and even conversational expression like nodding [86] (e.g., *"it was nodding its eyes in a 'yes' motion"*). Besides, additional eye details (pupils, eyebrows) were praised by experts for enhancing expression clarity (Section 4.3.3), aligning with prior work showing that more life-like robotic eyes can better indicate personable and emotional traits [62]. That said, the level of eye detail should be considered to prevent excessive cognitive load and ensure accessibility for a broader range of users [59]. Prior eHMIs using eyes simply designed the mechanical gazing movements, as their focus was signalling pedestrian awareness [10, 80] or advancing directions [9, 33]. In comparison, we suggest that AVs' emotional eyes would require additional design parameters, such as shape, movement, and extra eye details, to express emotions.

DR2. Base the design on familiar social robots: The eye representation transferred from Yumi the social robot conveyed familiarity - *"it was the classic cartoon angry eyes that we have all seen before and would be understandable to all languages and races"*. We found that participants were accustomed to the metaphors frequently used by robotic eyes mimicking human expressions; for example, *"the squiggly eyebrows represent furrowing in a way someone would if they were screaming in fear"*, *"its pupils got large like when a person cries"*. Thus, we recommend using familiar visual elements transferred from social robots to design AVs' emotional eyes that are easily understandable to users.

MR1. Include user scenarios to trigger vicarious experience: We found the the user scenarios evoked empathy in participants and triggered vicarious experience (i.e., experienced in the imagination through the feelings or actions of another person), which benefited interpreting and justifying the expressions. This can increase the realism of the video setting, as previous research found that users tend to imagine connections between robots' emotional expressions and the external environment (e.g., nearby humans, surroundings) even in decontextualised video settings [37]. Additionally, we based the scenarios on real-world evidence, which could have further supported their realism. Hence, we suggest including evidence-based user scenarios to develop a more realistic video setting for evaluating AVs' emotional expressions.

MR2. Consider the subjective nature of scenario interpretation: Participants' subjective narratives can affect the interplay between expressions and scenarios. For *Sadness* scenario, participants recognised that the conversing pedestrians stayed blocking the path, but some believed that the AV was *"disgusted"* or *"angered"* by the ignorant pedestrians, which might have contributed to the low recognition rate for sadness. Interestingly, the expression can in turn affect the scenario interpretation; for example, P34 used the sadness expression to make sense of the story: *"the vehicle overheard something saddening [from the two conversing pedestrians]"*. Moreover, some participants assigned relationships to the pedestrians, e.g., *"the couple were fighting with each other"*. Drawing from these instances, we suggest considering the subjective nature of scenario interpretation during scenario setup to encourage more convergent responses and more focused interface evaluation.

6.4 Limitations and Future Work

6.4.1 Anthropomorphic Design. The uncanny-valley effect is an inherent risk to anthropomorphic design in robots, described as a sense of dislike and eeriness in the close but not yet perfect resemblance of humans [64, 72]. Our results did not indicate an uncanny valley effect but rather showed the eyes were quite friendly and likeable. In fact, prior studies using eyes as eHMIs have reported divergent discussions around this effect; for example, Chang et al. [9] received positive feedback on the attractiveness of the eyes in their studies [9, 33], whereas Löcken et al. [60] observed an uncanny-valley effect in their comparative VR investigation. These inconsistencies may stem from various reasons, such as culture (Asian [9, 33] versus European [60] participants) and implementation (physical [9, 33] versus computer-generated [60]). We speculate several explanations to our findings: (1) we selected the style of the eyes rated most likable and friendly in a survey which also recruited US participants on MTurk [49]; (2) the video-based evaluation might have alleviated the uncanny-valley effect compared to the previous immersive VR implementation [60]; and (3) display-rendered animated eyes can be in nature more likeable, in contrast to mechanics robotic eyes shown to be on average dislikable [64]. Nevertheless, we suggest future work always consider implications from anthropomorphic designs and a continued investigation in the receptivity of such designs in AV-pedestrian research.

