2019-09-12

Exploring the Design of Autonomous Vehicle-Pedestrian Interaction

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Exploring the Design of Autonomous Vehicle-Pedestrian Interaction

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN COMPUTER SCIENCE

CALGARY, ALBERTA

SEPTEMBER, 2019

ABSTRACT

Autonomous vehicle research today places an emphasis on developing better sensors and algorithms to enable the vehicle to localize itself in the environment, plan routes, and control its movement. Surveying the general public reveals optimism about the technology but also some skepticism about its ability to communicate with vulnerable road users such as pedestrians and cyclists. In today's interaction with vehicles at crosswalks, pedestrians rely on cues originating from the vehicle and the driver. Vehicle cues relate to its kinematics such as speed and stopping distance while driver cues are concerned with communication such as eye gaze and contact, head and body movement, and hand gestures. In autonomous vehicles, however, a driver is not expected to be on-board to provide cues to pedestrians. We attempted to tackle the problem of designing novel ways to facilitate autonomous vehicle-pedestrian interaction at crosswalks. We propose interfaces which communicate an autonomous vehicle's awareness and intent as a means of helping pedestrians make safe crossing decisions.

Through our exploration, we make several contributions. First, we propose a design space for building interfaces using different cue modalities and cue locations. From an early exploration of this design space, we prototype interfaces designed to facilitate autonomous vehicle-pedestrian interaction. The interaction between vehicles and pedestrians will become more challenging during the transition period until all vehicles on the road are fully autonomous. During this period which we term mixed traffic, vehicles of varying levels of autonomy will occupy roads, some of which will have drivers, others

such as semi-autonomous which may have distracted drivers, and fully autonomous vehicles which may or may not have drivers. To study this problem, we contribute a virtual reality-based pedestrian simulator. Our final contribution relates to the evaluation of interfaces in the real and virtual world where we found their inclusion helped pedestrians make safe crossing decisions.

ON THE USAGE OF THE PRONOUN ’WE’

Much of the research described in my thesis was a collaboration between my supervisors, co-authors, and myself. I am very appreciative for their contributions and support over the course of the last two years. To recognize their efforts in shaping my research, I use the pronoun ’we’ throughout my thesis.

PUBLICATIONS

Some ideas and figures have appeared previously in the following publications.

P1 Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James. E. Young, and Ehud Sharlin. (2019). AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. *In Proceedings of the ACM Conference on Designing Interactive Systems (DIS).*

P2 Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. *In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI).*

P3 Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Enabling Pedestrian Communication with Autonomous Vehicles. *In CHI 2018 Workshop - Interacting with Autonomous Vehicles: Learning from other Domains.*

P4 Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Can Interfaces Facilitate Communication in Autonomous Vehicle-Pedestrian Interaction? *In Companion Proceedings of the ACM/IEEE International Conference on Human-Robot Interac-*

tion Pioneers Workshop (HRI).

P5 Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). "Fight-or-Flight": Leveraging Instinctive Human Defensive Behaviors for Safe Human-Robot Interaction. *In Companion Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI).*

ACKNOWLEDGMENTS

I am incredibly indebted to many people in my life who have provided me support and encouragement over the past two years. I owe the most to my supervisor, Ehud Sharlin, for taking me on as a volunteer two years ago. You've provided me with many wonderful opportunities to conduct exciting research, learn new skills, present my work, and travel. Without your support, none of this would have been possible. I also owe a lot to Sowmya Somanath, my co-supervisor, for being actively involved in my research from the beginning. You've constantly supported and encouraged me to pursue every opportunity. I've also learned much about how to conduct research from working with you.

I am especially thankful to have worked in the Interactions Lab which has always felt like a second home and not a workplace. Thank you to all the professors and students (past and present) for helping establish such a positive and fun atmosphere to work in. I've met many amazing people from my time in the lab and the neighboring labs, including, but not limited to: Martin Feick, Markus Tessmann, Jessi Stark, Sandeep Zachariah George Kollanur, Hooman Khosravi, Allan Rocha, Tiffany Wun, Kendra Wannamaker, Claire Mikalauskas, Kevin Ta, Michael Hung, Tim Au Yeung, Brennan Jones, and Katherine Currier. I'd also like to thank all my friends outside the lab for supporting my endeavors, especially Amjad Mohammed and Ellie Sanoubari. Last but not least, I am incredibly grateful to my parents Mahadevan and Lalitha, and my sister Ramya, for supporting me throughout the years.

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INTRODUCTION

1.1 CONTEXT AND MOTIVATION

Autonomous vehicles are vehicles capable of driving themselves without the need for human intervention. These vehicles utilize a complex suite of sensors to understand the world around them (see Figure 1), plan routes based on this understanding, and navigate from point to point. Research in the domain of autonomous vehicles (AV) is at the cusp of transformation from being a purely academic exploration to a viable commercial product. Companies such as Waymo, Google's self-driving car division, have been publicly testing autonomous vehicles since 2009 [1]. Since then, numerous technology and automobile companies have followed suit. Over $80 billion has been invested in the technology [2] and this number is expected to grow substantially in the coming years.

The obvious benefits of autonomous vehicles mean that their introduction will dramatically change the way people locomote. They offer the potential to save the time we currently spend driving, freeing us to engage in other activities. Perhaps more importantly, by eliminating the driver, they could significantly enhance the safety of our roads.

1 https://waymo.com/journey/
2 https://www.brookings.edu/research/gauging-investment-in-self-driving-cars/

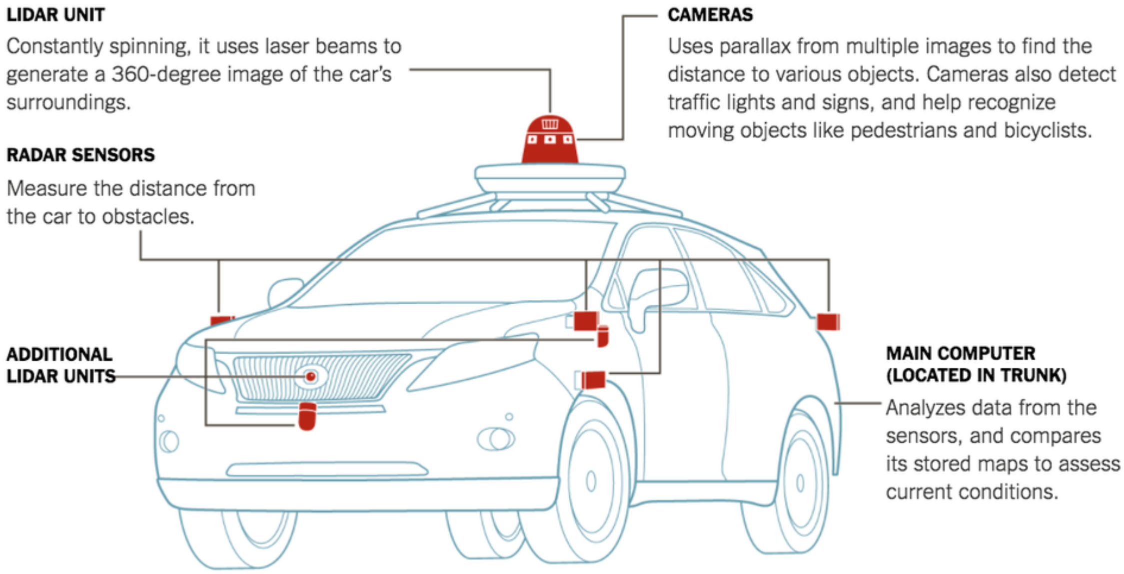


Figure 1: Google self-driving vehicle's sensors. [4].

Traffic data shows that over a million fatalities are recorded globally each year [3] with much of it attributed to human error. These vehicles could also empower those who are currently unable to drive such as those with visual impairments, the elderly, and children.

Surveying the general public reveals several insights about the perception of the technology [27, 55]. Overall, the surveyed audience seem to be optimistic and believe that autonomous vehicles will enhance road safety. Yet, they remain concerned about using such vehicles. Some of their concerns include safety consequences stemming from system failure, legal liability in the event of accidents, system security, and the interaction between these vehicles and other road users such as pedestrians.

The technology enabling autonomous vehicles fuses a bevy of sensors such as cameras, radar, and LIDAR with algorithms to help them make sense of their environment

3 https://www.asirt.org/safe-travel/road-safety-facts/
4 Source: https://nyti.ms/2MwYUfp

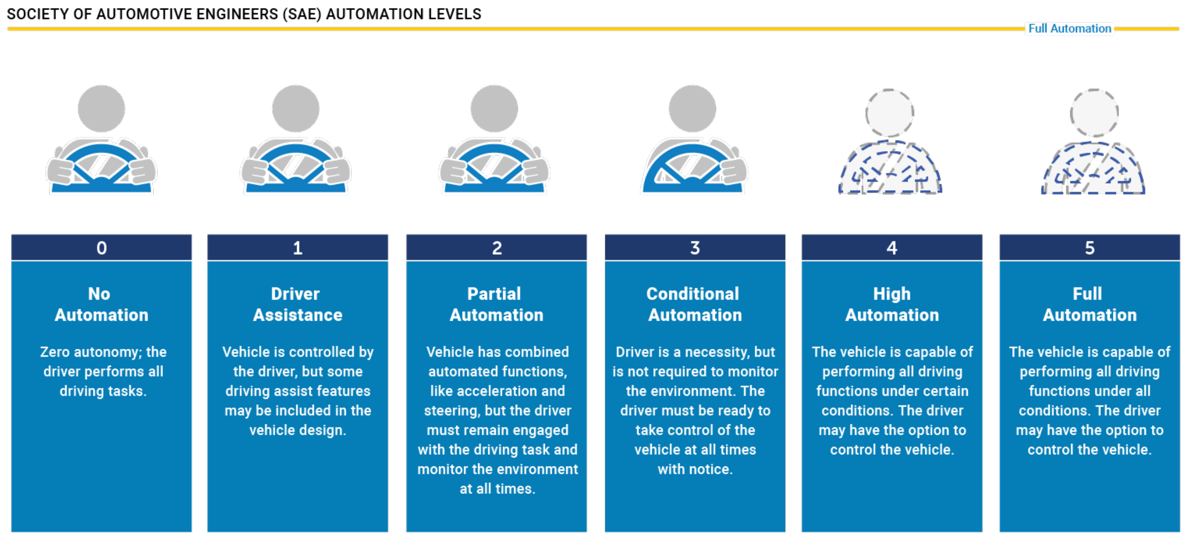


Figure 2: SAE classification of autonomy levels. [5]

and act accordingly. Currently, the research community is placing a significant focus on improving the reliability of the technology through the development of better sensors and algorithms. However, not all concerns echoed by the general public are related to the reliability of the technology. For instance, even if autonomous vehicles are perfectly capable of driving, road users such as pedestrians may need to understand what the vehicle is about to do, primarily upon their introduction when they are still novel. Hence, for autonomous vehicles to gain widespread acceptance, these issues will need to be addressed.

To benchmark the current and future development of autonomous vehicle technology, SAE International [52] has created a classification system (see Figure 2). In this system, today's vehicles are either SAE level 1 or 2 systems while fully autonomous vehicles of the future are SAE level 4 or 5 systems.

5 Source: https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety

In today's urban environments, pedestrians share the road with vehicles and interact with them in many ways. For instance, they may be situated near a crosswalk attempting to hail a taxi or be conversing with someone inside a parked vehicle. More commonly, they may interact with vehicles when crossing the street, especially at unsignalized crosswalks. Our research focus is this interaction in particular - pedestrian street crossing when faced with autonomous vehicles (SAE levels 0 to 5 as Figure 2 shows).

Past work has identified that pedestrians rely on two types of cues when attempting to cross the street, originating from the driver [24, 46] and the vehicle [54, 56]. Cues from the vehicle include information about its kinematics such as speed, deceleration patterns, and stopping distance with respect to where pedestrians are situated. Cues from the driver are another implicit information channel, through which pedestrians receive information about whether they have been seen as well as whether the vehicle will stop for them. These cues may include facial expressions, eye gaze and contact, gesture and body movement, or even voice in some road cultures. In addition to these cues, today's road and vehicle infrastructure, when present, also assist pedestrians in making crossing decisions. These could include traffic lights at crosswalks, pedestrian crossing buttons which may include a visual indication as well as auditory feedback, or vehicle indicator lights. Together, all these cues provide an *interface* or a means of communication [26] between vehicles and pedestrians.

Given that a considerable number of pedestrian fatalities are reported every year [6], it is clear that pedestrians today can face many challenges when attempting to cross the street. Upon the introduction of highly autonomous vehicles (SAE level 4 and 5 [52]), crossing the street may become even more challenging, primarily due to lack of driver-provided cues. During this stage, autonomous vehicles may not carry any passengers

6 https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812681

(such as when these vehicles are en-route to a passenger pickup) or may carry passengers who are not in control of its locomotion. Thus, pedestrians observing these vehicles will not receive useful information about its state or actions. Recent unfortunate incidents such as a jaywalking pedestrian being killed by an autonomous vehicle [7] highlight how significant the loss of driver cues may be.

We also do not expect to see our streets transformed from manually-driven vehicles inhabiting them today to fully autonomous vehicles tomorrow. Instead, we predict that there will be an incremental injection of autonomy on our streets [25]. While today's vehicles will include a driver on-board (SAE level 1, 2, and 3 [52]), eventually, all vehicles will be highly automated (SAE level 4 and 5 [52]). We term this transition period as *mixed traffic* in which vehicles of varying autonomy levels (SAE levels 0 to 5 [52]) may co-exist. During this transition, pedestrians may be further challenged in street crossing. To make a crossing decision, they may first need to distinguish highly automated vehicles from other vehicles. If a vehicle is manually-driven (SAE level 1 or 2 [52]), they could still rely on cues from the driver. If they encounter a semi-autonomous vehicle (SAE level 3 [52]), they may be unsure of who is in control. When seeing fully autonomous vehicles (SAE level 4 or 5 [52]), they will have to make decisions based on vehicle cues alone.

To address the lack of driver-provided cues in autonomous vehicles, some research in the newly founded field of autonomous vehicle and pedestrian interaction suggests that vehicle motion may be enough for pedestrians when making crossing decisions [48, 51]. Contrary to this, some researchers think that we may need to build interfaces to explicitly communicate autonomous vehicle state information to pedestrians [32, 38]. Thus, there is still no consensus on how we can facilitate autonomous vehicle-pedestrian interaction.

7 https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812681

When we began our research, the interaction challenge posed by autonomous vehicles to pedestrians at crosswalks was relatively less explored. Similar to the views held by the latter group of researchers who introduced interfaces [32, 38], we hypothesized that the lack of driver-provided cues in autonomous vehicles might need to be replaced so that pedestrians can continue to cross the street in the future safely. Our hypothesis is supported by research stating the importance of driver cues in the interaction [24, 46] in addition to the fact that motion cues alone may be difficult to perceive in poor weather or lighting conditions. Hence, the problem we attempted to tackle in this thesis is as follows.

PROBLEM STATEMENT: How can we design novel ways to facilitate autonomous vehicle-pedestrian interaction at crosswalks?

We derived several objectives originating from our problem statement:

OBJECTIVE 1: Expand our understanding of how pedestrians make street crossing decisions at unsignalized crosswalks when faced with autonomous vehicles that do not provide driver cues. Our hypothesis is that vehicle cues alone would not be sufficient to aid pedestrians in making their crossing decisions. Instead, we think that interfaces may be required to support the communication of vehicle state information to pedestrians.

OBJECTIVE 2: Explore how we can design interfaces that clearly and unambiguously communicate autonomous vehicle state information to pedestrians. Under our assumption that interfaces may be a potential solution, what information should these interfaces be communicating to pedestrians? How can we design interfaces that transform this complex state information into a simple form that pedestrians can understand and act upon? What cue modalities (such as visual and auditory) can serve us best in communicating state information? Where should these interfaces be situated? For instance, should they lie on the vehicle itself or as part of the street infrastructure?

OBJECTIVE 3: Build and evaluate a platform to study how these proposed interfaces may perform in scaled environments where there are several vehicles varying in autonomy level, as is the case in mixed traffic.

1.3 METHODOLOGY

Since the study of autonomous vehicle and pedestrian interaction is an emerging field, much of the work we describe here is exploratory in nature. However, our exploration in this thesis leans heavily on established techniques in the field of human-computer interaction and human-robot interaction. The backbone of this thesis is the mandate of user-centered design [65], whereby potential users of the technology are involved early and often when attempting to find solutions to a particular problem.

For instance, in brainstorming interfaces for autonomous vehicle and pedestrian interaction (see Chapter 4), we sought feedback from future users of the technology (pedestrians) who were also experts in interaction design research. Their sketches and feedback became the basis of our prototypes.

As this thesis focuses on solving a problem grounded in the physical world, much of our research involved field testing as a means to gauge the success of our proposed solutions. Since this research was conducted at a university, we did not have access to a real autonomous vehicle test platform partly due to monetary constraints but also due to safety concerns. Hence, to evaluate the interaction of autonomous vehicles and pedestrians, we utilized a well-known technique known as Wizard-of-Oz [13]. This technique is widely used in human-computer interaction research when rapid prototyping is desired, and one wants to provide the illusion of autonomous behavior in a system.

We used low-fidelity prototyping to help us rapidly iterate and evaluate proposed interfaces in the context of autonomous vehicle and pedestrian interaction. To measure the success of our prototypes, we utilized a combination of qualitative and quantitative metrics. For instance, we conducted interviews, asked participants to compare interfaces to each other, and quantified their level of comfort in crossing, all of which are qualitative metrics. We also used objective measures such as whether participants indicated that they would like to cross the street only when they were supposed to (i.e. the vehicle is stopping). Finally, we performed statistical analyses of much of our data, some of which was in the 5-point Likert scale [36].

1.4 CONTRIBUTIONS

In this thesis, we attempted to facilitate pedestrians in making safe crossing decisions at crosswalks. We make the following contributions:

1. A design space for building interfaces for autonomous vehicle and pedestrian interaction that proposes cue modalities that can be utilized as well as locations where they can be situated.

2. Interface prototypes designed to facilitate autonomous vehicle and pedestrian interaction based on our early exploration of the proposed design space.
3. The design and validation of a virtual reality-based pedestrian simulator to help study autonomous vehicle and pedestrian interaction in scaled environments such as those presented by mixed traffic.
4. An evaluation through 4 user studies with 42 participants providing support for the usefulness of interfaces in single autonomous vehicle and single pedestrian interaction as well as mixed traffic and pedestrian interaction.

1.5 THESIS OVERVIEW

The contents of this thesis are structured in 9 chapters. Chapter 2 provides a broad overview of relevant research in the domain of pedestrian and vehicle interaction. This includes a summary of the interaction of today's vehicles and pedestrians, early research into facilitating autonomous vehicle and pedestrian interaction, and the techniques being used to study these interactions. In Chapter 3, we detail our preliminary exploration aimed at facilitating the interaction of autonomous vehicles and pedestrians. Prior to placing our focus on the design of interfaces, we took a holistic view when considering solutions to facilitate autonomous vehicle-pedestrian interaction. We touch on several ideas such as the ability for pedestrians to initiate communication with autonomous vehicles as well as techniques for autonomous vehicles to communicate with pedestrians.

In Chapter 4, we describe a participatory design exercise with 10 participants aimed at understanding how we can build interfaces to help autonomous vehicles communicate awareness and intent to pedestrians. Chapter 5 summarizes our initial exploration of the proposed design space in an attempt to build useful interfaces for autonomous vehicle-pedestrian interaction. Here, we highlight the technical implementation of 4 interface prototypes as well as their evaluation on real-world platforms such as a Segway robot and a car.

Chapter 6 describes the process we undertook to design and validate a virtual reality-based pedestrian simulator to study autonomous vehicle-pedestrian interaction in scaled environments. Then, in Chapter 7, we describe how we prototyped and evaluated mixed traffic in our simulator.

We discuss the implications of our research in Chapter 8. Finally, in Chapter 9, we revisit the objectives of this thesis to determine to what extent we have succeeded in fulfilling our research goals. Additionally, we underline some promising directions that future researchers could pursue.

2

BACKGROUND

Researchers have long been investigating how pedestrians interact with vehicles at crosswalks. In this chapter, we review the state-of-the-art literature that studies how pedestrians make street crossing decisions in today's traffic. Based on this understanding, we point to some recent efforts from researchers aimed at facilitating autonomous vehicle-pedestrian interaction. Since traditional vehicle-pedestrian interaction has been studied for decades, we also overview techniques that researchers have been using to evaluate them as well as newer techniques to examine autonomous vehicle-pedestrian interaction.

2.1 CURRENT INTERACTION BETWEEN MANUALLY-DRIVEN VEHICLES AND PEDESTRIANS

Today's streets are governed by well-established rules that detail the role of drivers and other road users such as pedestrians. For instance, vehicles are expected to stop for pedestrians at crosswalks while pedestrians are expected not to jaywalk [1]. These rules work with the implicit assumption that all road users will behave in a responsible and law-abiding manner. There are also several informal rules prevalent in today's interac-

1 https://www.edmonton.ca/transportation/cycling_walking/pedestrian-safety.aspx

tions that drivers and pedestrians follow. For instance, it has been shown that drivers stop well ahead of crosswalks for pedestrians to cross [44] even though the formal rules do not mandate this. Pedestrians aggregate these cues when making crossing decisions, but in particular, rely on *vehicle cues* [54, 56] and *driver cues* [24, 46].

2.1.1 *Vehicle Cues*

Vehicle cues pertain to the kinematics of the vehicle or its motion. For instance, it has been shown that pedestrians may use gap acceptance, or the amount of gap in traffic that they consider safe when deciding to cross [44]. Research shows that this acceptance can be influenced by vehicle speed and distance, both of which are related to vehicle kinematics [14].

Vehicle cues may also refer to non-verbal communication initiated by the driver through movement such as driving forward, turning, or stopping [63]. Some of this movement is derived from social norms. As an example, in a video-based study, Risto et al. placed cameras on pedestrians to observe them in a naturalistic setting [48]. The authors included data from roadways varying in geometry and traffic control type. These included highly controlled four-way stops as well as completely uncontrolled intersections. In their analysis, they found that drivers utilize movement patterns, which manifest due to social norms, to communicate with pedestrians. One of these patterns is *slowing early* or the vehicle slowing down well ahead of the crosswalk to allow pedestrians to cross without ever fully stopping. Another is *stopping short* of the crosswalk so that pedestrians' gap acceptance is maximized, allowing them to feel comfortable in crossing.

Vehicle cues may also be communicated using technology on the vehicle. These include turn signals, emergency hazard lights, headlights, and the horn [21].

2.1.2 *Driver Cues*

Cues that originate from the driver are typically non-verbal. Such cues can be further delineated into 1) facial expression and eye contact, 2) gestures and body movement, and 3) voice and tone of speech [21]. We elaborate on the first two categories as they are most commonly used in these interactions.

Past research has identified that pedestrians attempting to cross the street use eye contact to signal their intention to drivers. When drivers return this eye contact, pedestrians assume they have been seen and that the vehicle will act appropriately [54]. Guèguen, Meineri, and Eyssartier conducted a study in France where pedestrians stood at a crosswalk and fixed their gaze on the driver's face until they stopped [24]. Their results show that overall drivers stopped more often when pedestrians gazed at them as opposed to when they did not. In a study situated in China, Ren, Jiang, and Wang asked confederates to stand by the side of the road and wait for approaching vehicles while varying two conditions [46]. In the first condition, confederates made eye contact with the driver while in the second condition, confederates looked above the oncoming vehicle. Their results suggest that eye contact influenced when vehicles began decelerating despite the fact that the experiment was conducted at a crosswalk where pedestrians did not have the right of way. Sucha, Dostal, and Risser found that a majority of participants in their study conducted in the Czech Republic sought eye contact from the driver, but only a minority of drivers sought eye contact from pedestrians [56] .

Gestures and body movement have also found support in the literature such as in the study by Rasouli, Kotseruba, and Tsotsos [43]. These cues are less commonly used when compared to eye contact but remain useful in situations where there may be some ambiguity about who has the right of way [21].

However, we note some recent work that contends the notion that pedestrians communicate with the driver using cues such as eye contact. Dey and Terken conducted a study at an uncontrolled crossing and on the middle of a street without an explicit crossing [16]. They placed a video camera at the edge of the pavement to collect naturalistic data of pedestrians at the two crossings. Through an analysis of the video sessions, they found that the explicit communication between vehicles and pedestrians was rare leading them to claim that pedestrians did not fixate on the driver but only looked in the direction of the vehicle. AlAdawy et al. conducted two photo-based experiments where they manipulated lighting conditions and distances [3]. In their studies, they found that most participants could not determine the presence of the driver nor the location of their gaze. They suggest that pedestrians are often unable to see through the windshield and make eye contact with the driver and hence rely entirely on vehicle cues alone.

2.2 SUPPORTING AUTONOMOUS VEHICLE-PEDESTRIAN INTERACTION

From prior work, there exists support for driver cues as well as vehicle cues in facilitating street crossing decisions. While there is some research suggesting that eye contact is not a cue that pedestrians and drivers use, measuring this effect is difficult in practice due to current limitations in eye-tracking technology. In highly autonomous vehicles (SAE Level 4 and 5 [52]), a driver is not expected on board so, even if no eye contact is sought, the lack of the driver's presence may still have an impact on pedestrians' crossing. In such vehicles, there may also be passengers on board. However, their actions may not map to the vehicle's current state. This could increase the complexity of making crossing decisions.

Researchers have recently begun investigating techniques to facilitate autonomous vehicle-pedestrian interaction in the absence of driver cues. We think that there are two distinct approaches that could be pursued to generate solutions. The first could be to allow pedestrians to initiate communication with autonomous vehicles as necessary. The other is assisting autonomous vehicles in initiating communication with pedestrians, which is the focal point of current research in the domain, and is highlighted below.

2.2.1 *Utilizing Vehicle Motion*

One mechanism to design for the loss of driver-provided cues in autonomous vehicles is by recognizing that motion is an invaluable cue that pedestrians already utilize when they make street crossing decisions. Rothenbücher et al. suggest that for autonomous vehicles, specialized interfaces for communicating missing driver cues may not be needed for the majority of pedestrians [51]. In their study, pedestrians were faced with a Wizard-of-Oz operated autonomous vehicle inside of which the driver wore a seat-cover costume. They found that most participants adhered to existing interaction patterns with manually-driven vehicles unless there was a breakdown in expectations of what the vehicle should be doing. Similarly, AlAdawy et al. state that pedestrians primarily rely on vehicle cues in deciding when to cross [3].

As we mentioned earlier, Risto et al. found that in today's roads, drivers use vehicle motion to signal their actions to pedestrians [48]. They suggest that developers of autonomous vehicles consider this when designing algorithms for vehicle movement. They also note that driving culture plays a huge role in the kinds of movement patterns drivers use.

Ackermann conducted multiple studies aimed at determining whether pedestrians can reliably detect deceleration maneuvers [2]. Their studies were video-based, and participants were asked to press a button when they sensed the test vehicle slowing down. Their study results show that pedestrians can detect deceleration rates fairly easily, although more abrupt deceleration rates are easier to spot than smooth braking patterns.

Pillai experimented with three vehicle driving behaviors in virtual reality in which the vehicle: 1) gradually slows down as it approaches the crosswalk, 2) suddenly slows down as it nears the crosswalk, and 3) suddenly speeds up before slowing down [41]. In their study, participants stood at one side of a crosswalk and walked over to the other side when electing to cross. They found that participants felt comfortable when faced with the first behavior and uncomfortable with the latter two. This work provides further proof that vehicle motion is already being used by pedestrians to gauge whether a vehicle is operating correctly or intends to stop.

Zimmermann and Wettach suggest that autonomous vehicles will be seen as social actors since they will share the road with manually-driven vehicles, especially in the transition period to full autonomy [72]. Hence, there will be an expectation that these vehicles behave similarly to vehicles with drivers. Parallel to work by Pillai [41], they prototyped the following motion behaviors on a small-scale autonomous vehicle: 1)"Peak", 2) "Valley", and 3) "Flatline" (as seen in Figure 3). Through a study, they found that these motion patterns elicited feelings such as trust and fear in participants. Considering these results were achieved with a small-scale vehicle, they provide interesting reflections about the power of motion in evoking emotion among road users.

Schmidt et al. suggest the use of motion to provide social cues to pedestrians [53]. They prototyped several vehicle behaviors, some that matched the social expectations of pedestrians and others that were mismatched. Behaviors matching social expectations

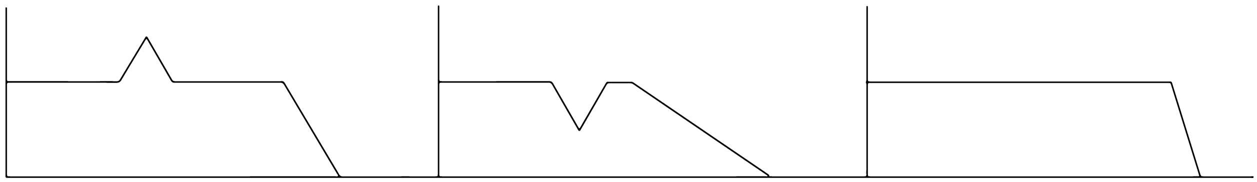


Figure 3: Our rendition of the figure by Zimmermann and Wettach [72] illustrating the motion behaviors of "Peak", "Valley", and "Flatline".

had motion trajectories that encouraged pedestrians to cross. Others varied between behaviors that appeared unusual to more malicious ones. They found that trajectories which provided adequate time for participants to cross resulted in success, even if some of these subverted social expectations. Their work supports the notion that vehicle kinematics are perceived as social cues to pedestrians and are a useful starting point for the design of algorithms that can support pedestrians.

Overall, we find that there is a growing body of literature utilizing motion cues to help pedestrians make safe crossing decisions at crosswalks and believe that it is an important cue in supporting the interaction. However, a caveat of the highlighted work on motion is that their studies were conducted under clear, daylight conditions in the real and virtual world. In such situations, it is easy for pedestrians to observe vehicle cues. Under poor lighting or weather conditions, vehicle movement may no longer be sufficient. We contend that interfaces can be designed such that they remain useful even in these conditions, which we highlight in this thesis.

2.2.2 *Explicit Communication Interfaces*

The idea of replacing driver-provided cues in autonomous vehicles through interfaces exists in industry and in academia. In 2015, Google patented the idea of pedestrian notifications, whereby the vehicle assesses a pedestrian's intentions and responds by explicitly communicating awareness and intent cues [59]. Car manufacturers such as Mercedes [2] and Nissan [3] have also proposed their visions for autonomous vehicle interfaces. The Mercedes F105 concept utilizes laser projection and an LED display. The laser projection alerts pedestrians of the vehicle's awareness and communicates to pedestrians when the vehicle is about to stop, while the LED display communicates the current state. Nissan's IDS concept utilizes visual cues in two ways: an LED indicator strip on both sides of the vehicle provides information about its awareness of pedestrians while a text display on top of the vehicle provides information about its intent.

To compensate for the loss of driver-provided cues, researchers have also proposed the design of explicit interfaces. Lagström and Lundgren placed an LED strip on the windshield of a vehicle [32, 37]. This LED strip could be lit using different patterns and was intended to communicate whether the vehicle was operating autonomously, about to stop, resting, or about to start. In a study, participants stood at the side of a crosswalk and observed the vehicle augmented with the LED strip. The interface was found to be effective in assisting pedestrians in understanding whether the vehicle was operating autonomously and to predict its next action. They argue that vehicle movement alone is not enough to compensate for the loss of driver cues in autonomous vehicles and suggest the use of specialized interfaces such as the one they prototyped.

Matthews et al. built an intent display with audio cues on a remote-controlled golf cart [38]. This interface provides suggestions to pedestrians through messages such as "Cross Now". They conducted a study in a parking lot where they found that the display helped pedestrians understand the vehicle's intent and trust it more.

Chang et al. prototyped animated eyes on a vehicle in VR [7]. They conducted a study where participants either saw a vehicle without an interface or a vehicle with eyes in

2 https://www.mercedes-benz.com/en/innovation/research-vehicle-f-015-luxury-in-motion/
3 https://www.nissanusa.com/vehicles/future-concept/ims-autonomous-car.html

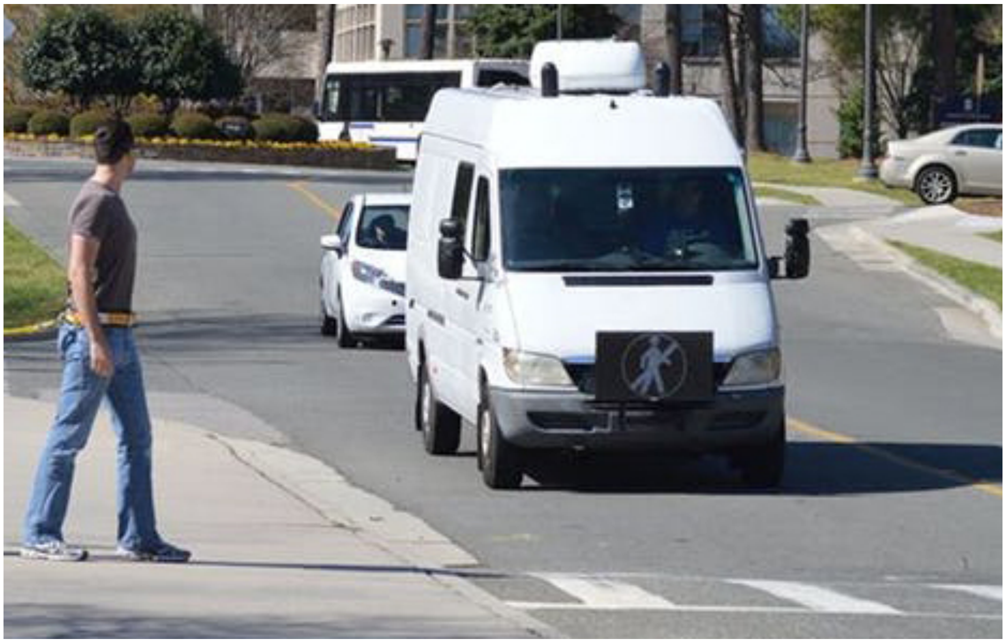


Figure 4: Interface display showing the symbol "don't cross" (Source: Clamann, Aubert, and Cummings [10]).

the place of headlights which made contact with them. Their findings illustrate that participants were able to make faster crossing decisions with an increased feeling of safety when encountering vehicles embedded with the interface.

