Multimodal Technologies and Interaction

Article

Smiles and Angry Faces vs. Nods and Head Shakes: Facial Expressions at the Service of Autonomous Vehicles

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Abstract: When deciding whether to cross the street or not, pedestrians take into consideration information provided by both vehicle kinematics and the driver of an approaching vehicle. It will not be long, however, before drivers of autonomous vehicles (AVs) will be unable to communicate their intention to pedestrians, as they will be engaged in activities unrelated to driving. External human–machine interfaces (eHMIs) have been developed to fill the communication gap that will result by offering information to pedestrians about the situational awareness and intention of an AV. Several anthropomorphic eHMI concepts have employed facial expressions to communicate vehicle intention. The aim of the present study was to evaluate the efficiency of emotional (smile; angry expression) and conversational (nod; head shake) facial expressions in communicating vehicle intention (yielding; non-yielding). Participants completed a crossing intention task where they were tasked with deciding appropriately whether to cross the street or not. Emotional expressions communicated vehicle intention more efficiently than conversational expressions, as evidenced by the lower latency in the emotional expression condition compared to the conversational expression condition. The implications of our findings for the development of anthropomorphic eHMIs that employ facial expressions to communicate vehicle intention are discussed.

Keywords: external human-machine interfaces; autonomous vehicles; pedestrians; traffic flow; virtual human characters; emotional facial expressions; conversational facial expressions

Citation: Rouchitsas, A.; Alm, H. Smiles and Angry Faces vs. Nods and Head Shakes: Facial Expressions at the Service of Autonomous Vehicles. *Multimodal Technol. Interact.* **2023**, *7*, 10. https://doi.org/10.3390/mti7020010

Academic Editors: Marius Hoggenmueller, Martin Tomitsch, Jessica R. Cauchard, Luke Hespanhol, Maria Luce Lupetti, Ronald Schroeter, Sharon Yavo-Ayalon, Alexander Wiethoff and Stewart Worrall

Received: 16 September 2022
Revised: 8 January 2023
Accepted: 9 January 2023
Published: 20 January 2023

1. Introduction

1.1. Interaction in Traffic

Interactions between road users are formally regulated by the traffic code, yet road users resort frequently to informal communication to ensure traffic safety and improve traffic flow, especially in ambiguous traffic situations where right-of-way rules are unclear and dedicated infrastructure is missing [1,2]. It is very common that communicating intention, negotiating priority, and resolving deadlocks is achieved through the casual use of informal communicative cues, such as eye contact, nodding, and waving [3,4].

It will not be long, however, before drivers of autonomous vehicles (AVs) will be unable to communicate their intention, as they will be engaged in activities unrelated to driving, such as reading, typing, or watching a movie [5,6]. This situation may prove difficult for pedestrians especially, because when deciding whether to cross the street or not, they take into consideration information provided by both vehicle kinematics, such as speed and acceleration [7–9], and the driver of an approaching vehicle, such as gaze direction and facial expression, according to a plethora of research conducted in different cultural contexts, such as France, China, the Czech Republic, Greece, the Netherlands, and the UK [4,10–19]. To make matters worse, there is ample evidence for the underestimation of vehicle speed on the part of pedestrians, as well as the overestimation of the time at their disposal to attempt crossing the street safely [20–22].

1.2. External Human–Machine Interfaces as a Substitute

External human–machine interfaces (eHMIs), i.e., human–machine interfaces that utilize the external surface of the vehicle, such as the headlights, the radiator grille, the hood, or the roof, have been developed to fill the communication gap that will result by offering information about the situational awareness and intention of an AV, mainly to ensure that pedestrians are safe and traffic flow is unhindered but also to promote public acceptance of the new technology [23–30]. Previous research has found AV–pedestrian interactions to be more effective and efficient and perceived as safer and more satisfactory when an AV is equipped with an interface compared to when it is not and any relevant information pedestrians have to extract solely from vehicle kinematics [31–48]; however see [49–51].

Importantly, relevant work has also provided evidence for the positive effect eHMIs have on AV–driver interactions, especially in ambiguous traffic situations. More specifically, Colley et al. [52] found that, in the context of an unsignalized four-way intersection scenario, drivers reported higher perceived safety, lower mental workload, and higher understanding of AV intention when interacting with an AV that was equipped with an interface compared to interacting with an AV that did not offer external communication. Similarly, drivers that were instructed to perform a left turn at a four-way intersection while an AV was approaching from the opposite side, maintained higher speed and completed their maneuver faster in the eHMI experimental condition [53]. Finally, Rettenmaier et al. [54] evaluated an eHMI in the context of an unregulated bottleneck scenario and showed that external communication led to shorter passing times and fewer crashes.

