A social robotic object for enhancing passengers' experience in autonomous vehicles

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ABSTRACT

One of the central challenges in designing autonomous vehicles (AVs) concerns passenger trust and sense of safety. This challenge is related to passengers' well-established past experience with non-autonomous vehicles, which causes them concern about the absence of a driver in the AV. We explored whether it is possible to address this challenge by designing an interaction with a simple robotic object positioned on the vehicle's dashboard. We leveraged the automatic human tendency to interpret non-verbal robotic gestures as social cues and designed an interaction with the robot in the AV. The robotic object greeted the passenger, indicated that the vehicle was attentive to its surroundings, and informed the passenger that the drive was about to begin. We evaluated whether the robot's non-verbal behavior would provide the signals and social experience required to support passenger trust in the AV and a sense of safety. In an in-person (in-situ) experiment, participants were asked to enter an AV and take the time to decide if they were willing to go for a drive. As they entered the vehicle, the robot performed the designed behaviors. We evaluated the participants' considerations and experience while they made their decisions. Our findings indicated that participants' trust ratings and safety-related experience were higher than those of a baseline group who did not experience the interaction with the robot. Participants also perceived the robot as providing companionship during a lonely experience. We suggest that robotic objects are a promising technology for enhancing passengers' experience in AVs.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in HCI*.

KEYWORDS

HRI, Autonomous vehicles, Trust, Sense of safety, Greeting

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Figure 1: ??

1 INTRODUCTION

In recent years, great efforts have been invested in the development of autonomous vehicles (AVs). AVs can react faster than humans to potential hazards, coordinate their movements with other vehicles, and serve multiple users throughout the day. They therefore have the potential to reduce the number of vehicles on the road, prevent accidents, and improve traffic flow [42, 43]. The technical development of such vehicles is progressing rapidly. However, their acceptance by potential users faces several challenges [4] related to passengers' trust in the AV and their sense of safety [12]. Passengers already have strong habits in the context of going for a drive. The most important one involves the presence of a human driver controlling the vehicle. Going for a drive in an AV is therefore not an entirely novel experience. Instead, it is a familiar experience with an important missing element: the human driver. Violating such strong habits can lead to a highly uncomfortable experience [40] and requires the activation of cognitively demanding inhibition processes [32]. In addition, passengers are expected to naturally trust an autonomous technology that is typically controlled by humans, which can be difficult [54].

Apart from the general control of a driver over the vehicle, passenger habits also involve the observation of signals concerning the driving status. For example, the driver's non-verbal behavior can signal that the driver is confident and focused on the road [26]. Such understanding of the driving status further increases a passenger's trust and sense of safety [26]. The experience in an AV is missing these important signals, which indicate that the vehicle can "see" its environment and inform the passengers of the vehicle's future intent. The absence of these important signals in the AV can lead to a dramatic decrease in a passenger's sense of control and, as a result, in their trust [26]. Since trust is one of the main factors contributing to a sense of safety [24], the lack of informative signals that passengers usually rely on may hinder their willingness to use AVs altogether.

Several solutions for increasing passenger trust and sense of safety have been suggested by designers and researchers [17, 32].

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The main method for enhancing trust has involved providing passengers with information about the vehicle's status. Previous studies indicated that it is possible to increase trust by communicating the vehicle's status via visual displays. A heads-up display, light bands, augmented reality, and regular screens [8, 37] have all been indicated as valid methods for enhancing passenger trust by providing information related to the AV and road. Trust was further enhanced when these displays were designed to have anthropomorphic and social features such as a name, gender, voice, and politeness [27, 51]. While these methods have various advantages, it has also been argued that they involve demanding learning processes, as they require the interpretation of unfamiliar interactions (social cues provided by a visual display) in a familiar context (a passenger in a vehicle) [32].