Clamann, Aubert, and Cummings designed and mounted a display on a vehicle that communicated intent cues in two ways: 1) through the road symbols "cross" or "don't cross", and 2) through the speed of the vehicle [10] (see Figure 4). In their study, participants stood at the side of the crosswalk in either a legal crossing position (near the crosswalk) or in a jaywalking position and waited for the test vehicle to appear. After seeing the vehicle, participants were asked to indicate when it was safe to cross. The authors conducted the study with the two interface conditions, a no-interface condition, and a condition where the vehicle had a driver on board. In contrast to the aforementioned works, they concluded that gap distance and crossing strategies that pedestrians had developed over time influenced their decision making more than the display.

From our early exploration of the literature, we found that the role of interfaces is still unclear; some researchers suggest using vehicle movement alone while others suggest building interfaces. While we think that interfaces may be a suitable solution and are influenced by past work, we extend these ideas by providing a more thorough and systematic exploration of the possibilities that exist to build these interfaces.

2.2.3 *Personifying Autonomous Vehicles*

Past research has identified that people ascribe human-like characteristics to technology through a phenomenon called *The Media Equation* [45]. Even without being intentionally designed in such a way, autonomous vehicles may be treated in a similar manner. In the domain of social robotics, researchers have looked at ways to design robots with a personality, by borrowing from classic taxonomies that describe personality such as the Big-Five [29]. For instance, researchers have proposed an iterative design process to endow personality in robots by combining technical, artistic, and user-centered approaches [39]. Their process involves creating a personality profile for the robot, prototyping it on a platform, and iterating it with user feedback until it is desirable. While personifying an autonomous vehicle to enhance the passenger experience has been examined [66], it has yet to be explored in the context of autonomous vehicle-pedestrian interaction. However, there are many perceived benefits of doing so, such as the ability to more intuitively communicate with road users. We provide an early exploration of personification in Chapter 3.

2.2.4 *Social Robot Navigation*

As we pointed to earlier, researchers have attempted to understand the social norms that exist in the interaction between drivers of today's vehicles and pedestrians. In turn, some of the work we highlighted incorporate these norms in autonomous vehicle movement to ease pedestrians in crossing. Researchers in social robotics have also looked at similar ideas but in the context of mobile robots navigating among people, which they term social robot navigation (Chapter 8 in [57]). Social robot navigation gives considerations to social conventions through ideas such as personal spaces (for individuals) and interaction space (between groups of people) [47]. We note, however, that social robot navigation has yet not been directly applied to the problem of autonomous vehicle-pedestrian interaction at crosswalks but promises to be useful.

2.3 Evaluating Vehicle-Pedestrian Interaction

2.3.1 *Today's Interaction*

Researchers have been studying the interaction of vehicles and pedestrians for decades. In the process, several evaluation methods have emerged, some of which have stood the test of time and remain used today such as written questionnaires [42, 69], interviews [11], and observational studies [48]. When safety needs to be ensured, video-based studies are also occasionally used [42]. We refer readers to a more detailed account of several methods that researchers have used and continue to use [44].

2.3.2 *Autonomous Vehicle-Pedestrian Interaction*

The most commonly used technique of evaluating autonomous vehicle-pedestrian interaction today is Wizard-of-Oz [13]. Through this technique, researchers present manually-driven vehicles as autonomous vehicles to user study participants. Through an operator, the vehicle appears to behave autonomously. Lagström and Lundgren added a driver feedback LED monitor to help the operator remain updated on what the vehicle should be doing [32]. Additionally, in their studies which were conducted in Sweden, they installed a dummy steering wheel on a right-hand drive vehicle so that participants would not suspect that a driver (in the passenger seat) was actually in control of the vehicle. Rothenbücher et al. hid the operator entirely using a seat-cover costume so that the vehicle appeared autonomous in their study [51]. Clamann et al. did not hide the driver in their study. Instead, they informed participants that the operator was only there to handle emergencies that could arise where driver intervention was required [10].

Recently, virtual reality (VR) has gained popularity as a tool to examine traditional vehicle-pedestrian interaction. Bhagavathula et al. compared pedestrian behavior in real and virtual environments [5]. They conducted a study where participants made crossing decisions when faced with a vehicle approaching a crosswalk and varied the environment between real and virtual between tasks. At a certain distance, the vehicle flashed its headlights and passed passengers, after which they answered questions such as whether they would have crossed at that moment. Overall, the authors found that there were mostly no differences between the environments, except in the case of speed estimation and the feeling of presence. This suggests that VR could be a suitable tool to examine this complex interaction. Deb et al. built a simulator utilizing the HTC Vive VR headset and the Unity game engine [15]. They conducted a study in which participants attempted to safely cross a virtual signalized intersection under different conditions: 1) no car, 2) stop, 3) near-miss in front, 4) near-miss in back, and 5) hit. They found that participants followed real-world convention, such as hesitating when a vehicle broke the rules of the road. Participants also recorded a high VR presence score indicating that such simulators can offer an immersive experience.

Researchers have recently begun employing VR to study specific problems pertaining to autonomous vehicle-pedestrian interaction such as trust. Jayaraman et al. conducted a study where they varied driving behavior and the presence of signalized and unsignalized crosswalks [28]. Their findings suggest that the presence of signalized crosswalks can increase trust in autonomous vehicles. They also found that pedestrian trust deteriorates more quickly when vehicles drive aggressively at unsignalized crosswalks. Recently, researchers have also utilized VR to build and test interfaces to facilitate autonomous vehicle-pedestrian interaction as we briefly highlighted in Sections 2.2.1 and 2.2.2. We leveraged this technique in our research to study the effects of scale and mixed traffic.

2.4 CHAPTER SUMMARY

In this chapter, we elucidated how pedestrians interact with vehicles today through vehicle cues and driver cues. We outlined some early work aimed at facilitating autonomous vehicle and pedestrian interaction through motion and explicit communication interfaces and spoke of the potential of personification and social robot navigation. We then reviewed some of the evaluation methods being used to study the interaction of vehicles and pedestrians today and in the future. Our review of the literature led us to identify that the role of interfaces for facilitating autonomous vehicle-pedestrian is still unclear. Some researchers propose the use of vehicle movement alone while other researchers propose explicit interfaces. Thus, our work focuses on clarifying the role of interfaces for the interaction.

3

PRELIMINARY EXPLORATION

As we briefly discussed in Chapter 1, the loss of driver cues upon the introduction of autonomous vehicles could dramatically alter the dynamics of vehicle and pedestrian interaction at crosswalks. In Chapter 2, we briefly highlighted the two approaches that may be used to facilitate autonomous vehicle-pedestrian interaction: 1) by way of pedestrians initiating the communication and 2) autonomous vehicles initiating the communication. In this chapter, we detail our first attempts for both approaches.

3.1 APPROACH 1 - PEDESTRIANS INITIATING THE COMMUNICATION

3.1.1 *Leveraging the Instinctive Human Response*

Today's robots (including autonomous vehicles) are becoming increasingly autonomous and independent entities. Hence, they are expected to behave in a safe and consistent manner, especially as some of their abilities (such as perceiving their environment) begin to surpass those of humans. In turn, this means that humans will have a smaller role in their operation [70]. While it is clear that autonomous vehicles are rapidly becoming more intelligent, they are far from matching human performance when faced with uncertainty. For example, autonomous vehicle perception breaks down in bad weather or lighting conditions or when faced with faded or covered lane markings. These are perception tasks that humans are currently better at. Thus, the functionality of autonomous systems could be compromised by the quality of the data they sense, algorithms that govern their behavior, and their computational prowess.

Given that robots can fail in uncertain situations, we wanted to explore whether humans could intervene as a fail-safe mechanism. In the context of automation in industrial settings, the classic fail-safe mechanism for operators is hitting a "kill switch", an easily accessible button designed to power it down. However, using such a mechanism with robots would effectively end any interaction between them and humans, which cannot be restored quickly.

Similar situations may arise when autonomous vehicles are faced with pedestrians at crosswalks. If we assume, as some of the related work does in Chapter 2 that vehicle cues are sufficient for pedestrians attempting to cross when faced with autonomous vehicles, then the interaction may mostly proceed smoothly. However, there may be instances where the vehicle does not behave as it is supposed to, due to a malfunction or because it violates the expectations of a pedestrian. For example, it is possible that the vehicle may stop too close to a pedestrian or too abruptly. While an easy solution may be to implement a "kill switch" for the pedestrian to use in these cases, there may be more subtle ways through which humans can inform autonomous vehicles of their unsafe behavior (which they may fail to recognize) and help them correct it. In this manner, the human-robot interaction can continue instead of ending abruptly. As a preliminary exploration, we propose leveraging humans' instinctive "fight-or-flight" responses - defensive maneuvers they take when faced with imminent threat [6] to assist in unsafe situations posed by robots such as autonomous vehicles.

3.1.1.1 *Background*

Lasota, Fong, and Shah surveyed the robot safety literature [33] and found that there are currently four major categories of methods to maintain safe human-robot interaction (HRI): 1) safety through control, 2) safety through motion planning, 3) safety through prediction, and 4) safety through the consideration of psychological factors. Most of these methods approach the problem of safety from a technical competency perspective - the better the technology that is involved, the safer the interaction can be. However, a robot may still behave imperfectly at times. Safety methods that determine whether an intentional or unintentional collision is occurring [23] may suffer from a momentary lapse in obtaining the data or an inaccuracy in collecting it. Such a lapse may, for instance, result in the robot misclassifying a collision as intentional and prevent it from activating its safety mechanism in a timely manner.

Past research in neuroscience suggests that humans display instinctive defensive behaviors when they perceive a threat. Several factors may influence this instinctive human response [6]. These may include the escapability of a threat, distance from a threat, and the ambiguity of the threat stimuli. Varying levels of threat stimuli may provoke different types of human defensive behaviors such as "run away", "attack", and "yell, scream, or call for help".

3.1.1.2 *Study Methodology and Procedure*

We conducted a design study to understand how we might incorporate the instinctive human response to unsafe situations posed by autonomous vehicles in their interaction with pedestrians. Our session was inspired by the technique of Research through Design (RtD) [71]. The hallmark of this technique is that interaction designers can make research contributions in the form of design artifacts that transform the world from its current state to the desired state. Here, design artifacts can be prototypes, models, products, or documentation.

We asked 5 interaction design researchers in the age range of 18 to 35 to brainstorm novel mechanisms to deal with various unsafe robot behaviors across several scenarios. All participants were recruited on a university campus through word of mouth and received a cash remuneration of $20. We briefed participants on the potentially dangerous scenarios arising from interacting with several autonomous platforms (see Figure 5): 1) an autonomous vehicle, 2) the Baxter humanoid, 3) the Roomba robotic vacuum cleaner, and 4) the NAO humanoid. While autonomous vehicles were our primary interest, we included other robotic platforms to prompt interesting solutions reflecting on size, form, functionality, and perceived intelligence.

To commence the session, we asked participants to reflect on how they would respond to a potentially dangerous situation posed by each of the platforms. We also asked them to design mechanisms through which they could communicate their concern to the robot as well as mechanisms that the robot could use to respond to their concern. We encouraged participants to demonstrate their mechanisms through low fidelity prototypes, which could include sketches or enactments. To aid the prototyping process, we provided them with office stationary such as pens, sticky notes, and sheets of paper.

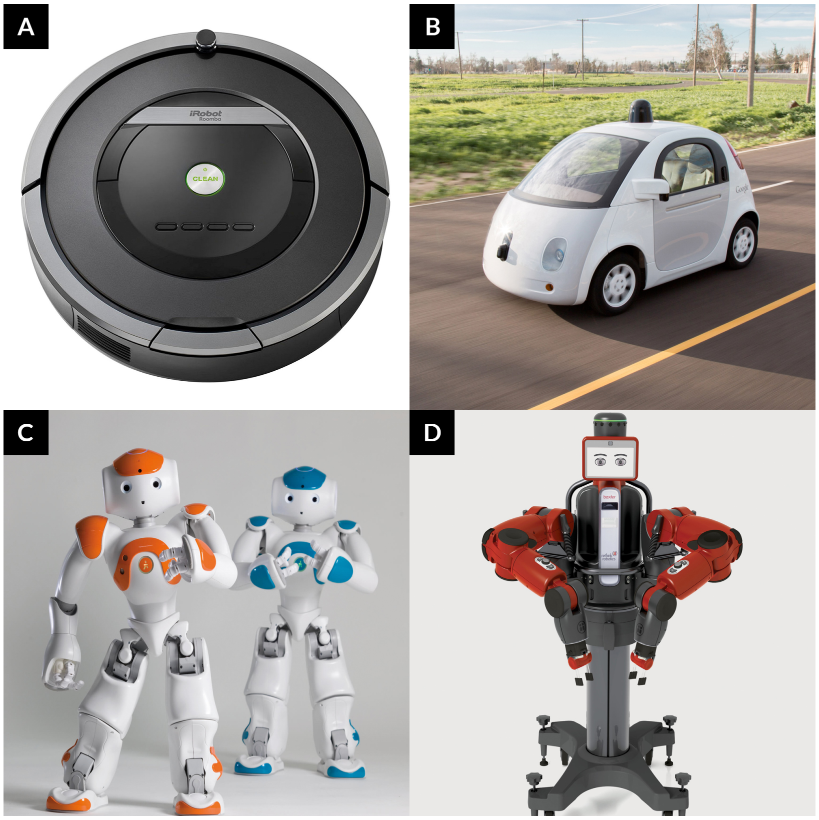


Figure 5: Platforms that participants brainstormed interfaces for: A - Roomba robotic vacuum cleaner, B - Autonomous Vehicle, C - NAO humanoid, D - Baxter humanoid.

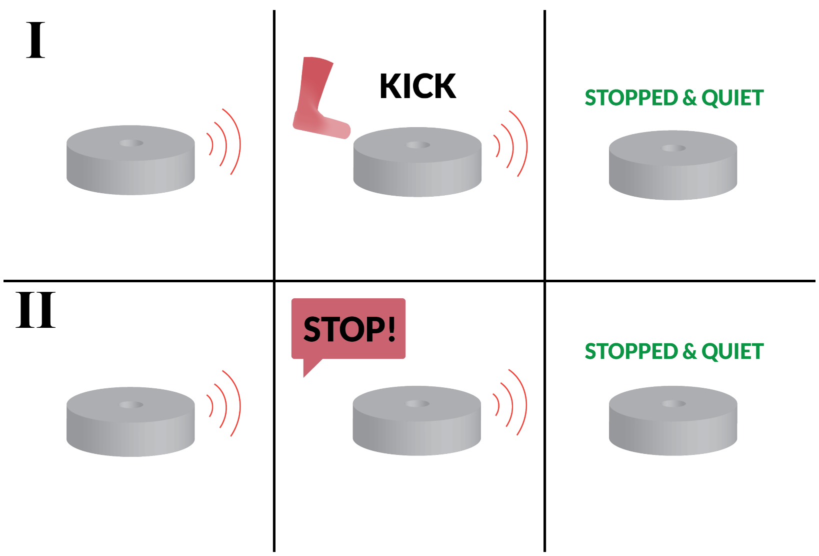


Figure 6: Participants' sample low-fidelity design idea reflecting on human response to a robotic vacuum cleaner acting unsafely.

3.1.1.3 *Implications for Autonomous Vehicle-Pedestrian Interaction*

We employed qualitative research methods to analyze the video-recorded session. We used open coding to identify common threads in participants' discussion [8, 22]. Examples of codes we used were, "initiating physical contact with robot", "form factor of robot", and "rate of approach". We identified two major criteria that participants used to ascribe threat levels in an interaction with a robot: form and rate of approach. Participants strongly associated form with the threat level a robot poses. For instance, a Roomba may run over a person's leg but would not cause them significant harm. Conversely, autonomous vehicles and the Baxter robot pose significantly more danger. Participants also associated a robot's rate of approach to its threat level. Roombas are easy to see "coming" since they are slow and follow random trajectories. However, autonomous vehicles can accelerate to significant speeds and become menacing as they approach people.

Participants proposed different solutions to handle potentially dangerous situations posed by the 4 platforms. As an example, participants proposed initiating physical contact prior to the Roomba hitting them to instantaneously initiate a stopping mechanism (see Figure 6). Participant 1 was quoted saying, "I don't feel bad about kicking it if it is endangering me". Similar ideas were echoed towards the NAO robot. However, participants vehemently opposed the idea of initiating any physical contact with autonomous vehicles as a stopping mechanism. Instead, they suggested indirect mechanisms such as gesturing, altering their body pose, or auditory commands to convey their concerns. As autonomous vehicles include sensors such as cameras, these techniques may be feasible and applicable in an event where a pedestrian notices that the vehicle is about to do something wrong, but the combination of its sensors does not detect it. Through simple actions taken by the human, the vehicle could be alerted of the problem.

3.1.2 *Interfaces for Pedestrians to Initiate Communication*

As we described in Chapter 1, in the transition period until full autonomy, pedestrians will have to gauge cues from manually-driven vehicles (through a driver on-board) as well as autonomous vehicles that do not provide driver cues. Figure 7 presents how this transition may unfold from the pedestrian perspective. Today, pedestrians mostly use implicit cues to communicate with drivers (such as eye contact and body movement) and occasionally explicit cues such as voice and hand gestures. In turn, drivers return these cues, which helps pedestrians cross safely. However, in the transition period where some vehicles will be autonomous, and others will have drivers, pedestrians may continue to use these cues but will not receive any feedback from vehicles that are autonomous.

Pedestrians mostly use such cues when attempting to cross but can also use them to indicate a change in their decision or to allow vehicles to pass them even when they have the right-of-way. Imagine a pedestrian situated near a crosswalk, engaged in conversation with another pedestrian. A quick look at their body language would inform a human driver that it is safe to continue driving. However, a risk-averse autonomous vehicle may stop after identifying the pedestrians and cause traffic to halt unnecessarily. Promising research in deep learning [19] suggests that this problem will eventually be solved such that autonomous vehicles can detect subtle body movement and implicit cues that pedestrians use. At the same time, prior research also suggests that there is no such thing as an average pedestrian [64]. Thus, aggregating the behavior of individuals from different pedestrian cultures into a unified model for vehicles to learn may be difficult.

We suggest a potential solution for the short-term through the use of specialized interfaces that pedestrians can utilize to communicate with autonomous vehicles in their

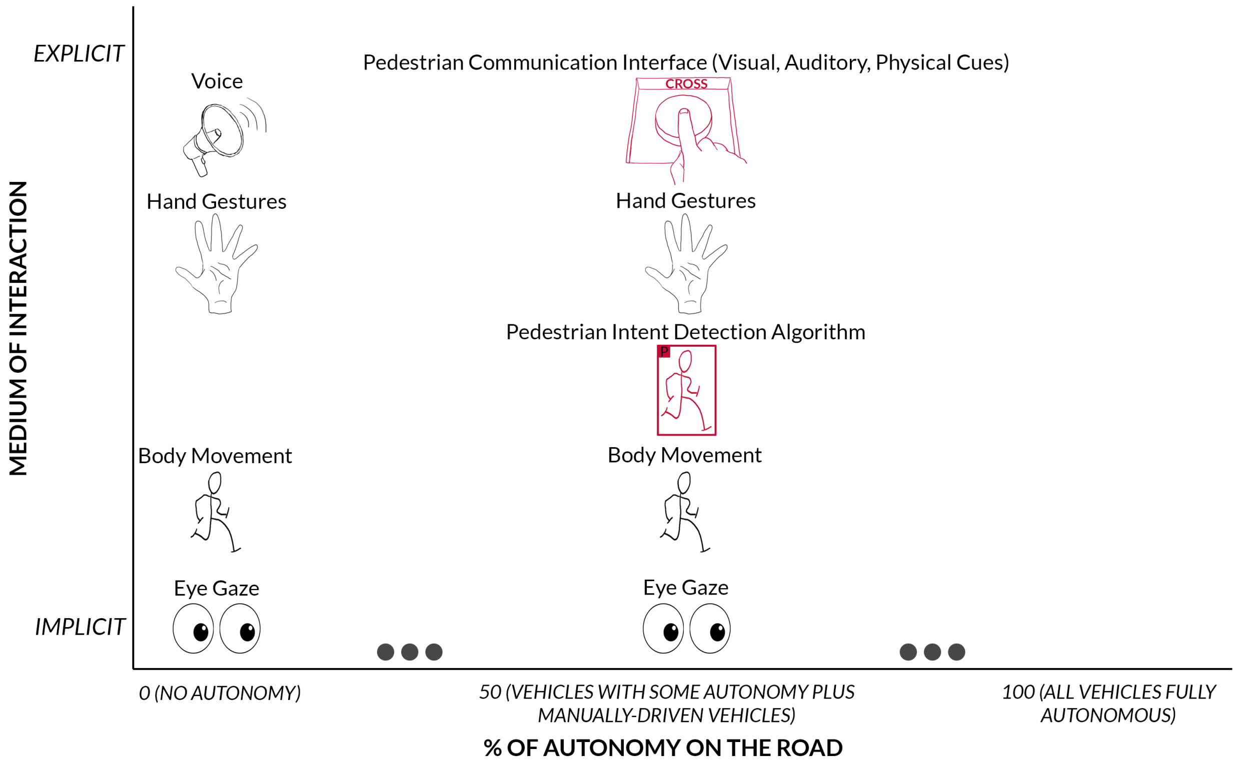


Figure 7: Mediums of interaction that a pedestrian may use, from implicit to more explicit, when faced with varying levels of vehicle autonomy.

vicinity. Even though autonomous vehicles do not provide explicit cues, pedestrians can use such interfaces to let the vehicle know what they intend or do not intend to do. Such interfaces can be particularly useful in certain situations. For instance, a specialized interface or an embedded one such as on a pedestrian's smartphone may allow them to signal if they change their mind about crossing the street or when they would like to cross (especially at unsignalized crosswalks). Of course, the design of the interface is an open research question as is an assessment of whether pedestrians would feel comfortable using it. Further, in mixed traffic where there are vehicles varying in autonomy level occupying the same street, pedestrians may need to use two types of cues when they encounter vehicles with differing levels of autonomy; when faced with manually-driven vehicles, they would use familiar cues such as eye gaze and gesturing, but to inform autonomous vehicles, they would need use the interface. This may increase pedestrian workload and may lead to its disuse.

3.2 Approach 2 - Autonomous Vehicles Initiating the Communication

3.2.1 *Personality as an Intentional Design Choice*

Trust is a crucial factor in enabling technology to gain widespread acceptance [9, 34]. In a similar manner, autonomous vehicles would need to be trusted by people before they become commonplace. Research exploring the factors that could influence the widespread acceptance of autonomous vehicles has identified several distrust factors that need to be addressed [35]. One of these distrust factors is the lack of information from the vehicle about its next actions or the inability to reason about its actions. This is especially important for pedestrians who will share the road with autonomous vehicles and are used to communicating with drivers.

The current design of autonomous vehicles focuses on minimizing its range of expressivity. In some ways, this can be good because all vehicles would look and drive in the same manner. However, there is the potential to increase their expressivity so that they are more understandable and trustworthy. Personifying autonomous vehicles would give them the ability to communicate more than just their state (such as stopping or not stopping). Vehicles such as an ambulance transporting an ailing patient, a vehicle that is about to be hijacked, and a police vehicle pursuing criminals may need to act aggressively and unpredictably at times. Through interfaces, they could communicate that they are not planning to stop, but through personality, they could also convey urgency without surprising or shocking other road users.

By embodying a personality, autonomous vehicles will have the ability to navigate tough social interactions with people and other vehicles. Since there is limited prior research on how autonomous vehicles may be designed to exhibit personality, we sought inspiration from science fiction. We aimed to answer the question: *what lessons can we learn from the depiction of autonomous vehicles in science fiction?*

3.2.1.1 *Methodology*

We considered movies and TV shows as they provide a visual depiction of futuristic autonomous vehicles. We chose the following pieces of science fiction: *Knight Rider, Inspector Gadget*, *Total Recall*, *Demolition Man*, *The Fifth Element*, *Minority Report*, and *I, Robot*. We also included two animated films that are not classified as science fiction but feature human-like autonomous vehicles: *Cars* and *Who Framed Roger Rabbit*.

3.2.1.2 *Design Considerations*

We coded thematic elements that commonly appear in these pieces of fiction [8]. We found that the depiction of personality assumes significant technological advancements in artificial intelligence and natural language processing. Since today's technology is not yet at that level of sophistication, it would be a challenge to replicate. Still, we found many design considerations that came to light from analyzing these sources of fiction.

Personifying the vehicle using techniques to mirror the passenger's personality or complement them could be a potential way of enhancing the user experience [61]. However, from a pedestrian's perspective, personification should not necessitate vehicles with unique profiles. This could present a nightmare to pedestrians attempting to understand

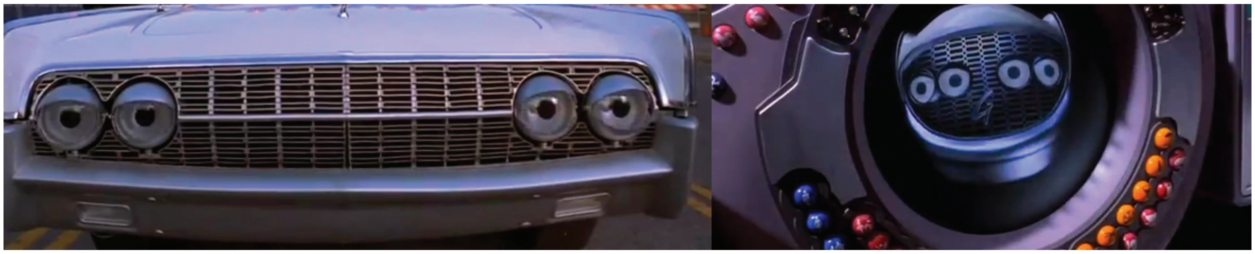


Figure 8: Embodiment of personality on the Gadgetmobile from Inspector Gadget through anthropomorphic eyes.

and trust autonomous vehicles. Instead, by building a consistent and recognizable set of behaviors, autonomous vehicles could employ them depending on the situation. For instance, if a pedestrian attempts to jaywalk, the vehicle could express disapproval. If this behavior is recognizable and consistent with what pedestrians expect, they would be able to reason that the vehicle's response is a consequence of their actions.

The level of embodiment needed to convey the personality of autonomous vehicles is very much an unexplored question. Today's vehicles embody personality through the driver and their actions. With social robots, anthropomorphism or human-likeness is a technique that can be used to embody personality. Past research suggests that vehicle design already employs anthropomorphism [17] such as the headlights of vehicles which resemble human eyes. However, there may be other ways to enhance how anthropomorphic these vehicles appear, perhaps through dynamically altering the vehicle's exterior.

Other mechanisms of personifying the vehicle may involve placing visual cues that can be modified. Visual, anthropomorphic cues such as eyes appearing on headlights as shown in the Gadgetmobile (see Figure 8) could convey emotions like anger or sadness. Motion is a less anthropomorphic cue that could also convey personality or mood. Zimmermann and Wettach experimented with velocity curves designed to convey different vehicle behavior such as "aggressive or unyielding", "predictable or yielding", and "uncertain or confusing" [72]. These associations were reaffirmed by participants in their study, suggesting that motion may be used to convey complex yet expressive behavior. However, this mechanism requires further investigation as an erratic motion that is not well understood by pedestrians could be construed as a vehicle that is malfunctioning.

3.3 CHAPTER SUMMARY

In this chapter, we reviewed some of our early attempts to facilitate safe crossing decisions for pedestrians when faced with autonomous vehicles. Solutions fitting the first approach assume that motion cues could be enough for the interaction except in specific situations where the pedestrian initiates a change. Personifying the vehicle (for the second approach), however, suggests that explicitly anthropomorphizing the vehicle and creating behaviors may be a powerful approach that could supersede the idea of building explicit interfaces for the interaction.

Most of this work is theoretical and did not result in physical prototypes, field deployments, or user evaluation, so it is difficult to ascertain whether any of these solutions are suitable. While leveraging instinctive human defensive behaviors is certainly promising, the current design of autonomous vehicles focuses on ensuring the safety of road users at all costs. Thus, vehicles that are uncertain of what they sense may come to a stop well before a situation become dangerous, and pedestrians would not need to act as a fail-safe mechanism. Further, any subtle interactions that pedestrians could use cannot be implemented with high fidelity due to current technological limitations. We think that although this solution is promising for specific situations, it may only be feasible in the longer-term future.

Designing interfaces to allow pedestrians to communicate with vehicles is also an interesting avenue of research. However, giving every pedestrian the ability to signal their actions to vehicles may bring new challenges. For instance, even if a single pedestrian accidentally changes an interface's state, vehicles nearby may be forced to stop. It may also mean that these interfaces would need to be embedded on the pedestrian when they are at crosswalks. If the interface is on a smartphone that has a low battery level or without reception, pedestrians would be unable to communicate with the vehicle at that moment. Even if such interfaces are functional, their performance in scaled environments where pedestrians may only be targeting a few vehicles of several is unknown.

Personifying autonomous vehicles offers an immense potential to make them more expressive. However, differences in road and pedestrian culture may present challenges in finding universally agreeable behaviors. These behaviors would also require significant testing before they can be placed in the real world.

Ultimately, we delved into the design of explicit communication interfaces for autonomous vehicle-pedestrian interaction. A significant reason why is that the technology needed to build interfaces which reflect the vehicle's state exists today. Further, interfaces can communicate a vehicle's state at every instant and are thus useful in most situations that pedestrians could encounter. Finally, pedestrians today are already used to reading vehicle and driver cues and reacting to them when crossing, so interfaces may be a natural extension.

4

AN INTERFACE DESIGN SPACE FOR AV-PEDESTRIAN INTERACTION

As we stated in Chapter 2, some researchers have proposed the use of explicit interfaces to facilitate street crossing decisions for pedestrians when faced with autonomous vehicles. Others have suggested that vehicle motion alone may be sufficient (see Chapter 2). Given that the role of interfaces in this interaction is still ambiguous, it became the focus of our exploration. Our hypothesis was that interfaces could be a suitable solution for facilitating autonomous vehicle-pedestrian interaction. Prior to evaluating the role of interfaces, there are several questions that remain unanswered. Assuming that interfaces are the solution, what information should they communicate with pedestrians? How should this information be communicated through these interfaces? We were also interested in understanding where such interfaces should be located, whether on the vehicle or elsewhere. We conducted a participatory design study with interaction design researchers where we probed these questions.

4.1 PARTICIPANTS

We recruited 12 participants for our study (7 male and 5 female). Due to a change in our study protocol and a participant refusing to provide consent, we discarded the data of 2 participants, leaving us with 10. The participants were aged 23 to 47 and had varying levels of research experience, from senior undergraduate students to postdoctoral scholars. At the end of the session, we provided them with a remuneration of $20.

4.2 STUDY PROCEDURE

We utilized a participatory study method called PICTIVE [40], where participants reflect on interface designs by sketching or altering existing sketches provided by researchers. Through PICTIVE, end-users (potential pedestrians) were provided with an early opportunity to pen their ideas on paper about the target implementation technology (interfaces for autonomous vehicles). In our efforts to utilize PICTIVE, we created renditions of a vehicle and pedestrian crossing scenario at a controlled intersection from two views - front and side (see Appendix B). These sketches played the role of a shared design surface on which participants put forth their ideas. To assist participants in creating their interfaces, we made eight labels of commonly-used design cues. Some cues were derived from prior work proposed for autonomous vehicle communication interfaces (such as LED lights and laser projection) while other cues were chosen as they are commonplace in user interface design. The labels were: haptic feedback, communication methods such as WiFi and Bluetooth, display, motion, speaker, actuator, laser projection, and LED. In addition to the labels, we provided participants with office stationary such as pens, sticky notes, and tape, so that they could place their labels on the design sheet and annotate them. The study setup can be seen in Figure 9. Each study was conducted in two phases: a paper prototyping session and an interview session.

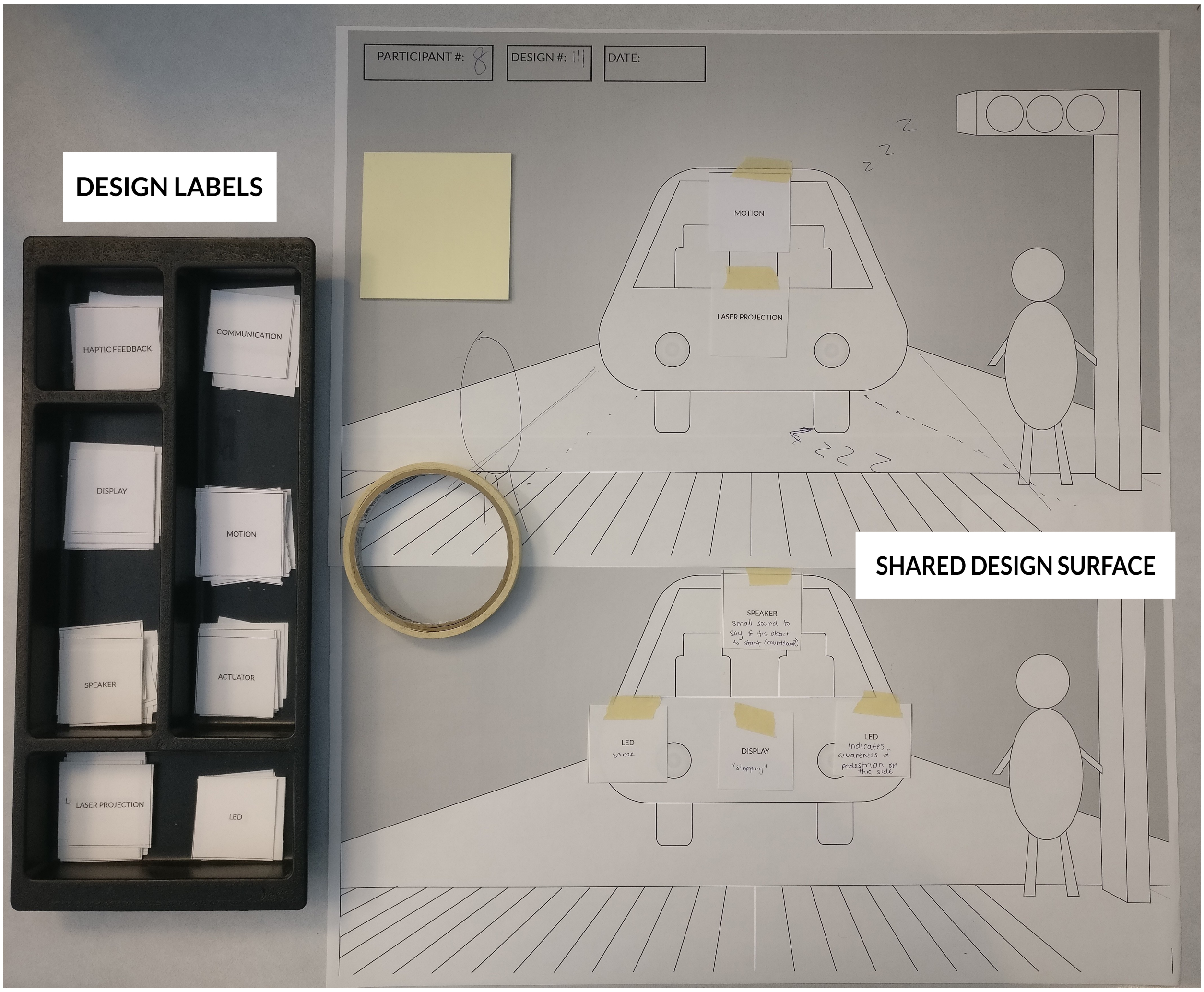


Figure 9: Design study setup showing two designs from participant P8.