1.3. The Case for Anthropomorphism in eHMI Development

Interface concepts that use text to communicate information to pedestrians have been shown to be easily comprehensible [15,34,36,41,55–58]. Nevertheless, said concepts tend to be effective and efficient only in the case of pedestrians who speak the specific language of presentation, and are also limited with respect to international marketability potential due to the language barrier [23,30]. Interface concepts that employ pictorial message coding, on the other hand, succeed in transcending local specificities by using widely recognized traffic symbols. Still, these traffic symbols represent advice or instruction directed at the pedestrian, which is inadvisable from a design perspective due to possible liability issues in the event of a traffic accident [59]. Finally, eHMI concepts that employ abstract message coding in the form of novel light patterns, such as pulsating or sweeping lights, attempt to simulate the functionality of a vehicle's turn signals and brake lights—that address other drivers mainly—and introduce it to the AV–pedestrian interaction domain. Even so, these concepts have been found lacking in comprehensibility due to the demand they place on pedestrians to establish new mental connections that do not draw from their experience of social or traffic interaction and, therefore, require their design rationale be explained beforehand and pedestrians be trained to use them successfully [31,35,41,47,48,51,60].

On the contrary, eHMI concepts that employ elements of human appearance and/or behavior take advantage of prior experience to facilitate AV–pedestrian interactions and, thus, require neither explanation and training nor cultural adaptation for pedestrians to use them successfully. Several eHMI concepts make use of eyes, facial expressions, and hand gestures to communicate pedestrian acknowledgement and vehicle intention [34,37,38,41,42,56,61,62]. For instance, Chang et al. [32] evaluated a concept where the headlights of the AV serve as its "eyes" and, accordingly, turn and look at the pedestrian to communicate they have been acknowledged and they will be yielded to. Even though the participants had not received any information regarding design rationale beforehand, the interface still led to them deciding faster whether to cross or not and reporting higher perceived safety compared to the baseline condition, namely interacting with an AV that offered no external communication. Moreover, according to relevant work, an effective design approach for increasing trust in a new technology is adding anthropomorphic elements to it [63–66], which also holds true for AVs and the placement of trust in their capabilities by the general public [67]. As trust is a mediating factor for automation acceptance, an even stronger case can be made for anthropomorphism in eHMI development, especially during the initial stages of AV deployment, so that skepticism and hesitation are allayed and the public reaps the full benefits of the new technology [68–73].

Virtual human characters (VHCs) have been utilized extensively in social neuroscience research for the purpose of studying mental and neural processes in both neurotypical and neurodiverse samples [74–80], due to being processed similarly to fellow conspecifics [81] and evoking a strong sense of social presence [82]. VHCs have also been established as tools for human–computer interaction research in the field of affective computing [83–90] and as end-products in the form of real-world solutions to address business, educational, entertainment, and healthcare challenges [91]. Despite their realism and sociability, however, they have been employed only once as an end-product in the field of eHMIs. More specifically, Furuya et al. [92] developed an eHMI concept where a full-sized VHC driver either gazes directly at the pedestrian or looks straight ahead, along the road. The participants had to cross the street at an unsignalized crosswalk while an AV that offered external communication was approaching. Results showed a higher preference for the VHC driver that engaged in eye contact to both the driver that did not and the baseline condition (no eHMI), while some participants suggested that it would be useful to add gestures to its social repertoire.

1.4. Facial Expressions and Vehicle Yielding Intention

Social neuroscience research has found mentalizing, i.e., attributing mental states, such as desires, beliefs, emotions, and intentions to others, to be crucial for the accurate interpretation or anticipation of their behavior [93–95]. The affective state of an expresser is generally considered to be manifested via their emotional facial expressions [96]. Furthermore, said expressions are also produced to provide information about an expresser's cognitive state and intentions [97]. During social interactions, for example, a Duchenne smile—the universally recognized facial expression of happiness—is produced to communicate friendliness or kindness [98], whereas an angry expression—the universally recognized facial expression of anger—is produced to communicate competitiveness or aggressiveness [99]. Accordingly, the smile has been utilized to signify yielding intention in various anthropomorphic eHMI concepts on the premise that, in a hypothetical situation where right-of-way is negotiated, a driver could smile at a pedestrian to communicate yielding intention [34,37,41,42,56,62,100]. Having considered the circumstances, the pedestrian would associate friendliness/kindness with being offered safe passage and would, thus, proceed to cross first [101].

Conversational facial expressions, such as the nod and the head shake, are universally utilized for providing information about an expresser's cognitive state and intentions [102–104]. For instance, during social interactions, a nod is produced to communicate agreement or cooperativeness, whereas a head shake is produced to communicate disagreement or unwillingness to cooperate [105–110]. Fittingly, a driver could also decide to nod at a pedestrian to let them know they will be yielded to [1,3,4]. In that case, the pedestrian would associate agreement/cooperativeness with relinquishing right-of-way and would, thus, go ahead and cross first [101]. Indeed, in Rouchitsas and Alm [101], the nod was shown to help pedestrians infer vehicle yielding intention highly effectively in the context of a self-paced crossing intention task, as evidenced by an accuracy of 96.3% in the nod experimental condition.