6.4.2 Video Evaluation. The video representation allowed us to easily replicate the scenarios identified from the real world and therefore ask participants for their impressions on the proposed interface within these user scenarios. Previous research prototyping shared space eHMIs suggests using video representation for more focused interface evaluation than immersive VR representations [41]. While we successfully gathered participants' perceptions, it should be considered that their attitudes might not necessarily correlate with their behaviours [97]. Additionally, to allow video viewers to clearly see the interface, we intentionally adjusted the perspective to frontal to the vehicle. This then leads to lower ecological validity than field studies, as real-world passersby might not always have a frontal view of the interface or have other environmental distractions. Further, despite the measures taken to ensure the quality of our online survey, it could still have been susceptible to inadequate attention and under-represented certain user groups, particularly those without internet access or less willing to interact with technology [98]. Meanwhile, while the questionnaires were evaluated per condition, which may have mitigated participant fatigue and survey abandonment [98], future research could evaluate each scenario separately to conduct scenario-specific analysis. Overall, we suggest future work extends our findings by engaging participants in the interaction (e.g., VR, field studies) and also further evaluate behavioural metrics.

6.4.3 Real-World Application. As with many other display-based eHMIs, our emotional eyes have limitations around scalability, i.e., beyond one-to-one interaction [16, 102], and accessibility, i.e., serving wider user groups such as people with visual impairment [15, 59]. That said, emotional expressions of autonomous vehicles are likely to be broadcast to and affect the cooperation and social acceptance of not only interaction subjects but also casual bystanders [5]. Still, different representations of emotional expressions should be further investigated to address pedestrians coming from different directions, for example, using 360 degree light disks [102]. To serve a broader range of users, such visual-based eHMIs can be further combined with eHMIs of other modalities, e.g., sound [15, 70], haptics [44]. Nonetheless, this study provides evidence for adding AVs' emotional eyes into the visual repertoire and expands current communication strategies with emotional expression through its first investigation. Future endeavours should consider exploring more scalable and multi-modal emotional expressions and also increasing the generalisability of our work, such as studying different vehicle forms, other VRUs like cyclists, and cultural preferences of emotional expressions.

7 CONCLUSION

With the arrival of autonomous mobility services, social challenges around AV-pedestrian interactions present a critical problem for the smooth integration of AVs into shared spaces. Our research suggests that equipping AVs with emotionally expressive eyes can improve their perceived sociability in shared spaces and subsequently pedestrian experience and attitude towards AVs in this context. Specifically, we show that animated eyes with anthropomorphic details (pupils, eyebrows), shapes and movements can effectively express emotions and increase the perceived sociability of AVs. Through specific shared space scenarios, we further discuss opportunities to apply the emotional eyes as eHMIs in shared space situations and highlight recommendations for future work. Insights from this study provide a foundation for adding emotional expression as a social layer of communication from AVs and serve to address current challenges of pedestrian interaction in social traffic environments like shared spaces.

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A APPENDIX

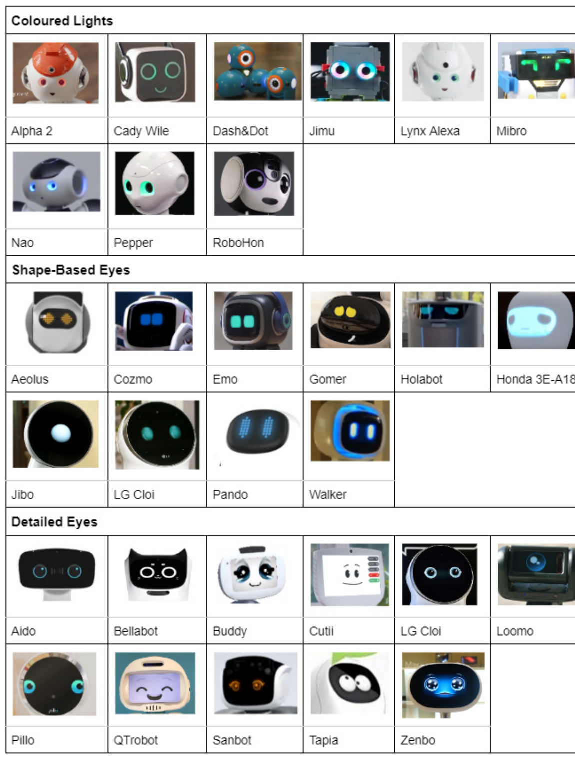


Fig. A.1. Commercial-grade social robots from online search.