4.2.1 *Paper Prototyping*

Once participants reached the study location, they provided consent to be involved in the study and completed a pre-study questionnaire. Then, we began video recording the session. Participants were first briefed about the design sheets and labels. Then, they were introduced to the terms awareness and intent. Awareness was described as the car providing acknowledgement to the pedestrian that it has seen them. Intent was described as the car communicating its next action to the pedestrian (such as stopping). We included these two terms as our hypothesis was that both awareness and intent would be important in the design of interfaces. Next, we allotted participants thirty minutes to create three interface designs that communicated the awareness and intent of an autonomous vehicle to pedestrians attempting to cross a street. We encouraged participants to use any of the provided labels or define their own. Participants placed labels on the design surface according to their real-world location (such as placing the LED label on the windshield of the vehicle). Participants were allowed to utilize all parts of the design surface, including the vehicle, the pedestrian, the crosswalk, or the traffic signal to house their interface elements. We also allowed participants to create designs that were iterative and which built off of previous designs. We asked them to describe their design process through a think-aloud protocol during the session [60].

4.2.2 *Interviews*

After participants created their prototypes, we presented them with eight events in which the vehicle had to communicate its awareness and intent to pedestrians, seen in Table 1. These events were designed to give a holistic view of the role of potential interfaces, not just in street crossing, but in a variety of situations in which pedestrians may interact with autonomous vehicles. For each event, we asked participants to rank their designs as a best, fair, or worst fit in being able to navigate the interaction successfully. Participants could then propose changes to improve their interfaces.

Event	Description
1	Red light - stopping
2	Turning with pedestrian walk sign - waiting
3	Parking lot - resting
4	Amber light - vehicle continuing
5	Jaywalker spotted - stopping
6	Bad road conditions - not stopping
7	Parking lot - reversing
8	Pedestrian spotted - uncontrolled intersection

Table 1: Events participants assessed in the design study.

4.2.3 *Data Sources and Analysis*

We collected designs from each participant and video-recorded their session. Afterwards, we transcribed all 10 sessions and utilized open coding to identify patterns emerging from participants' designs [8]. Then, two researchers (including myself) independently applied a coding schema to the designs and transcripts to ensure consistency in the analysis. Additionally, we counted the number of designs that incorporated the communication of awareness only, intent only, and both, as well as the themes present in each. We further categorized the designs we received into more abstract themes. The first category was the responsibility distribution for communicating to the pedestrian - the car is fully responsible, the pedestrian is fully responsible, or a mix. Another was the location of the interface cues - on the vehicle, on the vehicle and street infrastructure, on the vehicle and pedestrian, or on the vehicle, street infrastructure, and pedestrian. To identify these themes, we leveraged the technique of open coding [8].

Sample designs: We provide a debriefing of 3 of the 34 unique participant-provided designs. Seen in Figure 10, participant P5 placed anthropomorphic eyes in the front and back of the vehicle through a display. The eyes provide awareness information to the pedestrian (that they have been seen). Through LEDs on the front and back of the vehicle, the vehicle communicates its intent, such as whether it is about to stop as well as turning information.

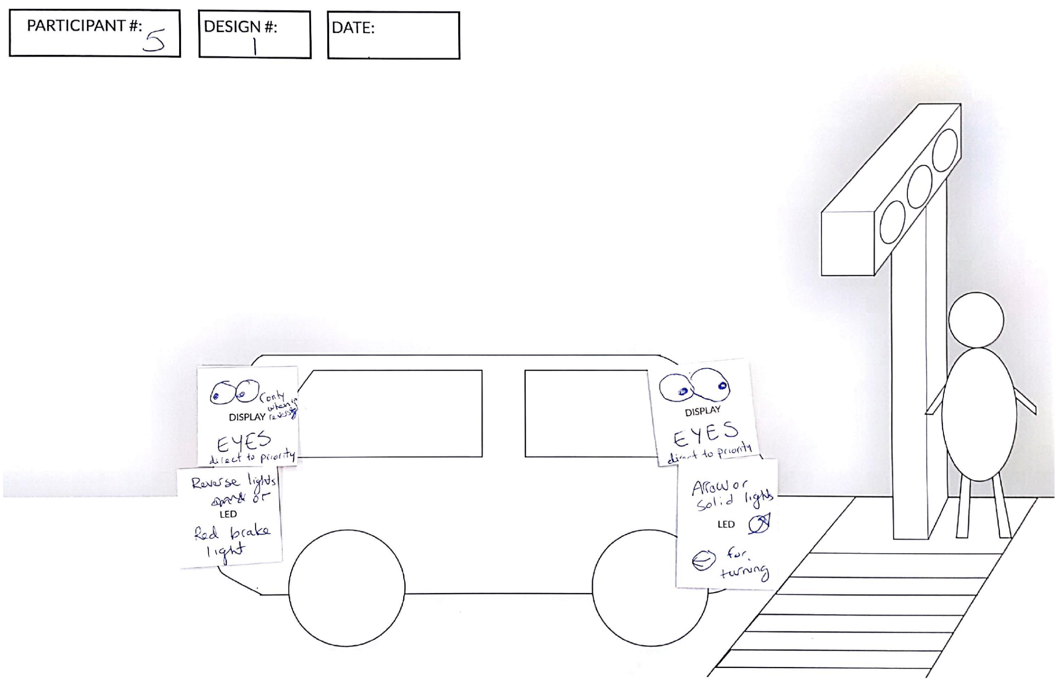


Figure 10: Sample design from participant P5 featuring cues on the vehicle.

In participant P12's design (see Figure 11), a speaker on the vehicle and traffic light, and a haptic cue on the traffic light, both provide intent information to the pedestrian. The speaker on the vehicle is meant to be omnidirectional and provides information

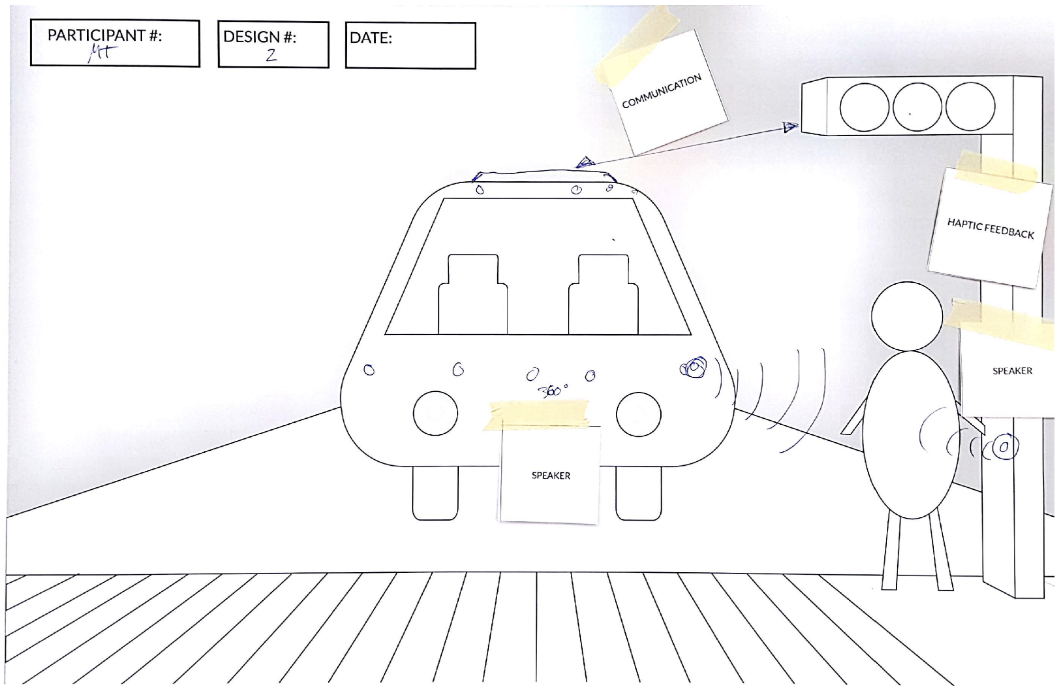


Figure 11: Sample design from participant P12 featuring cues on the vehicle and street infrastructure.

to pedestrians based on where they are currently standing. The speaker interfaces with the traffic light so that both sound cues operate synchronously. Here, the sound cue chosen are phrases such as "go ahead please". Additionally, there is haptic feedback on the traffic light, which is commonly used today. This feedback is also synchronized with the vehicle's intent cues.

Participant P10's design (see Figure 12) deals with the situation where there are several vehicles on the street which are autonomous. A speaker on the vehicle indicates its intent to pedestrians. In case of pedestrian distraction, the design also features direct communication to the pedestrian's earphones. The sound cue chosen to communicate intent is beeping patterns (which may present a steep learning curve for pedestrians). Additionally, in the side view of the same design (see Figure 13), the participant also

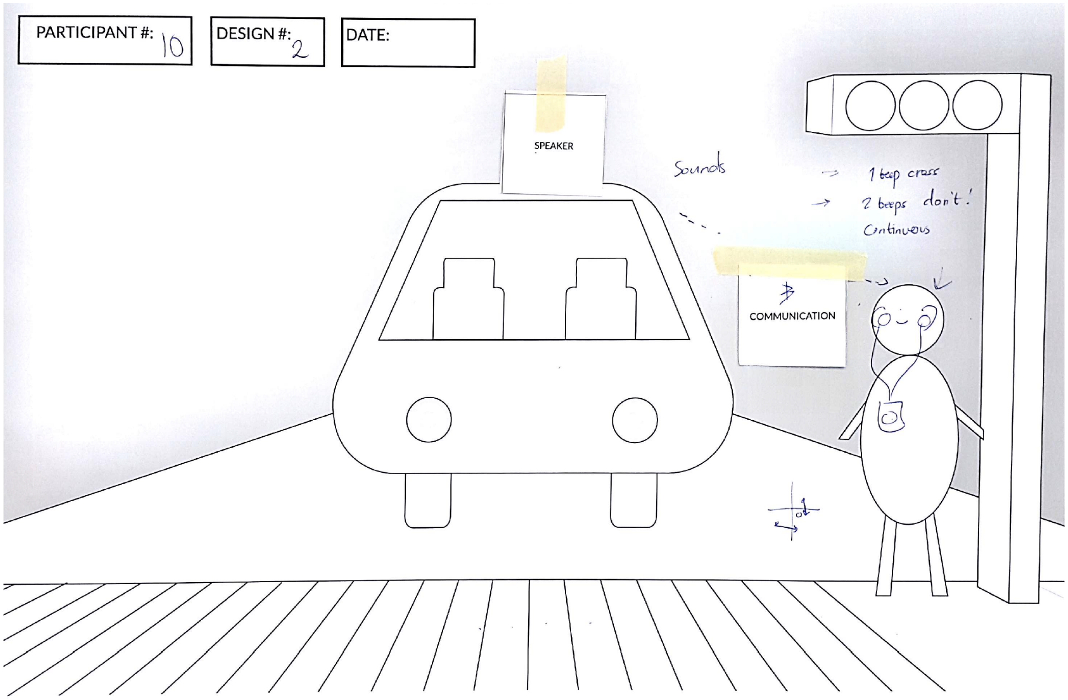


Figure 12: Front view of sample design from participant P10 featuring cues on the vehicle and pedestrian.

incorporated a display on the side of the vehicle that could provide simple intent information such as "go" or "don't go". This interface only provides intent cues to pedestrians and omits awareness communication.

From the 34 designs we received from participants, all incorporated the communication of vehicle intent while 22 designs featured the communication of vehicle awareness and intent. This provided us with early evidence that awareness and intent may both be important for pedestrians while also hinting that intent may be more important.

Findings: We reviewed all the designs and categorized the themes present, as seen in Table 2. To communicate awareness, participants used a visual display most commonly (in 9/34 designs), whereas to communicate intent, participants most commonly used an LED strip (in 14/34 designs). More interestingly, we also received designs from partici-

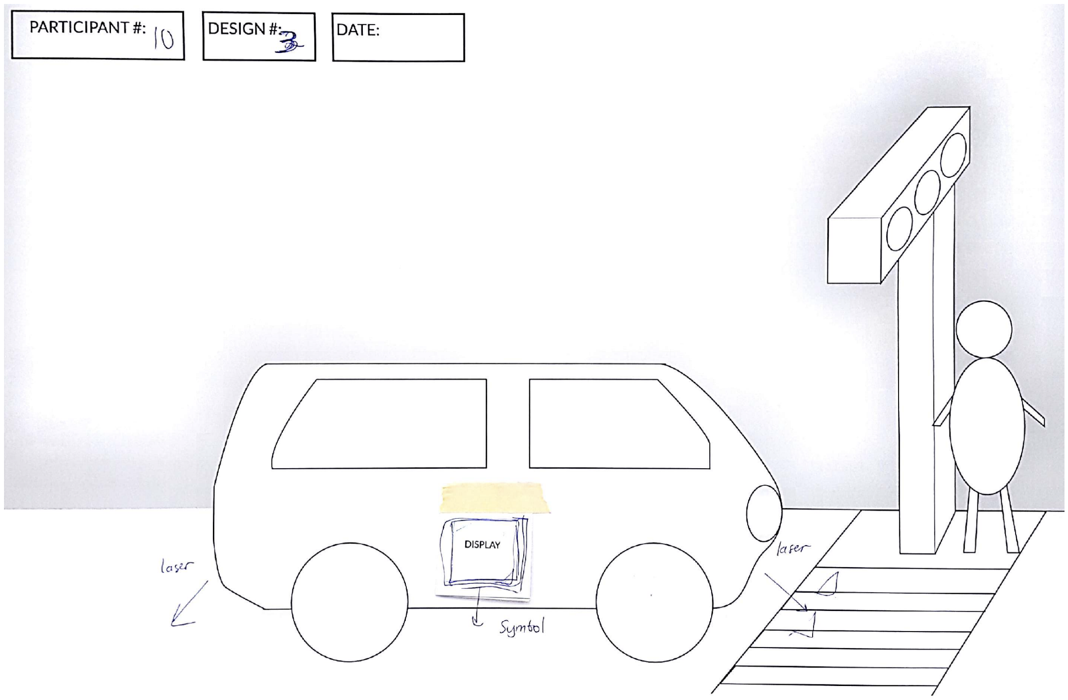


Figure 13: Side view of sample design from participant P10 featuring cues on the vehicle and pedestrian.

pants that featured other cue modalities to assist pedestrians who may suffer from visual impairment such as haptic feedback and auditory messages. Nearly all participants borrowed from cues that people are already familiar with. One participant said, *"I don't want to add more to the pedestrian or driver workload, so using cues they are already familiar with is better to train them" [P3]*. Participants also utilized other familiar cues that were anthropomorphic. These designs (10/34) featured the use of cues such as hand gesturing, eye gaze, and verbal messages. Motion appeared in 10/34 designs to communicate awareness and intent.

Through the analysis of participants' designs and interviews, we propose a design space to build interfaces for autonomous vehicle-pedestrian interaction, shown in Figure 14. The design space has two dimensions. The first refers to the modality of cues that can be utilized. We found three cue modalities that participants used in their designs - *visual, auditory,* and *physical*. The *visual* modality primarily leverages cues such as color, patterns, and text, which pedestrians can perceive visually. The *auditory* modality aims to provide auditory feedback through verbal and non-verbal messages. The *physical* modality may leverage visual cues but primarily provides additional feedback through actuation or vibration (such as through an actuated artificial hand or haptic feedback through smartphone vibration). The second dimension refers to the location of cues that make up the interface. From participants' designs, we found that interfaces could lie

Theme	**Instances**
Display to show awareness	9
Display to show intent	6
Projection to show awareness	3
Projection to show intent	10
Communication not trustworthy, possibility of failure	1
Communicating awareness through actuation	1
Communicating intent through actuation	3
Communication between car and embedded technology on human	9
Bracelet and sound to aid the visually-impaired	1
Motion to communicate awareness and intent	9
LED to communicate awareness	5
LED to communicate intent	14
Haptic feedback for awareness	1
Haptic feedback for intent	1
Speaker for awareness	1
Speaker for intent	11
Use of new/upcoming technology	2
Use of communication to communicate awareness/intent	3
Motion capture sensor to detect gestures	1

Table 2: Themes that emerged from analyzing the designs in the study.

Cue Category	Cues	Vehicle-Only	Vehicle & Street	Vehicle & Pedestrian	Mixed
Visual	Display with road signs/symbols				
	Display with text				
	Embodiment of human face/eyes on display				
	LED strip on car				
	Projecting lines on street				
	Projecting car speed				
	Google Glass on pedestrian				
	Traffic lights				
Auditory	Human-like voices				
	Nonverbal sounds				
	Car sounds				
	Bracelet w/ speaker on pedestrian				
	Pedestrian's phone playing message/sound				
Physical	Car lowering/rising				
	Actuated hand				
	Movement/motion of car				
	Haptic feedback on bracelet				
	Haptic feedback of pedestrian's phone				
	Haptic feedback on traffic light				

Figure 14: Proposed design space emerging from the design study featuring various cue modalities and cue locations.

on the vehicle alone, vehicle and street infrastructure, vehicle and pedestrian, or on a combination of the three.

Vehicle-Only: these interfaces involve placing cues on the vehicle, such as an LED strip or a display. The responsibility of communicating with pedestrians rests entirely on the vehicle (see Figure 10).

Vehicle and Street Infrastructure: these interfaces involve the placement of cues on both the vehicle and street infrastructure, including but not limited to, traffic lights, laser projection on the street, and the road on which the vehicle traverses. This interface type divides the responsibility of communicating cues between the vehicle and street infrastructure (see Figure 11).

Vehicle and Pedestrian: these interfaces incorporate cues on both the vehicle and pedestrian. An example of such an interface is the use of haptic feedback on a pedestrian smartphone, through which they receive direct feedback about the vehicle's state (see Figs. 12 and 13).

Mixed: interfaces in this category leverage a combination of cues from the previous categories. Cues in this interface lie on the vehicle, street infrastructure, and the pedestrian.

4.4 CHAPTER SUMMARY

In this chapter, we described a participatory design study we conducted to better understand how to build interfaces and where to place interfaces to facilitate autonomous vehicle-pedestrian interaction. Through this study, we propose a design space to assist in prototyping such interfaces through two dimensions - cue modalities and cue locations.

5

EVALUATING INTERFACES FOR AV-PEDESTRIAN INTERACTION

5.1 INTERFACES: DESIGN AND IMPLEMENTATION

We proposed a design space to aid prototyping interfaces for autonomous vehicle-pedestrian interaction in Chapter 4. Looking at the design space (Figure 14), there are infinitely many ways to build interfaces that utilize a combination of cue modalities and locations. In this thesis, our goal was not to test all combinations of cues as this is infeasible. Instead, as a starting point, we implemented 4 prototypes that encompass several of the possibilities that the design space affords. The concept of using a smaller subset of instances to demonstrate a design space is a valid methodology as discussed by Wiberg and Stolterman [68]. To implement these interfaces, we chose cues that could be easily prototyped using readily available off-the-shelf hardware (such as an LED strip, a speaker, and a motor for actuation).

The 4 prototypes were fundamentally different in terms of the locations where cues were placed (on the vehicle, street infrastructure, and pedestrian). To select the cues for each interface, we included popular elements as suggested by our participants from the design study (see Chapter 4). We also ensured that all cue modalities were represented

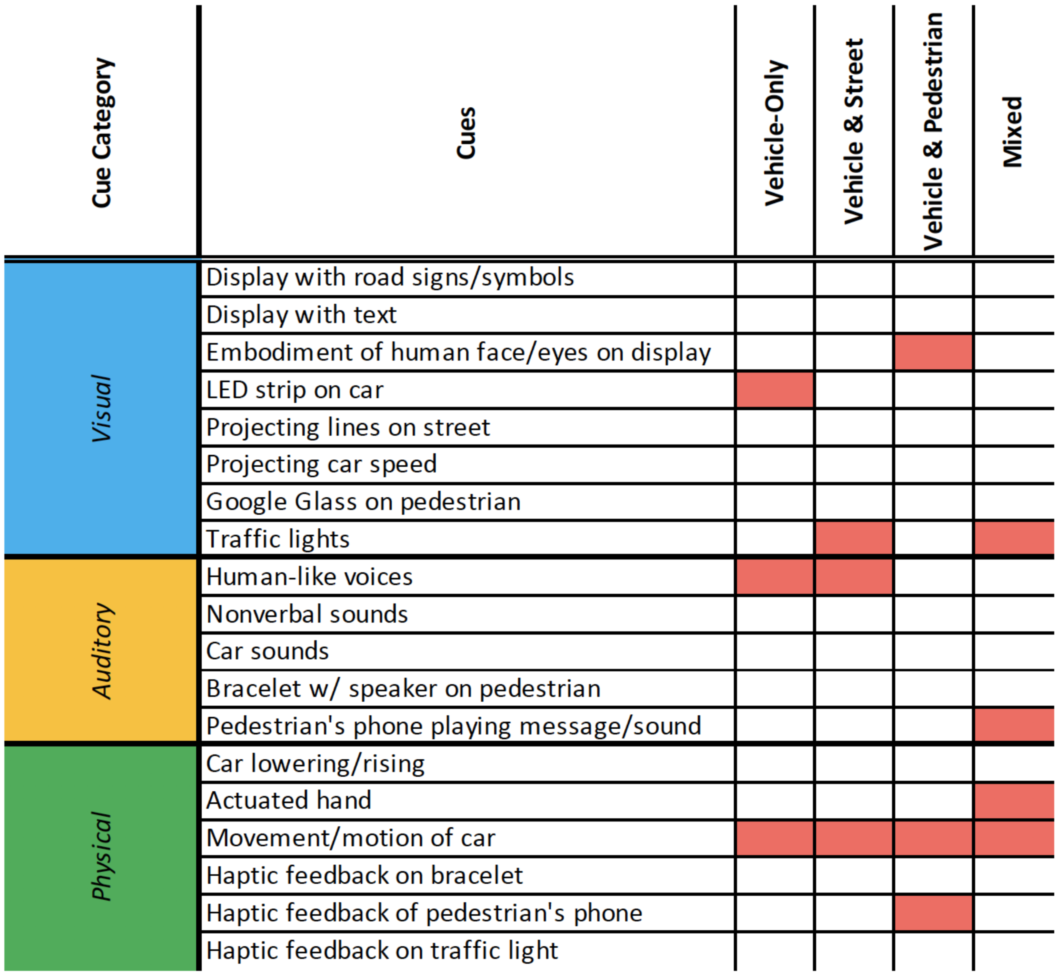


Figure 15: Proposed design space showing the cues chosen (in red) for each interface prototype.

(visual, auditory, and physical) as well as all cue locations. The final choice of cues and locations is shown in the Figure 15.

In all the prototypes, we incorporated awareness and intent cues. Vehicle movement was also present in all the interface prototypes. Similar to the work by Risto et al. [48], we utilized common social behaviors that drivers exhibit today in their interactions with pedestrians, such as stopping short at a crosswalk. To build the prototypes, we used a combination of hardware such as Arduino microcontrollers and components such as LED light strips and programmed them to function accordingly. The prototypes were implemented on two different platforms, a Segway robot and a car, and evaluated through user studies which we describe in this chapter.

5.1.1 *Prototype 1: Vehicle-Only*

This interface prototype featured cues placed only on the vehicle (see Figure 16). The cue modalities included were visual and auditory. We used an LED strip and a speaker to represent these modalities respectively. We mounted the LED strip on the vehicle, which exhibited four states:

- Solid red lights indicated that the pedestrian should not cross as the vehicle was moving.
- Blinking blue lights indicated that the vehicle was aware of the pedestrian.
- Green lights flashing from left to right indicated that the vehicle had come to a full stop and that it was safe for pedestrians to cross.
- Purple lights moving from right to left meant that the vehicle would start soon.

However, two of our color choices were not conventional. The choice of blue was intended to be unambiguous as it is not a standard color used in traffic lights while the purple lights were chosen since they could be seen in daylight. In the second evaluation study with the car, we eliminated the animations and used solid lights to make the strip more visible in outdoor conditions. We also replaced the purple lights with yellow lights as some participants in the first study with the Segway felt yellow represented the state of "be cautious" better than purple. To control the LED strip, we utilized an Arduino microcontroller and programmed it using the Arduino IDE. The lights changed state in a timed fashion.

For the auditory cue, we used a Bluetooth speaker which played the recorded messages "about to stop" and "about to start" to indicate to pedestrians that the vehicle would stop or start soon respectively. In the car study, we shortened the messages to "stopping" and "start" as participants in the Segway study felt the audio messages were too long. Additionally, the message repeated four times. In this interface, the visual cue communicated awareness through the blue light and intent through the other colors, while the auditory cue communicated intent through voice.

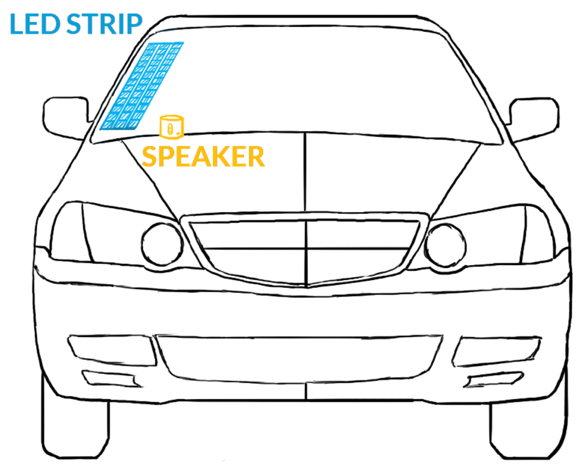


Figure 16: Vehicle-only interface prototype with an LED strip as a visual cue and a speaker as an auditory cue.

5.1.2 *Prototype 2: Vehicle and Street Infrastructure*

This interface featured cues that were placed on the vehicle as well as on street infrastructure and utilized an auditory and visual cue (see Figure 17). An auditory cue played through a speaker mounted to the vehicle. The speaker played the messages "I can see you" and "you can cross now" to indicate that the pedestrian had been seen and could cross. In the car study, we shortened the messages to "I see you" and "cross" to make it easier for participants to understand the vehicle's state quickly.

For the visual cue, we placed a street cue in the form of three LEDs. We placed this cue on top of a chair near the participant in both studies. These lights were toggled with an Arduino. This cue functioned similarly to a traffic light with a timer. Red meant it was not safe to cross, green meant it was safe to cross, and white meant it was about to become unsafe to cross. In the car study, we replaced the white light with yellow because participants preferred traditional traffic light colors. In this interface, the auditory cue communicated awareness and intent through verbal messages, while the visual cue communicated intent through color.

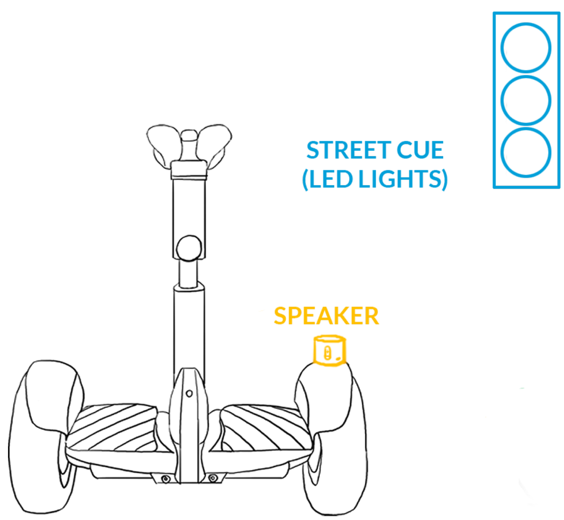


Figure 17: Vehicle-Street Infrastructure interface prototype featuring LED lights as a visual cue and a speaker as an auditory cue.

5.1.3 *Prototype 3: Vehicle and Pedestrian*

This interface featured cues placed on the vehicle and the pedestrian featuring visual and physical cues (see Figure 18). We mounted a display in front of the vehicle on which we prototyped an animated face. In its default state, the eyes of the animated face were fixed. When approaching a pedestrian, the eyes began moving from one side to the other after which they moved in the direction of the participant and finally fixed their gaze on them. For the physical cue, we utilized a smartphone with haptic feedback. Using a simple API, we could choose when the phone vibrated, which was meant to indicate to pedestrians that it was safe to cross in conjunction with the animated face. In this interface, the visual cue communicated awareness through the animated face, while the physical cue communicated intent through haptic feedback.

5.1.4 *Prototype 4: Mixed*

This interface featured a combination of cues placed on the vehicle, street infrastructure, and the pedestrian (see Figure 19). We used a visual cue in the form of three LEDs (street cue), a physical cue via a printed artificial hand mounted to the vehicle and an auditory cue through a smartphone on the participant. The street cue functioned as described in Prototype 2. We controlled the smartphone through a simple API on which we played the message "I can see you" to indicate that the pedestrian had been seen. We mounted the hand to a Servo motor to imitate the waving of a hand. The hand rotated from left to right three times before stopping to indicate to the pedestrian that it was safe to cross. We controlled the timing of the movement and the angles through an Arduino. In this

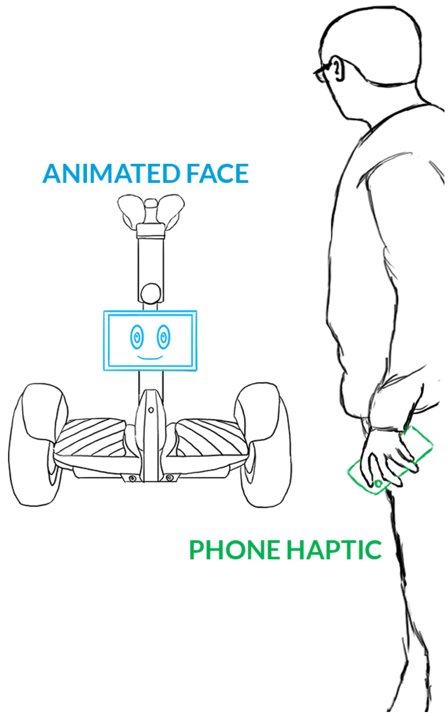


Figure 18: Vehicle-Pedestrian interface prototype featuring an animated face as a visual cue and smartphone haptic feedback as a physical cue.

interface, the auditory cue communicated awareness, while the visual and physical cues communicated intent.

5.2 STUDIES TO EVALUATE AV-PEDESTRIAN INTERACTION

To evaluate the design space and the interface prototypes we built, we conducted two user studies on a Segway and a car. Our goal here was to demonstrate the interfaces to participants in a street crossing scenario and elicit their feedback about the effectiveness and role of interfaces in facilitating the interaction. To conduct these studies, we utilized the technique of Wizard-of-Oz, which we introduced in Chapter 1.

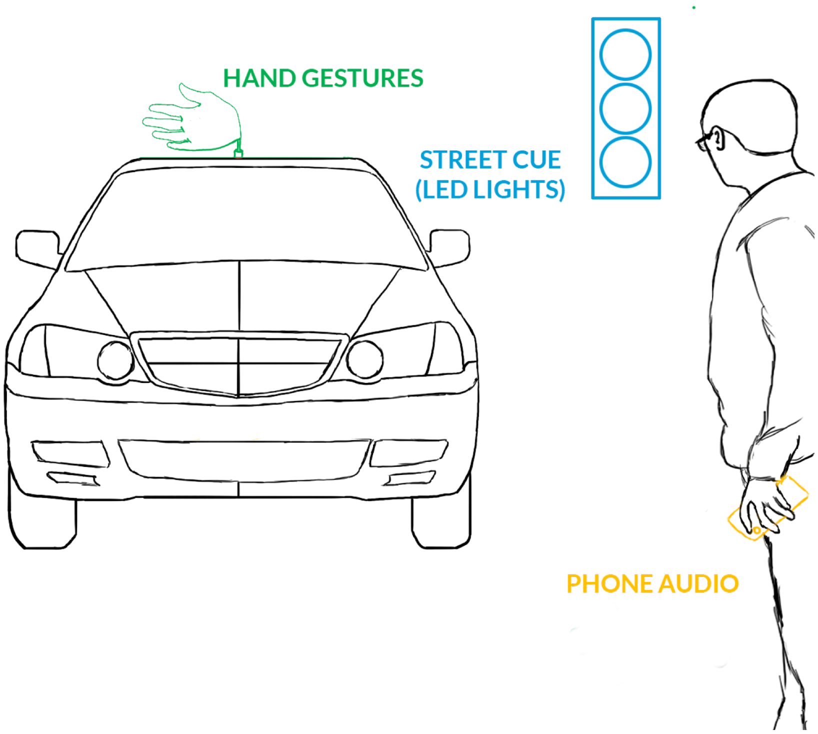


Figure 19: Mixed interface prototype with LED lights as a visual cue, smartphone audio as an auditory cue, and an artificial hand as a physical cue.

5.2.1 *Testing Platforms*

We conducted our first study using a Segway robot as it offered two distinct advantages. First, we could have participants physically cross in front of it through permission from our ethics board, which was not the case for the car study. Additionally, the Segway could be teleoperated to appear fully autonomous while the car was manually-driven and required a driver and a researcher on board to control the interfaces. Still, the Segway is a small vehicle and could be perceived as harmless, introducing a confounding variable to our studies. In addition, the Segway could only be operated indoors since it is not legally permitted on Alberta roads [1]. Thus, we conducted a second evaluation study with a car in outdoor conditions.

5.2.2 *Participants*

We recruited 10 participants (3 male and 7 female) in the age range of 18 to 65 for the Segway study and 10 participants (5 male and 5 female) in the age range of 18 to 55 for the car study. The participants came from a variety of backgrounds, including actuarial science, psychology, engineering, mathematics, accounting, and computer science. Our recruitment process entailed posters placed around our university campus, social media ads, and word of mouth. Participants received $20 in remuneration for their efforts.

