VRoad: Gesture-Based Interaction between Pedestrians and Automated Vehicles in Virtual Reality

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AutomotiveUI '19 Adjunct, September 21–25, 2019, Utrecht, Netherlands

ACM ISBN 978-1-4503-6920-6/19/09.
https://doi.org/10.1145/3349263.3351511

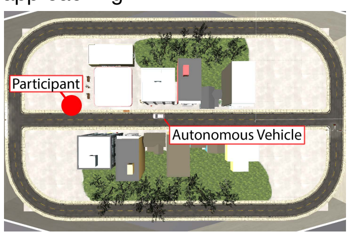
Abstract
As a third party to both automated and non-automated vehicles, pedestrians are among the most vulnerable participants in traffic. Currently, there is no way for them to communicate their intentions to an automated vehicle (AV). In this work, we explore the interactions between pedestrians and AVs at unmarked crossings. We propose a virtual reality testbed, in which we conducted a pilot study to compare three conditions: crossing a street before a car that (1) does not give information, (2) displays its locomotion, or (3) displays its locomotion and reacts to pedestrians' gestures. Our results show that gestures introduce a new point of failure, which can increase pedestrians' insecurity. However, communicating the vehicle's locomotion supports pedestrians, helping them to make safer decisions.

Author Keywords
Automated vehicle (AV), pedestrian-interaction, virtual reality (VR), gestures

CCS Concepts
•Human-centered computing → Human computer interaction (HCI); Gestural input; *Virtual reality;*

Motivation
In recent years, we have seen enormous progress in the field of automated driving. Some of the current cars can al-

(a) The user's view with a car approaching.



(b) An aerial overview of our test environment.

Figure 1: User study in our virtual pedestrian-vehicle interaction environment.

ready take over complex tasks such as parking [15] and are expected to soon take over parts of a ride, such as highway driving [13]. Some countries have allowed higher levels of automation in their traffic or set up test tracks for AVs. However, AVs are not the only actors in traffic. They are embedded in our social space and affect the humans with whom they interact. Vulnerable road users (VRUs), such as pedestrians and cyclists, but also drivers of other vehicles are affected by the automated vehicle and its actions [10]. Cooperation and social acceptance of both human interaction partners are crucial in many situations. Effects such as irritation, anxiety or frustration may be easily invoked by the automated object if this interaction is not done well. The interaction will also impact the individual and the overall societal acceptance of AVs and even pose safety risks. While current interaction concepts focus on communicating the AVs' intentions to outside traffic participants (e.g., [2, 11, 7, 4]), it is not yet clear whether it would be beneficial when pedestrians can also interact with AVs.

The scope of our research is to investigate: **(RQ) How does the communication between pedestrian and vehicle influence the behavior of pedestrians at an unmarked crossing?** We developed a Virtual Reality (VR) testing environment to investigate the pedestrian-vehicle interaction (see Figure 1). Our environment simplifies prototyping and immerses participants into a realistic environment without risk of injury. In a pilot study, we augment AVs with light displays to convey information about the vehicles' locomotion and control the yielding of the vehicle with either a distance sensor or a gesture performed by a pedestrian.

Related work

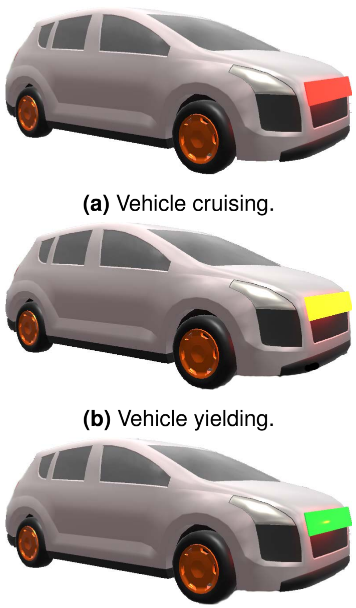
In recent years, we experienced a growing interest in future interactions between vehicles and pedestrians [12]. However, more research is required because communication with pedestrians is an essential ability of AVs and the behavior of pedestrians is hard to predict for an autonomous vehicle, especially in urban environments [14].