Table 1. Measures employed in our online study.

Variable	Items
Anthropomorphism	Fake-Natural, Machinelike-Humanlike, Unconscious-Conscious, Artificial-Lifelike, Moving rigidly-Moving elegantly
Animacy	Dead-Alive, Stagnant-Lively, Mechanical-Organic, Artificial-Lifelike, Inert-Interactive, Apathetic-Responsive
Likeability	Dislike-Like, Unfriendly-Friendly, Unkind-Kind, Unpleasant-Pleasant, Awful-Nice
Perceived intelligence	Incompetent-Competent, Ignorant-Knowledgeable, Irresponsible-Responsible, Unintelligent-Intelligent, Foolish-Sensible
Social information processing	This vehicle is socially competent. This vehicle notices human presence. This vehicle recognises individual people. This vehicle knows if someone is part of a social group. This vehicle notices when people do things. This vehicle adapts effectively to different things people do. This vehicle anticipates people's behaviour. This vehicle can figure out what people think. This vehicle adapts its behaviour based upon what people around it know. This vehicle anticipates others' beliefs. This vehicle recognizes human emotions. This vehicle responds appropriately to human emotion. This vehicle anticipates others' emotions.
Social presentation	This vehicle enjoys meeting people. This vehicle tries to be helpful. This vehicle cares about others. This vehicle is trustworthy. This vehicle is impolite. This vehicle thinks it is better than everyone else. This vehicle tries to hurt people.
Communication	The communication was adequate. The communication was clear. The communication was effective. I trust the communication of the car. The communication offers safety.

The video below shows **an autonomous vehicle interacting with pedestrians with an LED display attached to its front.** Please watch the whole video carefully from the beginning to the end. You will answer questions based on this video.

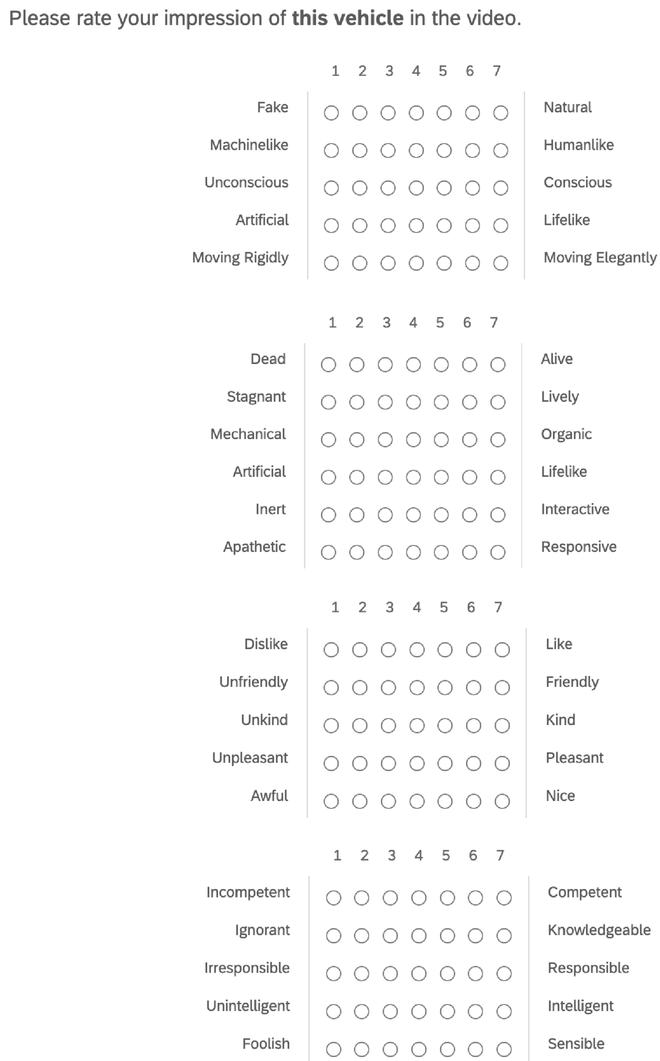
What can you notice about **this vehicle** in the video?