5.2.3 *Study Tasks*

In both studies, participants attempted 5 tasks with 2 trials each (giving a total of 10 trials). The first task set the baseline in which the vehicle approached participants without an interface on board, forcing them to rely on vehicle cues alone. The next four tasks featured the four interface prototypes described above, which appeared in a randomized fashion. In these tasks, participants evaluated each interface by itself in addition to vehicle cues. Each task lasted ten minutes and involved two trials, one in which the vehicle did not stop and another in which the vehicle stopped. We conducted the Segway study in a corridor of our department's building. Participants could physically cross the corridor when electing to cross. For the car study, we utilized a closed-off parking lot and asked participants to verbally and visually express their crossing decisions instead of physically crossing for safety reasons.

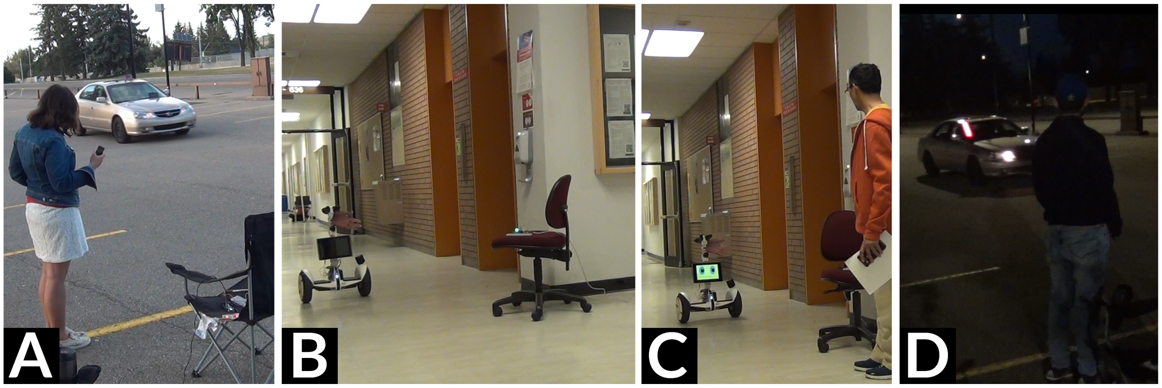


Figure 20: Images of participants interacting with all four interface prototypes in the Segway and car studies, where - A: Vehicle-Only, B: Vehicle-Street Infrastructure, C: Vehicle-Pedestrian, and D: Mixed.

5.2.4 *Study Procedure*

As we previously mentioned, we utilized Wizard-of-Oz in both studies because neither the Segway nor the car have autonomous capabilities. For the Segway, this meant controlling its movement through teleoperation and for the car, this meant informing participants that the vehicle was autonomous but required people on board for data collection. In the Segway study, we used a combination of manually activated and timed cues. For instance, the LED strip was timed, but the smartphone's vibration was triggered using an API when the vehicle was about to stop. For the car study, we had two researchers on board, one of whom controlled the vehicle while the other controlled the interfaces. Figure 20 shows the interfaces on the Segway and car platforms.

Figure 21 shows the setup of the Segway study which was conducted in a corridor. We mounted a camera to a tripod and placed it in front of the corridor to capture both the Segway and the participant. We operated the Segway at 5 km/h in each trial. In all tasks, we teleoperated the Segway using the official Ninebot mobile application with the aid of video feed from a camera mounted to it. We asked participants to stand at position C before each trial. The Segway began each trial at position A, and upon reaching position B, we alerted the participant that the trial had begun by verbalizing the message "Go". We used this protocol so that participants could not see the Segway from a distance and cross well before interacting with it. Once the pedestrian arrived at the corridor, they could observe the Segway and make one of two decisions: cross or not cross. When electing to cross, we asked participants to announce this verbally after which they could walk over to the other side of the corridor. Otherwise, they were asked to utter the phrase "I'm not crossing" and stay at the same spot. In the trials where the Segway would stop, it would conclude the trial at position D. At the end of the trial, we asked participants to head back to position C and moved the Segway back to position A.

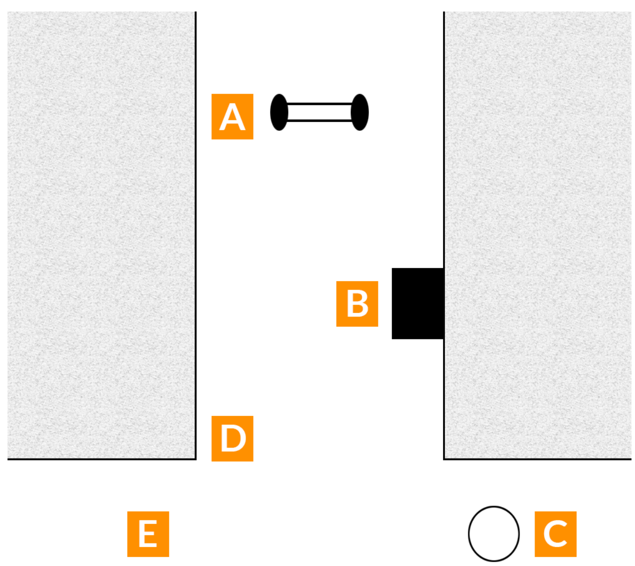


Figure 21: Segway study setup, where: A: Segway start position, B: Researcher says "Go", C: Participant start position, D: Segway stop position, E: Pedestrian end position when crossing.

Figure 22 shows the setup of the car study. We conducted this study in a closed-off section of a parking lot during the evenings (so that the interfaces were clearly visible). We placed a camera to capture the pedestrian and the vehicle, and another across from the participant to capture their pose and reactions. We drove the vehicle at 10 km/h and informed participants that both researchers were only on board to collect data. The vehicle would start the trial at position A. At the start of the trial, participants faced away from the vehicle and stood at position C. After the vehicle approached position B, we used the vehicle's horn to indicate that the trial had commenced so participants could turn to face it, observe the cues it presented, and make a crossing decision. In trials where the vehicle stopped, it would stop at position D. At the end of the trial, the vehicle was always at position E. We asked participants to indicate that they would like to cross through a raise of their arm and a "thumbs up" gesture. Otherwise, they were asked to stand at the same spot without gesturing.

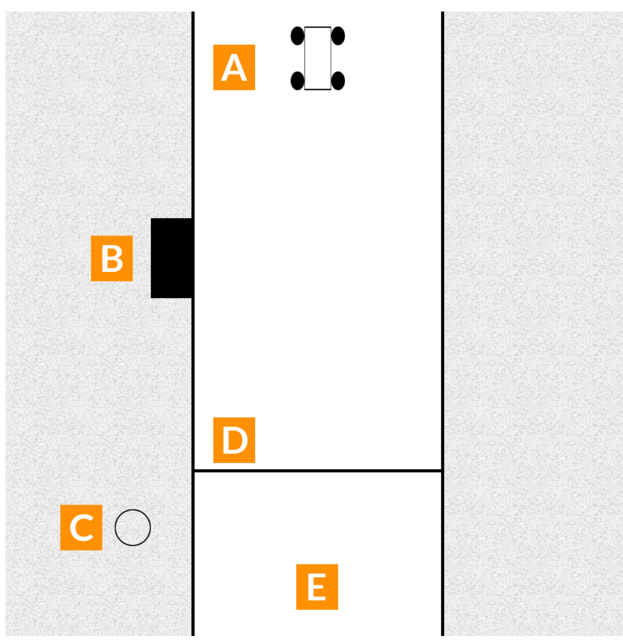


Figure 22: Car study setup, where: A: Car start position, B: Car "honks", C: Participant position, D: Car stop position, E: Car end position.

At the start of the study, participants completed a pre-study questionnaire through which we collected demographic information. Some of this information included how often they crossed the street, how often they interacted with the driver when crossing, and the types of cues they expect to receive that indicate awareness and intent from the vehicle or driver. Between each task, we briefed participants on the specifics of the task being evaluated. We informed them that in each trial, the vehicle may or may not choose to stop. We introduced our interface prototypes via a description sheet which we provided them to refer to between trials. We also informed participants that the interfaces merely provided suggestions and that the final decision to cross was theirs. At the end of each task, we asked participants to complete a mid-study questionnaire which included five-point Likert scale questions about their confidence in the vehicle's awareness and intent and two written questions asking them which cue was most and least effective in that task. At the end of the study, participants completed a post-study questionnaire with four five-point Likert scale questions comparing the interfaces to the baseline task (no interface) and one five-point Likert scale question comparing the importance of awareness and intent. Additionally, we conducted a semi-structured interview with participants through which we gathered overall feedback on the perceived strengths and weaknesses of each interface, the effectiveness of different cue modalities, and participants' reflections on their real-world implementation.

5.2.5 *Data Sources and Analysis*

We collected the following data from participants - responses to a pre-study questionnaire, mid-study questionnaires between tasks, a post-study questionnaire, and a video recording of the session, including the interview. We also kept track of participants' crossing decisions, including correctly and incorrectly made decisions in each trial. From the interview, we created a transcription and used open coding to identify themes emerging from participants' evaluation of the prototypes [8]. Some examples included "human-like vs machine-like cues", "cues with binary states vs cues with several states" and "cues from the vehicle vs cues in several locations". From the questionnaires, we analyzed the five-point Likert scale questions [36] quantitatively to identify significant effects emerging from the use of interfaces. In our analysis, we refer to specific participants in the Segway study as SP# and participants in the car study as CP#.

5.3 FINDINGS FROM THE SEGWAY AND CAR STUDIES

5.3.1 *Significance of Awareness and Intent Communication*

In both our evaluation studies, we found that all participants felt the communication of awareness and intent were both important. More specifically, they felt that communicating intent was more important than communicating awareness. In the Segway study, 6 out of 10 participants felt that intent was more important while in the car study, 7 out of 10 participants felt that intent was more important. To understand why, we probed participants about their choices in the interview. Many stated that while communicating awareness was important to them, awareness did not provide assurance that the vehicle would stop for them. A participant stated, *"I don't think it's [awareness] the most important, because once you know the driver sees you, you have these expectations that they would slow down but you never know" [SP6].*

Despite participants noting the importance of awareness and intent, some also pointed out that the explicit communication of these cues might be necessary only upon the

Question	Platform	Comparison	df	t	p
Awareness	*Segway*	Base (M = 3.3, SD = 0.68) vs VO (M = 4.2, SD = 1.07)	17	2.11	0.046
		Base (M = 3.3, SD = 0.68) vs VS (M = 4.1, SD = 0.77)	18	2.10	0.049
		Base (M = 3.3, SD = 0.68) vs Mix (M = 4.2, SD = 1.07)	17	2.11	0.046
Intent	*Segway*	Base (M = 3.1, SD = 0.77) vs VO (M = 4.2, SD = 0.40)	16	2.12	0.005
	Car	Base (M = 2.8, SD = 1.29) vs VO (M = 4, SD = 0.67)	16	2.12	0.015
		Base (M = 2.8, SD = 1.29) vs VS (M = 3.9, SD = 1.21)	16	2.10	0.041
		Base (M = 2.8, SD = 1.29) vs Mix (M = 3.9, SD = 1.21)	18	2.10	0.041

Table 3: Significance testing of confidence in vehicle awareness and intent comparing baseline and interface conditions through the t-test ($\alpha = 0.05$). VO: Vehicle-Only, VS: Vehicle and Street Infrastructure.

introduction of autonomous vehicles. A participant, SP8 said, *"[autonomous vehicles] being a new thing to the pedestrian, significant cues are required in the beginning. Maybe after some time, when it becomes familiar, not much is required"*. In some sense, we could consider interfaces in a similar manner to the training wheels of a bicycle, which can gradually be removed once pedestrians are comfortable interacting with autonomous vehicles.

5.3.2 *Importance of Interfaces*

Our findings from the two studies support the notion that participants prefer to receive cues from an explicit communication interface rather than relying on vehicle cues alone.

Comparison to the baseline: on average, participants rated all 4 interfaces higher than the vehicle alone in both studies on the Likert scale. However, we found significant effects for participant confidence in awareness and intent in some of the interface conditions in both studies (as Table 3 shows). We also asked participants to compare the interface scenarios to the baseline scenario without a driver (scenario 3). We used a comparison question on the Likert scale where: 1 - interface was significantly worse than the baseline, and 5 - interface was significantly better than the baseline. The results from both studies are summarized in Table 4. In our analysis of crossing decisions, we found that participants crossed incorrectly more frequently without interfaces as opposed to with interfaces (as Table 5 shows).

	Vehicle-Only	Vehicle-Street Infrastructure	Vehicle-Pedestrian	Mixed
Segway	4.5 ± 0.71	4.3 ± 1.06	4.4 ± 0.84	4.5 ± 0.85
Car	4 ± 1.05	4.5 ± 0.53	3.5 ± 0.97	3.4 ± 1.17

Table 4: Means and standard deviations of comparisons between interfaces and the baseline condition in the Segway and car studies.

	Baseline		Vehicle Only		Vehicle Infrastructure		Vehicle Pedestrian		Mixed	
	C	*DC*	*C*	*DC*	*C*	*DC*	*C*	*DC*	*C*	*DC*
Segway	1	3	0	0	1	2	0	0	0	1
Car	2	1	1	1	0	0	0	0	0	0

Table 5: Number of incorrect crossing decisions made by participants in each study in each condition. C - crossing condition (vehicle stops), DC - not crossing condition (vehicle does not stop).

Comparison between interfaces: When asked to compare the interface prototypes against each other, participants provided different answers for the best interface in both studies. In the Segway study, 6 out of 10 participants felt the mixed interface was most effective while in the car study, 5 out of 10 participants found the vehicle and street infrastructure interface to be the most effective. In contrast, participants in both studies found the vehicle and pedestrian interface to be the least effective (5 out of 10 in the Segway study and 6 out of 10 in the car study).

5.4 CHAPTER SUMMARY

In this chapter, we provided an overview of our first attempts at building and evaluating interfaces from our proposed design space. We detailed our prototyping efforts in the first half of the chapter. Later, we described our evaluation of these prototypes on two study platforms - a Segway robot and a car. Our results from these studies suggest that incorporating explicit interfaces on autonomous vehicles is beneficial for pedestrians making street crossing decisions.

6

DESIGNING A VR SIMULATOR TO STUDY AV-PEDESTRIAN INTERACTION

In the previous chapter, we provided insights generated from two Wizard-of-Oz studies evaluating interfaces in autonomous vehicle-pedestrian interaction. However, several issues emerged from these studies. The most limiting of them was the presence of the wizard in the studies and the inability to isolate the researcher and participant. Another drawback of this approach was that we could only evaluate single-vehicle single-pedestrian interaction. Pedestrians rarely make crossing decisions standing alone and faced with a single vehicle. In reality, autonomous vehicles will need to co-exist with many vehicles in scaled environments that may vary in autonomy level, especially in mixed traffic. To study these effects, Wizard-of-Oz is not a promising approach. This inspired the development of a virtual reality-based simulator. In this chapter, we describe the process of building the simulator as well as our attempts to validate it as a suitable platform.

6.1 SIMULATOR AND VR SPECIFICATIONS

We built the simulator using Unity (version 2018.2.17f1), a popular open-source game engine. Since our goal was to make the simulator immersive, we utilized virtual reality technology. Unity supports the integration of virtual reality through a software development kit which includes several scripts and game objects to enable rapid prototyping.

We used the Oculus Rift headset to enable VR. To determine what to show the wearer, the VR headset incorporates the sensor fusion of a gyroscope, accelerometer, and magnetometer to track head position. Based on this data, the headset renders images to each eye at a resolution of 1080x1200 (90 Hz) to generate a stereoscopic image. Additionally, to determine where the wearer is positioned with respect to the virtual environment, the headset and controllers are equipped with infrared lights which are tracked by a USB-connected camera.

6.2 DESIGN OF THE SIMULATOR IN UNITY

Prior to building the simulator, we considered several factors that may affect vehicle-pedestrian interaction both for manually-driven vehicles and autonomous vehicles [44]. From this literature review, we incorporated several factors which could be manipulated in the simulated environment. These factors can fit into four categories and are visualized in Figure 23.

The first set focuses on vehicle factors: vehicle autonomy level, color, size, speed, slowdown characteristic at a crosswalk, and stopping distance. The next set is based on traffic and street characteristics: the number of vehicles on the street, traffic direction, number of lanes, lane order of vehicles with varying autonomy level, type of crosswalk, type of

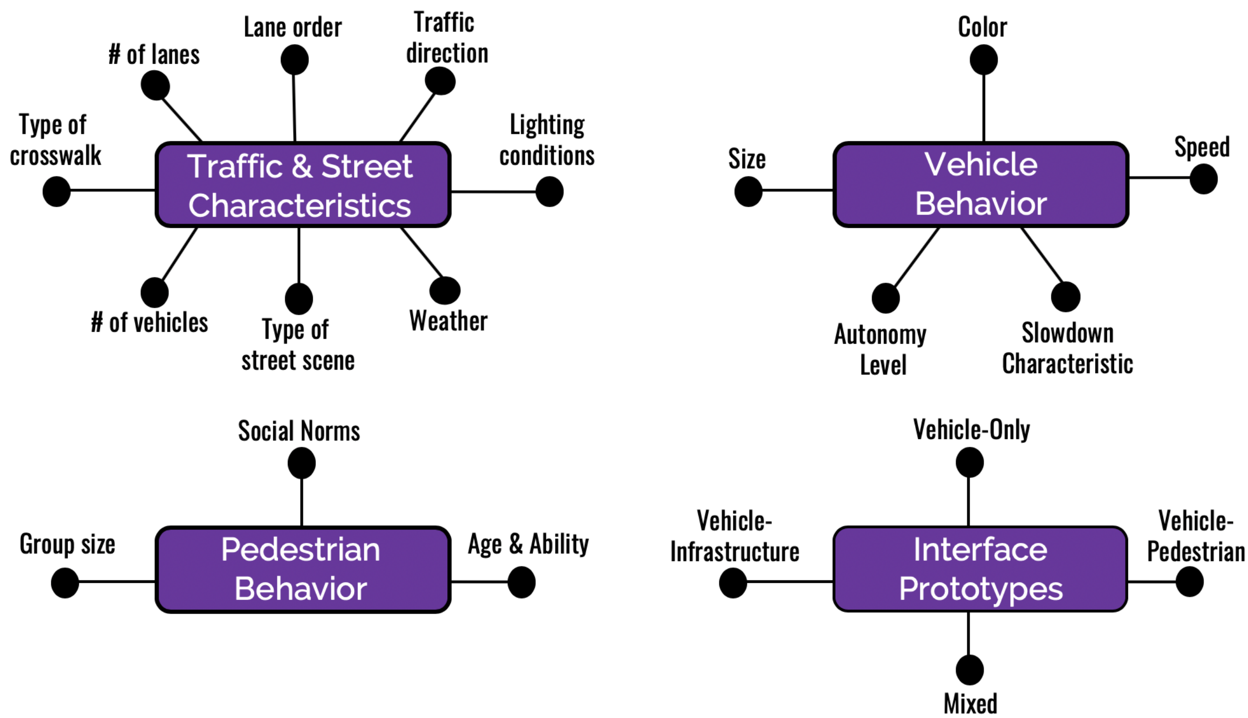
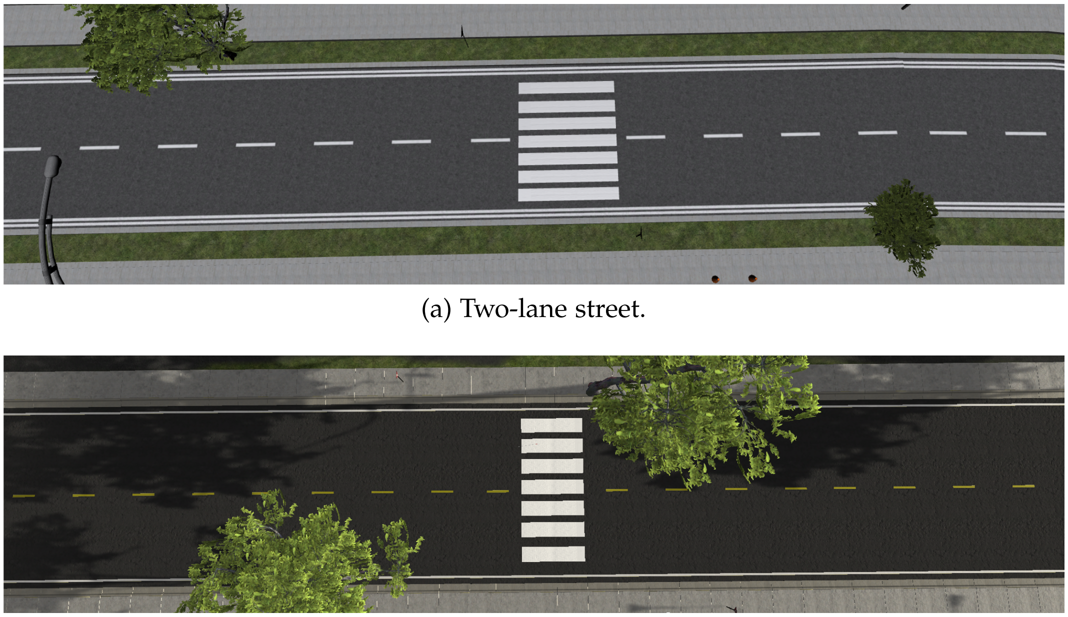


Figure 23: Our simulator allows for the control of several factors under 4 categories.

street scene, lighting conditions, and weather. The third set of factors relate to pedestrians: group size, age and ability, and social norms. We also considered the presence and design of interface prototypes as proposed in our design space (see Chapter 4). Our simulator supports the manipulation of all these variables. We provide the details of these categories below.

6.3 TRAFFIC AND STREET CHARACTERISTICS

In our simulator, one can simply change the layout of the street, including the number of lanes present. Further, it is also simple to specify how many lanes vehicles on each side of the road can occupy. Figure 24(a) shows a one-way street with two lanes while Figure 24(b) shows a two-way street with one lane. The type of crosswalk on the street



(a) Two-lane street.

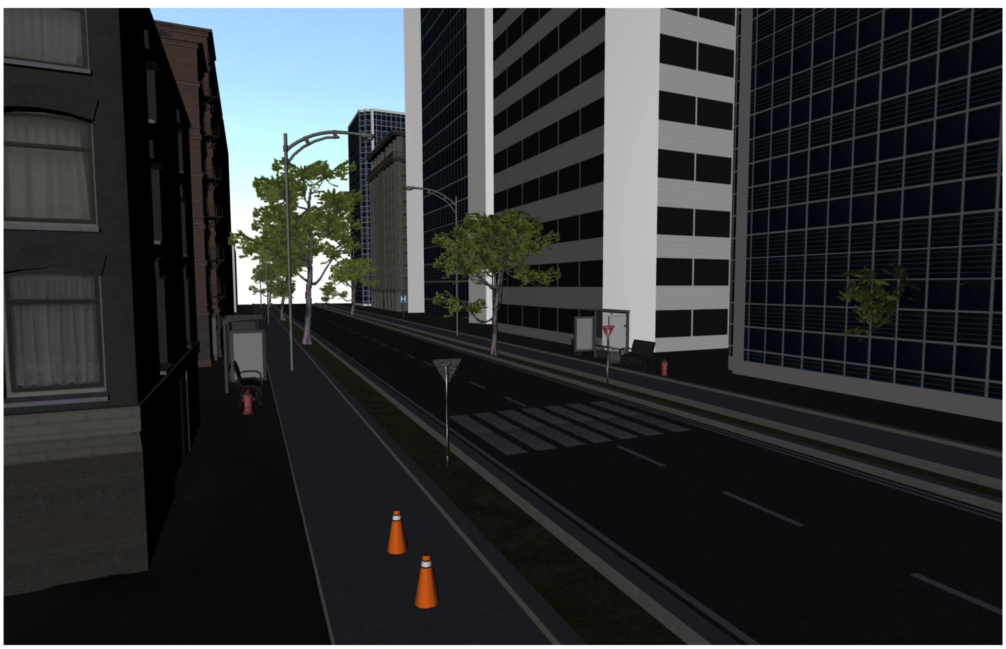
(b) Single-lane street.

Figure 24: Simulated road environment where: (a) one-way street, and (b) two-way street.

can be modified to be signalized or unsignalized. If signalized, we can add traffic signs (such as yield or stop) or even traffic lights. The direction of traffic is easy to manipulate, and vehicles can appear from both sides of the street. We can also dedicate lanes to vehicles of a specific autonomy level as we will show in our evaluation of mixed traffic in Chapter 7. The number of vehicles in the environment can be modified so that it is possible for several vehicles to spawn in the scene at once.

In a similar manner, it is also simple to transform the virtual environment that participants are placed in. Using simple pre-made or custom assets, one can rapidly prototype new environments. For instance, one could test crossing in a busy urban environment or a more quaint residential one (as Figure 25 shows). One can also alter the weather conditions so that it may be foggy or clear, or toggle between day and night conditions.

(a) Residential environment.



(b) Urban environment.

Figure 25: Different virtual environments in the simulator, where: (a) Residential scene, and (b) Urban scene.

Figure 26: Vehicle type chosen for our research - a mid-sized white sedan.

6.4 VEHICLE BEHAVIOR

Our simulator allows us to modify the appearance and behavior of vehicles. For instance, the vehicle can be a sedan or a semi-trailer truck. Each of these vehicle types can have their own characteristics such as weight, top speed, and the sensitivity of acceleration, deceleration, or steering. These different vehicle types can, for instance, be placed in the same environment to examine the effect of vehicle size or dynamics. For our work, however, we opted for a mid-sized sedan as it is a commonly seen vehicle type on today's streets (as Figure 26 shows). We fixed the color of the vehicle to white so that it would be clearly visible through the headset. We set its speed to 50 km/h, a standard urban speed limit in Canada. We can also prototype movement patterns for when they approach a crosswalk such as those that adhere to social norms as previously highlighted [48].

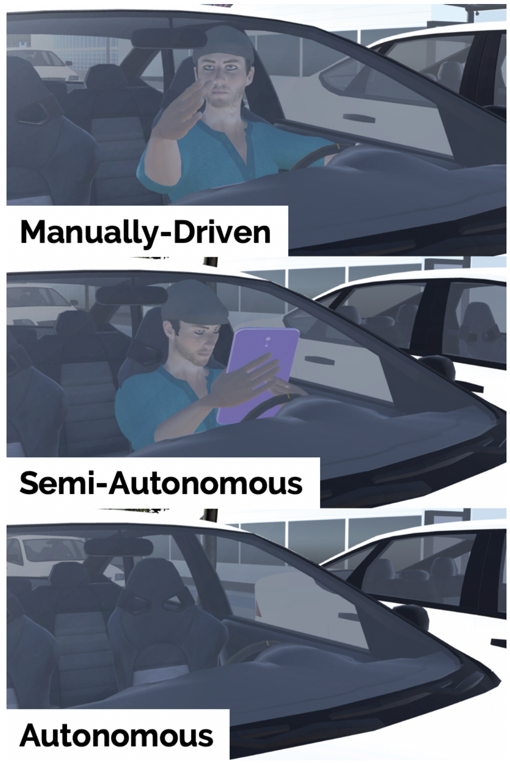


Figure 27: Vehicle autonomy levels: 1) Manually-driven vehicle with attentive driver, 2) Semi-autonomous (SAE level 3 [52]) vehicle with distracted driver, 3) Autonomous vehicle (SAE level 5 [52]).

Unity ships with several Standard Asset packages including one for vehicles. We used the standard vehicle asset provided by Unity and modified it accordingly. To control the vehicle's trajectory, we used a simple system of waypoints to specify where the vehicle starts and stops. We prototyped specific behaviors for the vehicle by modifying the standard AI script. These behaviors include stopping at intersections, stopping for pedestrians (including jaywalkers), and following vehicles ahead of them.

Functionally, vehicles of all autonomy levels drive in the same manner. However, we modify their appearance with a driver avatar to affect the perception of their autonomy level (as Figure 27 illustrates). In manually-driven vehicles, there is a driver on board who performs two actions - scanning the road ahead through head and eye movement while the vehicle is moving and initiating eye contact and gesturing with their hand when stopping. In semi-autonomous vehicles (SAE Level 3 [52]), the driver avatar appears distracted and stares at a tablet screen regardless of the vehicle's state. Autonomous vehicles do not feature a driver avatar. The actions that drivers take are animations that we prototyped in Unity.

6.5 PEDESTRIAN BEHAVIOR

To provide a realistic feeling of crossing, we can add virtual pedestrians to our street environment. Using Adobe Fuse CC [1], we could model unique pedestrians and rig them with skeletons that could then be animated [2]. Each pedestrian can have their own set of animations (such as of walking or standing). With this feature, we can, for example, model pedestrians of a specific demographic or with different abilities and examine how this affects participants' crossing decisions.

Similar to the approach for vehicle navigation, we can use waypoints to specify where pedestrians start and end in a scenario. In addition, with the help of the navigation mesh feature in Unity, we can specify areas of the street environment that are traversable such as crosswalk lines while prohibiting navigation on other parts. We can also trigger pedestrian movement based on specific events such as the vehicle coming to a stop near the crosswalk. This allows us to prototype movement patterns for pedestrians. For instance, we could easily set up a behavior where a pedestrian jaywalks at mid-block by running across as a vehicle approaches, to examine how this affects participants' crossing decisions. With several pedestrians, we can begin to test group behavior and

1 https://adobe.ly/2yoX1ZF
2 https://www.mixamo.com/

social norms. For instance, past research has shown that pedestrians tend to jaywalk at traffic lights, which are red if they are alone instead of in a group [50].

6.6 INTERFACE PROTOTYPES

We incorporated all cues from the interfaces that we used to evaluate autonomous vehicle-pedestrian interaction in Chapter 5. Each cue operates individually and can be mixed with others to produce interfaces as our design space shows (see Figure 15). Beyond this, we also have the ability to create new cues such as projecting cues on the street (via laser projection).

The LED strip cue can be placed on the vehicle and communicates four states through color as before (see Chapter 5). The street LED resembles traffic lights of today but provides state information to the pedestrian instead of the vehicle. For instance, the color green reflects that the pedestrian is safe to cross, whereas the color red means that it is dangerous for the pedestrian to cross and permissible for the vehicle to continue driving. We can also add sound cues on the vehicle, street infrastructure, and pedestrian to affect how participants perceive them.

We prototyped an artificial hand that can be placed on the vehicle (typically stationary) which resembles the hand gestures of drivers when signalling to pedestrians that it is safe to cross. We also created an animated face cue placed in the front of the vehicle that initiates a smile when urging pedestrians to cross. Finally, we incorporated a smartphone whose vibration can be controlled through an API using networking features in Unity. The phone vibrates to signal that it is safe for pedestrians to cross but otherwise does not vibrate.

All cues are automated and change state based on the vehicle's current state. These states include: the vehicle is currently moving, the vehicle has seen a pedestrian, the vehicle is about to stop, and the vehicle is about to start. Vehicle awareness is communicated upon seeing the pedestrian (fixed at a specific distance that can be varied).

6.7 Validating the simulator

To validate the simulator as a useful research tool, we replicated our own study of autonomous vehicle-pedestrian interaction described in Chapter 5. Our goal of replicating the study was to arrive at similar results about the usefulness of interfaces in autonomous vehicle-pedestrian interaction. The setup involved immersing participants in a street crossing environment. Participants stood at the corner of a crosswalk and made crossing decisions when faced with a single vehicle in VR.

6.7.1 *Participants*

We recruited 10 participants aged 18 to 35 (8 male, 2 female). The participants came from a variety of backgrounds, including engineering and computer science. Our recruitment process involved placing posters on our university campus and word of mouth. Participants received a remuneration of $10 for their efforts.

6.7.2 *Study Tasks*

We designed two tasks for participants to complete in the study. The first task was designed to familiarize participants with the virtual environment. In this task, participants experienced sample scenarios of an attentive driver, an autonomous vehicle without a driver, and an autonomous vehicle with a randomly selected interface. At the end, we asked participants to reflect on our simulator to gauge whether it provided a realistic crossing experience.

In the second task, participants experienced 7 scenarios, each of which involved 2 trials (yielding a total of 14 trials). Within each scenario, in one of the trials, the vehicle stopped at the crosswalk while in the other, the vehicle did not stop. In scenarios 1 and 2, participants faced a manually-driven vehicle with a driver on board, which demonstrated attentive and distracted behaviors (see Figure 27). In scenario 3, participants encountered an autonomous vehicle without a driver or interface. In scenarios 4-7, participants were faced with the same four interface prototypes described in Chapter 5. Scenarios 1-3 appeared in a fixed manner while scenarios 4-7 appeared in a randomized but balanced fashion. The study scenarios are visualized in Figure 28.

6.7.3 *Vehicle Characteristics*

In the study, vehicle speed was fixed to 50 km/h. When displaying a stopping behavior, the vehicle started slowing down within 20 meters of the crosswalk and fully stopped within 10 meters. The vehicle stayed stopped for 6 seconds. When not stopping, the vehicle maintained a fixed speed.