1.5. Facial Expressions and Vehicle Non-Yielding Intention

With respect to employing facial expressions for communicating not relinquishing right-of-way, several anthropomorphic eHMI concepts have employed the neutral expression to signify both non-yielding and cruising intention, i.e., intention to carry on with operating in automated mode [37,41,42,100]. A neutral expression, i.e., an alert but blank expression, is a social stimulus that is evaluated as indifferent with respect to valence and does not provide a perceiver with any insight as to what an expresser is feeling, thinking, or planning on doing [97,111,112]. Nonetheless, when employed side by side with a smile in a concept, it is reasonable for the neutral expression to act as a signifier of non-yielding or cruising intention, as it is doubtful that a pedestrian would try crossing the street without having received some confirmation from the driver first [101], and will most likely adopt a look-before-you-leap strategy instead, based on ambiguity aversion [113]. Even so, communicating safety-critical information via an ambiguous expression is inadvisable, as misjudging the intention of an oncoming vehicle may have severe consequences [114,115]. In fact, Rouchitsas and Alm [101] found the neutral expression to not communicate vehicle cruising intention effectively, as evidenced by an accuracy of only 82.3% for interpretation of vehicle intention, which is lower than the 85% criterion for effectiveness proposed by Kaß et al. [116]. Accordingly, more unambiguous expressions for communicating vehicle non-yielding and cruising intention will have to be explored as alternatives if anthropomorphic eHMI concepts are to be utilized safely in the soon-to-be mixed-autonomy traffic.

Regarding employing emotional expressions to communicate non-yielding intention, Chang [62] evaluated an interface concept where a smile signifies yielding intention and a sad expression signifies non-yielding intention. However, it is highly unlikely that a driver would be saddened by a pedestrian [101], given that sadness is typically felt as a result of loss while a sad facial expression communicates need of help or comfort [97]. Accordingly, it comes as no surprise that said concept was not found to be effective in helping pedestrians decide appropriately whether to cross or not, as evidenced by an accuracy of only 75% for interpretation of vehicle intention. Therefore, a sad expression is not a wise design choice for signifying non-yielding intention.

On the contrary, in real-life traffic situations, it makes great sense that the reckless or inconsiderate behavior of a pedestrian would make a driver angry. In fact, previous research has shown that drivers experience anger very often when driving around the city [117]. This is to be expected, given the high traffic density that characterizes urban roads and the overabundance of situations where a driver may be delayed or even subjected to harm [99]. Interestingly, braking for a jaywalker, i.e., a pedestrian that attempts to cross the street at an illegal location, has been shown to elicit anger in drivers [118,119]. If found in this situation, a driver could produce an angry expression to communicate non-yielding intention to the potential jaywalker [101]. Having considered the circumstances, the pedestrian would associate competitiveness/aggressiveness with not relinquishing right-of-way and would, thus, not attempt to cross the street first. However, a driver could also decide to shake their head at the jaywalker to let them know they will not be yielded to [120]. In that case, the pedestrian would associate disagreement/unwillingness to cooperate with not relinquishing right-of-way and would, thus, not attempt to cross the street first. Accordingly, Rouchitsas and Alm [101] evaluated the effectiveness of the angry expression and the head shake in signifying vehicle non-yielding intention. Both expressions were shown to help pedestrians infer vehicle non-yielding intention highly effectively in the context of a self-paced crossing intention task, as evidenced by an accuracy of 96.2% for the angry expression and 99.7% for the head shake.

1.6. Aim and Approach

Having said that, in real-world traffic, deciding appropriately is not sufficient; pedestrians should decide whether to cross or not in a timely manner, so that both main ambitions of the traffic system, namely traffic safety and traffic flow, are satisfied [121]. Hence, the present study set out to evaluate the efficiency of emotional and conversational expressions in communicating vehicle intention, i.e., their effectiveness with respect to temporal resources expended [122]. Participants performed a speeded crossing intention task where latency and accuracy for crossing intention responses were measured. Latency in the smile and the nod conditions is indicative of efficiency in communicating yielding intention, whereas latency in the angry expression and the head shake conditions is indicative of efficiency in communicating non-yielding intention [123].

The employed task was performed in the laboratory, a situation that ensures maximum participant safety, and allows researchers to control confounding and extraneous factors more effectively and manipulate factors of interest more efficiently compared to field experiments employing physical prototypes of eHMIs. These qualities are invaluable at the early stages of the development of a new technology. Furthermore, to ensure that other traffic and expectations about priority would not interfere with their responses, our participants were presented with an oversimplified traffic scenario that involved only one oncoming vehicle and one pedestrian intending to cross the street at a random uncontrolled location [116]. Similarly, the stimuli were presented out of context, so that responses would not be compromised by visual elements of secondary importance or cues from vehicle kinematics [58]. Additionally, we employed a male and a female VHC as stimuli to control for possible gender effects on participant performance, as previous research has shown male and female gender cues to affect the identification of facial expressions differentially [124,125], while research on gender fluidity and androgyny in the context of human–VHC interactions is still lacking [126]. Finally, we followed the common practice in the field and framed participant behavior in binary terms, namely "cross/not cross", because, regardless of traffic situation complexity and decision formula, crossing the street is a binary decision [127].