Understanding the behavior of pedestrians
Rothenbücher et al. [16] developed a Wizard-of-Oz technique for investigating the interaction between AVs and traffic participants. They found that most pedestrians were able to decide whether or not to cross the road without explicit communication, but also that it is important to acknowledge that a pedestrian was noticed. On the contrary, Dey et al. [5] showed that in cases of manual driving, pedestrians do not look at the driver to make sure they are acknowledged. They also state that explicit communication is rare to non-existent. Instead, they found that motion patterns and behaviors of vehicles play a more significant role for pedestrians in efficient traffic negotiations. However, other studies show that more information exchange between driver/vehicle and pedestrian is necessary [1]. Studies also reveal that behavior of pedestrians is influenced by various factors, such as pedestrians' demographics, traffic dynamics, time [14], and cultural or environmental differences [3].

Communicating the status of AVs to pedestrians
The decision of whether or not to cross relies on visual cues given by the vehicle and not necessarily the driver [16, 3]. For example, Chang et al. [2] equipped cars in VR with eyes to help pedestrians assess if they were acknowledged and showed that pedestrians made quicker decisions and felt safer. This is especially beneficial in situations in which negotiation is needed [6]. Explicit signals help pedestrians to make faster decisions and improve perceived safety in pedestrian encounters with AVs independent of the used interface [11, 7, 4]. Therefore, we will add a visual display to communicate the locomotion of the vehicle in our study, in line with [5].

Interaction between AVs and pedestrians
When pedestrians intend to cross the road at unmarked crossings, it becomes harder for the AV to predict the behavior [1]. Here, pedestrians may be able to support AVs by showing their intent to the AV (e.g., with gestures [4, 9]).

Our Virtual Reality Testing Environment
We created a laboratory environment in VR to reduce risk of injury and enable rapid prototyping of various interaction techniques (e.g., gestures). Our environment consists of of three components: a virtual environment, a VR head-mounted device (HMD), and a VR-capable PC. Using Unity3D, we created a three-dimensional urban part of a city with freely available assets. Figure 1a shows the environment from the user's perspective, Figure 1b from the bird's eye view. Unity3D also makes it easy to enhance the testing environment with other hard- and software. The software is available as open source on GitHub [17].



(a) Vehicle cruising.

(b) Vehicle yielding.

(c) Vehicle stopped.

Figure 2: Light display attached to the autonomous vehicle.

Pilot Study: Gesture-based Interaction
To investigate the road crossing behavior of pedestrians at unmarked crossings, we conducted a pilot study.

Study Design and Procedure
Our pilot study was a within-subjects controlled laboratory study and had one independent variable, Communication, with three levels (*Gesture* vs. *Sensor* vs. *Baseline*). In the *Gesture* and *Sensor* condition, a light display was attached to the front of the car (see Figure 2). The display shows a red color when the vehicle is cruising, an amber color when it is yielding, and a green color when it is stopped. In the *Gesture* condition, participants could stop the car by performing a gesture. For the *Sensor* condition, the car stopped automatically, based on the distance to the participant. In the *Baseline* condition, no light display was active and the car stopped based on distance. The study was divided into three blocks, each block testing one condition. We counter-balanced all blocks across all participants.

Before every block, we explained the tested condition and participants were asked to cross the street a couple of times to become familiar with the condition. In each trial, participants were immersed in our virtual environment including surrounding buildings and a two-lane road with no crosswalk (see Figure 1). Participants were asked to cross the road in front of the AV, generated to their left (cp. Figure 1a). They were told to behave as realistically as possible (e.g., to avoid colliding with the vehicle). The car stopped in every trial unless no gesture was detected in the *Gesture* condition. However, to make the vehicle locomotion less predictable, we tested four trials, with two times 15 km/h (5 seconds to stop) and two times 20 km/h (7 seconds to stop) in a randomized order in each block. After each block, we conducted a Raw-TLX questionnaire [8] to assess the perceived workload. In the beginning and the end of the study, participants were asked to fill out a questionnaire. Each participant took approximately 30 minutes to finish.