Recently, the AV community has also begun to explore social robots that perform non-verbal gestures as a method for indicating an AV's intent and status [6, 50]. Robots can have several advantages in the context of increasing passenger trust and sense of safety. The main advantage of this approach concerns the ability to design an interaction that is compatible with people's existing habits [6]. Passenger habits are strongly based on the social cues provided by the driver. By observing the driver's non-verbal behavior, passengers deduce the level of focus on the road, intent, and stress. Social robots can be leveraged to communicate similar cues, leading to a more familiar experience without the need to inhibit previous habits and learn novel communication methods. Research has shown that even very simple robots can easily communicate clear and consistent social cues [1, 10, 19, 41]. Because of the human tendency to perceive the world through a social lens, non-verbal robotic gestures are automatically interpreted as social cues. This phenomenon is observed even when the robot has a non-humanoid appearance and cannot directly mimic human behavior (these robots are also known as robotic objects; [10]). Clear and consistent understanding of social cues has been documented with robots designed as a desk lamp [45], a microphone [49], a robotic arm [22], and a small ball rolling on a dome [1]. Participants naturally perceived the interaction with such robots as acknowledging their presence, greeting them [1], and caring for them [9, 11].

In the context of AVs, a simple non-humanoid robot was suggested as a method for communicating an AV's intent to pedestrians [6]. This work indicated that a simple social robot could be used for designing communication that is perceived as familiar and natural. The robot's gestures were adjusted to leverage existing pedestrian habits, and the interaction was perceived as clear and easy-to-understand communication with an AV. The researchers suggest that simple non-humanoid robots should be further explored as a simple and cost-effective way to overcome the communication challenges with AVs. Following this work, we suggest that the tendency to perceive simple non-humanoid robots as social entities can also be leveraged for designing high-quality AV-passenger communication. Using the robot as a social entity in control of the vehicle and providing common social cues, we could enhance passenger trust and sense of safety.

Another advantage of using social robots for AV-passenger communication concerns the sense of companionship related to social interactions with them. Previous studies indicated that even simple non-humanoid robots can provide a strong sense of companionship by performing minimal non-verbal gestures [3, 16, 18, 35, 55]. It was also found that social qualities and a sense of companionship in human–robot interaction (HRI) are closely related to trust [30]. In fact, several studies showed that when it comes to trusting the robot, companionship and social capabilities are more important than the robot's practical functioning [15].

In this work, we explore the possibility of using a robotic object to design a familiar experience in an AV and provide social signals to passengers. We focused on the initial interaction in the vehicle immediately after participants entered an AV and tested their experience when considering whether or not to go for a drive in the AV. Our focus on the beginning of the interaction allowed for an in-person (in-situ) evaluation. In addition, multiple studies have indicated that opening encounters and first impressions have a profound impact on the rest of the interaction. It is argued that the experience in the opening encounter has a long-lasting effect that shapes the nature of the interaction that follows [13, 25, 47] including the level of trust [53] and the perceived competence [39] of the autonomous technology. It has therefore been suggested that the opening encounter is the cornerstone for the entire relationship [2].

Accordingly, we designed an opening interaction between a passenger and a non-humanoid robot placed on the vehicle's dashboard. We used the simple non-humanoid robot designed by Chakravarthiku et al. [6] for mediating an AV's communication with pedestrians (used with permission, see Figure 1). We tested whether the robot's simple non-verbal gestures could mediate the social cues required for passengers to feel that there is an entity in control of the AV and to support their trust and sense of safety. The results of a pilot study were used to design a set of gestures for the robotic object to perform as soon as the passenger entered the vehicle: greeting the passenger, checking the road in front of the vehicle for safety, and turning back to the passenger to indicate that the vehicle is ready to go. We compared the participants' level of trust and sense of safety to those of a baseline group who had a similar experience without the opening encounter with the robotic object.

2 RELATED WORK

Trust in AVs and the social interpretation of non-verbal gestures performed by non-humanoid robots have been studied in previous work.

2.1 Trust in AVs

Previous studies investigated factors contributing to trust in AVs and their impact on AV acceptance. For example, Choi and Ji conducted a large-scale survey to map factors that contribute to acceptance and trust in AVs [7]. They found that system transparency, technical competence, and situation management had a positive impact on the trust of potential passengers. An AV's perceived usefulness and personal traits as a locus of control emerged as significant determinants of an individual's intention to use one [7].

In another study, Morra et al. investigated the factors that contribute to building trust in AVs [32]. They focused on the possibility of leveraging human–machine interfaces to enhance trust by providing information about the status of the vehicle. Participants who engaged in a VR-based driving simulation received visual cues informing them about the vehicle's sensory input and planning systems. Morra et al.'s findings indicated that a participant's ability to form a mental model of the AV was crucial for establishing trust. Participants were able to build such a mental model when they interacted with a system designed for enhancing user-vehicle communication. The information concerning the vehicle's surroundings provided by the system had a strongly positive impact on participant stress despite the cognitive demands to process a lot of information. The increase in participant trust (due to the information provided by the system) also increased their willingness to experience a real AV [32].