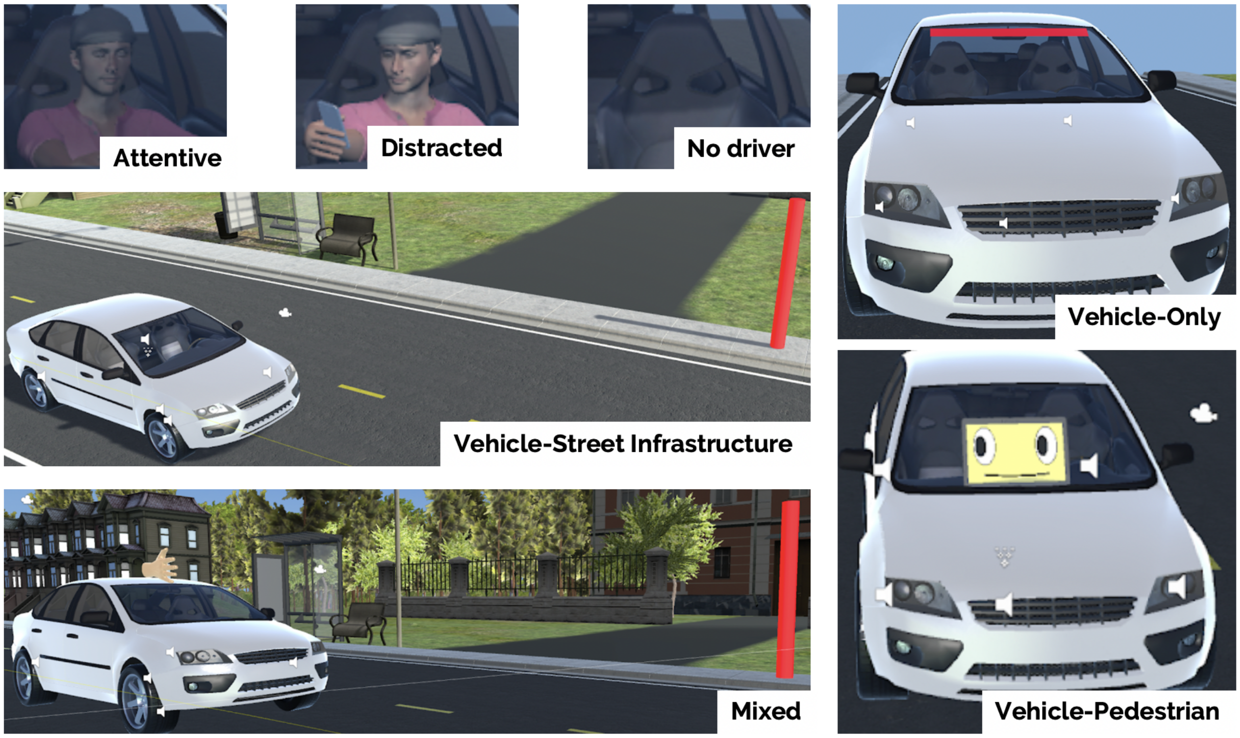


Figure 28: Scenarios that participants encountered in the validation study.

6.7.4 *Data Collection*

In our simulator, we built a simple mechanism to allow participants to provide immediate feedback on crossing (visualized in Figure 29). Using the Oculus Remote, participants could provide us with two metrics. We term the first metric as *comfort score* or how comfortable a participant feels at any given moment. During each trial, we collected comfort score from the start of the trial until the end. To collect this data, we presented a slider on the participant's screen that ranged from 1 (least comfort) to 5 (most comfort). At the start of each trial, the score was reset to 3 to indicate a neutral level of comfort. The second metric is the crossing decision that participants made during trials. The crossing decision was initiated through a button press. Prior to a press, the button was colored red but changed to green upon being pressed.

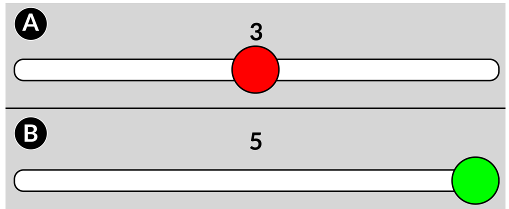


Figure 29: Slider that participants used to assess their level of comfort and crossing decision, where: A – indicates comfort score of 3 and not crossing (red), and B – indicates comfort score of 5 and crossing (green).

6.7.5 *Study Procedure*

The experimental setup can be seen in Figure 30. At the start of the study session which lasted an hour, we collected demographic information from the participant through a pre-study questionnaire. We then administered a simulation sickness questionnaire (SSQ) [31] to identify those who might be highly susceptible of becoming sick during the VR experiment. If their score was below the sickness threshold, we continued the study and briefed the participant on the experiment they would be partaking in.

Participants completed Task 1 first, which lasted five minutes. Participants then reflected on the similarities and differences between crossing in the real world and in the virtual environment we prototyped. Next, we introduced participants to Task 2, which took ten minutes to complete. The study setup can be visualized in Figure 31. At the start of each trial, the vehicle spawned away from the participant who stood at point P. In the stopping trials, the vehicle came to a stop ahead of the crosswalk. When stopping,

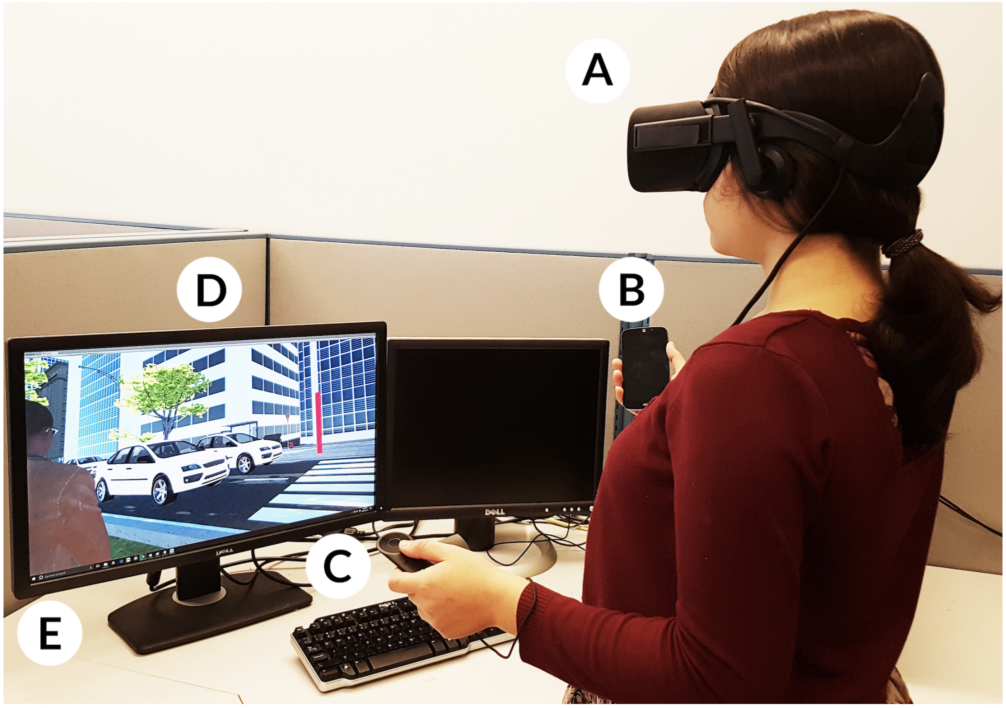


Figure 30: Study setup where: A – VR headset, B – Phone for physical cues (haptic feedback), C – Remote for providing comfort score and crossing decision, D – Virtual environment, E - Other pedestrians sharing the road with the participant.

the vehicle remained at the crosswalk for 6 seconds. Afterwards, the vehicle drove away until it reached the end of the street after which it respawned for the next trial.

At the end of the experiment, participants completed two questionnaires. In the first, we elicited information about their confidence in the vehicle's awareness and intent in each of the 7 scenarios through 5-point Likert scale questions. We also asked participants to list a cue they found most useful and least useful in each scenario. Then, participants completed a questionnaire comparing the four interface prototypes against the two baseline scenarios. The first comparison participants made was between the four interfaces and scenario 1, featuring an attentive driver. In the second, participants compared the four interface prototypes against scenario 3, featuring an autonomous vehicle without a driver or interfaces. Participants also reflected on the importance of awareness and intent.

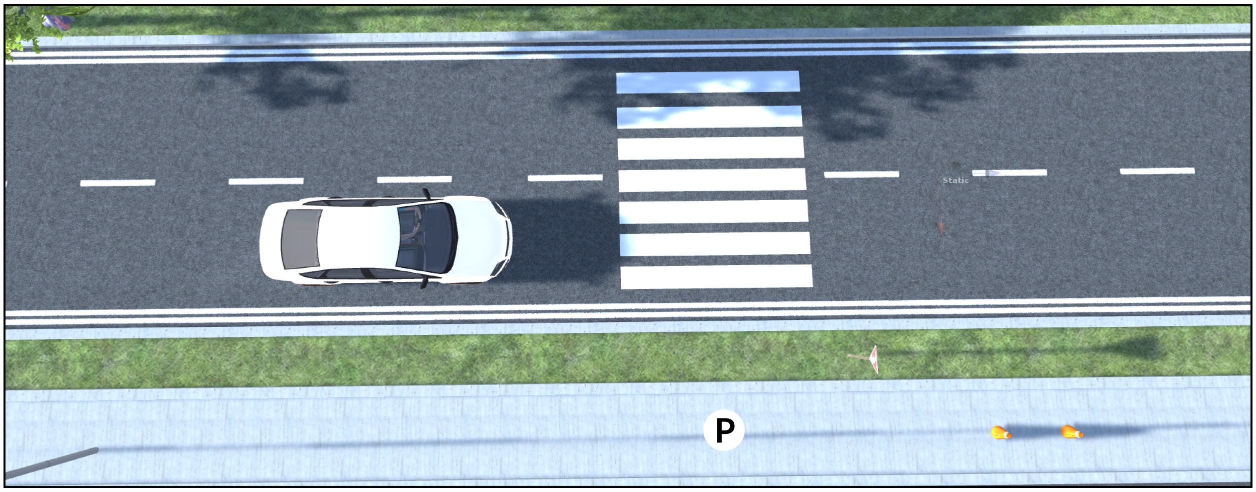


Figure 31: Top-down view of the study setup in which the participant stood at point P and made crossing decisions.

After completing the questionnaires, participants took part in a short semi-structured interview where we asked them about their experience.

6.7.6 *Findings*

Importance of awareness and intent: we found that all participants acknowledged awareness and intent to be important factors that affected their crossing decisions. However, 6 out of 10 participants felt that intent was more important. These results mirror what we found in Chapter 5.

Mid-study questionnaires: we asked participants two questions about their confidence in the vehicle's awareness and intent in each of the 7 scenarios. Due to a potential interdependence between these two questions, we conducted a multivariate repeated measures ANOVA with Bonferroni correction to account for the 7 scenarios. We found that the interfaces (in scenarios 4-7) significantly increased how confident pedestrians felt in the vehicle's awareness and intent (Wilk's lambda = 0.388, $F(12, 106) = 5.357$, $p < 0.001$). We found that participants felt significantly more confident in vehicle awareness when faced with the vehicle-only interface (M: 3.7) compared to the no driver scenario (M: 1.5; $p < 0.001$). Similarly, they felt significantly more confident in vehicle awareness when faced with the mixed interface (M: 3.9) compared to the no driver scenario (M: 1.5; $p < 0.004$). In terms of vehicle intent, participants felt significantly more confident when faced with the vehicle-only interface (M: 4.0) when compared to the no driver scenario (M: 2.0; $p < 0.008$). The same effect was prevalent when comparing the mixed interface (M: 4.1) to the no driver scenario (M: 2.0; $p < 0.008$).

Participants' comfort: for participant comfort score data, due to the correlated and unbalanced nature of the data, we employed a Generalized Estimating Equation with Bonferroni Correction to assess scenario and trial effects (of stopping or not stopping). We found a statistically significant scenario x condition interaction ($\tilde{\chi}^2(6) = 48.494$, $p < 0.001$). This indicates that the effect of each scenario varied depending on the trial (stopping or not stopping). We performed pairwise comparisons of the comfort scores when the vehicle stopped. We found that participant comfort, when faced with the vehicle-pedestrian interface (M: 3.44) was significantly higher when compared to the no driver scenario (M: 2.46; $p < 0.017$). The same effect was observed for participant scores when faced with the mixed interface (M: 3.53) compared to the no driver scenario (M: 2.46; $p < 0.017$).

Post-study questionnaires: in the post-study questionnaire, we asked participants to compare the interface scenarios to the baseline scenario without a driver (scenario 3). We found that participants preferred the interface in 3 out of 4 interface scenarios with the exception of the vehicle-pedestrian interface. The comparison scale was as follows: 1 - interface was significantly worse than the baseline, and 5 - interface was significantly better than the baseline. The scores we received from participants were: vehicle-only (M: 4.8, SD: 0.42), vehicle-street infrastructure (M: 4.3, SD: 0.67), vehicle-pedestrian (M: 3.3, SD: 1.06), and mixed (M: 4.6, SD: 0.51). We also asked participants to rank the four interfaces plus the baseline condition (scenario 3) in terms of preference. The vehicle-only and vehicle-street infrastructure interfaces were most preferred (4 out of 10 participants voted for them each). The baseline scenario of no driver (scenario 3) received 6 out of 10 votes for last place while the vehicle-pedestrian interface received 4 out of 10 votes for last place.

Interviews: we probed participants about the most and least useful cues for communicating awareness and intent. 8 out of 10 participants felt that the vehicle LED strip was most effective in providing awareness (through the color blue). 6 out of 10 participants found the animated face the least effective in providing awareness information. For most effective at communicating intent, 7 out of 10 participants voted for the street LED while 5 out of 10 participants felt that the phone vibration was least effective.

6.7.7 *Comparison with Prior Studies*

In this study and prior studies, participants echoed the importance of awareness and intent. Similar to previous studies, however, intent seemed to be considered more important. From the mid-study questionnaires, we found that participants felt more confident in vehicle awareness and intent when faced with interfaces than without. The vehicle-pedestrian interface remained the least effective in all three studies but the choice of most effective changed between the studies. When comparing autonomous vehicles without an interface to those with an interface, participants in all studies found that having interfaces was better than not having interfaces, though the ranking of the best interface was slightly different. Broadly, this supports our hypothesis that interfaces which communicate awareness and intent are useful in autonomous vehicle-pedestrian interaction.

More importantly, we arrived at these findings even when placing participants in a virtual environment suggesting that our simulator could be a useful tool for examining these interactions.

6.8 Chapter Summary

In this chapter, we detailed the design of our VR-based pedestrian simulator to aid in the study of autonomous vehicle-pedestrian interaction. We validated our simulator through a study in which we replicated our own Wizard-of-Oz studies from Chapter 5. We found that the results roughly matched which signifies that the simulator provides a suitable testbed to study autonomous vehicle-pedestrian interaction.

7

EVALUATING MIXED TRAFFIC IN THE VR SIMULATOR

Having shown that our virtual reality simulator is a suitable tool to examine autonomous vehicle-pedestrian interaction, we turned our focus towards studying the problem of mixed traffic, which we have foreshadowed throughout this thesis. Before evaluating mixed traffic, our aim was to understand how to prototype it in our simulator. In the first part of this chapter, we highlight a brainstorming session we conducted to achieve this goal. Based on these results, we implemented mixed traffic and evaluated it in the simulator through a user study.

7.1 BRAINSTORMING SESSION

We conducted a brainstorming session with 6 participants who were all researchers, some (4 out of 6) of whom were experienced in interaction design.

7.1.1 *Materials*

To facilitate the brainstorming session, we provided participants with several design aids (see Appendix F for details). We provided them with two shared design surfaces as Figure 32 shows, depicting a multi-lane street with an unsignalized crosswalk. To aid them in prototyping, we designed a variety of labels. We included pedestrians: regular, child, visually-impaired, and hearing-impaired. We provided vehicle types as labels: attentive driver in manually-driven vehicle, distracted driver in manually-driven vehicle, semi-autonomous vehicle (SAE Level 3 [52]), and fully autonomous vehicle (SAE Level 5 [52]). Additionally, we included crosswalk types: signalized crosswalk or crosswalk with a stop sign. Since the goal of the session was to prototype communication mechanisms for autonomous vehicles, we also provided participants with interfaces as described in Chapter 5 as well as cues from the categories in our proposed design space in Chapter 4. These aids are visualized in Figure 33.

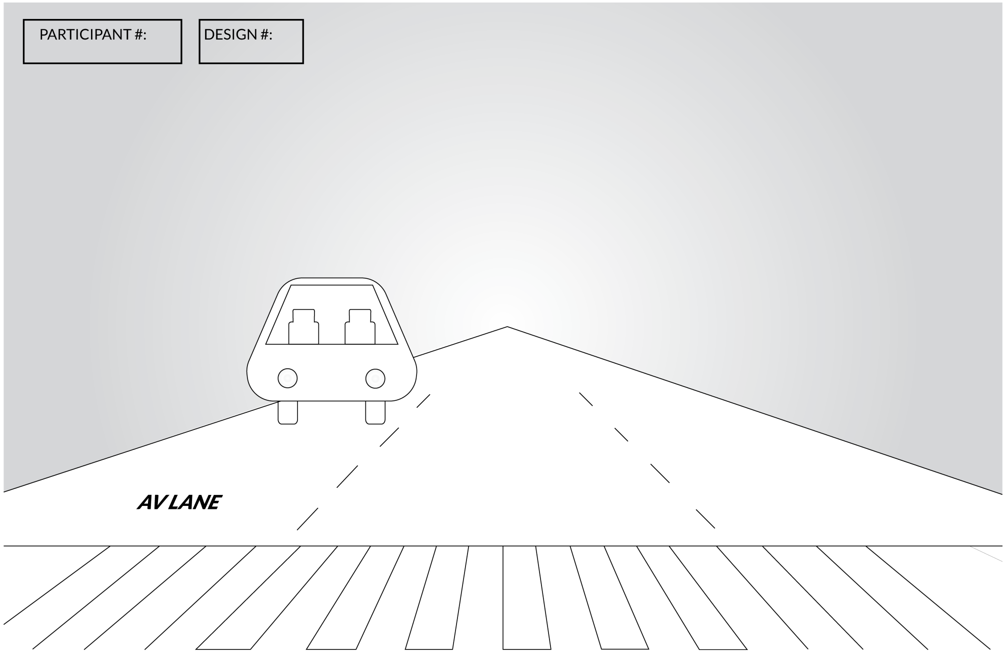
7.1.2 *Protocol*

Our brainstorming session protocol was loosely inspired by the methodology of Design Charrettes [49]. In Design Charrettes, participants collaborate in a group setting and quickly sketch designs to explore a variety of ideas and approaches. For the session, we recruited six participants (all male) aged 18 to 35 through word of mouth. We provided participants with a briefing of mixed traffic and the terms awareness and intent. Then, we asked them to design scenes of mixed traffic along with what they felt were the best communication mechanisms to facilitate pedestrian street crossing in mixed traffic. The design session lasted an hour and was comprised of two parts. In the first, participants designed for a scenario in which autonomous vehicles are designated to a specific lane. In the second, participants designed for a scenario where autonomous vehicles are mixed with other vehicles. At the end of sketching each scenario, we asked participants to present their ideas to the group to receive design critique.

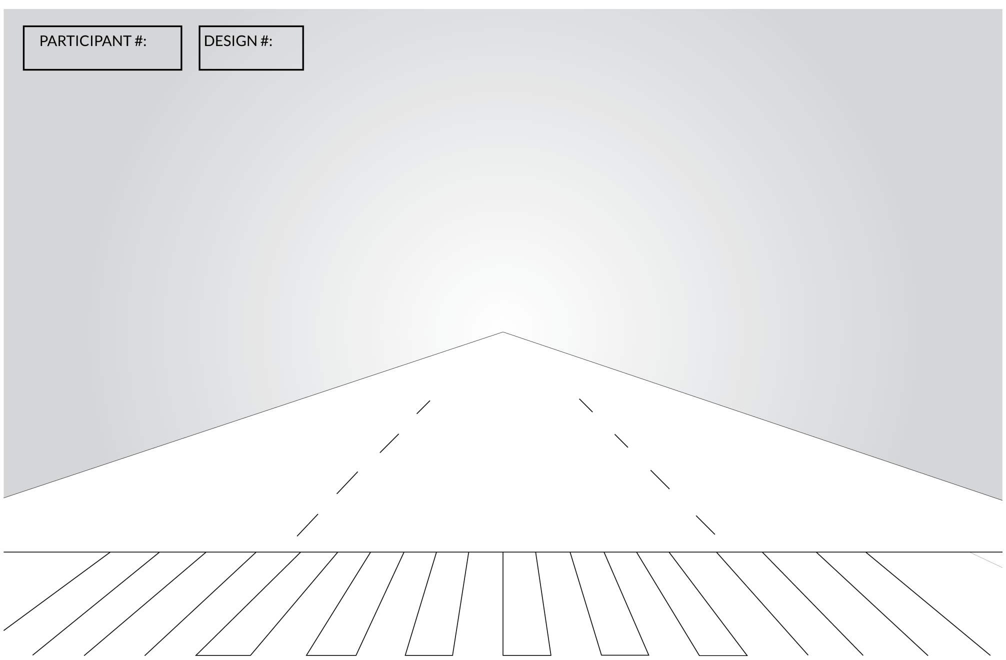
7.1.3 *Results*

We found that all participants incorporated communication interfaces on autonomous vehicles in mixed traffic, further supporting our previous results from the first design study described in Chapter 4. The interface designs varied across participants and incorporated visual, auditory, and physical cue modalities. The interfaces were placed on both the vehicle and street infrastructure similar to the designs in our design study (see Figure 9), suggesting that interfaces may exist in other places than the vehicle alone. Perhaps a more interesting result is that participants incorporated interfaces on semi-autonomous vehicles so that they can communicate with pedestrians when the driver is not in control.

During the session, participants brought insightful ideas on how mixed traffic may manifest. As an example, participants were free to imagine the kinds of vehicles that may exist on the street. Yet, participants incorporated vehicles of all autonomy levels in their designs, indicating that autonomous vehicles may need to co-exist with vehicles of other autonomy levels in the transition period. Participants also provided interesting ideas on the ways to facilitate mixed traffic and pedestrian interaction. For instance, participants incorporated multimodal cues to accommodate pedestrians with different communication requirements. Sometimes, pedestrians cross after the pedestrian walk



(a) Design sheet with AV restricted to the left lane.



(b) Design sheet with free flow of traffic.

Figure 32: Design sheets participants used in the brainstorming session.

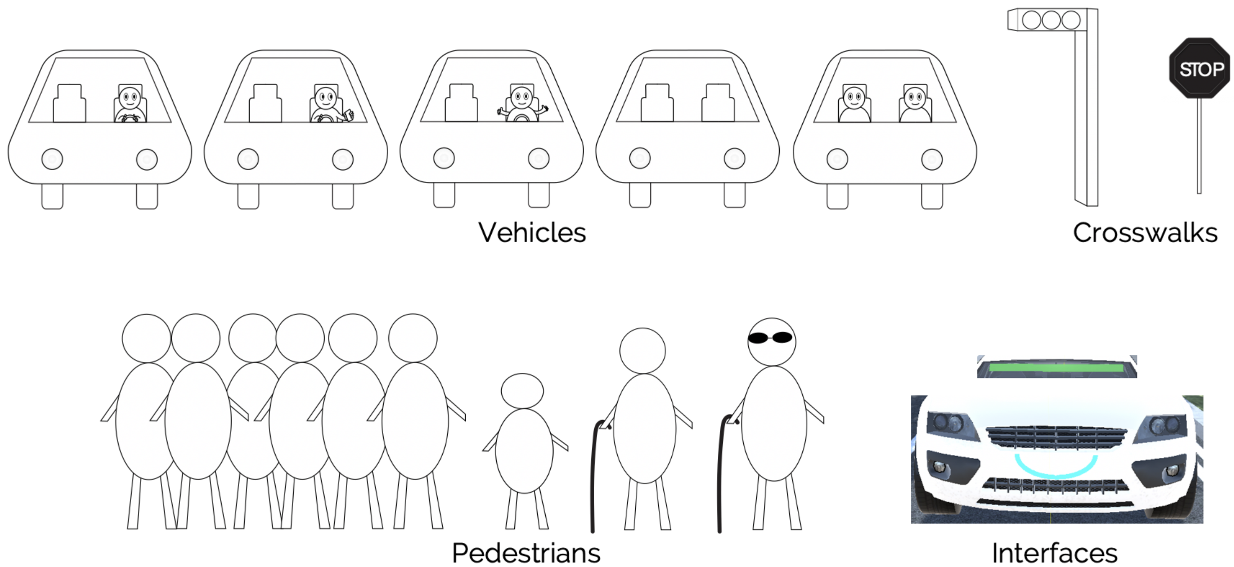


Figure 33: Design aids that we provided participants to use when prototyping in the brainstorming session.

Figure 34: Participant design where multimodal cues are utilized to communicate awareness and intent of all autonomous vehicles (regardless of autonomy level).

sign expires. Participants proposed a modification to this scenario today whereby visual cues replace honking to create a more pleasant interaction (as seen in Figure 34).

Based on the results of the brainstorming session, we prototyped mixed traffic in our simulator. As we highlighted in Chapter 6, our simulator offers us the ability to manipulate several factors. However, designing a study to examine such a large number of factors is challenging. So, we narrowed our focus to three factors of particular importance to our exploration. As we are interested in mixed traffic-pedestrian interaction, we varied the autonomy level of vehicles in the street as an independent variable. Since we were also interested in whether the presence of interfaces would be useful for pedestrians crossing in mixed traffic, this became a second independent variable. Finally, as group pedestrian behavior is often cited as a factor that can influence individual pedestrian behavior [50], we were interested in seeing whether these effects could be observed in mixed traffic. Participants' crossing decisions were the dependent variable in our study. We describe these in further detail below and visualized them in Figure 35.

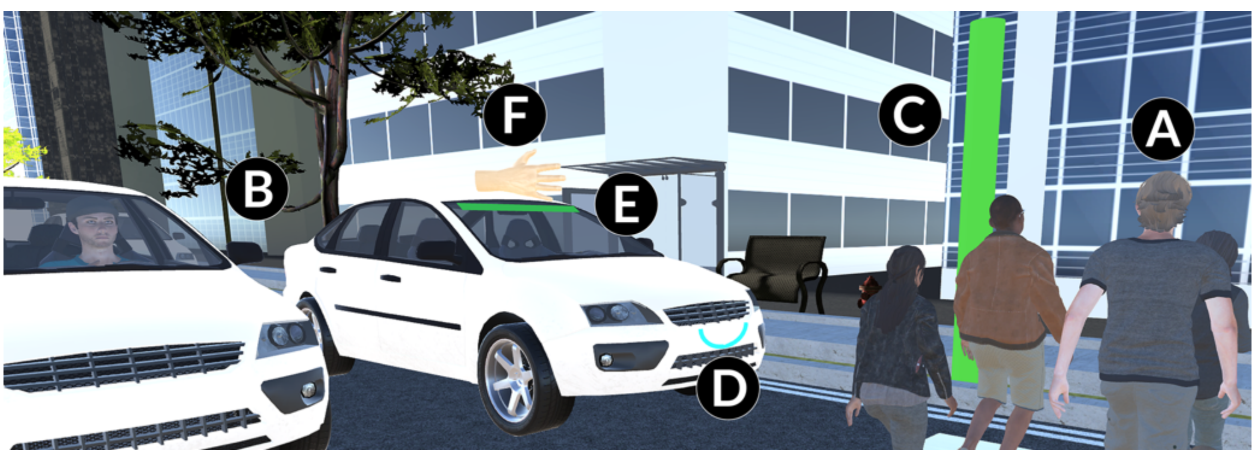


Figure 35: Our simulation of mixed traffic where: (A) other pedestrians, (B) AV and non-AVs, (C) street signals, and (D, E, F) interface cues communicating AVs' awareness and intent.

7.2.1 *Traffic Characteristics*

In our simulation of mixed traffic, vehicles of the same autonomy level occupied the same lane, making them easy for participants to recognize. Additionally, we placed manually-driven and semi-autonomous vehicles on the lane closest to where participants stood so that the driver was easily visible to them. In our study, each lane was occupied by two vehicles for a total of four at a time. As mentioned in Chapter 6, all vehicles drove in the same manner regardless of autonomy level.

7.2.2 *Vehicle Behavior*

In mixed traffic, vehicle speed was fixed to 50 km/h with small variations up to 5 km/h to resemble organic traffic flow when multiple vehicles were on the road. Vehicles behind the first set of vehicles maintained a fixed following distance which we set to 10 meters. When displaying stopping behavior, vehicles started slowing down within 20 meters of the crosswalk, and fully stopped within 10 meters. When not stopping, vehicles maintained a fixed speed.

7.2.3 *Pedestrian Characteristics*

To examine the effect of groups of pedestrians, we modeled eight unique pedestrians who varied in gender, ethnicity, and age. We created three conditions to study the effect of groups. In the first or no-pedestrian condition, participants made crossing decisions without the presence of virtual pedestrians. In the early crossers condition, virtual pedestrians stood next to the participant and began crossing well before the vehicle came to a full stop at the crosswalk. In the timely crossers condition, virtual pedestrians stood near the participant and crossed only once the vehicle fully came to a stop at the crosswalk. These behaviors can be seen in Figure 36.

7.2.4 *Interfaces*

We made one change to the interface cues between the VR validation study (see Chapter 6) and the mixed traffic study. We replaced the animated face cue (see Figure 28) with an animated smile (see Figure 35) because participants found the face hard to see in VR.

7.3 EVALUATING MIXED TRAFFIC

7.3.1 *Participants*

For the evaluation, we recruited 12 participants aged 18 to 45 (7 male, 5 female) from a variety of backgrounds, including engineering, computer science, and psychology. We recruited participants through word of mouth and posters placed around our university. Participants received a remuneration of $20 at the end of the study.

7.3.2 *Study Tasks*

In the first portion of the study, we introduced participants to the simulator through a sample task with a few trials showcasing vehicles varying in autonomy level, groups of

(a) Early crossers begin crossing as soon as the vehicle hints that it will slow down.

(b) Timely crossers wait until vehicles have fully stopped before crossing.

Figure 36: Group pedestrian crossing behaviors in mixed traffic.

pedestrians, and randomly chosen interfaces. We also explained to participants how they could use the Oculus Remote to provide the comfort score and crossing decision metrics (see Figure 29). Then, they were immersed in the VR experience for forty minutes. During this period, participants encountered 90 trials which we split into 3 sets of 30 trials each. In each set, participants saw four vehicles (two in each lane). In set 1, participants encountered manually-driven vehicles in the closest lane and autonomous vehicles in the other lane. In set 2, participants faced semi-autonomous vehicles (SAE Level 3 [52]) in the closest lane and autonomous vehicles in the farthest lane. In set 3, participants saw autonomous vehicles in either lane.

In each set of 30 trials, we varied group pedestrian behavior every 10 trials as there were 3 conditions (none, early crossers, timely crossers). Within each group pedestrian behavior condition of 10 trials, we presented participants with 5 scenarios (no interface, vehicle-only, vehicle-street infrastructure, vehicle-pedestrian, and mixed). Within each scenario of 2 trials, the vehicle stopped in one trial and did not stop in the other. Since there are 3 independent variables, we could only achieve a partial balancing of learning effects. We achieved this by randomly generating one combination of 90 trials from which we built a 3 x 3 Latin square based on the set order (sets 1-0-2, sets 2-1-0, and sets 0-2-1). Hence, 4 participants saw each set order.

7.3.3 *Study Procedure*

Figure 37 illustrates the study setup. At the start, participants completed a demographic questionnaire and a simulation sickness questionnaire (SSQ) [31]. Next, we familiarized participants with the study after which they completed the sample task. Then, participants completed set 1 (trials 1-30) after which they completed a questionnaire reflecting

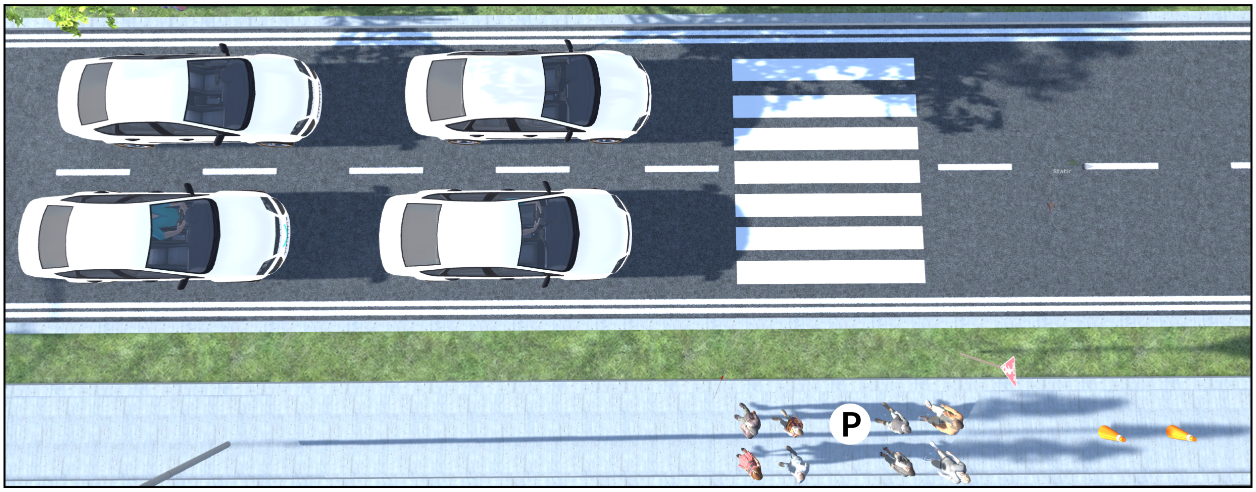


Figure 37: Top-down view of the mixed traffic study setup in which the participant stood at point P and made crossing decisions.

on the trials they encountered with questions pertaining to the cues they received from the vehicles, interfaces, and pedestrians around them. Similarly, participants completed sets 2 and 3. At the end of the study, we interviewed participants on their experience in the simulator.

7.3.4 *Data Sources and Analysis*

Each study session featured 90 trials, out of which the vehicle stopped in 45 trials. Hence, over the course of the study across all participants, there were 540 unique crossing opportunities that we analyzed (45 x 12). From these opportunities, we calculated two metrics. The first is the time difference between when the vehicle stopped at the crosswalk and when participants signalled their intent to cross through the Oculus Remote. The other is the comfort score that participants selected at the exact moment the crossing decision was made. We analyzed this data for trends and statistical significance. In addition, we transcribed all the interview sessions and analyzed them through open coding [8].

7.4.1 *Crossing Decisions and Comfort Scores*

11 out of 12 participants crossed the street in each stopping trial. The one exception was participant P10 who did not cross in 2 of the 45 trials, one of which was accidental (as stated post-trial). In the other trial, P10 iterated that upon seeing a semi-autonomous vehicle with a seemingly distracted driver and an autonomous vehicle without an interface in the other lane, they elected to wait until the vehicles passed before crossing.

To determine whether interfaces, which appeared in 36 out of the 45 stopping trials, affected pedestrians' crossing decisions, we conducted a one-way repeated measures ANOVA on participant comfort score at the time of crossing. Our results show that participants reported a significantly higher comfort score when faced with trials where there was an interface ($F(1,11) = 7.597$, $p < 0.019$) agnostic of the set or group pedestrian behavior or even the interface they faced. A similar analysis on time difference revealed that participants crossed before the vehicle stopped in trials with an interface ($F(1, 11) = 15.875$, $p < 0.002$). Table 6 shows the average values of our metrics.

	No Interface	**Interface**
Comfort (out of 5)	3.855	4.256
Time Difference (s)	0.1296	-0.446

Table 6: Average comfort score and time difference for the No Interface and Interface conditions in the mixed traffic study.