2. Method

2.1. Design

We employed a 2 × 2 × 2 within-subject design, where the factors "VHC gender" (male; female), "vehicle intention" (yielding; non-yielding), and "expression type" (emotional; conversational) served as the independent variables. When crossed, the three factors yielded a total of 8 experimental conditions.

2.2. Stimuli

A total of 10 animated sequences were used as stimuli in the experiment (see Appendix A). Eight 3D animated sequences were developed in Poser Pro 11 (Bondware Inc., Murfreesboro, TN, USA). The development and validation of the VHC stimuli we used in the experiment are described in full detail in Rouchitsas and Alm [101]. An additional two sequences were developed in Poser Pro 11, where an initially grey circle of 28.5 cm diam. (1500 ms) turned either green or red (1134 ms), before turning grey again (500 ms). Via resembling the operation of a typical traffic light, these sequences served the purpose of regularly reminding the participants that the facial expressions were to be processed in the context of interaction in traffic.

2.3. Apparatus

We used a Lenovo ThinkPad P50s (Intel® Core™ i7-6500U CPU @ 2.5 GHz; 8 GB RAM; Intel HD Graphics 520; Windows 10 Education) to run the task, and a 24″ Fujitsu B24W-7 LED monitor to present the stimuli. We also used a Chronos response box (Psychology Software Tools Inc.) to collect participant responses. E-Prime 3.0 (Psychology Software Tools Inc.) controlled the presentation of stimuli and the collection of data.

2.4. Procedure

The introductory and familiarization phases of the procedure were identical to the ones described in Rouchitsas and Alm [101]. After assuming a standing position—to facilitate pedestrian perspective adoption—the participants performed a crossing intention task (speeded, two-alternative forced choice). (Relevant research has found that assuming a standing position does not affect performance in a primary cognitive task [128,129]).

The traffic scenario they were presented with was the following: "Imagine you are a pedestrian about to cross a one-way street at a random uncontrolled location when you see an autonomous car approaching from the right. The autonomous car is equipped with our communication system. A smile, a nod (down-up head movement), and the green circle, mean that the autonomous car will stop to let you cross first. An angry expression, a head shake (left-right head movement), and the red circle, mean that the autonomous car will not stop to let you cross first.” (It has been shown that green is suitable for indicating that a pedestrian may cross in front of an AV, whereas red is suitable for indicating that a pedestrian may not cross in front of an AV [130]).

In each trial, after a fixation point of variable duration (1000–1400 ms) appearing at the location that coincided with the center of the interpupillary line of the VHC, participants were presented with one of the sequences (Figure 1). Their task was to respond as fast and accurately as possible whether they might cross or not, by pressing the correct button within the duration of the sequence. The two rightmost buttons of the Chronos response box were used for data collection. The buttons were counterbalanced between participants. A blank white screen was presented for 1200 ms before the start of the next trial. Each sequence was presented 24 times, yielding a total of 240 experimental trials. The participants completed a round of 20 practice trials before the actual task. Feedback on performance was provided during practice and achieving a level of minimum 0.9 accuracy was a requirement for progressing to the actual task. The duration of the procedure was about 45 min.

Figure 1. Experiment set-up.

2.5. Dependent Variables

We measured the latency and accuracy (total correct trials/total trials) for crossing intention responses. We programmed “cross” to be the correct response for the green circle, the smile, and the nod, irrespective of VHC gender condition, and “not cross” to be the correct response for the red circle, the angry expression, and the head shake, irrespective of VHC gender condition.

2.6. Participants

The Umeå Research Ethics Committee approved the study (Ref: 2020-00642). We used a convenience sample of 45 participants (30 male, 15 female; mean age = 25.8 years, SD = 6.5 years). All participants volunteered to participate in the study and provided written informed consent. All participants reported normal or corrected-to-normal vision. A total of 24 participants were Swedish nationals, 3 German, 3 Greek, 3 Italian, 2 Russian, 2 Mexican, 1 French, 1 Macedonian, 1 Colombian, 1 Brazilian, 1 Iranian, 1 Pakistani, 1 Indian, and 1 Nepalese. A total of 44 participants assumed the role of a pedestrian on a daily basis and 1 on a weekly basis.