Another example was presented by Häuslschmid et al., who tested the possibility of increasing trust using the projection of visual information on the road in front of the passenger (outside the vehicle) [17]. In their video study, they indicated the vehicle's responsiveness to objects in the environment either by presenting a visualization of an animated chauffeur or by a visual representation of the vehicle and its surroundings outside (a world in miniature). They compared participants' trust to that of a baseline group that could only watch a display of the vehicle's indicators. They found that only the vehicle's visualization in its surroundings enhanced participants' trust [17].

Additional methods that have been suggested for increasing passenger trust in AVs include different methods for communicating the vehicle and road status (conversational agents [46], screens [37], augmented reality, a heads-up display, and light bands [8]) and adding anthropomorphic features to the vehicle, for instance, naming the vehicle or associating it with a specific gender [51].

In this work, we extend these previous studies and explore whether it is possible to enhance trust and a sense of safety by leveraging existing passenger habits. Our AV–passenger communication interface involved a robotic object that could provide clear and consistent social cues that passengers already use when taking a ride with a human driver.

2.2 Social interpretation of non-verbal gestures performed by non-humanoid robots

Prior research has highlighted the human tendency to perceive non-humanoid robots as social agents [11, 23, 36, 55]. Regardless of whether the robot was configured to resemble a familiar object or had a more abstract and unfamiliar form, its non-verbal gestures tended to be uniformly perceived as distinct and consistent social signals [11, 21]. It has therefore been suggested that robotic gestures can be easily designed as social cues commonly used in human–human communication, leading to clear and natural communication even with very simple robots [1].

For instance, Ju and Takayama demonstrated that the motion of an automated door can be designed to provide social cues associated with an opening encounter [21]. Participants in their study interpreted the movement of the door as a greeting behavior based on its speed and trajectory. When designed appropriately, participants perceived the movement as inviting and welcoming [21]. Another example was presented by Sirkin et al., who showed that a robotic ottoman performing non-verbal gestures can be perceived as a social agent [48]. The movement trajectory was interpreted as indicating its willingness for interaction. Indirect, curved movements toward a participant were interpreted as a social cue signaling it was interested in social interaction [48]. Social experiences have also been observed in interactions with a lamp-like robot that performed minimal gestures. Manor et al. designed robotic movements mimicking "lean," "gaze," and "nod" gestures [29]. In their study, the robot performed gestures in the direction of the participants, who shared their future plans. Participants interpreted the movements as signs of the robot's interest and care [29]. Non-verbal gestures have also been interpreted as social signals when introduced by abstract, unfamiliar, non-humanoid robots. In a study by Anderson et al. [1], participants attributed social interpretations to the gestures of a robot designed to take the form of a small ball moving on a dome. When participants faced this robot, the small ball exhibited motion either from the rear of the dome to the front or vice versa. Despite the robot's unconventional and abstract appearance, participants consistently interpreted the robot's gestures as conveying social cues pertinent to initiating an interaction. When the small ball rolled to the front of the dome (towards the participant), participants perceived it as a sign of willingness to engage in interaction. If it moved toward the back of the dome, they perceived it as an indication of reluctance to interact [1].

In the context of AVs, the non-verbal gestures of a non-humanoid robot have been used as a method for mediating the vehicle's intent to pedestrians interested in crossing the road in front of it. Chakravarthiku et al. conducted an in-situ experiment in which participants were asked to cross in front of an AV [6]. The robot was placed on the vehicle's dashboard in a location where pedestrians habitually look when making a crossing decision. It performed simple non-verbal gestures indicating that it recognized the pedestrian's presence and whether or not it was safe to cross in front of the vehicle. Participants easily understood the robot's social cues and reported a strong sense of safety when crossing in front of the AV [6].

These studies indicate the strong potential of using a simple robotic object to provide clear and consistent social cues. We followed Chakravarthiku et al. [6], who leveraged a social robotic object in the context of AV communication, and tested whether a robot could also enhance trust and a sense of security for passengers who are about to go for a drive in the vehicle.