7.4.2 *Qualitative Results*

We asked participants to evaluate the usefulness of the following individual cues between sets through a mid-study questionnaire - 1) vehicle motion, 2) cues on the vehicle, 3) cues on the street, 4) cues on the pedestrian, and 5) pedestrian behavior. For the set with a driver on board in one of the lanes (set 1), we also asked participants about the usefulness of driver cues. In this set, participants felt that driver cues were most effective. Considering all sets, however, vehicle motion and cues on the vehicle were most preferred. Further details can be seen in Table 7. When we asked participants about cue modalities, visual and auditory cues were well received, whereas physical cues were not. When asked to rank the interfaces, the vehicle-only interface was most popular while the vehicle-pedestrian interface was least popular. In the interview, we asked participants whether they considered awareness and intent to be important. 10 out of 12 participants stated that both were important while 2 out of 12 believed only one of the two to be important. P13 said, *"Usually, I don't look for that (intent). If I know I've been seen (awareness), then it's enough"*. In contrast, P9 said, *"Awareness can lead to intent, but not necessarily. Once you've seen me (awareness), what are you going to do (intent)?"*.

	Driver	**Vehicle Motion**	**On Vehicle**	**On Street**	**On Pedestrian**
Manual + AV	3.89	3.67	3.27	2.75	3.40
SemiAV + AV	2.57	3.50	3.56	2.83	2.71
All AV	NA	3.67	3.25	3.13	2.88
Average	2.72	3.59	3.44	2.98	2.83

Table 7: Average Likert scores of participants' cue preferences across 3 sets of trials in the mixed traffic study.

7.5 CHAPTER SUMMARY

In this chapter, we provided an initial evaluation of mixed traffic. Informed by a brainstorming session, we prototyped mixed traffic in our simulator and evaluated it in a study with 12 participants. Our results suggest that the role of interfaces remains important for pedestrians attempting to cross despite the increased complexity of the street environment. However, some of the interface cue and location preferences are influenced by the introduction of scale and vehicles with varying levels of autonomy.

8

DISCUSSION

In this chapter, we provide a nuanced discussion on the design of interfaces based on our evaluation through four studies as well as reflections on our methodologies. In this chapter, we refer to participants in the Segway study as SP#, in the car study as CP#, and in the mixed traffic study as MP#.

8.1 REFLECTIONS ON THE DESIGN OF INTERFACES

8.1.1 *Revisiting our Design Space*

Our design space (seen in Figure 14) incorporates two categories: 1) modality of cue, and 2) cue location. In this section, we revisit our findings in the context of the proposed design space, solidifying its validity and proposing implications for future design.

8.1.1.1 *Cue Modalities*

We observed that all three modalities of cues could be useful for building interfaces that explicitly communicate an autonomous vehicle's awareness and intent to a pedestrian.

However, each modality has specific trade-offs that designers should consider when building interfaces.

Visual cues: In our Segway and car studies, the LED strip was often ranked higher than the other auditory and physical cues. In the Segway study, 6 out of 10 participants ranked it as the best cue for awareness, and for intent, 7 out of 10 participants ranked it as the best cue. The same result was observed in the VR validation study where the LED strip was rated by 8 out of 10 participants as the best awareness cue. Similarly, 7 out of 10 participants found the street LED the most effective intent cue. This is not surprising as visual cues are the primary means of perceiving and making decisions for most pedestrians. For instance, pedestrians currently receive visual information from vehicle movement, traffic signals, pedestrian crossing signals, and vehicle turn signals when they attempt to cross.

In mixed traffic, the LED strip similarly provided cues clearly distinguishing awareness and intent information through color changes. This allows pedestrians to easily recognize whether a single car in a fleet of AVs fails to acknowledge them. However, visual cues, especially if they are colors, have to correctly and unambiguously reflect vehicle awareness or intent. For example, we designed the colors red and green on the LED strip in the simulator to indicate that the vehicle was not stopping and stopping, respectively. Yet, some participants found it counter-intuitive, since brake lights are usually red and indicate that the vehicle is stopping.

There is also an inherent bias in our studies from all participants being sighted which may have contributed to the popularity of visual cues. However, we often heard participants comment about the disadvantage of visual cues for those who might be color blind, visually impaired, or distracted pedestrians (a problem also discussed by Thompson et al. [58]). Based on this, while familiarity with visual cues might be a reason to consider them as the primary modality of communication in interfaces, designers should consider pedestrians with different information needs and include alternative modalities.

Auditory cues: In the car study, 6 out of 10 participants liked audio feedback from the vehicle for awareness communication. One participant mentioned that a voice message saying "cross" felt like a clear signal (*"when the speaker said I see you and cross, it was like a direct acknowledgement that the vehicle wants me to do this" [SP2]*).

Participants also expressed positivity towards auditory cues, especially in mixed traffic with several vehicles. MP11 said, *"Even though the street LED turned green, I waited until both cars said 'cross' before I decided to cross"*. However, we think that scale and mixed traffic both present major implementation challenges for auditory cues. While they could support pedestrians with visual impairment or distracted pedestrians, auditory cues may be drowned out by the number of vehicles on the street or ambient noise (which we did not include in our simulator). Despite this, we think that auditory cues could still be used along with dedicated street infrastructure in less busy intersections, assuming that autonomous vehicles in its vicinity will adjust their actions based on it.

From these results and considering the traditional usage of auditory cues (such as on emergency vehicles), we think that auditory cues could also be included on vehicles. However, they might be reserved to provide clear commands to the pedestrian during specific situations such as an emergency, or as a secondary modality in conjunction with visual cues. When placed on the vehicle, however, there may be situations where multiple unsynchronized autonomous vehicles try to communicate with pedestrians using auditory cues and the result could be a cacophony rather than useful information.

Physical cues: These cues attempt to add physical expression to the vehicle, sometimes through anthropomorphism. If well designed, we think there is value in integrating them in interfaces for autonomous vehicles. From the Segway study, we found that half our participants (5 out of 10) liked the actuated hand because it was clearly visible and straightforward to interpret. In contrast, smartphone vibration was typically not preferred. In the VR validation study, 5 out of 10 participants expressed that it was the least useful intent cue. Similarly, interviewing participants in the mixed traffic study revealed that it was the least popular cue. Participants cited several reasons for this. For instance, participants stated that since the communication was subtle, they were not confident about whether the phone had vibrated. Other participants stated that their phones always vibrated, so it would be hard to associate the feedback with an autonomous vehicle's state. We think that part of the issue with physical cues such as the phone may have been implementation. For instance, a smartwatch that vibrates has fewer associations of an incoming notification (such as a text message) than a smartphone that vibrates. Based on this, we suggest that if physical cues are to be used, they should be clearly sensed, be easy to interpret, and used as a secondary means of communication along with other cues.

8.1.1.2 *Interface Location*

Our proposed design space outlines that interfaces can be positioned on the vehicle, on street infrastructure, on the pedestrian, or on a combination of the three locations. When placing cues on entities other than the vehicle, pedestrians consider the reliability of the information they receive when making crossing decisions. When we asked participants about the reliability of cues originating from the vehicle as opposed to cues that communicated information through a third party, such as cues on the pedestrian, participants were split on the issue. This was especially evident in the case of the audio message, "I can see you", which played through a speaker mounted on the vehicle and as an audio message that played through a phone held by the participant. In the car study, 4 out of 10 participants mentioned that they preferred hearing the audio message from the vehicle or the "source". A possible explanation is that people trust the audio message coming from the vehicle since they feel it is tied to the vehicle's operation as opposed to an audio message which is sent to and received through a "second-hand" source. Still, 5 out of 10 participants mentioned that they preferred the phone audio message because it could be more practical in the real world (since relative to a hand-held phone, sounds projecting from a speaker on the car could be more affected by background noise, distance, and multiple cars playing the same message). From the Segway and car studies, it was clear that interface cues could exist on or off the vehicle,

However, our mixed traffic study results suggest that the vehicle could be the best location for interface cues. By endowing each vehicle with clear awareness and intent information in mixed traffic, pedestrians may be able to gauge individual vehicle awareness and intent to identify autonomous vehicles from other vehicles (especially if there are visual cues). In mixed traffic, pedestrians would already be looking for driver cues from some vehicles (with drivers on board), so placing interface cues on the vehicle seems most practical. Their exact placement on the vehicle remains unclear, however. We found success placing the LED strip on the vehicle's windshield, but some participants felt that the animated smile on the vehicle's grill was placed inappropriately. MP5 said, *"I didn't find it obvious enough. Plus, you had to actually look down at the car, and in Europe, we have number plates on the front as well"*.

As an alternative, interface cues could exist on the street, which received support from 9 out of the 12 study participants in the mixed traffic study. We suggest that street cues only be used at busier intersections where it may be difficult for pedestrians to gauge individual vehicles' awareness and intent. However, in order for cues on the street to be effective, pedestrians would need to trust that autonomous vehicles are well integrated and will base their actions on it. This is a shift from today's traffic lights where, for instance, drivers could see a red light and ignore it. MP10 pointed out, *"The idea I got was it said that it was safe to stop, but it didn't feel like the cars were basing their decision on that. It's more of a rule than definitive action"*. However, placing cues on the street may distract pedestrians from observing vehicle movement, which is still an important cue.

8.1.2 *Number of Interface Cues Provided*

Management-related research on the phenomenon of *information overload* [20] suggests that the decision-making performance of an individual improves with respect to the amount of information they receive up to a certain point. After this "threshold", an individual's performance rapidly declines. Our findings suggest that additional information supported pedestrian crossing decisions but also that information overload may become a factor when pedestrians are provided with too many cues.

We noticed this trend with the mixed interface (that included three cues). While participants found the mixed interface in the Segway study to be the most effective, they did not find it to be the most effective interface in the car study. One explanation accounting for the mixed interface's popularity in the Segway study is the presence of multiple cues, allowing participants that missed one of the cues to compensate for it (*"Because there are many cues to tell you when it's safe and when it can see you. There are many tools to increase your safety and boost your confidence" [SP7]*). Its popularity may also have been influenced by participants' lack of familiarity with the Segway platform. In contrast, we attributed the mixed interface's lack of popularity in the car study to the presence of too many cues, which several participants stated (*"I had to wait for all of them [the cues] to give me the go-ahead. First the light, then the phone, and then the hand. I think it takes a lot of time and could* *be confusing to many people" [CP9]*). In the mixed traffic study, participants did not report information overload. Instead, many filtered any additional cues that were not useful to them, which suggests that having extra cues may not be a problem for some pedestrians.

Once we begin considering a wider net of pedestrians, especially vulnerable road users such as the elderly, this challenge may become acute. A study assessing the effect of age on crossing [18] found that declines in particular perceptual and cognitive abilities caused older pedestrians to overestimate bad crossing opportunities while missing good crossing opportunities. For such pedestrians, overly complicated interfaces may not be very effective. Simultaneously, as older pedestrians have trouble perceiving a vehicle's speed correctly, especially at higher speeds [18], providing additional cues beyond the vehicle's movement could prove to be essential. Our findings do not point to a specific cue threshold for the design of interfaces. Rather, they emphasize the possibility of information overload for some pedestrians as additional cues are provided.

8.1.3 *Complexity of Interface Cues*

Cues exhibiting only a few states that were clearly communicated were generally more popular among participants in the Segway and car studies than cues with multiple states or cues that were ambiguous. A simple cue from our prototypes is the actuated hand (see Figure 19), which 5 out of 10 participants said was the best intent cue in the Segway study. Although the phone vibration was not a popular cue due to its impracticality as a cue in the real world, it was a simple cue with two states. One participant said, *"Because it's immediate (phone vibration). You don't have to process four different colors. It's a yes or no, vibrating or not" [CP3].*

In contrast, the LED strip and the animated face had multiple states which participants sometimes found difficult to interpret. The LED strip showed four clear states, yet one participant felt it was too complex. CP3 said, *"Because those LED's - there were too many colors, so I had to look at the sheet [interface description] and decide. In reality, I cannot bring a sheet"*. The animated face was the worst-performing cue in both Segway and car studies. CP6 said, *"The reason I don't like eye contact as much as hand gestures is because eye contact is kind of ambiguous. I don't know if you see me or someone next to me or if you're actually making eye contact. A gesture is very explicit when driving"*. A participant in the car study suggested an improvement to the animated face through fixing the number of states (*"It has to be logical, like one, two, and three. Only three positions or states" [CP9]*).

Our finding that autonomous vehicle interfaces need to provide stable and clear cues to pedestrians is not surprising and is aligned with the basic principle of clear and continuous feedback in human-computer interaction [30]. Hence, we suggest that designers should include easy-to-interpret cues with a few distinct states.

8.1.4 *Responsibility Distribution During the Interaction*

In traditional driver-pedestrian interaction, both the driver and pedestrian share some responsibility for ensuring a safe interaction. Drivers are expected to observe pedestrians and make a rational decision based on the rules of the road. This implies, for instance, that they should yield to pedestrians at an intersection with painted crossing lines and a yield sign. Pedestrians are equally expected to observe vehicles before crossing even if they have the right of way since it is far more dangerous to be a pedestrian that it is to be the driver of a vehicle. However, our findings indicate that the current distribution of shared responsibility may be changing in the case of autonomous vehicles. In the no interface task of the car study, 2 out of 10 participants mentioned that they felt more responsibility for making the crossing decision (*"Normally it's 50-50, but with autonomous vehicles, it's more on the pedestrian. I mean, I cannot speak to the autonomous vehicle, since there is no driver inside. Otherwise, I could wave my hand or something" [CP5]*).

In contrast, 5 out of 10 participants felt that the presence of interfaces reduced their responsibility when making crossing decisions. CP10 said, *"I think if the car gives me all the cues that I should cross, and I follow it, and there's something wrong, it's the full responsibility of the car. They reduce my responsibility to zero because I was induced into taking action based on what I saw".* This suggests that there is a possible overreliance that people may develop towards autonomous vehicles with interfaces. When the interface mirrors the vehicle's actions, this would actually drop the vehicle's responsibility since it is clear about its intentions. However, in the event that the interface sends the wrong message, pedestrians' overreliance may impact their crossing decisions. Our expectation is that in the transition period until full autonomy, pedestrians will continue to remain cautious and assume equal responsibility for their safety as some vehicles on the road may have a driver on board and could behave unpredictably. However, once all vehicles are fully autonomous, the question of overreliance may arise.

8.1.5 *Usefulness of Anthropomorphic Cues*

While prototyping, we borrowed heavily from the cues that drivers may use in their daily interaction with pedestrians. For instance, we used an animated face as a cue on the vehicle and pedestrian interface (Figure 18), verbal cues for our speaker messages, and hand gestures in the mixed interface (Figure 19). The animated face we implemented in the vehicle and pedestrian interface was not well received in either the Segway or car studies. However, the actuated hand performed well in both studies, with participants citing its familiarity and the explicit communication of intent as reasons for its effectiveness. Similarly, audio cues were especially popular in the car study. One participant said, *"My confidence increased when I heard a familiar voice like a human" [CP10]*. Auditory cues remained popular in our validation and mixed traffic studies, behind only the motion and visual cues. While we observed positivity towards some human-like cues, we do not have a clear answer about their use in interfaces for autonomous vehicle-pedestrian interaction. While they may be useful when autonomous vehicles are introduced, we expect that machine-like cues will eventually take their place since they clearly communicate vehicle state information.

8.1.6 *Significance of Vehicle Movement*

Our findings from all four studies suggest that vehicle movement remains a significant cue in autonomous vehicle-pedestrian interaction even when interfaces are present. In our studies, participants experienced both the *slowing early* and *stopping short* movement patterns that Risto et al. highlighted [48]; when intending to stop, the vehicle slowed down early, and always stopped at a considerable distance away from the designated crosswalk. In the no interface condition, a majority of all study participants pointed to vehicle speed and stopping distance as reasons for their confidence in the vehicle's awareness and intent. One participant in the Segway study argued that vehicle speed was the most crucial cue. This was reflected in their crossing behavior. In some trials with interfaces, they crossed before some or all of the cues had been communicated (*"If the vehicle was too far away, you wouldn't see the driver, but if it was close, then I'd base my decision on eye gaze and hand gestures. But mainly it's the speed and how close it is" [SP7]*). In the mixed traffic study, vehicle movement was one of the most popular cues along with cues on the vehicle. However, given that some vehicles in mixed traffic may have drivers and others may not, we think that movement alone may not be sufficient especially in the transition period. However, we stress that designers should consider autonomous vehicle movement as a key layer of interaction with pedestrians, providing baseline information that should be reinforced by other explicit communication cues.

8.2 PEDESTRIAN BEHAVIOR IN MIXED TRAFFIC

8.2.1 *Crossing Strategies*

Our findings suggest that pedestrians deal with mixed traffic by assessing the types of vehicles on the road and the cues they provide. In our mixed traffic study, we found that most participants were timely crossers (9 out of 12) - they waited for vehicles to fully stop before crossing irrespective of the types of vehicles, interfaces, or group pedestrian behaviors they encountered. Still, we found some interesting trends from analyzing the study results that we summarize below.

8.2.1.1 *Influence of Group Vehicle Behavior*

We have early results suggesting that pedestrians may have made crossing decisions based on the autonomy level of the vehicles they encountered. Although our results are not statistically significant, our classification of participants' crossing decisions shows that participants made more early crossing decisions in the presence of manually-driven vehicles with attentive drivers in one lane and autonomous vehicles in the other (in 68 out of 538 trials) than when there were vehicles with a distracted driver in one lane (in

48 out of 538 trials). In our video analysis, we found individual instances where participants made decisions based on the mix of vehicles present. For instance, a participant crossed the street when faced with an autonomous vehicle that communicated it was safe to cross through an interface alongside a vehicle with a distracted driver which also slowed down and stopped but did not explicitly communicate awareness or intent. MP11 said, *"So there I saw the smiley face and decided to cross, but then I realized that the other car had a distracted driver. I could have definitely endangered my life"*. Even though the participant had a clear view of both vehicles, their decision to cross was made by observing the autonomous vehicle, hinting at an overreliance that pedestrians may develop when seeing autonomous vehicles next to other vehicles.

In another example, an autonomous vehicle indicated to a participant that they could cross through an interface, but the participant waited until the vehicle next to it with a driver on board also explicitly communicated its intent to stop before crossing. Here, the distrust of human-driven vehicles (with drivers on board who could be distracted or make mistakes) may have prevented the participant from crossing quickly.

In our studies, we included semi-autonomous vehicles whose drivers appeared to be distracted, making it ambiguous for participants to identify its autonomy level. While some participants interacted with the vehicle in mixed traffic as though the driver was distracted, others assumed that the vehicle was autonomous at that instant. This highlights a potential problem with semi-autonomous vehicles sharing the road in mixed traffic, as our brainstorming session predicted (see Chapter 6) – the difficulty for pedestrians to assess who is in control of the vehicle's operation. As semi-autonomous vehicles (SAE Level 2 or 3 [52]) will allow for switching control of vehicle operation between driver and automation, pedestrians may not be used to the idea of drivers appearing so distracted inside them especially upon their introduction. For example, MP3 said, *"I'm* *pretty skeptical about software bugs in autonomous vehicles, but distracted drivers were scarier"*. While prior work and our results suggest that fully autonomous vehicles (SAE level 5 [52]) will need to communicate with pedestrians, we think the same will extend to semi-autonomous vehicles (SAE level 3 [52]). Similar to the ideas suggested by Lagström and Lundgren [32], we think such SAE level 3 vehicles will need to indicate whether they are autonomous at any given moment, and if so, would need to communicate in a manner similar to fully autonomous vehicles.

8.2.1.2 *Influence of Interfaces*

Vehicles with and without interfaces also impacted pedestrians' crossing strategy in mixed traffic. 11 out of 12 mixed traffic study participants explicitly stated in the interview that seeing vehicles without interfaces made them more cautious when crossing. When seeing vehicles with distracted drivers and autonomous vehicles without interfaces, the issue was exacerbated as both types of vehicles did not explicitly communicate with participants beyond movement.

8.2.1.3 *Influence of Group Pedestrian Behavior*

Though our results were not statistically significant, 6 out of 12 mixed traffic study participants cited the presence of a group of pedestrians as a factor that may have influenced their crossing strategy. MP12 said, *"I just followed the other pedestrians' actions. You can feel social pressure. If people are waiting, you are going to wait, but if you are alone, you can make the decision and not be observed"*. We found small variations in crossing patterns based on the presence of the group. Participants made crossing decisions earlier (in 64 out of 538 trials) when other pedestrians crossed slightly earlier, compared to when there were no other pedestrians (in 55 out of 538 trials) or timely crossers (in 54 out of 538 trials).

However, we qualify these findings by stating that some participants did not feel that the presence of other pedestrians impacted their crossing. MP5 said, *"I would rather rely on my own eyes than follow other pedestrians blindly"*.

8.3 Reflection on Our Evaluation Methodologies

8.3.1 *Pedestrian Simulators as a Design and Evaluation Tool*

All participants stated that the crossing experience in our simulator was similar to their real-world experience partly due to its graphical fidelity and but also due to the fairly accurate behavior of vehicles and pedestrians. For instance, MP11 said, *"When there was a driver, I behaved basically the same as I would in the real world"*. Similar quotes were echoed throughout our validation and mixed traffic studies. We see our findings as evidence that pedestrian simulators can be valuable tools to gauge real-world pedestrian behavior and could be immensely useful in autonomous vehicle-pedestrian interaction research.

From a researcher's perspective, our simulator offers incredible flexibility in study design. Adding a test variable is as simple as writing a few lines of code. For example, designing or modifying the behavior of an interface prototype in VR can be done with ease, whereas in the real world could be limited by hardware or monetary constraints. One of the defining characteristics of mixed traffic is scale – the number of vehicles and pedestrians on the street. In our VR environment, there is comparatively no cost to scaling so we can add as many vehicles and pedestrians as our hardware supports. VR also enables us to more accurately capture participant data in real-time such as the time it takes to make a crossing decision or other qualitative measurements such as comfort level. Arguably the most beneficial aspect of the simulator and the Unity3D game engine is its support for the reproducibility of user studies. In our mixed traffic study, each participant encountered 90 trials, but they experienced them in an identical fashion.

Beyond crosswalks, it is evident that many other interesting autonomous vehicle-pedestrian interaction problems could be studied and validated in VR with a high standard of realism. For example, in the longer-term future, if all vehicles are autonomous, it is possible that we may no longer need fixed intersections. Instead, since autonomous vehicles could stop anywhere at any time, they could create dynamic intersections. One could safely prototype and test this in a simulated environment, whereas it would be infeasible in the real world.

8.4 LIMITATIONS

Our work demonstrates that explicitly communicating autonomous vehicle awareness and intent information to pedestrians can help them make safe crossing decisions. However, we only looked at a small slice of the wider autonomous vehicle-pedestrian interaction space by focusing on crossing scenarios at unsignalized intersections. The first set of two studies were conducted in controlled settings using Wizard-of-Oz, which limits realism and the generalizability of study results. In addition, participants did not physically cross the street in most of our studies, except in the Segway study. In the car study, participants could only indicate their crossing decisions due to safety constraints.

In the VR studies, our aim was to understand the process that leads to the crossing decision, so participants did not physically cross. Further, although our simulator offers a high level of graphical fidelity and sense of presence, we were still limited by hardware from the headset. Its inability to provide a wide field of view, its low display resolution making it difficult to see vehicles from afar, and its poor sound localization all reduced the realism of the crossing experience. The simulator also failed to capture the randomness of the real world or its intricacies such as background noise or the behavior of traffic participants. One of our participants stated *"There is more randomness in real life such as a [driver] who speeds up or a [driver] who cuts red lights" [MP8]*.

Beyond this set of limitations, we recruited a small number of participants for all our studies. Another limitation of our work is that it is grounded in vehicle-pedestrian interaction in a North American context. In this context, pedestrians generally obey the rule of the road, and our interface prototypes reflect this. We think that differences in road culture will undoubtedly affect many of the design considerations for building future interfaces. In other road cultures, drivers may need to honk and flash their lights to prevent pedestrians from jaywalking. Autonomous vehicle interfaces in such driving cultures may need to imitate some of these behaviors in order to hold their ground. This may also be seen as an opportunity to build interfaces that can shift driving and pedestrian culture towards a more safe and favorable one.

9

FUTURE WORK AND CONCLUSION

In this thesis, we provide a first exploration into the design of interfaces to facilitate autonomous vehicle-pedestrian interaction. As such, there are many interesting avenues of research that one could pursue. Some of these directly follow from the results of our studies. Others are more radical and are inspired by our initial exploration.

9.1 FUTURE RESEARCH DIRECTIONS

9.1.1 *Examining Crossing Interactions in the Real World*

In all our studies, we maintained a controlled environment to measure the effect of interfaces on participants' crossing decisions. Past research has shown that laboratory studies have several limitations [4], one of them being the inability to naturalistically evaluate an interaction involving humans and technology. However, we opted for this approach to ensure participant safety and control over testing conditions. A possible extension is "in-the-wild" evaluation on actual autonomous vehicles in less controlled environments.

For instance, drive.ai [1] is currently evaluating the interaction of autonomous vehicles and pedestrians by embedding explicit interfaces on the vehicle. Similarly, Ford [2] placed an LED strip on a vehicle that appears autonomous (through a driver wearing a seat costume) and is currently evaluating their interaction with pedestrians. Studying these interactions over a long duration will help designers understand how information flows from vehicles to pedestrians and help them design future interfaces that could succeed in the real world.

9.1.2 *Replication of Studies in Other Cultures*

In our design studies, we sought feedback from interaction design researchers based in North America, which may have influenced the designs we received. Replicating this study in other cultural contexts may yield different results. Instead of approaching experts in interaction design to brainstorm design ideas, one could also approach the general public as Verma et al. [62] did in their recent work.

Driving culture is also a determining factor in how interfaces should be designed for autonomous vehicle-pedestrian interaction. As we stated in Chapter 8, our research is rooted in a North American context. Hence, the interfaces we have proposed may suffice but could potentially fail in other road cultures. In order to design interfaces that will succeed in other road cultures, it is important to study how the interaction currently flows and will unfold in the future when autonomous vehicles are introduced. We are beginning to see such studies such as the one by Currano et al. in Mexico [12] and by Weber et al. in China [67].

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1 https://www.drive.ai
2 https://engt.co/2YFoJvX

9.1.3 *The Design of Future Vehicle-Pedestrian Interfaces*

We proposed a design space to facilitate autonomous vehicle-pedestrian interaction. Such a design space affords infinitely many possibilities to build interfaces, but we only evaluated a small selection of them. An extension that future researchers could explore is other combinations of cues and locations that make up an interface. Eventually, we hope to accumulate a stronger understanding of what makes an interface design useful, whether it is the cue modality which is chosen or its location.

9.1.4 *Applying Concepts from Social Robot Navigation*

As we stated in Chapter 2, researchers in social robotics have been studying problems parallel to that of autonomous vehicle-pedestrian interaction. There are many interesting concepts that future researchers could directly apply to this domain. For instance, once autonomous vehicles are introduced, especially without a driver on board, they would need to approach crosswalks in a way that is most comfortable to pedestrians through the consideration of their personal or interaction spaces [47]. There may even be the possibility of incorporating explicit human verbal instructions (Section 8.4 in [57]) to learn or understand social norms in different road and pedestrian cultures.

9.1.5 *Expanding the Simulator to Study AV-Pedestrian Interaction*

In our examination of mixed traffic thus far, we have only explored a subset of factors that could affect pedestrian behavior at an unsignalized crosswalk. There are many more factors at play when pedestrians decide to cross. In the future, one could explore a larger subset of factors such as vehicle size and speed, all of which are easily supported by simulators such as ours. We also did not have participants physically cross in our studies. One obvious extension may be to enable room-level tracking so that one can study pedestrian dynamics such as their trajectories and speed profiles in mixed and autonomous traffic. To further enhance the realism of the crossing experience and hence the evaluation, one could combine the benefits of the virtual with the real through technology such as augmented reality. It is possible, for instance, to study the effect of scale through synthetic vehicles on real roads.

Using a simulator-based approach, we can begin to explore the interaction of other road users with autonomous vehicles and mixed traffic. Currently, participants can only play the role of pedestrians in our simulator. However, it is possible to explore the perspective of other road users, such as cyclists or passengers inside autonomous vehicles. For instance, cyclists today make merging decisions in road traffic while surrounded by many vehicles. This is a fairly dangerous maneuver in which the cyclist does not receive much feedback from the vehicle or driver such as whether it is safe to merge at a given moment. Through a simulator like ours, it is easy to place participants in the role of a cyclist and study whether interfaces similar to the ones we propose could help them make safe merging decisions in autonomous and mixed traffic.

9.2 CONCLUSION

We set out to understand how to develop novel ways of facilitating autonomous vehicle-pedestrian interaction at crosswalks. Informed by the literature and preliminary exploration, we arrived at interfaces as a potential solution to the interaction problem. Upon prototyping and evaluating these interfaces, we found that interfaces explicitly communicating awareness and intent can be useful in autonomous vehicle-pedestrian interaction.

Our first objective in this thesis was to *expand our understanding of how pedestrians make street crossing decisions at unsignalized crosswalks when faced with autonomous vehicles that do not provide driver cues*. Indeed, we found that while vehicle motion is a very powerful cue, most participants did not feel comfortable crossing when faced with autonomous vehicles that did not explicitly communicate with them. Instead, the use of interfaces generally made participants more confident about the vehicle's awareness and intent and helped them make safe crossing decisions.

As part of the second objective, *we explored how to build interfaces for autonomous vehicle-pedestrian interaction.* We were informed through our design study that there are infinitely many ways to build interfaces for this interaction. However, in practice, we examined only a small segment of these interfaces. Although we do not have a definitive answer for how to build the ideal interface, we have a strong sense of the components that comprise it. First, we think that the interface must communicate awareness and intent as both are important for pedestrians. Next, we think that they should be multi-modal and provide easy-to-understand cues without overloading pedestrians. In terms of the cues that should be used, we think that visual cues are generally preferable as a primary modality, while auditory cues are a good secondary modality. The location of the interface is still unclear, though we have evidence suggesting that at least in mixed traffic, interfaces on the vehicle seem to be preferred.

Our last objective was to *build and evaluate a platform to study how interfaces may perform in scaled environments.* To accomplish this, we built a VR-based pedestrian simulator where we can manipulate several factors such as traffic and street characteristics, vehicle behavior, pedestrian behavior, and the presence of interfaces. Through this simulator, we were able to verify our previous Wizard-of-Oz study results about the usefulness of interfaces. We also provided a first examination of mixed traffic in the literature through which we found that interfaces continue to remain useful for pedestrians attempting to cross in such environments. We have early evidence suggesting that pedestrians develop varying crossing strategies to help them deal with the intricate mix of vehicles they are faced with, the behavior of pedestrians around them, and the presence of interfaces on these vehicles.

The introduction of autonomous vehicles on our streets will dramatically change the dynamics of vehicle-pedestrian interaction. To facilitate safe street crossing, our thesis proposes a potential future where interfaces will communicate autonomous vehicle state information to pedestrians. Our methodology and results provide a strong starting point for future researchers or practitioners in building and evaluating interfaces for the interaction and are already being used within the community. We hope that this thesis will continue to be useful to researchers navigating the complex yet important problem of autonomous vehicle-pedestrian interaction and lead to novel solutions in facilitating it.

Part II

APPENDIX

A

ADDITIONAL MATERIAL FOR THE "FIGHT-OR-FLIGHT" DESIGN STUDY

Here, we include the study protocol and consent form used in the design study session on "Fight-or-Flight" described in Chapter 3.

Study Protocol
Hello! Thank you very much for participating in this study. My name is Karthik Mahadevan. I am a researcher at the University of Calgary. For the sake of consistency and clarity, I will read the details of the study from this sheet.

The goal of this study is for us to learn about how safety in human-robot interaction can be maintained throughout the course of the interaction. All of you may have seen videos of robots interacting with humans or interacted with them in person. Such robots offer us many possibilities, from being aids in our home to taking us to work (such as vacuum cleaners or autonomous vehicles). They can even be companions in our time of need (such is the case with robot pets).

Robots are being designed to act safely in many ways; through control (pre-collision methods, post-collision methods), safety through motion planning (collision avoidance), safety through prediction, and safety through consideration of psychological factors (by making its features more anthropomorphic for example, separation distances, speeds).

However, one area that seems to be relatively unexplored is the human response. All the above is from the perspective of the robot and its technical competencies. To some extent, we limit a robot's capabilities by focusing on making its core competencies less powerful/less fast, etc.

Ground Rules
As we would like to capture conversation, we would request that you speak aloud, and one at a time (when possible). All comments and discussion are welcome. The session will last an hour and a half. You will be presented with 4 scenarios throughout the session of different robotic platforms. My request is for you to provide your thoughts and ideas based on a few questions which I will ask you. In all of these questions, you will work as a group. In a few of them, you will be asked to prepare a rendition or solution that will be recorded on camera.

If this sounds acceptable to you, please sign this consent form asking permission to record video and audio of the study session. Also please fill out a short pre-study questionnaire about your background.

Stationary
Here is some stationary:
1) Sticky Notes
2) Sheets of paper
3) Pens
4) String
5) Tape

If are ready, we can now begin.

Scenario 1

Okay, so the first platform we will discuss is a vacuum cleaner type of robot. Here is a photo of the Roomba, and a video of it in action. A Roomba is just one type of robot vacuum cleaner. Essentially, it can drive around autonomously and clean floors (ideally anyway). Now, I'd like you to imagine a situation where the Roomba may be dangerous. For example, you could be walking into a room and the Roomba suddenly hits you because you have surprised it. Or perhaps you are sitting on the couch and it just drives aimlessly and ends up hitting you. Or it is about to hit something important to you (glass objects, etc.).

- Q1) How would you respond to a potentially dangerous situation or action that may cause you harm?
    - Would you express fear?
    - Would you walk away from it?
    - Would you terminate it?
- Q2) How would you want to communicate to the robot in a dangerous or seemingly dangerous HRI scenario?
    - Would you want it to recognize certain things? Like gestures, eye contact, voice?
    - Please come up with a rendition of what this would look like
- Q3) How should the robot respond to your concern?
    - Should it use specific actions (motion) or gestures or voice? Interface?
    - Please come up with a rendition of what this would look like.
- Q4) Should the robot behave in a more predictable manner so that you can sense more easily when the situation is becoming dangerous?
    - How would you achieve this predictability?
    - Would you want it to communicate using specific motion patterns, etc.? An interface?