2.7. Data Analysis

Overall mean accuracy in the task was 0.969. We excluded the data from 2 participants from further analyses due to low accuracy (>2 SDs below the overall mean). Only RTs of correct trials were analyzed [131]. Correct RTs that were generated in the first 1500 ms of each sequence, i.e., before the VHC had begun producing a facial expression or the grey circle had changed color, were discarded as premature. We excluded the data from 1 participant from further analyses due to high mean latency (>2 SDs above the overall mean). Outliers, defined as correct RTs that were 2 SDs above or below each individual mean per condition, were excluded from further analyses [132,133]. We excluded the data from 1 participant from further analyses due to a high percentage (>21%) of excluded RTs in a single condition. To test the effects of VHC gender, vehicle intention, and expression type on the dependent variables, a 2 (male; female) × 2 (yielding; non-yielding) × 2 (emotional; conversational) repeated-measures analysis of variance (ANOVA) was conducted [134]. Excel (Microsoft) was used to process the data and SPSS Statistics 28 (IBM) was used to analyze the data.

3. Results

3.1. Latency

In the yielding intention condition, mean latency (standard error) was 595 ms (11.4) for the emotional expression (smile) and 618.1 ms (13.7) for the conversational expression (nod) (Figure 2). In the non-yielding intention condition, mean latency (standard error) was 599.7 ms (11.3) for the emotional expression (angry expression) and 632.2 ms (13.2) for the conversational expression (head shake) (Figure 2). Mean latency (standard error) was 605.7 ms (11.7) for the male VHC and 616.9 ms (10.9) for the female VHC. A 2 × 2 × 2 repeated-measures ANOVA revealed a significant main effect of expression type, $F(1, 40) = 11.985$, $p = 0.001$, $\eta_p^2 = 0.231$, a significant main effect of VHC gender, $F(1, 40) = 16.008$, $p < 0.001$, $\eta_p^2 = 0.286$, and a significant interaction between VHC gender and intention, $F(1, 40) = 4.759$, $p = 0.035$, $\eta_p^2 = 0.106$. To unpack the interaction, we performed simple effects analyses. Results showed that the non-yielding intention was responded to significantly slower in the female VHC compared to the male VHC condition (M = 17.7, SE = 3.7), $F(1, 40) = 22.594$, $p < 0.001$, $\eta_p^2 = 0.361$, which was not the case for the yielding intention (M = 4.7, SE = 4.4), $F(1, 40) = 1.115$, $p = 0.297$, $\eta_p^2 = 0.027$ (Figure 3).

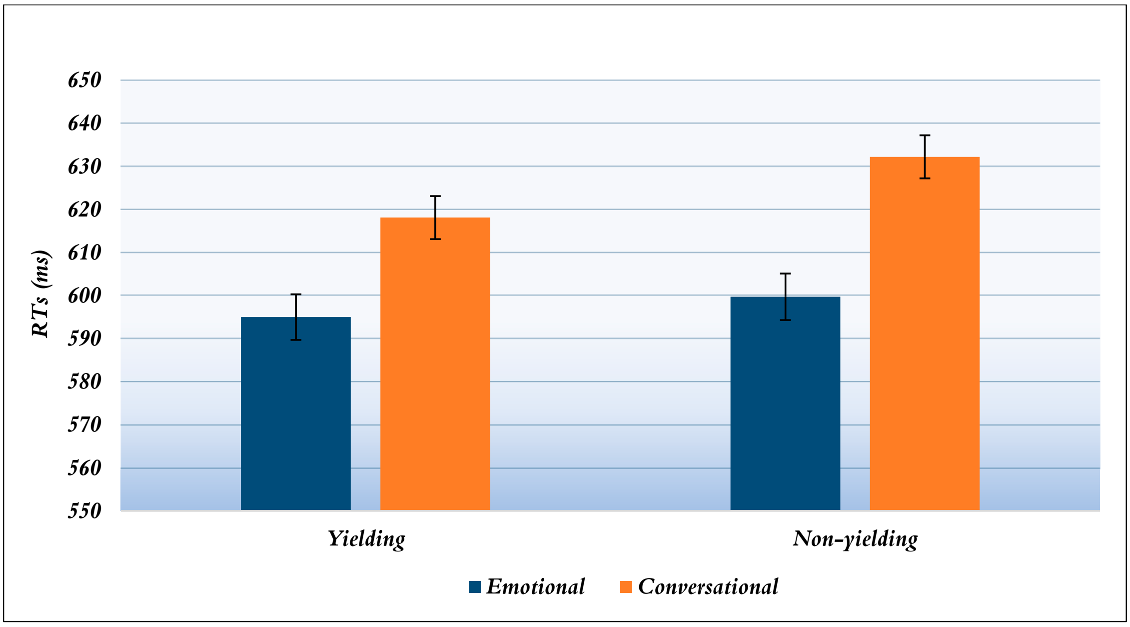


Figure 2. Mean RTs for crossing intention in the presence of yielding and non-yielding AVs for emotional and conversational facial expressions. Error bars represent standard error.