3 GESTURE DESIGN AND TECHNICAL IMPLEMENTATION

We used, with permission, the robotic object that was designed by Chakravarthiku et al. for mediating AV communication [6] (see Figure 2). The robot is composed of two parts: (1) a "body" with a curved shape for indicating directionality that can rotate horizontally and (2) a thin top part that can perform vertical movements. The robot was attached to the vehicle's dashboard using a 3D-printed black base.

3.1 Gesture design

The gesture design process began with a pilot study that was conducted to better understand people's existing expectations when going for a drive as a passenger. In this pilot study, we mapped the passenger experience when entering vehicles in general, especially in cases where there was no previous experience with the driver. We interviewed 10 participants (5 male and 5 female) and asked them to describe their experience when using a taxi (as they would be passengers and the driver would be unfamiliar). We further asked them to describe what would make them feel comfortable and what factors would influence their sense of safety. All the participants mentioned the opening encounter with the driver and explained that being greeted and and having their presence acknowledged is important. They additionally talked about the driver's attentiveness to the environment. They stated that there is an added value when the driver checks whether they are ready to go and informs them before starting the drive.

Based on the insights from the pilot study, we decided to design three robotic behaviors for the opening encounter with the participants after they entered the vehicle:

(1) *Greeting*: Acknowledging the passenger's presence in the vehicle and greeting him/her.
(2) *Indicating Attentiveness*: Focusing attention on the environment outside the vehicle and its surroundings. Indicating that the AV is aware of its surroundings and verifying that it is safe to start the journey.
(3) *Affirmation*: Turning toward the passenger to indicate that it is safe to go and that the drive is about to begin.

The design process included four iterations with an animator and an HRI expert. After each iteration, the gestures were tested with five participants and updated according to their feedback. The iterations mostly involved updating the speed, range, and number of repetitions of each movement.

The process resulted in the following final robotic behaviors (see Figure 3):

(1) *Greeting*: The robot turns towards the passenger from its initial base position (a horizontal rotation of 145°), followed by a vertical up-down movement of the top part (a vertical rotation of 50°), simulating a nod.
(2) *Indicating Attentiveness*: The robot turns towards the left and then right in the direction of the road (−60° to +60°, covering a total horizontal rotational range of 120°). This gesture is repeated twice, simulating a head scanning the road.
(3) *Affirmation*: The robot turns towards the passenger (a horizontal rotation of 145°), followed by a vertical up-down movement of the top part (a vertical rotation of 50°). This is similar to the Greeting gesture, but twice as fast.

Figure 2: ??

Figure 3: ??

To validate the understanding of the gestures, we conducted another pilot study with eight additional participants. Participants were invited to enter a vehicle that was presented as autonomous. As they took a seat, the robot performed an opening encounter interaction that was composed of all three robotic behaviors. All participants understood the robot's designed intent for all three gestures.

3.2 Technical Implementation

We used the Butter Robotics platform as the robot's infrastructure [31]. Each of the robot's two degrees of freedom (DoF) was rigidly connected to a Dynamixel robotic servo motor. The DoFs were daisy-chained together and terminated in the Butter Robotics hardware controller. The Butter Composer directly translated Blender animations to motor movements. The robotic object was controlled wirelessly, and the vehicle's auxiliary power outlet was used to supply the robot's power.

4 METHOD

To gain insights into the potential of using robots for enhancing passenger experience in an AV, we conducted an in-person (in-situ) study with the robot installed on the vehicle's dashboard (see Figure 1). Participants were invited to enter a vehicle that was presented as autonomous and were asked to decide whether they would be willing to go for a drive in the vehicle and inform the researcher of this decision. Participants' trust in the AV and sense of safety were evaluated under two conditions: (1) the *Robot* condition, where the robot performed the designed behaviors for the opening encounter, and (2) the *No robot* condition, where the robot was placed as a stationary object that is a part of the vehicle's dashboard. The study was approved by the ethics committee of the research institute.

4.1 Participants

Forty undergraduate students from the university participated in the study (20 males, 20 females, mean age = 28.21, SD = 10.42). They received a 15 USD gift card for local stores. We verified that participants had no previous experience with robots or AVs. All participants signed a consent form and were informed that recorded material would be deleted after data analysis.