Fig. A.2. Online survey Task I - manipulation check question. This is an example screenshot from *video c, emotional eyes*. The other two conditions followed the same structure.

Please rate the communication made by **this vehicle** in the video.

	Strongly Disagree 1	2	3	Neutral 4	5	6	Strongly Agree 7
The communication was adequate.	○	○	○	○	○	○	○
The communication was clear.	○	○	○	○	○	○	○
The communication was effective.	○	○	○	○	○	○	○
I trust the communication of the car.	○	○	○	○	○	○	○
The communication offers safety.	○	○	○	○	○	○	○

Fig. A.3. Online survey Task I - perception of communication [65, 90].


Please rate your impression of **this vehicle** in the video.

	1	2	3	4	5	6	7	
Fake	○	○	○	○	○	○	○	Natural
Machinelike	○	○	○	○	○	○	○	Humanlike
Unconscious	○	○	○	○	○	○	○	Conscious
Artificial	○	○	○	○	○	○	○	Lifelike
Moving Rigidly	○	○	○	○	○	○	○	Moving Elegantly

	1	2	3	4	5	6	7	
Dead	○	○	○	○	○	○	○	Alive
Stagnant	○	○	○	○	○	○	○	Lively
Mechanical	○	○	○	○	○	○	○	Organic
Artificial	○	○	○	○	○	○	○	Lifelike
Inert	○	○	○	○	○	○	○	Interactive
Apathetic	○	○	○	○	○	○	○	Responsive

	1	2	3	4	5	6	7	
Dislike	○	○	○	○	○	○	○	Like
Unfriendly	○	○	○	○	○	○	○	Friendly
Unkind	○	○	○	○	○	○	○	Kind
Unpleasant	○	○	○	○	○	○	○	Pleasant
Awful	○	○	○	○	○	○	○	Nice

	1	2	3	4	5	6	7	
Incompetent	○	○	○	○	○	○	○	Competent
Ignorant	○	○	○	○	○	○	○	Knowledgeable
Irresponsible	○	○	○	○	○	○	○	Responsible
Unintelligent	○	○	○	○	○	○	○	Intelligent
Foolish	○	○	○	○	○	○	○	Sensible

Fig. A.4. Online survey Task I - anthropomorphism, animacy, likability and perceived intelligence scales [3].

Please rate your impression of **this vehicle** in the video.