Participants
We recruited 10 participants (3 female), aged between 24 and 31 (M=27.2, SD=2.2). 8 participants had tried a VR HMD before. Participants did not receive a compensation.

Results
Experiment observations Each of the 10 participants tested 4 trials, resulting in overall 40 trials per condition. We observed that for the *Sensor* condition, participants crossed before the vehicle more often than for the other conditions (see Table 1). Further, participants had the most difficulties in the *Gesture* condition, where they were sometimes unable to perform the gesture correctly (28/40, 70%), and thus the car did not stop in front of them. Overall, participants crossed the road in 90% of the cases with a light display

Figure 3: A participant performing the stop gesture.

Condition	Result
Baseline	38/40 (95%)
Sensor	40/40 (100%)
Baseline	32/40 (80%)

Table 1: Overview of participants crossing in front of the vehicle per condition.

Condition	Result
Baseline	24/40 (60%)
Sensor	18/40 (45%)
Baseline	10/40 (25%)

Table 2: Overview of participants crossing before the vehicle stopped per condition.

and in 95% of the cases without a display. We also counted how many times participants were confident enough to start walking before the car had completely stopped (Table 2). Interestingly, most of them did so in the *Baseline* condition.

Questionnaires We asked participants to answer questions with 10-point Likert-scale items (10=strongly agree, 1=strongly disagree). Before the study, participants stated that they would feel comfortable as a pedestrian with AVs on the road (Mdn=8, IQR=3) and that they believe that an AV is more reliable than a human driver (Mdn=8, IQR=4). After the study, participants stated that the environment felt like a real road (Mdn=7, IQR=4.5). Furthermore, participants found it easy to interpret the colored lights (Mdn=9, IQR=2). Interestingly, they trusted the vehicle in the *Gesture* condition the most (Mdn=6.5, IQR=2), while trusting the vehicle in the *Sensor* condition (Mdn=5.5, IQR=2.75) and the *Baseline* condition (Mdn=4, IQR=3.75) less. This is interesting because participants struggled with performing the gesture correctly. The light display, however, improved the trust of the participants in the vehicle (P1: "The lights were extremely clear and really helped me.").

Raw-TLX For NASA Raw-TLX [8] scores, the *Baseline* condition scored the best (M=23.0, SD=8.0), the *Sensor* condition scored in between the other two (M=25.5, SD=10.8), and the *Gesture* condition scored worst (M=26.3, SD=10.4).

Discussion

Task performance We observed that the *Sensor* condition worked best for safe crossing behavior. In this condition, all participants crossed before the vehicle and almost half of them were confident enough to cross the street before the car had completely stopped. Interestingly, for the *Baseline* condition, more participants started crossing before the car stopped. We think this is due to the missing light display that did not show a red color when it was distant, and therefore was not communicating that it was unsafe to cross the road. In future work, it might be interesting to turn on the light display as soon as the vehicle detects a pedestrian in order to give additional feedback (similar to [2]) and to use red or amber color only to indicate danger.

Visual feedback The technical issue that participants struggled to perform the gesture to stop the AV revealed a weakness of our approach. In line with previous research [11, 7, 4], we attached a visual display to the front of our AV. However, the display only encoded the state of the vehicle, not if the gesture was perceived correctly. No feedback in combination with technical difficulties led to participants being confused and feeling unsafe.

Virtual Reality The VR environment is useful to test the interaction between pedestrians and AVs because even though the system failed, participants avoided collisions with the vehicle and waited until the car had passed to cross the street. We see this as an advantage of VR.

Conclusion

In our work, we found that participants struggled with performing the gesture correctly and were irritated by missing feedback. This in turn led to a higher workload and more hesitation to cross the road. We did not intend for the gesture recognition to be unreliable and thus can not extrapolate how much the results can be explained by the missing robustness and how much by the idea of using gesture recognition. In the future, we would like to identify more reliable gestures and what kind of feedback AVs need to give.

Acknowledgements

This work was supported in part by NSF CMMI grant 1840085.

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