4.2 Experimental design

In a between-participants study, we evaluated passengers' experience in an AV. In both conditions, participants were asked to enter a vehicle that was presented as autonomous and take the time to decide if they felt comfortable enough to go for a drive. In the *Robot* condition, the robot performed the three robotic gestures for the opening encounter (*Greeting* > *Indicating Attentiveness* > *Affirmation*). In the *No robot* condition, participants sat in the vehicle for a similar amount of time but did not experience any interaction with the robot, which was located on the dashboard at an angle that did not indicate any directionality.

Participants were randomly assigned to one of the two conditions while balancing their early trust in intelligent machines [52] and gender (see Figure 4).

4.3 Experimental settings

Following Chakravarthiku et al. [6], we conducted the experiment in the university's parking lot and used a hybrid Hyundai Kona as the autonomous vehicle. To convincingly present the vehicle as autonomous, we performed the following modifications: 1) We added five 3D printed objects simulating LIDAR sensors to the vehicle's roof. 2) We placed large stickers on all sides of the vehicle (on the vehicle's doors and front part) that said in large text: *"This is an autonomous vehicle, please be cautious."* 3) We activated the vehicle's navigation system, and a clear route was presented on the vehicle's display system.

The vehicle was positioned on the far end of a road in the parking lot with the engine running. The robot was placed on the center of the dashboard with a slight offset toward the driver's direction, where it could be clearly seen by the passenger. Audio and video recorders were placed in the vehicle to document each participant's responses (see Figure 5).

4.4 Dependent measures

To assess the robot's impact on participants' trust and sense of safety, we used four measures: (1) the Trust in AVs questionnaire; (2) the Trust between People and Automation questionnaire; (3) spontaneous mentions of safe/unsafe experiences; and (4) a semi-structured interview.

Figure 4: ??

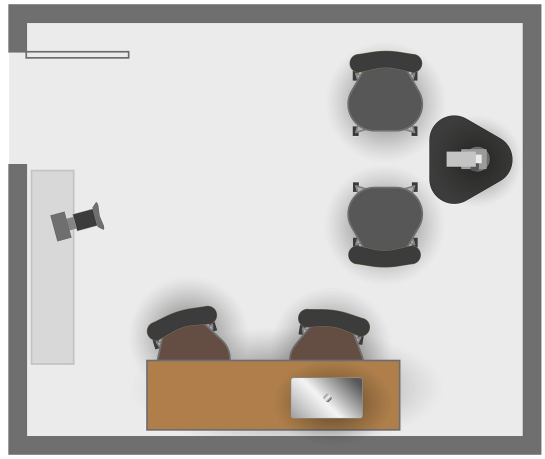

Figure 5: ??

4.4.1 *Trust evaluation.*

To evaluate participants' trust, we used two questionnaires.

(1) The Trust in AVs questionnaire: This questionnaire was designed to directly evaluate trust in AVs. It is a seven-item Likert scale ("Completely Agree" to "Completely Disagree") [28].

(2) The Trust Between People and Automation questionnaire: This questionnaire was designed to evaluate people's trust in autonomous systems. It is also a seven-item Likert scale ("Completely Agree" to "Completely Disagree") [20].

4.4.2 *Spontaneous mentions of safe/unsafe experiences.*

To evaluate participants' sense of safety, we coded the frequency of participants who spontaneously described their experience in the vehicle as safe or unsafe in their immediate report of the experience.

4.4.3 *Semi-structured interview.*

We conducted a semi-structured interview, allowing participants to freely describe their experience while remaining in line with a particular framework [14]. The interview provided an opportunity to better understand the participants' thoughts, emotions, and attitudes. The interview included questions concerning the overall experience, the autonomous vehicle, and the robot (e.g., "Describe the experience," "Describe your thoughts about the vehicle," and "How would you describe the robot to a friend?").