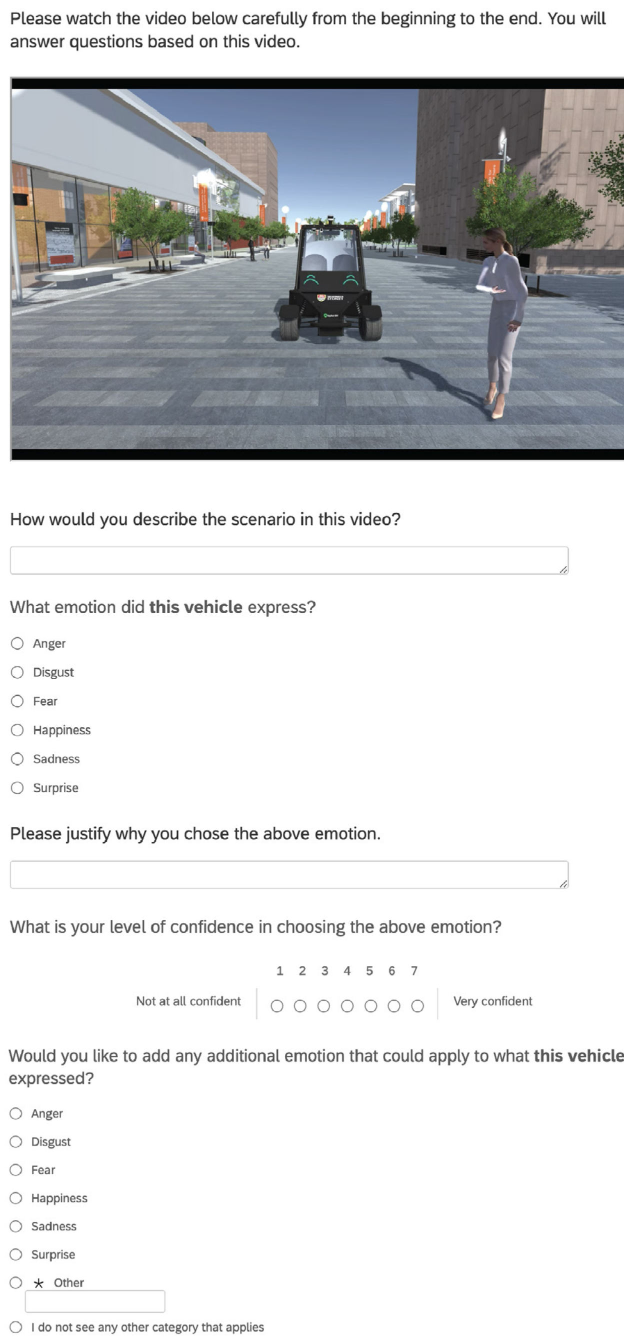
	Strongly Disagree 1	2	3	Neutral 4	5	6	Strongly Agree 7
This vehicle notices human presence.	○	○	○	○	○	○	○
This vehicle enjoys meeting people.	○	○	○	○	○	○	○
This vehicle recognizes individual people.	○	○	○	○	○	○	○
This vehicle notices when people do things.	○	○	○	○	○	○	○
This vehicle adapts effectively to different things people do.	○	○	○	○	○	○	○

	Strongly Disagree 1	2	3	Neutral 4	5	6	Strongly Agree 7
This vehicle anticipates people's behavior.	○	○	○	○	○	○	○
This vehicle tries to be helpful.	○	○	○	○	○	○	○
This vehicle is trustworthy.	○	○	○	○	○	○	○
This vehicle cares about others.	○	○	○	○	○	○	○
This vehicle recognizes human emotions.	○	○	○	○	○	○	○

	Strongly Disagree 1	2	3	Neutral 4	5	6	Strongly Agree 7
This vehicle responds appropriately to human emotion.	○	○	○	○	○	○	○
This vehicle anticipates others' emotions.	○	○	○	○	○	○	○
This vehicle tries to hurt people.	○	○	○	○	○	○	○
This vehicle can figure out what people think.	○	○	○	○	○	○	○
This vehicle knows if someone is part of a social group.	○	○	○	○	○	○	○

	Strongly Disagree 1	2	3	Neutral 4	5	6	Strongly Agree 7
This vehicle adapts its behavior based upon what people around it know.	○	○	○	○	○	○	○
This vehicle thinks it is better than everyone else.	○	○	○	○	○	○	○
This vehicle anticipates others' beliefs.	○	○	○	○	○	○	○
This vehicle is impolite.	○	○	○	○	○	○	○
This vehicle is socially competent.	○	○	○	○	○	○	○

Fig. A.5. Online survey Task I - perceived social intelligence scales. Note that items from the two sub-scales were mixed. See Barchard et al. [2] for items involved in each of the sub-scales.


Please watch the video below carefully from the beginning to the end. You will answer questions based on this video.

How would you describe the scenario in this video?

What emotion did **this vehicle** express?

- Anger
- Disgust
- Fear
- Happiness
- Sadness
- Surprise

Please justify why you chose the above emotion.

What is your level of confidence in choosing the above emotion?

	1	2	3	4	5	6	7	
Not at all confident	○	○	○	○	○	○	○	Very confident

Would you like to add any additional emotion that could apply to what **this vehicle** expressed?

- Anger
- Disgust
- Fear
- Happiness
- Sadness
- Surprise
- * Other
- I do not see any other category that applies

Fig. A.6. Online survey Task II. This is an example screenshot from the Happiness scenario. The other three scenarios followed the same structure.

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