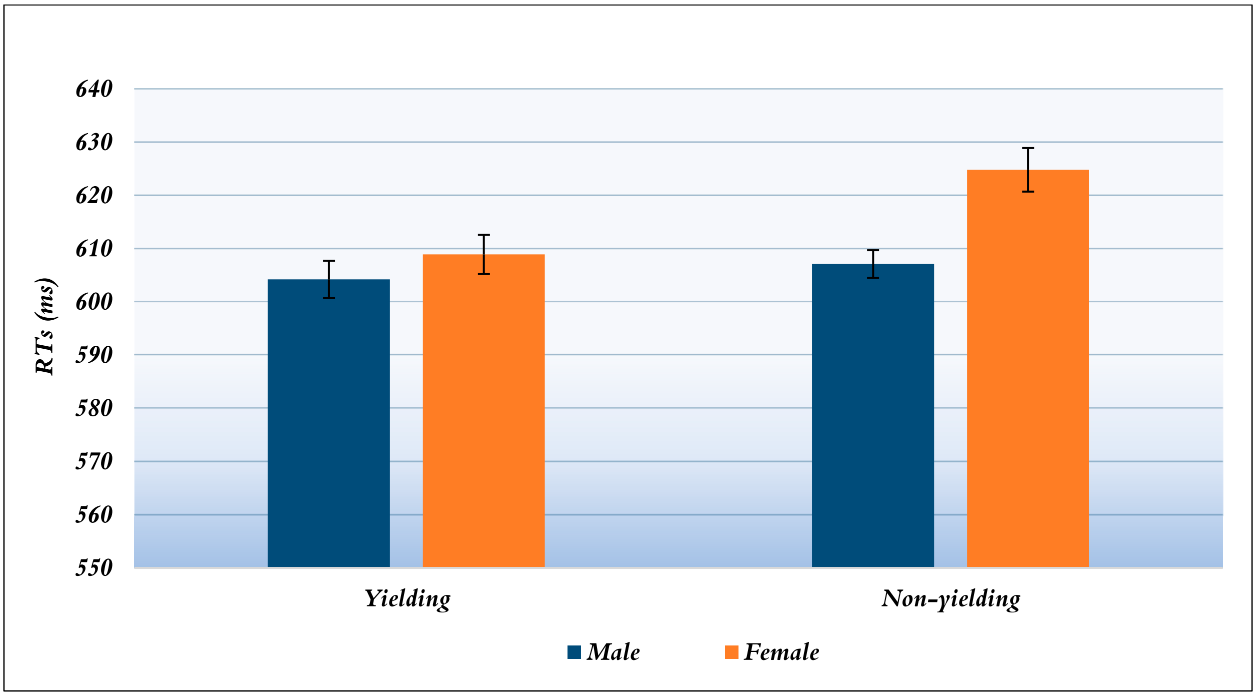


Figure 3. Mean RTs for crossing intention in the presence of yielding and non-yielding AVs for male and female VHCs. Error bars represent standard error.

3.2. Accuracy

In the yielding intention condition, mean accuracy (standard error) was 0.983 (0.003) for the emotional expression (smile) and 0.970 (0.004) for the conversational expression (nod). In the non-yielding intention condition, mean accuracy (standard error) was 0.974 (0.004) for the emotional expression (angry expression) and 0.983 (0.004) for the conversational expression (head shake). Mean accuracy (standard error) was 0.975 (0.004) for the male VHC and 0.979 (0.004) for the female VHC. A 2 × 2 × 2 repeated-measures ANOVA revealed a significant interaction between intention and expression type, $F(1, 40) = 7.174$, $p = 0.011$, $\eta_p^2 = 0.152$. To unpack the interaction, we performed simple effects analyses. Results showed that, in the yielding intention condition, the emotional expression (smile) was responded to significantly more accurately than the conversational expression (nod) (M = 0.012, SE = 0.005), $F(1, 40) = 6.988$, $p = 0.012$, $\eta_p^2 = 0.149$, whereas, in the non-yielding intention condition, the emotional expression (angry expression) was responded to less accurately compared to the conversational expression (head shake) (M = 0.009, SE = 0.006), $F(1, 40) = 2.225$, $p = 0.144$, $\eta_p^2 = 0.053$, albeit non-significantly.

4. Discussion

4.1. Findings

In the present study, we evaluated emotional and conversational expressions with respect to their efficiency in signifying vehicle intention. Emotional expressions were shown to be more efficient than conversational expressions in helping pedestrians decide appropriately whether to cross or not, as evidenced by a significantly lower latency in the emotional expression compared to the conversational expression condition. More specifically, with respect to communicating yielding intention, the smile was shown to be more efficient than the nod. However, Rouchitsas and Alm [101] found that the smile does not communicate yielding intention effectively, as evidenced by an accuracy of only 76% for interpretation of vehicle intention, which is considerably lower than the 85% criterion for effectiveness proposed by Kaß et al. [116]. On the other hand, the nod was shown to be highly effective in communicating yielding intention, as evidenced by an accuracy of 96.3% for interpretation of vehicle intention. As far as communicating non-yielding intention is concerned, the angry expression was shown to be more efficient than the head shake. Although Rouchitsas and Alm [101] found both angry expression and head shake to be highly effective in communicating vehicle non-yielding intention, we report here a clear advantage for the angry expression over the head shake with respect to their efficiency in doing so.