4.5 Procedure

A few days before the experiment, participants received the Trust in Intelligent Machines questionnaire [52] by email (to balance the groups in the different conditions). When participants arrived at the experiment, they signed a consent form, giving their consent to be recorded by audio and video. They were then invited to the parking lot, where the vehicle was positioned as if were ready to go for a drive. The researcher explained that the vehicle was autonomous and capable of self-driving. Participants were asked to enter the vehicle and take the time to decide whether they would like to go for a drive. They were directed toward the passenger's seat (next to the driver's seat) and entered the vehicle. In the *Robot* condition, the robot performed the three robotic behaviors designed for the opening encounter. The robot was triggered wirelessly by a research assistant using the Wizard-of-Oz technique [33, 44]. In the *No robot* condition, there was another plain object that did not move, and the participant sat in the vehicle quietly for the same amount of time (approximately two minutes). The researcher then entered the back seat and explained that before reporting their decision (to go for a drive or not), the researcher would like for them to report their thoughts and considerations. The researcher asked them to first share their immediate experience and to fill in two questionnaires on a tablet (trust questionnaires). At the final stage of the experiment, the researcher conducted a semi-structured interview, verified that the participants believed the vehicle was fully autonomous, and then debriefed them.

5 ANALYSIS

We conducted a Bayesian analysis to verify the lack of early differences between groups in their ratings of the Trust in Intelligent Machines questionnaire.

Our main analyses tested the impact of the robotic object (with vs. without a robot) on participants' experience when required to decide whether they were willing to go for a drive in the AV. The trust questionnaires were analyzed using a one-way ANOVA. Sense of safety was analyzed using a chi-square test for the frequency of participants who spontaneously mentioned feeling safe or unsafe when describing the immediate experience in the AV.

The qualitative analysis of the semi-structured interviews was performed by three coders. We used a thematic coding methodology for the analysis [5]. The analysis included four stages: (1) Two coders transcribed the interviews to develop an initial understanding of the data. The transcriptions were read several times before the coding process began. (2) Initial themes were extracted from the data and discussed in depth. Inconsistencies were resolved in discussion with a third researcher. (3) The coders used those themes to independently analyze part of the data, verifying inter-rater reliability (kappa=84%). (4) The two coders analyzed the rest of the data.

Figure 6: ??

Figure 7: ??

6 FINDINGS

The Bayesian analysis indicated no early differences between groups in the ratings of the Intelligent Machines questionnaire: $BF_{10} = 0.04$. The quantitative and qualitative main analyses indicated an impact of the robot on the participants' trust in the AV and their sense of safety.

6.0.1 Trust in the AV. The presence of the robot had a significant influence on the trust ratings in both questionnaires. The ratings of the Trust in AVs questionnaire indicated higher trust levels in the *Robot* condition, compared to the *No robot* condition $F(1,38) = 26.6$, $p < 0.001$ (see Figure 6).

The ratings of the Trust Between People and Automation questionnaire indicated a similar pattern $F(1,38) = 27.4$, $p < 0.001$ (see Figure 7).

6.0.2 Sense of safety. The analysis revealed that the presence of the robot had a significant influence on the spontaneous perception of the vehicle as safe or unsafe ${\chi^2}_{(2)} = 19.01, p < 0.001$. Most of the participants in the *Robot* condition and none of the participants in the *No robot* condition used the word "safe" when describing their immediate experience in the AV. Moreover, a few of the participants in the *No robot* condition and none of the participants in the *Robot* condition used the word "unsafe" when describing their immediate experience in the AV (see Table 1).

Table 1: Distribution of participants' use of the words "safe" and "unsafe" in different conditions

	Sense of safety		
Robot condition	Safe	Unsafe	Total
Robot	13	0	13
No robot	0	6	6
Total	13	6	19

6.1 Thematic analysis of the semi-structured interview

The thematic analysis revealed three main themes: *sense of safety and confidence*, *perception of the robotic object and its behavior*, and *social experience*.

6.1.1 Sense of safety and confidence. More than half the participants in the *Robot* condition (13/20) explicitly stated that the robot made them feel safe and increased their confidence. They associated this sense of safety with the robot's social cues and explained that it indicated that someone in the vehicle was "watching the road" and "aware of its surroundings."

- *"It gave me confidence. I knew that it was aware of the space around us."* (p. 38, *Robot* condition)
- *"It made me feel safe, as if everything is under control."* (p. 32, *Robot* condition)
- *"It gave me a sense of safety because I felt like it was checking what was happening around."* (p. 34, *Robot* condition)
- *"He made me feel like he's here watching over us, watching the environment and the road."* (p. 30, *Robot* condition)
- *"Without it, I would find it hard to feel that the vehicle is seeing what is going on in the space around us."* (p. 22, *Robot* condition)

A sense of safety was not mentioned by any of the participants in the *No robot* condition. A few participants in this condition explicitly described the opposite experience (6/20).