Scenario 2

Most of you know self-driving cars. They can offer the potential to take people from point A to B. There are two possible ways you could interact with a self-driving car. One, is where you are a passenger inside the vehicle. Another is where you are a pedestrian trying to cross. In both situations, the car can act recklessly and put you in danger. For example, in a car, this could be through very aggressive driving (e.g. high speeds, cutting lanes, etc.). Another example is, where you are trying to cross an uncontrolled intersection (perhaps with painted lines or without) and the vehicle for some reason has failed to detect you or detects you later on (which makes you feel at risk or in danger), or has an aggressive driving mode where it will not stop.

- Q1) How would you respond to a potentially dangerous situation or action that may cause you harm?
    - Would you walk away from it?
    - Would you terminate it?

- Q2) How would you want to communicate to the robot in a dangerous or seemingly dangerous HRI scenario?
    - Would you want it to recognize certain things? Like gestures, eye contact, voice?
    - Please come up with a rendition of what this would look like
- Q3) How should the robot respond to your concern?
    - Should it use specific actions (motion) or gestures or voice? Interface?
    - Please come up with a rendition of what this would look like.
- Q4) Should the robot behave in a more predictable manner so that you can sense more easily when the situation is becoming dangerous?
    - How would you achieve this predictability?
    - Would you want it to communicate using specific motion patterns, etc.? An interface?

Scenario 3
The NAO is a humanoid robot designed to interact with humans on various tasks. The NAO can behave dangerously as well (despite its tiny profile). Its body is strong, and it has limbs and arms which can certainly cause damage when used inappropriately. Further, they can also be psychologically damaging because they have speech abilities. One example is in a room with small children where the NAO is instructing them in playing a game. Small children in the close vicinity of a robot.

- Q1) How would you respond to a potentially dangerous situation or action that may cause you harm?
    - Would you walk away from it?
    - Would you terminate it?
- Q2) How would you want to communicate to the robot in a dangerous or seemingly dangerous HRI scenario?
    - Would you want it to recognize certain things? Like gestures, eye contact, voice?
    - Please come up with a rendition of what this would look like
- Q3) How should the robot respond to your concern?
    - Should it use specific actions (motion) or gestures or voice? Interface?
    - Please come up with a rendition of what this would look like.
- Q4) Should the robot behave in a more predictable manner so that you can sense more easily when the situation is becoming dangerous?
    - How would you achieve this predictability?
    - Would you want it to communicate using specific motion patterns, etc.? An interface?

Scenario 4
The Baxter is a collaborative robot designed to help specifically with automation tasks where there is repetitive work being done. Mostly found in industrial and factory settings but also around in research environments. The Baxter definitely has a potential to injure people around it because it has large 7DOF arms which can damage fairly easily. An example of a possibly

dangerous action comes when they are working with humans on an assembly line or completing a task like washing dishes or cleaning something together (where arms may get tangled or come in contact).

- Q1) How would you respond to a potentially dangerous situation or action that may cause you harm?
  - Would you walk away from it?
  - Would you terminate it?
- Q2) How would you want to communicate to the robot in a dangerous or seemingly dangerous HRI scenario?
  - Would you want it to recognize certain things? Like gestures, eye contact, voice?
  - Please come up with a rendition of what this would look like
- Q3) How should the robot respond to your concern?
  - Should it use specific actions (motion) or gestures or voice? Interface?
  - Please come up with a rendition of what this would look like.
- Q4) Should the robot behave in a more predictable manner so that you can sense more easily when the situation is becoming dangerous?
  - How would you achieve this predictability?
  - Would you want it to communicate using specific motion patterns, etc.? An interface?

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Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Sowmya Somanath, PhD Student – Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Exploring Safety in Human-Robot Interaction

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how to achieve safety in human-robot interaction.

What Will I Be Asked To Do?

- Participants will participate in a group of 5.
- Participant will be presented with scenarios of robots acting in an unsafe manner, and be asked to provide their thoughts through discussion and video prototyping.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 90 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results:	Yes: ___ No: ___
I agree to let video/audio recordings or parts of it from the session to be used, for data analysis only:	Yes: ___ No: ___
I agree to let my conversations during the study be quoted, in presentation of the research results:	Yes: ___ No: ___
I wish to remain anonymous, but you may refer to me by a pseudonym:	Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There are no known harms associated with participating in this research. Feel free to ask questions about this study at any time.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you. TCPS advises that data from participants who have chosen to withdraw from the study not be retained.

All data received from this study will be kept for five years in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project. Data will be destroyed once it is of no further use (e.g., by erasing files and shredding paper copies).

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this

research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ______________________________________

Participant's Signature: ____________________________________ Date: ____________

Researcher's Name: (please print) ____

Researcher's Signature: __________________________________ Date: _____________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
(403)210-9404, ehud@ucalgary.ca

Sowmya Somanath
PhD Student - Department of Computer Science
University of Calgary
ssomanat@ucalgary.ca

Karthik Mahadevan
Research Associate – Department of Computer Science
University of Calgary
karthik@ualberta.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

B

ADDITIONAL MATERIAL FOR THE INTERFACE DESIGN STUDY

Here, we include all the supplementary materials we used to conduct the design study described in Chapter 4.

- Study protocol
- Design sheets
- Pre-study questionnaire
- Consent form

Design Study Protocol

Hello! My name is (Karthik or Sowmya or both). Thank you for participating in our study. For the sake of consistency across all our participants, I will read out the study details from this sheet.

The goal of our study is to understand how interaction designers design interfaces to communicate awareness and intent of an autonomous vehicles to pedestrians and passerby's.

Awareness: The car communicates that it is aware of the pedestrian's presence, to the pedestrian. Eg: human drivers show awareness with gaze.

Intent: The car communicates the next action it is about to take, to the pedestrian. Eg: human drivers slow down/use arm movements/etc. to show intent to stop/go.

The study today will consist of two parts:

(1) First, you will be a given a design brief and in 30 minutes you must create 3 unique lo-fi interface designs.

(2) Second, you will be given 4 scenarios and you will reconsider your created interface designs to see if the designs can stay as it is or if the design needs to be modified.

Throughout the study, we please ask you to talk aloud – tell us what you are designing, your considerations etc.

The study today should take about ~60 minutes. If at any point you have questions, please feel free to ask.

Any questions so far?

Today, we will first begin with the consent form. This is to get permission to record video, audio and take pictures of your lo-fi prototypes. Then pre-study questionnaire.

Let's begin.

Part 1:

There is an autonomous car that can drive around without a driver. You have to create 3 unique interface designs that allow this car to communicate: that it is aware of the pedestrians and its next action to the pedestrian. For this activity, you will be provided with this design sheet (show them the sheet) and a set of labels. You can create your interface by sticking these labels on the car. Please annotate to tell us about interactions between the different labels. You are also free to create new labels or sketch directly on this sheet.

For this activity, you have 30 minutes. Please remember to talk aloud about your design process.

Definitions of tokens:

1. Display: Anything that provides visual information to the pedestrian.
2. LED: Lights that can be arranged and lit in a variety of ways.
3. Laser projection: The use of laser to project on a surface.
4. Actuator: Any object that moves or rotates.
5. Speaker: Capable of playing live messages, recorded messages, or sounds.
6. Haptic feedback: Something that can provide a sense of touch to the pedestrian.
7. Communication: Variety of communication methods, such as Bluetooth, wireless, etc.
8. Motion: Could include variations in speed, movement, direction, etc.

Crucial reminder: Each design must be independent of another in terms of functionality. Each design should be able to communicate both intent and awareness to the pedestrian.

Also, write # design, participant, date.

Car Actions:

1. I'm about to yield/stop
2. I'm resting
3. I'm about to start
4. I will continue driving

Any questions?

You should annotate interactions. You can create new labels if you like. Remind them to talk aloud. Place token in the position you'd expect it to be in the car.

Part 2:

Now let's begin the second part of the study. In this part, we will present 8 scenarios. You have to tell us which design of yours best fits this scenario and why? Are there any changes you'd like to make? As you explain, please make those changes to your designs.

For each scenario, rank the most effective to least effective design capable of handling it.

Scenario 1:
I see a red light, and I will stop so pedestrians can cross.

Which design of yours best fits this scenario and why? Are there any changes you'd like to make? Please make the necessary design changes (if they mentioned any).

Scenario 2:
I am turning left/right but I see the pedestrian walk signal is on. I will wait until everyone has crossed and proceed.

Scenario 3:

I am at the parking lot, and I am at rest.

Which design of yours best fits this scenario and why? Are there any changes you'd like to make? Please make the necessary design changes (if they mentioned any).

Scenario 4:
I see an amber signal, but I am half way through the signal so I will go.

Which design of yours best fits this scenario and why? Are there any changes you'd like to make? Please make the necessary design changes (if they mentioned any).

Scenario 5:
I see a jaywalker, so I will stop and let them pass.

Which design of yours best fits this scenario and why? Are there any changes you'd like to make? Please make the necessary design changes (if they mentioned any).

Scenario 6:
Due to bad road conditions, it would be dangerous to stop. I will not stop.

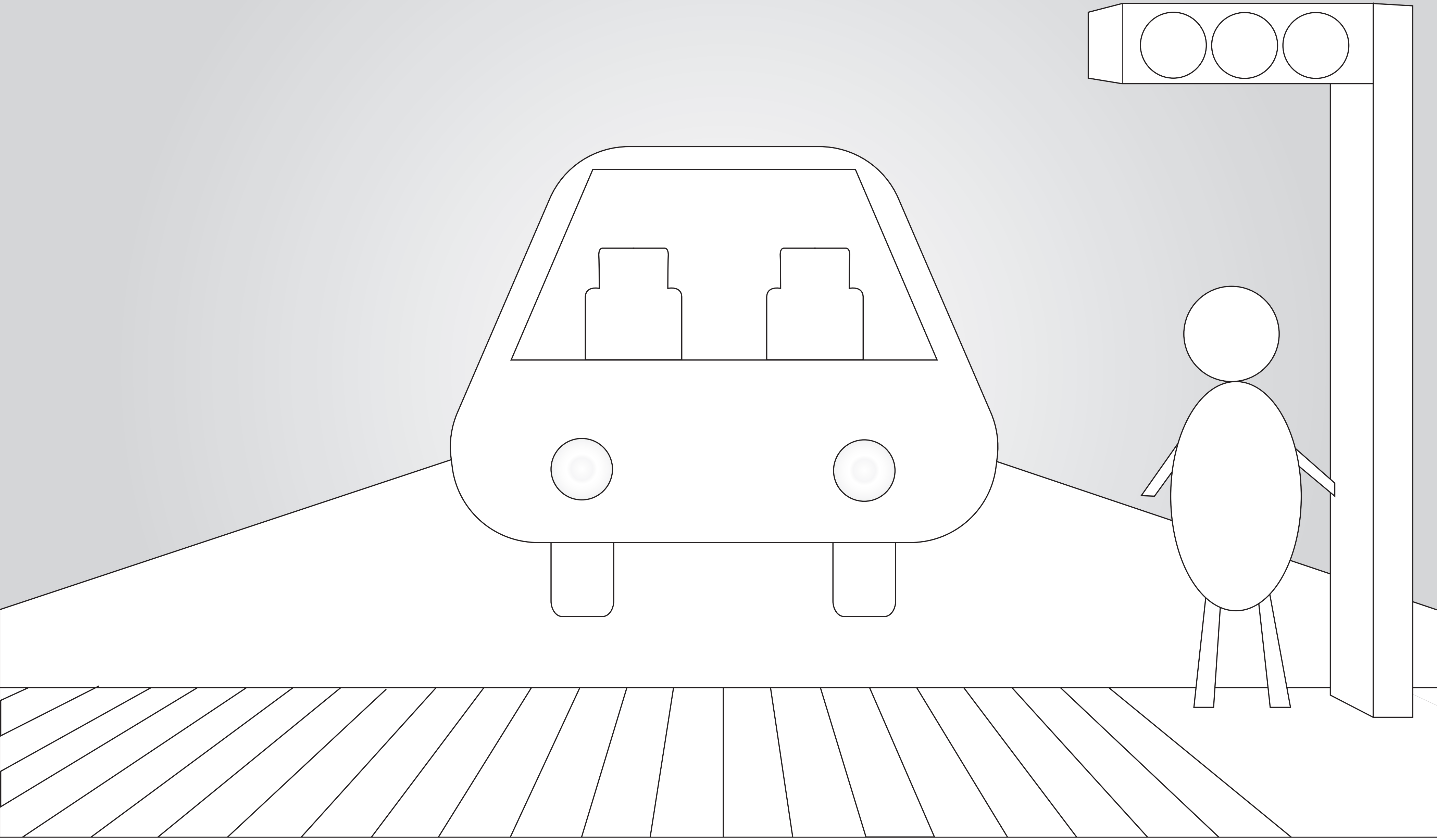
Which design of yours best fits this scenario and why? Are there any changes you'd like to make? Please make the necessary design changes (if they mentioned any).

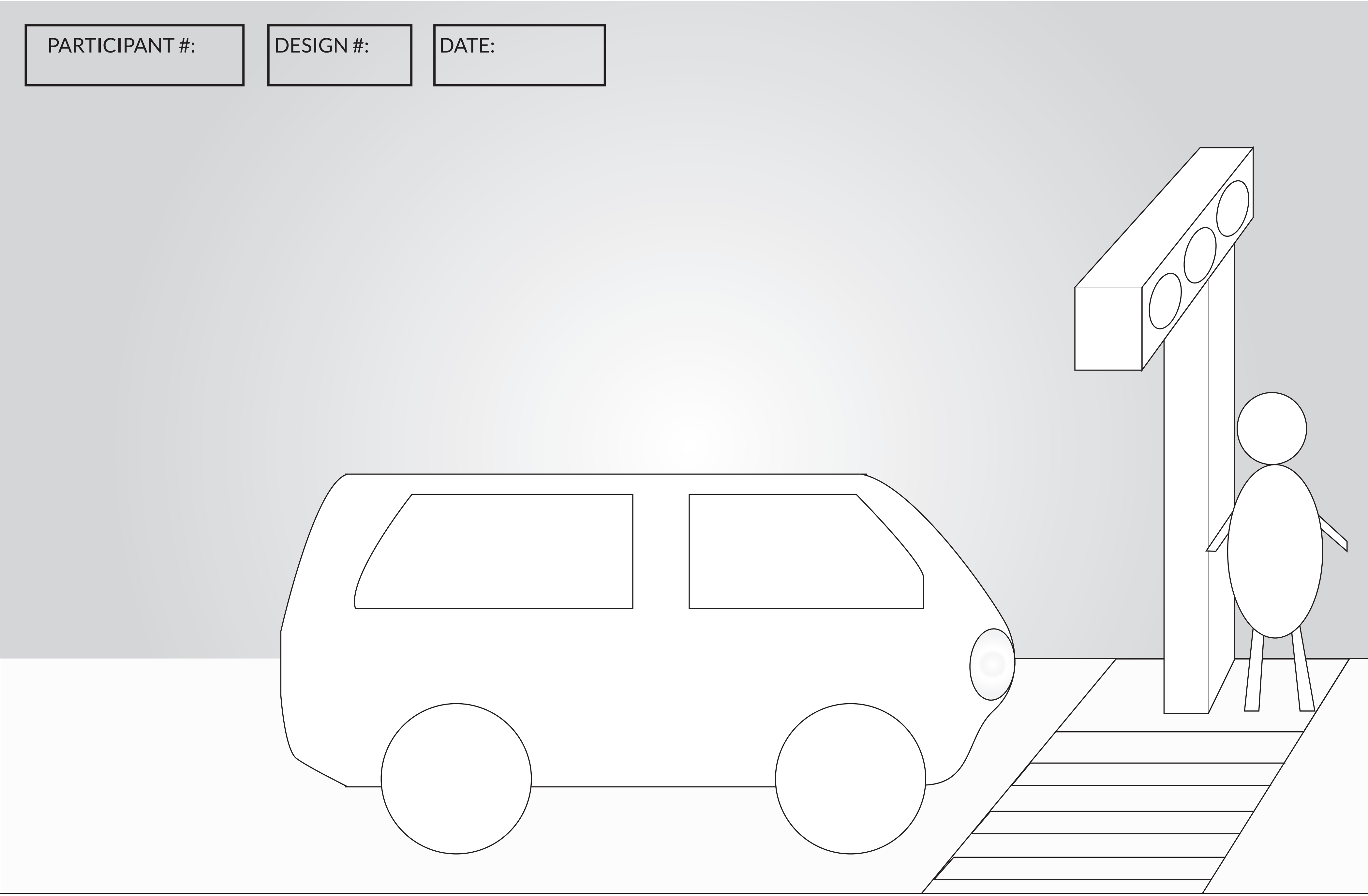
Scenario 7:
I am reversing at a parking lot.

Scenario 8:
Unmanned intersection.

---- End of study.

PARTICIPANT #:	DESIGN #:	DATE:




PARTICIPANT #:
DESIGN #:
DATE:

Project Title: Exploring Awareness Communication by Autonomous Vehicles

Pre-Study Questionnaire

Participant number:

1. Age:

2. Gender (M/F/Prefer Not to Say):

3. Profession:

4. How often do you drive a car? Please choose one from the below options.
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always

5. How often do you interact (e.g. signal them to cross, make eye contact to indicate you will stop the car etc.) with pedestrians on the street?
    a. Never
    b. Rarely
    c. Sometimes
    d. Often
    e. Always

6. As a pedestrian what kinds of signals do you expect to receive from the car to indicate its intent (i.e. the next action the car will take – stop, move, turn etc.)?

7. As a pedestrian how do you know that the car is aware of its surroundings?

Project Title: Exploring Awareness Communication by Autonomous Vehicles

Participant Number:

Scenario Ranking

Scenario	Best Fit	Fair Fit	Poor Fit
Scenario 1			
Scenario 2			
Scenario 3			
Scenario 4			
Scenario 5			
Scenario 6			
Scenario 7			
Scenario 8			

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of computer science, University of Calgary
Sowmya Somanath, PhD Student – Department of computer science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of computer science, University of Calgary

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Exploring Awareness Communication by Autonomous Vehicles

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The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how pedestrians envision awareness and intent to be communicated by autonomous vehicles (AV).

What Will I Be Asked To Do?

- Participant will develop low-fidelity paper prototypes on printed sheets with the aid of labels, pens, and sticky-notes.
- Participant will then be presented scenarios and asked to rank designs that best handle each.
- At the end of the session, participant will discuss their experience and ask questions.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 60 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results: Yes: ___ No: ___

I agree to let video recordings or parts of it from the session to be used, for data analysis only: Yes: ___ No: ___

I agree to let my conversations during the study be quoted, in presentation of the research results: Yes: ___ No: ___

I wish to remain anonymous, but you may refer to me by a pseudonym: Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

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What Happens to the Information I Provide?

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In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature: ______________________________________ Date: _____________

Researcher's Name: (please print) ____

Researcher's Signature: ____________________________________ Date: ______________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
(403)210-9404, ehud@ucalgary.ca

Sowmya Somanath
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ssomanat@ucalgary.ca

Karthik Mahadevan
Research Associate – Department of Computer Science
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karthik@ualberta.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

C

ADDITIONAL MATERIAL FOR THE SEGWAY STUDY

Here, we include all the supplementary materials we used to conduct the Segway evaluation study described in Chapter 5.

- Study protocol
- Interface description sheet
- Pre-study questionnaire
- Mid-study questionnaire
- Post-study questionnaire/interview
- Consent form

STUDY PROTOCOL

Hello! First off, thank you very much for participating in this study. My name is Karthik. I am a researcher at the University of Calgary. For the sake of consistency across all our participants, I will read the details of the study from this sheet.

The goal of our study is to understand how pedestrians and autonomous vehicles interact, in the presence of a driver/no driver, and interfaces.

For this study, you will be interacting with a Segway robot. In this experiment, the Segway will display autonomous capability in some trials. It has the ability to navigate from point a to point b.

Awareness: The car communicates that it is aware of the pedestrian's presence, to the pedestrian. Eg: human drivers show awareness with gaze.

Intent: The car communicates the next action it is about to take, to the pedestrian. Eg: human drivers slow down/use arm movements/etc. to show intent to stop/go.

The study should take between 60-75 minutes.

You will be presented with several scenarios. However, your task is the same each time. The Segway will drive from that point in the corridor (show) and stop here. You will be asked to observe the vehicle and make a decision about whether/not to cross the corridor. The Segway may or may not stop. Once you make the decision, you will announce it to us. If you decide to cross, you will say "cross" and walk over to the other side of the corridor. If you decide not to cross, you will stay in the same spot and say "won't cross". In between some trias, you will be requested to fill in a short questionnaire.

Does it make sense so far?

If you wish to participate, you will need to fill out this consent form. This is providing us permission to record audio and video. If we do use any of this for any paper publication or presentation, we will not use your names or personal information.

PROVIDE CONSENT FORM TO SIGN

Begin video recording.

Next, we would like you to fill a short questionnaire about your background.

HAND PRE-STUDY FORM

<u>TRIALS</u>
These are prototypes so it is possible for the system to break at any time. They are not perfect. The goal of our study is to understand how interfaces can replace a human driver. Today, we will show you 4 categories of interfaces, and we would like to know your thoughts on which category is better and why. Explain each category. Keep in mind that each interface of the four types is just one instance. There are many possibilities to make interfaces of these four categories. We would like you to focus on the categories themselves and how they impact your crossing decisions instead of the implementation.

We would like to go over the pause protocol. The Segway at times may lose track of its route and stop. Or else, a person may be crossing the corridor. If this happens during any of the trials, I will yell pause and the trial will be halted. We will restart it after the interruption has been fixed.

<u>Trial 1 & 2:</u>
- No driver on Segway **Stop/Don't Stop**

ASK TO FILL MID-QUESTIONNAIRE

<u>Trial 3 & 4:</u>
- Interface 1: Car Only
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>Trial 5 & 6:</u>
- Interface 2: Car & Infrastructure
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>Trial 7 & 8:</u>
- Interface 3: Car & Pedestrian
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>Trial 9 & 10:</u>

- Interface 4: Mixed
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>POST-STUDY</u>
Conduct an interview and ask questions as per the sheet. Try to gauge answers to the questions:

- When we test these designs, we need to determine what factors contribute to making a design successful.
- We want to figure out if awareness mattered at all or if intent mattered more, or both.
- We also want to explore the question of whether there is too much responsibility placed on one entity versus another to ensure the viability of that design. This would be a shift from the way we today think of intent and awareness, as the responsibility is mostly on the driver.

<u>POST-INTERVIEW</u>
Here is your remuneration; please sign on the receipt form.

Interface 1: Car-Only

LED: Red	Do not cross
LED: Blinking Blue	Segway has seen you
LED: Moving Green	It is safe to cross
LED: Moving Purple	Segway will start soon

Speaker: About to stop	Segway will stop soon
Speaker: About to start	Segway will start soon

Interface 2: Car & Infrastructure

Speaker: I can see you	Segway has seen pedestrian
Speaker: You can cross now	Segway will wait for you to cross

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: White	About to become unsafe to cross soon

Interface 3: Car & Pedestrian

Display: Animated face	Will interact with you
Phone: Vibrating	You can cross now

Interface 4: Mixed

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: White	About to become unsafe to cross soon

Phone Audio: I can see you	The Segway has noticed you

Hand: Stationary	Do not cross
Hand: Moving	You can cross

UNIVERSITY OF CALGARY

Study ID: REB17-0324

Pre-Study Questionnaire

Project Title: Exploring Awareness Communication by Autonomous Vehicles

This information is collected for demographics purpose only. All questions are optional.

Participant #:

1. Age: ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ 66 or older
2. Gender (M/F):
3. Profession:
4. What is your field of study or expertise?

5. How often do you cross the street?
   a. Never
   b. Once a day
   c. Multiple times a day
6. How often do you interact with the driver of a car when crossing?
   a. Never
   b. Rarely
   c. Sometimes
   d. Often
   e. Always
7. What type of cues do you expect to receive from a car or the driver of a car to indicate their next action?

8. What type of cues do you need to determine that a car or the driver of a car is aware of their surroundings?

9. Are you familiar with autonomous vehicles?

10. Are you familiar with the Segway robot?

UNIVERSITY OF CALGARY

Study ID: REB17-0324

Mid-Study Questionnaire

Participant #: **Trial #:**

1. How confident are you that you understood that the Segway could see you?
   1-5 (Not confident to somewhat confident to very confident)

   ○ Not confident ○ A little confident ○ Average confidence ○ Confident ○ Very confident

2. How confident are you that you understood what the Segway was about to do next?
   1-5 (Not confident to somewhat confident to very confident)

   ○ Not confident ○ A little confident ○ Average confidence ○ Confident ○ Very confident

---

Interface Questions

3. When the Segway **stopped**, the interface was useful.

   ○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

4. When the Segway **did not stop**, the interface was useful.

   ○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

5. Which part of the interface was most useful?

6. Which part of the interface was least useful?

Post-Study Questionnaire

Participant #:

1. How important was it to get awareness cues in crossing the corridor? Why?

2. How important was it to get intent cues in crossing the corridor? Why?

3. Rank the interfaces you saw in the order of most to least effective in helping you make a crossing decision.

4. Which element from all interfaces was most effective in communicating awareness with you? Why?

5. Which element from all interfaces was least effective in communicating awareness with you? Why?

6. Which element from all interfaces was most effective in communicating intent with you? Why?

7. Which element from all interfaces was least effective in communicating intent with you? Why?

8. Compared to the case with a driver on board, did you feel that you had to be more alert and spend more time processing the intent and awareness cues on board?

9. Did you trust the Segway at any point during the study?

10. Do you think any of the interfaces prototyped here could be applied to a self-driving car?

11. Other comments:

12. Comparing awareness and intent cues:

○	○	○	○	○
Awareness cues are significantly more important	Awareness cues are slightly more important	Equal	Intent cues are slightly more important	Intent cues are significantly more important

13. Comparing our Car-Only interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

14. Comparing our Car & Street Infrastructure interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

15. Comparing our Car & Pedestrian interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

16. Comparing our Mixed interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

17. Comparing our Car-Only interface to the trial with no driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

18. Comparing our Car & Street Infrastructure interface to the trial with no driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

19. Comparing our Car & Pedestrian interface to the trial with no driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

20. Comparing our Mixed interface to the trial with no driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Sowmya Somanath, PhD Student – Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Exploring Awareness Communication by Autonomous Vehicles

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The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how pedestrians envision awareness and intent to be communicated by autonomous vehicles (AV).

What Will I Be Asked To Do?

- Participant will be introduced to the Segway miniPro.
- Participant will take part in a study where they will evaluate the intent and awareness cues attached to the Segway in various crossing scenarios.
- At the end of the session, participant will discuss their experience and ask questions.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 60-75 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results: Yes: ___ No: ___

I agree to let video recordings or parts of it from the session to be used, for data analysis only: Yes: ___ No: ___

I agree to let my conversations during the study be quoted, in presentation of the research results: Yes: ___ No: ___

I wish to remain anonymous, but you may refer to me by a pseudonym: Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There are no known harms associated with participating in this research. Feel free to ask questions about this study at any time.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you. TCPS advises that data from participants who have chosen to withdraw from the study not be retained.

All data received from this study will be kept for five years in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project. Data will be destroyed once it is of no further use (e.g., by erasing files and shredding paper copies).

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this

research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ______________________________________

Participant's Signature: ____________________________________ Date: ____________

Researcher's Name: (please print) ____

Researcher's Signature: ___________________________________ Date: _____________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
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University of Calgary
(403)210-9404, ehud@ucalgary.ca

Sowmya Somanath
PhD Student - Department of Computer Science
University of Calgary
ssomanat@ucalgary.ca

Karthik Mahadevan
Research Associate – Department of Computer Science
University of Calgary
karthik@ualberta.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

D

ADDITIONAL MATERIAL FOR THE CAR STUDY

Here, we include all the supplementary materials we used to conduct the car evaluation study described in Chapter 5.

- Study protocol
- Interface description sheet
- Pre-study questionnaire
- Mid-study questionnaire
- Post-study questionnaire/interview
- Consent form

STUDY PROTOCOL

Hello! First off, thank you very much for participating in this study. My name is Karthik. I am a researcher at the University of Calgary. For the sake of consistency across all our participants, I will read the details of the study from this sheet.

The goal of our study is to understand how pedestrians and autonomous vehicles interact, in the presence of a driver/no driver, and interfaces.

For this study, you will be interacting with a self-driving car. It has the capability to drive forward and backward at a fixed speed of 10 kmh. There will be a driver on board at all times in case any emergency actions need to be taken. There will also be a researcher on board to collect data.

Awareness: The car communicates that it is aware of the pedestrian's presence, to the pedestrian. E.g.: human drivers show awareness with gaze.

Intent: The car communicates the next action it is about to take, to the pedestrian. E.g.: human drivers slow down/use arm movements/etc. to show intent to stop/go.

The study should take between 60-75 minutes.

You will be presented with several scenarios. However, your task is the same each time. The car will drive from that point in the parking lot to this point (near where you're standing). You will start by looking this way (away) and after the car honks, you can turn around and have a look. Once you have made your decision (cross/not) you can signal this by showing a thumb's up if you cross and nothing if you won't cross. However, **you should not physically cross** as this is not allowed in our study for safety reasons. The car may or may not stop throughout the experiment so it is up to you to look at the vehicle and decide. In between trials, you will be requested to fill in a short questionnaire.

Does it make sense so far?

If you wish to participate, you will need to fill out this consent form. This is providing us permission to record audio and video. If we do use any of this for any paper publication or presentation, we will not use your names or personal information.

PROVIDE CONSENT FORM TO SIGN

Begin video recording.

Next, we would like you to fill a short questionnaire about your background.

HAND PRE-STUDY FORM

TRIALS

These are prototypes so it is possible for the system to break at any time. They are not perfect. The goal of our study is to understand how interfaces can replace a human driver. Today, we will show you 4 categories of interfaces, and we would like to know your thoughts on which category is better and why. Explain each category. Keep in mind that each interface of the four types is just one instance. There are many possibilities to make interfaces of these four categories. We would like you to focus on the categories themselves and how they impact your crossing decisions instead of the implementation.

We would like to go over the pause protocol. The car at times may lose track of its route and stop. Or some other interruption may result. If this happens during any of the trials, the car will honk twice and we will redo the trial.

Trial 1 & 2:

- Driver on car **No signals**

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

Trial 3 & 4:

- Interface 1: Car Only
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

Trial 5 & 6:

- Interface 2: Car & Infrastructure
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

Trial 7 & 8:

- Interface 3: Car & Pedestrian
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>Trial 9 & 10:</u>

- Interface 4: Mixed
- Show participant sheet with colors and meanings plus speaker message

RANDOMIZE STOP AND GO

ASK TO FILL MID-QUESTIONNAIRE

<u>POST-STUDY</u>

Conduct an interview and ask questions as per the sheet. Try to gauge answers to the questions:

- When we test these designs, we need to determine what factors contribute to making a design successful.
- We want to figure out if awareness mattered at all or if intent mattered more, or both.
- We also want to explore the question of whether there is too much responsibility placed on one entity versus another to ensure the viability of that design. This would be a shift from the way we today think of intent and awareness, as the responsibility is mostly on the driver.

<u>POST-INTERVIEW</u>

Here is your remuneration; please sign on the receipt form.

Interface 1: Car-Only

LED: Red	Do not cross
LED: Blue	Car has seen you
LED: Green	It is safe to cross
LED: Yellow	Car will start soon

Speaker: Stopping	Car will stop soon
Speaker: Start	Car will start soon

Interface 2: Car & Infrastructure

Speaker: I see you	Car has seen pedestrian
Speaker: Cross	Car will wait for you to cross

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: Yellow	About to become unsafe to cross soon

Interface 3: Car & Pedestrian

Display: Animated face	Will interact with you
Phone: Vibrating	You can cross now

Interface 4: Mixed

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: Yellow	About to become unsafe to cross soon

Phone Audio: I can see you	The Car has noticed you

Hand: Stationary	Do not cross
Hand: Moving	You can cross

UNIVERSITY OF CALGARY

Study ID: REB17-0324

Pre-Study Questionnaire

Project Title: Exploring Awareness Communication by Autonomous Vehicles

This information is collected for demographics purpose only. All questions are optional.

Participant #:

1. Age: ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ 66 or older
2. Gender (M/F):
3. Profession:
4. What is your field of study or expertise?
5. How often do you cross the street?
   a. Never
   b. Once a day
   c. Multiple times a day
6. How often do you interact with the driver of a car when crossing?
   a. Never
   b. Rarely
   c. Sometimes
   d. Often
   e. Always
7. What type of cues do you expect to receive from a car or the driver of a car to indicate their next action?
8. What type of cues do you need to determine that a car or the driver of a car is aware of their surroundings?
9. Are you familiar with autonomous vehicles?

UNIVERSITY OF CALGARY

Study ID: REB17-0324

Mid-Study Questionnaire

Participant #: **Trial #:**

1. How confident are you that you understood that the car could see you?

○	○	○	○	○
Not confident	A little confident	Average confidence	Confident	Very confident

2. How confident are you that you understood what the car was about to do next?

○	○	○	○	○
Not confident	A little confident	Average confidence	Confident	Very confident

---

Interface Questions

3. When the car **stopped**, the interface was useful.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

4. When the car **did not stop**, the interface was useful.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

5. Which part of the interface was most useful?

6. Which part of the interface was least useful?

UNIVERSITY OF CALGARY

Study ID: REB17-0324

Post-Study Questionnaire

Participant #:

1. How important was it to get awareness cues in crossing the corridor? Why?

2. How important was it to get intent cues in crossing the corridor? Why?

3. Rank the interfaces you saw in the order of most to least effective in helping you make a crossing decision.

4. Which element from all interfaces was most effective in communicating awareness with you? Why?

5. Which element from all interfaces was least effective in communicating awareness with you? Why?

6. Which element from all interfaces was most effective in communicating intent with you? Why?

7. Which element from all interfaces was least effective in communicating intent with you? Why?

8. Did you feel that you had to be more alert and spend more time processing the intent and awareness cues on board for the interface trials?

9. Did you trust the car at any point during the study?

10. Do you think any of the interfaces prototyped here could be applied to a real self-driving car?

11. Other comments:

12. Comparing awareness and intent cues:

○	○	○	○	○
Awareness cues are significantly more important	Awareness cues are slightly more important	Equal	Intent cues are slightly more important	Intent cues are significantly more important

13. Comparing our Car-Only interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

14. Comparing our Car & Street Infrastructure interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

15. Comparing our Car & Pedestrian interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

16. Comparing our Mixed interface to the trial with a driver on board and no interface, it was:

○	○	○	○	○
Significantly better	Slightly better	Equal	Slightly worse	Significantly worse

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Sowmya Somanath, PhD Student – Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Exploring Awareness Communication by Autonomous Vehicles

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The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how pedestrians envision awareness and intent to be communicated by autonomous vehicles (AV).