We also found that non-yielding intention was responded to significantly faster in the male VHC compared to the female VHC condition, whereas VHC gender did not affect latency in the yielding intention condition differentially. This result is consistent with relevant research that has found anger to be more readily identified on male compared to female faces [125], and men to be perceived as more dominant and, thus, likelier to show anger [124]. Considering that both the angry expression and the head shake denote dominance and opposition by signifying non-yielding intention, a perceived incongruence between propensity and VHC gender could explain the higher latency in the female VHC condition [135].

4.2. Implications

Future implementations of anthropomorphic eHMI concepts that aim to communicate vehicle intention via facial expression would benefit from employing the angry expression as a signifier of non-yielding intention, both on grounds of superiority in effectiveness compared to the industry standard anthropomorphic signifier of not relinquishing right-of-way, namely the neutral expression, and of superiority in efficiency compared to another highly effective facial expression, namely the head shake. Moreover, designers of anthropomorphic eHMI concepts should proceed with caution when considering employing the smile to communicate yielding intention, as they may be improving traffic flow at the expense of pedestrian safety, and instead minimize ambiguousness in AV–pedestrian interactions by exploring the nod as a worthy alternative.

While Rouchitsas and Alm [101] found no effect of VHC gender on accuracy—the dependent variable that served as an indicator of effectiveness—the effect on latency we report here—the dependent variable that served as an indicator of efficiency—implies that design choices regarding VHC gender could affect traffic flow. More specifically, it appears that communication of vehicle intention via facial expression will be at its most efficient, i.e., at its fastest, when realized via a male VHC compared to a female VHC, thus suggesting that incorporating male gender cues into the design of anthropomorphic eHMI concepts would maximize their ability to support pedestrians decide appropriately in a timely manner and, hence, improve the flow of mixed-autonomy traffic.

Relevant research has shown that gendering social robots tends to elicit stereotypical user responses about personality traits and task appropriateness [136]. For instance, a female social robot is expected to be more compassionate than its male counterpart, whereas a male social robot is expected to be more competent that its female counterpart. Similarly, in people's minds, heavy lifting is typically reserved for a male social robot and tending to the elderly for its female counterpart. On the other hand, however, a familiar and relatable physical appearance tends to facilitate both human–robot and human–VHC interactions and lays the foundation for the public to accept and eventually adopt these new technologies [91,137,138]. Furthermore, recent work has provided evidence for the diminishing gap in gender stereotypes regarding personality traits and social roles of men and women [139], which, interestingly enough, has been shown to apply to gendered VHCs as well [126]. Therefore, given that research on gender fluidity and androgyny in the context of human–VHC interactions is still lacking, and that the traffic system is a relatively balanced environment with respect to gender representation, we deem it beneficial to assign gender to anthropomorphic eHMI concepts, especially during the initial stages of AV deployment.

Despite the fact that concepts using light patterns or text do help pedestrians decide appropriately, they call either for their design rationale to be explained or their content to be adapted culturally. On top of that, introducing additional stimuli in a traffic environment that is already overwhelming the senses of road users will most likely create more confusion and frustration, and affect the public acceptance of AVs negatively [30]. Anthropomorphic concepts, on the other hand, bypass explanation and adaptation by taking advantage of previous experience of social and traffic interaction. For instance, as far as pedestrians are concerned, a VHC displayed on the windshield of an AV references directly their everyday experience of resorting to informal communication in the context of driver–pedestrian interactions to ensure traffic safety and improve traffic flow. What is more, considering that the VHC will occupy the space reserved typically for the driver of a conventional vehicle, no extra mental workload will be placed on road users.

Nevertheless, as previous research has shown that anthropomorphism affects evaluations of trustworthiness positively [140], it is probable that the VHC will lead to overtrusting the AV, i.e., to underestimating the likelihood and consequences of a malfunction, which may jeopardize pedestrian safety if the AV does not grant passage after all. Additionally, there is high chance that the VHC will arouse considerable interest or curiosity in bystanders, and lead to them being distracted while trying to navigate traffic safely and efficiently [141]. Designers of eHMIs should take into consideration possible negative effects on trust or attention to maximize their potential for successful integration into the traffic system.