- *"It's weird since there is no driver. It is a little stressful."* (p. 17, *No robot* condition)
- *"I experienced uncertainty and a lack of confidence."* (p. 11, *No robot* condition)

6.1.2 Perception of the object and its behavior. All participants in the *Robot* condition reported that they noticed the robot easily and understood its intent clearly. While the *Greeting* and *Indicating Attentiveness* robotic behaviors were consistently interpreted similarly to their intended design, the *Affirmation* gesture was perceived either as an indication that the vehicle was about to drive or as a request to get approval to begin the drive.

- *"I felt like it was recognizing that there was a passenger, greeting me."* (p. 6, *Robot* condition, *Greeting gesture*)
- *"Like it's recognizing me. Letting me know it's aware of my presence somehow."* (p. 18, *Robot* condition, *Greeting gesture*)
- *"It was looking and checking the surroundings."* (p. 12, *Robot* condition, *Indicating Attentiveness*)
- *"It wanted me to feel that the car knows exactly what was going on in its surroundings, everything around."* (p. 24, *Robot* condition, *Indicating Attentiveness*)
- *"It turned back towards me since it wanted my approval to start driving."* (p. 40, *Robot* condition, *Affirmation*)

Some participants also mentioned that the robotic object was a mediator between the AV and passenger. They explicitly described it as responsible for controlling the vehicle:

- *"I think it some kind of a driver controlling the vehicle and communicating."* (p. 14, *Robot* condition)
- *"It is something that replaces the driver, it's there for me."* (p. 36, *Robot* condition)
- *"He is like a bridge between me and this vehicle."* (p. 10, *Robot* condition)

6.1.3 Social experience. Participants in the *Robot* condition (13/20) also associated their positive experience in the AV with a sense of companionship provided by the robot. They described the robot as another entity that made them feel that they were not alone in this unfamiliar experience.

- *"I think I felt like I had company, I wasn't alone."* (p. 2, *Robot* condition)
- *"I felt like there was someone else with me – someone I can interact with."* (p. 26, *Robot* condition)
- *"It gives you confidence since there is someone else here with you."* (p. 40, *Robot* condition)

Interestingly, most participants in the *No robot* condition (17/20) stated that they felt alone and described a need for companionship and communication.

- *"I was a little anxious since I was all alone."* (p. 21, *No robot* condition)
- *"I needed someone to communicate with. Someone in the vehicle, related to the vehicle, someone to talk to."* (p. 5, *No robot* condition)

7 DISCUSSION

In this work, we demonstrate the potential of using a non-humanoid robot to enhance the passenger experience in an AV. Our findings show that a simple robotic object can providethe social cues that passengers expect when entering a vehicle due to their vast past experience. The social interaction with the robot highly contributed to participants' trust and sense of safety. Their trust ratings were higher and they stated feeling "safe," "comfortable," and "confident." A very different experience was reported in the *No robot* condition. Participants provided lower trust ratings, and none of them described the vehicle as safe. A few participants explicitly stated that the vehicle was not safe and expressed their concern about going on a drive in the autonomous vehicle. They reported an emotional experience that involved stress and a lack of confidence.

Participants in the *Robot* condition directly attributed their experience in the AV to the robot. They explained that their sense of safety and trust was due to having "someone" who was "controlling the vehicle," "watching over them," and "making sure they know that the AV is aware of its surroundings." They perceived the robot as an entity controlling the vehicle and appreciated its communication with them. In the *No robot* condition, participants attributed their experience to the absence of the driver or "someone controlling the vehicle." They expressed their concern about the highly irregular experience of being a passenger in a vehicle without a driver. These results further enhance the need to consider passengers' past experiences when designing the experience in an AV. People's already well-established habits as passengers in non-autonomous vehicles create a schema of going for a drive in a vehicle, and the driver who controls the vehicle and communicates with the passengers is an integral part of this schema. Designing an experience that triggers this schema but misses such a central part can easily threaten the experience in the AV and lead to various negative effects (i.e., a decrease in trust and sense of safety).

Our findings suggest that, if designed appropriately, a social robot could assist in overcoming the violation of a passenger's schema when entering an AV. The social cues provided by the robot can support the passenger's need to be noticed and greeted. They can also provide signals indicating that the vehicle is controlled and aware of the environment outside. While a robot would not replace a driver, it could minimize the gap created due to the driver's absence by preserving a somewhat familiar social experience. The possibility of using a social robot to enhance the experience in the AV was further supported by participants' need for companionship. In the *Robot* condition, participants associated their positive experience with the robot's "friendliness" and its "communication" with them. They explicitly stated that it relieved their sense of loneliness in the vehicle. Interestingly, the opposite pattern was observed in the *No robot* condition, where participants reported feeling lonely and explained that this created a negative experience. Therefore, social robots can also be leveraged to comply with passenger expectations and need for a social experience. Previous studies indicated that such a sense of companionship may further contribute to enhancing trust in the AV [15].

Our findings also indicate that the advantages associated with a social robot in an AV can be easily achieved with a very simple (2-DoF) non-humanoid robot. The social experience constructed by the robot's minimal movements was sufficient to provide the signals indicating that the AV is in control and aware of the environment. Despite the lack of language in the interaction, participants perceived the robot as providing companionship, communicating with them, and mediating the AV's intent and status. We note that this simple and easy-to-understand robotic behavior did not require the novel design of a robot for communication with passengers. Instead, we leveraged an existing robot that was initially designed to communicate with pedestrians [6]. By applying small adjustments to the robot's movements, it was possible to design clear social communication with passengers. We, therefore, suggest that using a social robot to enhance an AV experience can be accessible and cost-effective.

Taken together, this work indicates that a social robotic object can compensate for several challenges associated with the absence of a driver in an AV. The robot's non-verbal behavior can provide the missing signals and social atmosphere required for designing a safe and comfortable experience that does not conflict with passengers' well-established past experiences. The human tendency to assign social interpretations to robotic gestures and their flexible design position non-humanoid robots as great candidates for enhancing the experience in an AV by considering and accounting for people's existing habits as passengers. Our novel approach was physically tested on a real roadway with a functioning robot in a real vehicle. The increase in participants' trust and sense of safety suggests that this promising direction should be further explored.

8 LIMITATIONS

This study has several limitations. First, the study focused on the first stages of the experience with an AV without experiencing an actual drive. We acknowledge that this is the main limitation of the study, as participants based their responses on their perception of the drive that was about to take place before experiencing it. However, this allowed us to test participants' responses in an in-person, in-situ setting where they believed that the vehicle was autonomous and that they had the opportunity to experience a drive in an AV. Due to the high impact of opening encounters on the interaction that follows [2], we decided that such an experimental setting was preferred over a more comprehensive simulator experience in which participants are required to imagine that they are going for a drive. Our findings indicated a strong difference in participants' experience based on this initial experience. Future studies should further test the impact of the robotic object during an actual drive in an AV.

Another limitation concerns the external environment. While participants believed that they were about to go for a drive outside the campus, the initial experience took place on the road leading to the parking lot, which had little traffic and few pedestrians. Future studies should evaluate if the impact of the robot on passengers' sense of safety and trust would persist in busier environments that involve other vehicles and pedestrians. Future studies should also explore if the combined effect of the robot with other existing methods for supporting trust could further enhance passengers' experience. As these methods address somewhat different needs, it is possible that a combination of visual displays with a social robot can highly contribute to participants' sense of safety and trust.

Lastly, interviews may be biased by the interviewers' expectations and the "good subject effect" [34, 38]. We minimized this risk by following a strict protocol, ensuring the interviewer used neutral language, and telling participants that all answers were helpful. Indeed, our findings show variance in responses, with participants assigning the experience in the AV as positive in some cases and negative in others.

9 CONCLUSION

We presented the potential of using simple robotic technology to enhance a passenger's experience in an AV. The automatic tendency to perceive non-verbal robotic gestures as social cues positions such a robot as a strong candidate solution for communicating that the AV is in control and can be trusted. Even simple robotic objects can be designed to provide the social cues that passengers expect when entering a vehicle due to their rich experience as passengers in non-autonomous vehicles. This in turn can provide a sense of familiarity when using a highly novel and unfamiliar technology, which is likely to facilitate a positive experience. An AV that would provide a social experience that involves companionship and attention to the environment outside has great potential to enhance passenger sense of safety, increase trust, and assist in overcoming acceptance challenges.

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