4.3. Limitations

We must acknowledge a number of limitations that could jeopardize our findings' potential for generalization [142]. Firstly, the crossing intention task was performed in the laboratory and the stimuli were presented on a monitor. This approach is characterized by poor ecological validity, on account of being minimally immersive and highly artificial, and susceptibility to data contamination due to the absence of concerns about safety. Therefore, it would be advisable to have participants perform the task in a virtual reality (VR) environment as well—known for combining high experimental control with a more realistic experience—to increase the ecological validity of the findings [143]. Secondly, as the stimuli were presented out of context, no comparison could be made to a condition where an approaching AV without an interface would communicate its intention solely via vehicle kinematics. For this reason, the employed VHCs should also be presented as part of more detailed virtual scenes, to evaluate their efficiency more comprehensively. Lastly, because of temporal limitations, we did not conduct explicitation interviews as part of the procedure [144,145], which may have deprived us of the opportunity to access valuable information regarding the mental calculations that underpinned responses. Having said that, we are planning to include said technique in future work, so that participants can provide detailed accounts of their subjective experience when interacting with the VHCs.

4.4. Future Work

Previous work has shown that when children interact with an AV, they tend to make street-crossing decisions based entirely on information provided by the interface, without taking into consideration any information provided by vehicle kinematics [146]. It is highly probable that an anthropomorphic eHMI will startle or intrigue children and, thus, make moving safely and efficiently through traffic more challenging for them than it already is. Accordingly, we are also planning on evaluating the efficiency of emotional and conversational expressions in communicating vehicle intention with a relevant sample to determine the degree to which children may be at an unfavorable position during interactions with an anthropomorphic eHMI concept due to their inexperience, playfulness, and carelessness [147,148].

Previous work has also found communication and social interaction skills to be characteristically impaired in autistic patients [77,149,150]. Considering that successful interaction with an anthropomorphic eHMI concept presupposes that the pedestrian's socio-perceptual and socio-cognitive abilities are intact, we are also planning on evaluating emotional and conversational expressions with respect to their efficiency with a relevant sample to determine the degree to which autistic patients may be at an unfavorable position compared to neurotypical pedestrians, especially given that pedestrians with neurodevelopmental disorders are already likelier to become injured in traffic compared to the general population [151].

5. Conclusions

In the context of AV-pedestrian interactions, emotional facial expressions were shown to communicate vehicle intention more efficiently than conversational facial expressions. Moreover, a male VHC was shown to communicate vehicle non-yielding intention more efficiently than its female counterpart. Therefore, designers of anthropomorphic eHMI concepts that aim to communicate vehicle intention via facial expression would maximize their potential for improving traffic flow if they were to employ emotional expressions, ideally produced by a male VHC.

Author Contributions: A.R. contributed to conceptualization, experimental design, stimuli creation, experiment building, data collection, data processing, data analysis, manuscript preparation, and manuscript revision. H.A. contributed to manuscript revision and supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Umeå Research Ethics Committee (Ref: 2020-00642).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The authors do not have permission to share data.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Stills Taken from the Animated Sequences

1. Rex looking directly at the participant while smiling.

2. Roxie looking directly at the participant while smiling.

3. Rex looking directly at the participant while nodding.

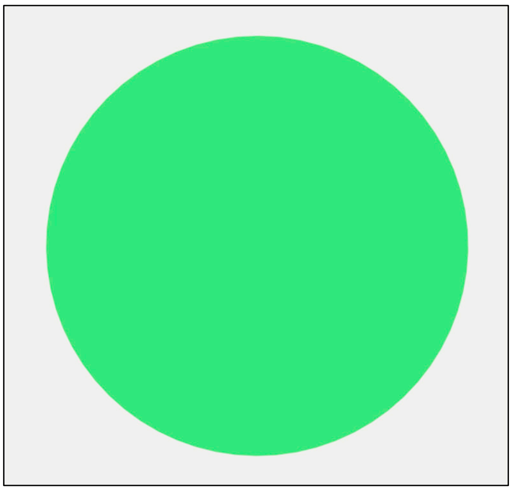
4. Roxie looking directly at the participant while nodding.

5. Rex looking directly at the participant while making an angry expression.

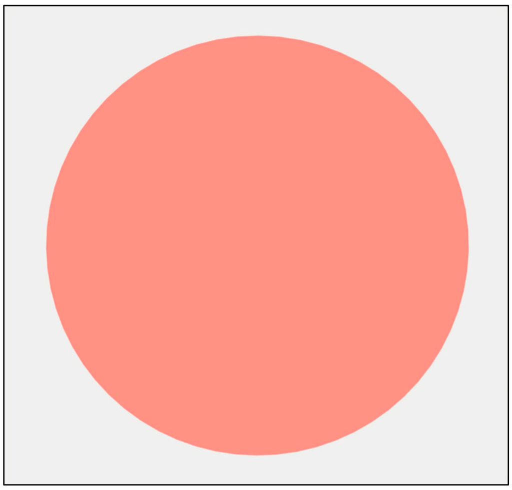
6. Roxie looking directly at the participant while making an angry expression.

7. Rex looking directly at the participant while shaking its head.

8. Roxie looking directly at the participant while shaking its head.



9. Green circle.



10. Red circle.

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