What Will I Be Asked To Do?

- Participant will be introduced to a self-driving car.
- Participant will take part in a study where they will evaluate the intent and awareness cues attached to the car in various crossing scenarios.
- At the end of the session, participant will discuss their experience and ask questions.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 60-75 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results: Yes: ___ No: ___

I agree to let video recordings or parts of it from the session to be used, for data analysis only: Yes: ___ No: ___

I agree to let my conversations during the study be quoted, in presentation of the research results: Yes: ___ No: ___

I wish to remain anonymous, but you may refer to me by a pseudonym: Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There are no known harms associated with participating in this research. Feel free to ask questions about this study at any time.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you. TCPS advises that data from participants who have chosen to withdraw from the study not be retained.

All data received from this study will be kept for five years in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project. Data will be destroyed once it is of no further use (e.g., by erasing files and shredding paper copies).

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this

research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature: ____ Date: _______________

Researcher's Name: (please print) ____

Researcher's Signature: ____ Date: ________________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
(403)210-9404, ehud@ucalgary.ca

Sowmya Somanath
PhD Student - Department of Computer Science
University of Calgary
ssomanat@ucalgary.ca

Karthik Mahadevan
Research Associate – Department of Computer Science
University of Calgary
karthik@ualberta.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

E

ADDITIONAL MATERIAL FOR THE VR VALIDATION STUDY

Here, we include all the supplementary materials we used to conduct the validation study described in Chapter 6.

- Study protocol
- Interface description sheet
- Pre-study questionnaire
- Mid-study questionnaire
- Post-study questionnaire
- Interview form
- Consent form

Communicating AV Awareness/Intent to Pedestrians in VR - Study Protocol

Hello! First off, thank you very much for participating in this study. My name is Karthik. I am a researcher at the University of Calgary. For the sake of consistency across all our participants, I will read the details of the study from this sheet.

The goal of our study is to understand how pedestrians and autonomous vehicles interact. In the near future, we will see several of these cars on our street. Since they will likely not have a driver on board, we are trying to learn how they can effectively communicate to pedestrians so that they can make safe crossing decisions.

In this study, you will be wearing a Virtual Reality (VR) headset, the Oculus Rift and be immersed in a virtual environment.

Two terms to be familiar with:

Awareness: The car communicates that it is aware of the pedestrian's presence, to the pedestrian. Eg: human drivers show awareness with gaze.

Intent: The car communicates the next action it is about to take, to the pedestrian. Eg: human drivers slow down/use arm movements/etc. to show intent to stop/go.

The study should take between 60-75 minutes.

Does this make sense so far?

Since this study is being conducted in a VR environment, there is a small possibility of experiencing VR sickness. To make sure that you are not at a high risk of experiencing this sickness, here's a questionnaire that has to be filled out.

VR Sickness questionnaire

If the score is too high, recommend that the participant doesn't continue with the study.

Pre-Phase

Provide Consent Form to Sign

Begin video recording.

Next, we would like you to fill a short questionnaire about your background.

Pre-Study form

Participant will fill in short form about their background and some basics of crossing decision making.

Familiarization Phase

Put on the headset. Make sure it is comfortable and ask them to move around head.

Show the scene without a moving car and allow them to look around, get a sense of the environment.

Tell them the goal - you will be interacting with an autonomous vehicle.

Phase I

The vehicle may do a few different things.

Trial 1:
For example, the vehicle may have a driver on board

Trial 2:
The car could drive by without anyone inside.

Trial 3:
Or it could display something that would communicate information to you.

First Impressions of the Simulator:
The participant will go through the different possibilities the vehicle can do. Then, we sit down and discuss the simulator and whether it is realistic enough or not. What parts appeal to you? What parts do not appeal to you? Does this do a good job of replicating a real world crossing setup?

Observations Interview

Phase II

Participants will observe cars in different scenarios and will have to make crossing decisions accordingly. You will encounter different scenarios involving an autonomous vehicle driving on a road with you standing on the sidewalk. In each scenario, there will be two trials. The vehicle may or may not stop so observe the vehicle and decide whether you would like to cross the street or not.

Your task will always be the same. You will wear the headset, observe an autonomous vehicle approaching you, and make a crossing decision (through a controller button press).

There are 7 scenarios to complete for the experiment. Between each scenario, I will ask you to fill out a short questionnaire

We will track pedestrian comfort in making a crossing decision through a navigation bar on the Oculus Remote. We will also plot these out of 5 in a Likert scale which can be adjusted...or not.

<u>Give participant a chance to test out the comfort scale</u>

Trials

<u>Trial 1: Driver Attentive</u>

- Two trials, nothing special - there will be a driver on board.

<u>Trial 2: Driver Inattentive</u>

- Two trials, again featuring a driver.

<u>Trial 3: No Driver</u>

The goal of our study is to understand if interfaces can replace a human driver. Today, we will show you 4 categories of interfaces, and we would like to know your thoughts on which category is better and why.

Show the four categories of interfaces on the interface information sheet.

<u>Vehicle-Only Interface</u>

- Two trials each

<u>Vehicle-Infrastructure Interface</u>

- Two trials each

<u>Vehicle-Pedestrian Interface</u>

- Two trials each

<u>Mixed</u>

- Two trials each

Between-Trials

In the pilots, I can record their evaluations.

Mid-Study questionnaire either through the Rift or recorded by me (answers)

Post-Study

Presence Questionnaire

Post-Study questionnaire (ask questions and then record microphone response).

Conduct an interview and ask questions as per the sheet. Try to gauge answers to the following questions:

- When we test these designs, we need to determine what factors contribute to making a design successful, if at all.
- Do interfaces help versus not having them versus having a driver?
- We want to figure out if awareness mattered at all or if intent mattered more, or both.
- We also want to explore the question of whether there is too much responsibility placed on one entity versus another to ensure the viability of that design. This would be a shift from the way we today think of intent and awareness, as the responsibility is mostly on the driver.
- Ask them to draw an interface out for you.

Attentive

Distracted

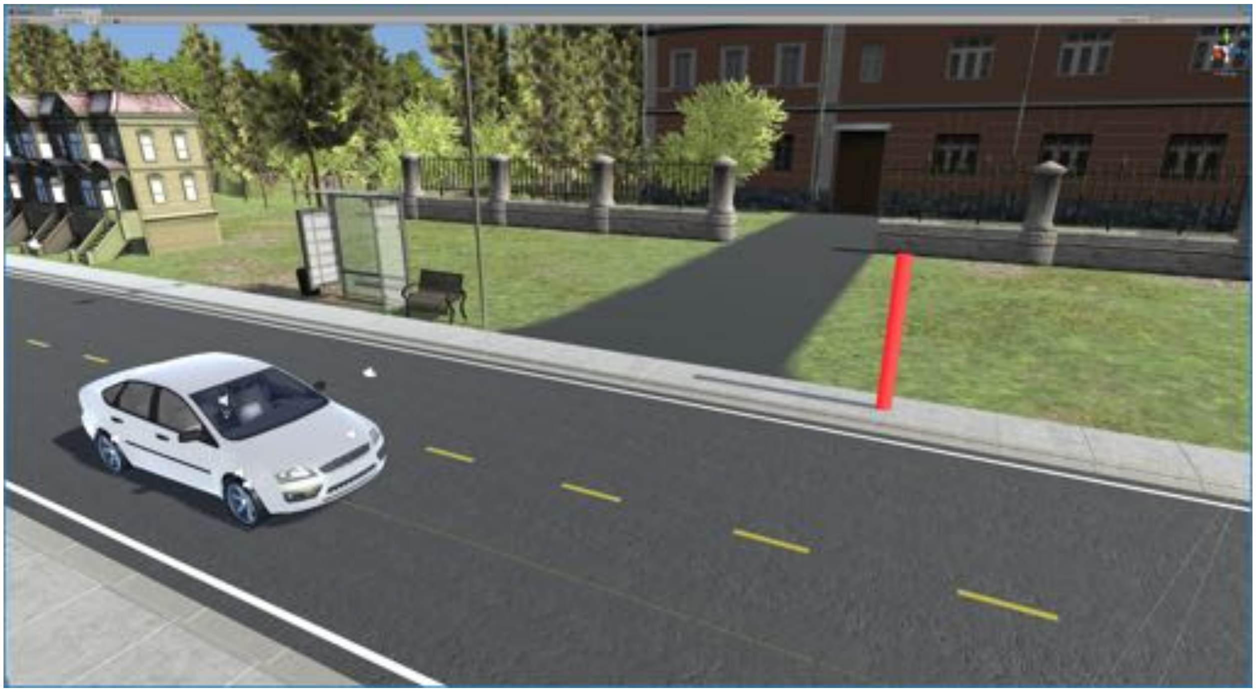
No Driver

Vehicle-Only

LED: Red	Do not cross
LED: Blue	Car has seen you
LED: Green	It is safe to cross
LED: Yellow	Car will start soon

Speaker: Stopping	Car will stop soon
Speaker: Start	Car will start soon

Vehicle-Infrastructure



Speaker: I see you	Car has seen pedestrian
Speaker: Cross	Car will wait for you to cross

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: Yellow	About to become unsafe to cross soon

Vehicle-Pedestrian

Display: Animated face	Will interact with you
Phone: Vibrating	You can cross now

Mixed

Traffic Light: Red	Not safe to cross
Traffic Light: Green	Safe to cross
Traffic Light: Yellow	About to become unsafe to cross soon

Phone Audio: I can see you	The Car has noticed you

Hand: Stationary	Do not cross
Hand: Moving	You can cross

Pre-Study Questionnaire

1. **Participant Number**

2. **Nationality**

3. **Age**
   Mark only one oval.
   - 18-25
   - 26-35
   - 36-45
   - 46-55
   - 55-65
   - 65+

4. **Gender**
   Mark only one oval.
   - Male
   - Female
   - Prefer not to say

5. **Area of study or work**

6. **How often do you cross the street?**
   Mark only one oval.
   - Once a day
   - Once a week
   - Multiple times a day
   - Rarely (once a month)

7. **When making a street crossing decision, what information do you expect from the driver?**

8. **When making a street crossing decision, what information do you expect from the car?**

9. **Describe your street crossing process.**

10. **Are you aware of autonomous vehicle driving technology?**

    Mark only one oval.

    - Yes
    - No

Scenario 1 - Driver Attentive

1. **Participant Number**

____

Driver Attentive

2. **How confident were you that the vehicle could see you? (awareness)**
   Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

3. **How confident were you about what the vehicle would do next? (intent)**
   Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

4. **Which cue(s) aided your crossing decision most?**

Mark only one oval.

- Driver
- Vehicle Motion
- Other: ______________________

5. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

- Driver
- Vehicle Motion
- Other: ______________________

Scenario 2 - Driver Distracted

Driver Distracted

6. **How confident were you that the vehicle could see you? (awareness)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

7. **How confident were you about what the vehicle would do next? (intent)**
Mark only one oval.

	1	2	3	4	5	
Least	⬭	⬭	⬭	⬭	⬭	Most

8. **Which cue(s) aided your crossing decision most?**
Mark only one oval.

⬭ Driver
⬭ Vehicle Motion
⬭ Other: ____________________

9. **Which cue(s) least aided your crossing decision?**
Mark only one oval.

⬭ Driver
⬭ Vehicle Motion
⬭ Other: ____________________

Scenario 3 - No Driver

No Driver

10. **How confident were you that the vehicle could see you? (awareness)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

11. **How confident were you about what the vehicle would do next? (intent)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

12. **Which cue(s) aided your crossing decision most?**

Mark only one oval.

◯ Lack of a driver

◯ Vehicle Motion

◯ Other: ____________________

13. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

◯ Lack of a driver

◯ Vehicle Motion

◯ Other: ____________________

Scenario 4 - Vehicle-Only

Vehicle-Only Interface

14. **How confident were you that the vehicle could see you? (awareness)**
Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

15. **How confident were you about what the vehicle would do next? (intent)**
Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

16. **Which cue(s) aided your crossing decision most?**
Mark only one oval.

- ◯ LED strip
- ◯ Voice
- ◯ Vehicle Motion
- ◯ Other: ____________________

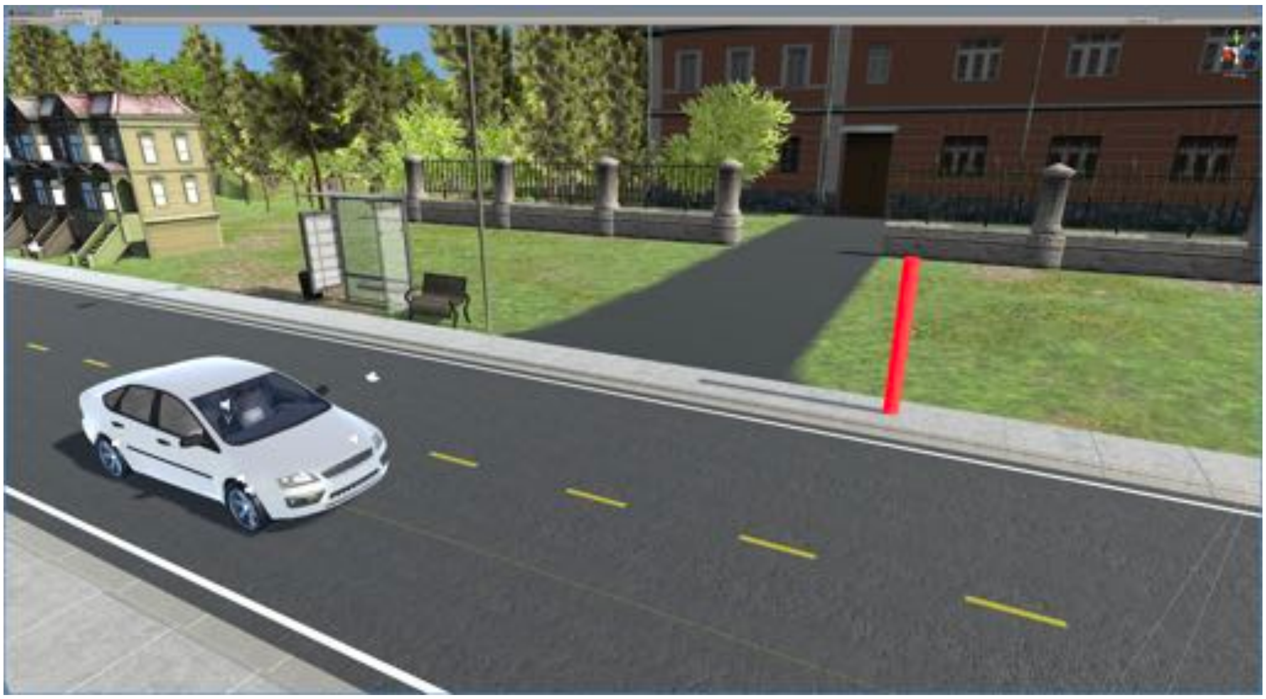
17. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

- ◯ LED strip
- ◯ Voice
- ◯ Vehicle Motion
- ◯ Other: ______________________

Scenario 5 - Vehicle-Infrastructure

Vehicle-Infrastructure Interface



18. **How confident were you that the vehicle could see you? (awareness)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

19. **How confident were you about what the vehicle would do next? (intent)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

20. **Which cue(s) aided your crossing decision most?**

Mark only one oval.

- ( ) Street LED
- ( ) Voice
- ( ) Vehicle Motion
- ( ) Other: ______________________

21. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

- ( ) Street LED
- ( ) Voice
- ( ) Vehicle Motion
- ( ) Other: ______________________

Scenario 6 - Vehicle-Pedestrian

Vehicle-Pedestrian Interface

22. **How confident were you that the vehicle could see you? (awareness)**

Mark only one oval.

	1	2	3	4	5	
Least	( )	( )	( )	( )	( )	Most

23. **How confident were you about what the vehicle would do next? (intent)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

24. **Which cue(s) aided your crossing decision most?**

Mark only one oval.

- ◯ Animated Face
- ◯ Phone Vibration
- ◯ Vehicle Motion
- ◯ Other: ______________________

25. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

- ◯ Animated Face
- ◯ Phone Vibration
- ◯ Vehicle Motion
- ◯ Other: ______________________

Scenario 7 - Mixed

Mixed Interface

26. **How confident were you that the vehicle could see you? (awareness)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

27. **How confident were you about what the vehicle would do next? (intent)**

Mark only one oval.

	1	2	3	4	5	
Least	◯	◯	◯	◯	◯	Most

28. **Which cue(s) aided your crossing decision most?**

Mark only one oval.

- ◯ Animated Hand
- ◯ Voice from headphones
- ◯ Street LED
- ◯ Vehicle Motion
- ◯ Other: ____________________

29. **Which cue(s) least aided your crossing decision?**

Mark only one oval.

- ◯ Animated Hand
- ◯ Voice from headphones
- ◯ Street LED
- ◯ Vehicle Motion
- ◯ Other: ____________________

Post-Study Questionnaire

* Required

1. **Participant Number**

2. **Comparing awareness and intent cues:**
   Mark only one oval.

	1	2	3	4	5	
Awareness cues are significantly more important	⬭	⬭	⬭	⬭	⬭	Intent cues are significantly more important

Comparing our Vehicle-Only interface to the scenario with a driver on board and no interface, it was:

3. **Comparing our Vehicle-Only interface to the scenario with a driver on board and no interface, it was:**
   Mark only one oval.

	1	2	3	4	5	
Significantly worse	⬭	⬭	⬭	⬭	⬭	Significantly better

Comparing our Vehicle & Street Infrastructure interface to the scenario with a driver on board and no interface, it was:

4. **Comparing our Vehicle & Street Infrastructure interface to the scenario with a driver on board and no interface, it was:**
Mark only one oval.

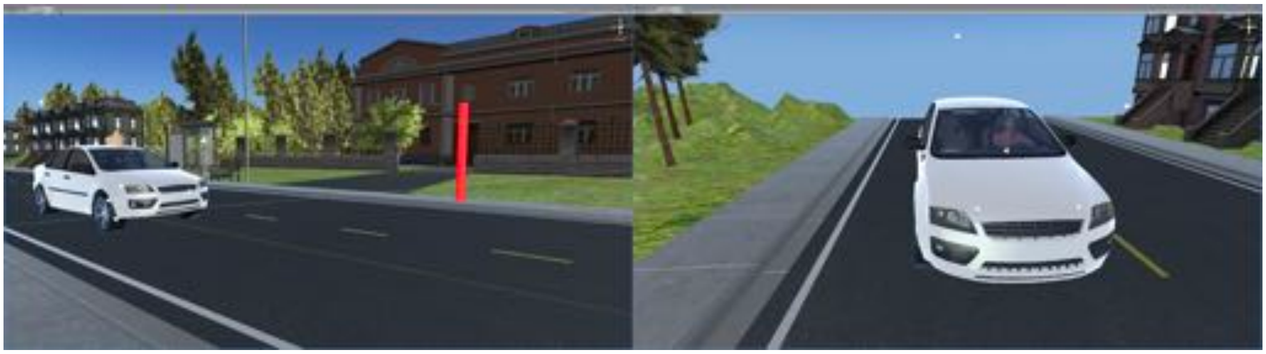
	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Vehicle & Pedestrian interface to the scenario with a driver on board and no interface, it was:

5. **Comparing our Vehicle & Pedestrian interface to the scenario with a driver on board and no interface, it was:**
Mark only one oval.

	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Mixed interface to the scenario with a driver on board and no interface, it was:



6. **Comparing our Mixed interface to the scenario with a driver on board and no interface, it was:**
   Mark only one oval.

	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Vehicle-Only interface to the scenario without a driver on board and no interface, it was:

7. **Comparing our Vehicle-Only interface to the scenario without a driver on board and no interface, it was:**
   Mark only one oval.

	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Vehicle & Street Infrastructure interface to the scenario without a driver on board and no interface, it was:

8. **Comparing our Vehicle & Street Infrastructure interface to the scenario without a driver on board and no interface, it was:**

Mark only one oval.

	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Vehicle & Pedestrian interface to the scenario without a driver on board and no interface, it was:

9. **Comparing our Vehicle & Pedestrian interface to the scenario without a driver on board and no interface, it was:**

Mark only one oval.

	1	2	3	4	5	
Significantly worse	◯	◯	◯	◯	◯	Significantly better

Comparing our Mixed interface to the scenario without a driver on board and no interface, it was:

10. **Comparing our Mixed interface to the scenario without a driver on board and no interface, it was:**

Mark only one oval.

	1	2	3	4	5	
Significantly worse	⬭	⬭	⬭	⬭	⬭	Significantly better

Interfaces

11. **Rank the 4 interfaces in order of most effective to least effective in helping you make a crossing decision** *

Mark only one oval per row.

	1st (Most preferred)	2nd	3rd	4th	5th (Least preferred)
Vehicle-Only	⬭	⬭	⬭	⬭	⬭
Vehicle-Infrastructure	⬭	⬭	⬭	⬭	⬭
Vehicle-Pedestrian	⬭	⬭	⬭	⬭	⬭
Mixed	⬭	⬭	⬭	⬭	⬭
None	⬭	⬭	⬭	⬭	⬭

Post-Study Interview Form

1. **Participant Number**

2. **How important was it to get awareness cues in crossing the street?**

3. **How important was it to get intent cues in crossing the street?**

4. **Which element from all interfaces was most effective in communicating awareness with you? Why?**

5. **Which element from all interfaces was least effective in communicating awareness with you? Why?**

6. **Which element from all interfaces was most effective in communicating intent with you? Why?**

7. **Which element from all interfaces was least effective in communicating intent with you? Why?**

8. **Did you feel that you had to be more alert and spend more time processing the awareness and intent cues on board for the interface trials?**

9. **Did you trust the car at any point during the study?**

10. **Do you think any of the interfaces prototyped here could be applied to a real self-driving car?**

11. **What kinds of interfaces or cues would work at scale? I'm imagining real world conditions with several cars, several pedestrians, and different autonomy levels of cars if you were asked to come up with such a design, how would it look?**

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary
Sowmya Somanath, Assistant Professor – Faculty of Design, OCAD University

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Designing for Smart Machine-Human Interactions

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The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how pedestrians envision awareness and intent to be communicated by autonomous vehicles (AV) in street crossing scenarios.

What Will I Be Asked To Do?

- Participant will be introduced to a Virtual Reality (VR) Headset (HTC Vive, Oculus Rift).
- Participant will wear the headset and interact with vehicles while standing at a crosswalk.
- Participant will take part in a study where they will evaluate the intent and awareness cues attached autonomous vehicles in a virtual environment. Participants will make crossing decisions in different trials.
- At the end of the session, participant will discuss their experience and ask questions.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 60 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results: Yes: ___ No: ___

I agree to let audio and video recordings or parts of it from the session to be used, for data analysis only: Yes: ___ No: ___

I agree to let my conversations during the study be quoted, in presentation of the research results: Yes: ___ No: ___

I wish to remain anonymous, but you may refer to me by a pseudonym: Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There is a small possibility of experiencing simulation sickness while wearing the headset for extended periods of time. If this is encountered at any point in the study, the simulation sickness protocol will be followed. Feel free to ask questions about this study at any time.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you. TCPS advises that data from participants who have chosen to withdraw from the study not be retained.

All data received from this study will be kept for five years in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project. Data will be destroyed once it is of no further use (e.g., by erasing files and shredding paper copies).

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this

research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature: ____ Date: _______________

Researcher's Name: (please print) ____

Researcher's Signature: ____ Date: ________________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
ehud@ucalgary.ca

Sowmya Somanath
Assistant Professor – Faculty of Design
OCAD University
ssomanath@faculty.ocadu.ca

Karthik Mahadevan
Research Assistant & MSc Student – Department of Computer Science
University of Calgary
karthik.mahaedevan@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

F

ADDITIONAL MATERIAL FOR THE MIXED TRAFFIC BRAINSTORMING

Here, we include all the supplementary materials we used to conduct the mixed traffic brainstorming session described in Chapter 7.

- Study protocol
- Study materials
- Design Sheets
- Consent form

<u>Design Study Protocol</u>

Script
Welcome everyone to the design study. We expect the session to last an hour. The goal of this study is to understand how you (as pedestrians) would like autonomous vehicles in mixed traffic scenarios to convey their **awareness** & **intent** to you in realistic street settings/environments.

In this design study, we will use a technique called design charrettes. This entails the following:

1) I'll give you design briefs (there are 2). For each design brief, you will be given **10 minutes** to sketch out your ideas (on paper). Everyone works in groups of 2 for this part. Then they present their sketch and explain their thought process. **2 minutes max x 3 = 6 minutes.**
2) Then everyone walks around and evaluates the designs that were done based on the technique of **Rose**, **Bud** and **Thorn**. You'll receive **10-15 minutes** for this activity as well. Using sticky notes of different colors for RBT. Here you can refine your individual sketches into a few designs that work based on the RBT you did for the individual sketches.

First let's begin with some definitions:
a. **Rose** = something that is working well or something positive
b. **Bud** = an area of opportunity or idea yet to be explored
c. **Thorn** = something that isn't working or something negative

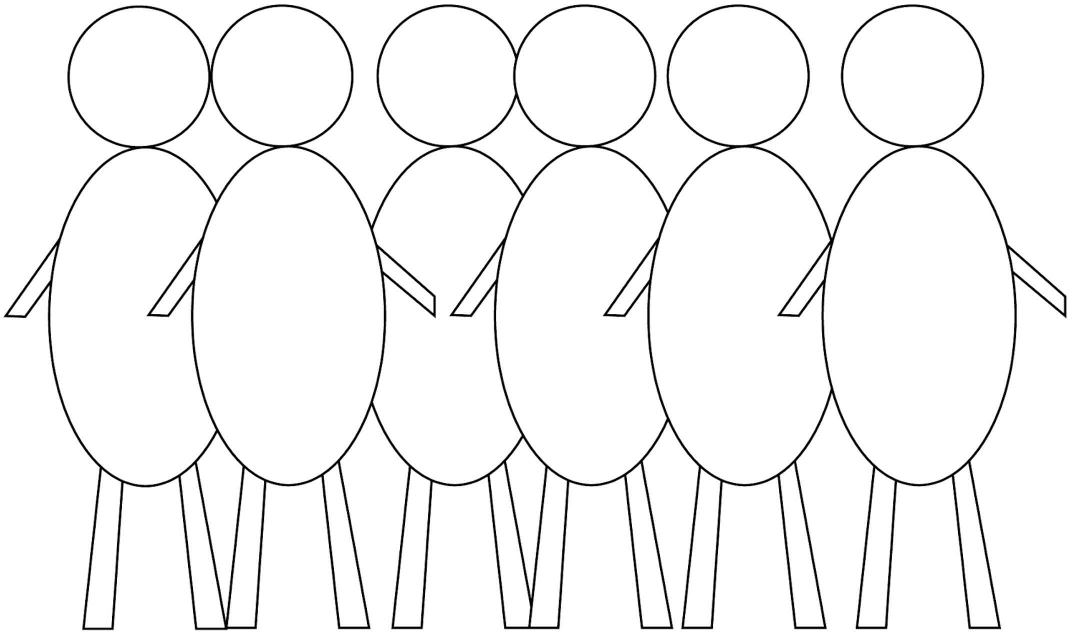
Activity 1: 26 minutes
Activity 2: 26 minutes
Total: *74 minutes (over the limit)*

What are we looking for? We want your input on how you expect crossing scenarios will play out with autonomous vehicles in the mix. Specifically, how are you expecting these vehicles to communicate to you through awareness and intent, but also what aspects of these vehicles (or others such as the one with the driver on board) are you expecting to pay most attention to.

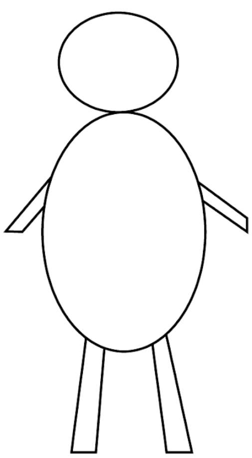
Label the participants and write the code down.

Sample sheets:
1) Locations that are possible for interfaces
2) Types of pedestrians (single v/s crowd, persona details)
3) Cue types (visual, auditory, physical)
4) Vehicle characteristics? (speed, size?)
5) Our current interfaces (VO, VI, VP, M)
6) Types of stop (traffic light, stop sign, none)
7) Types of vehicles (AV, semi AV, driver, distracted, AV with passenger)

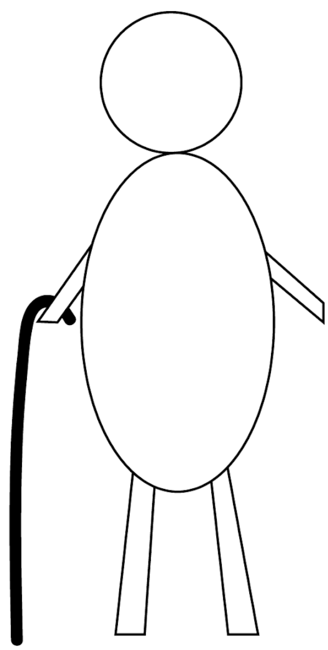
Study Materials



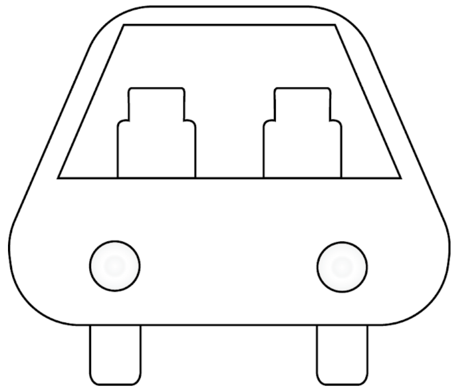
CROWD OF PEDESTRIANS



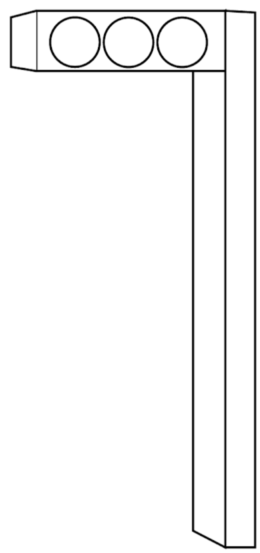
CHILD



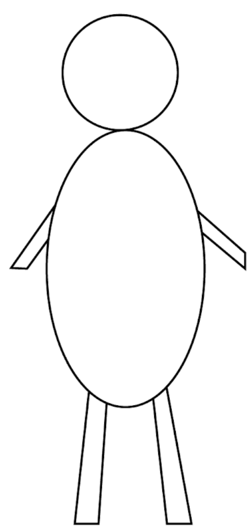
ELDERLY



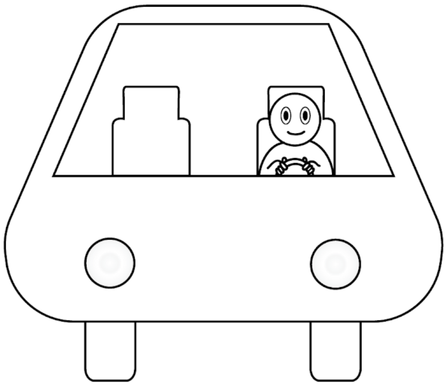
VEHICLE



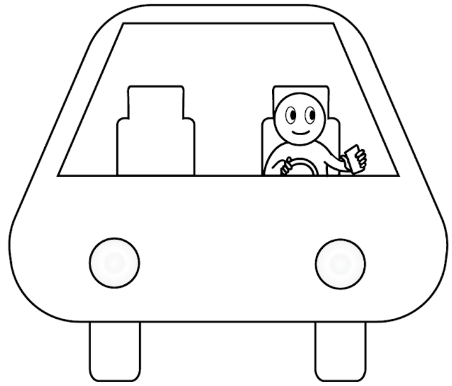
INFRASTRUCTURE



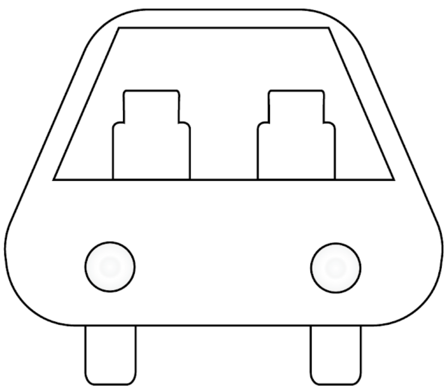
PEDESTRIAN



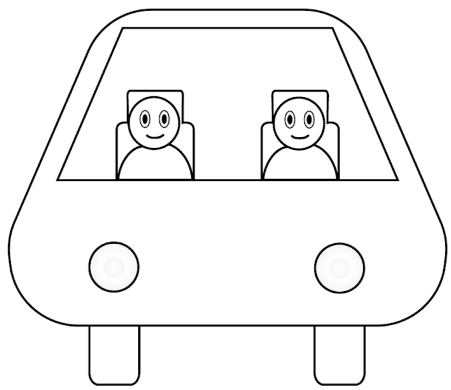
ATTENTIVE DRIVER



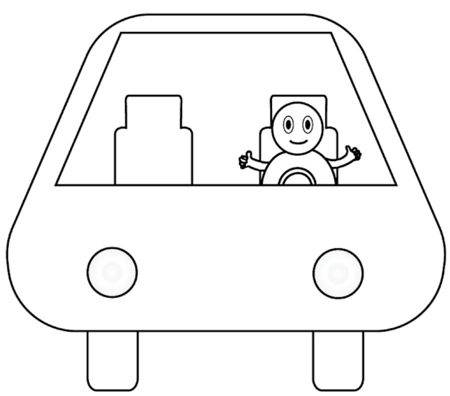
DISTRACTED DRIVER



AUTONOMOUS VEHICLE



AUTONOMOUS VEHICLE WITH PASSENGER



SEMI-AUTONOMOUS VEHICLE

VISUAL	**VISUAL**	**VISUAL**	**VISUAL**
VISUAL	**VISUAL**	**VISUAL**	**VISUAL**

AUDITORY	**AUDITORY**	**AUDITORY**	**AUDITORY**
AUDITORY	**AUDITORY**	**AUDITORY**	**AUDITORY**

PHYSICAL	**PHYSICAL**	**PHYSICAL**	**PHYSICAL**
PHYSICAL	**PHYSICAL**	**PHYSICAL**	**PHYSICAL**

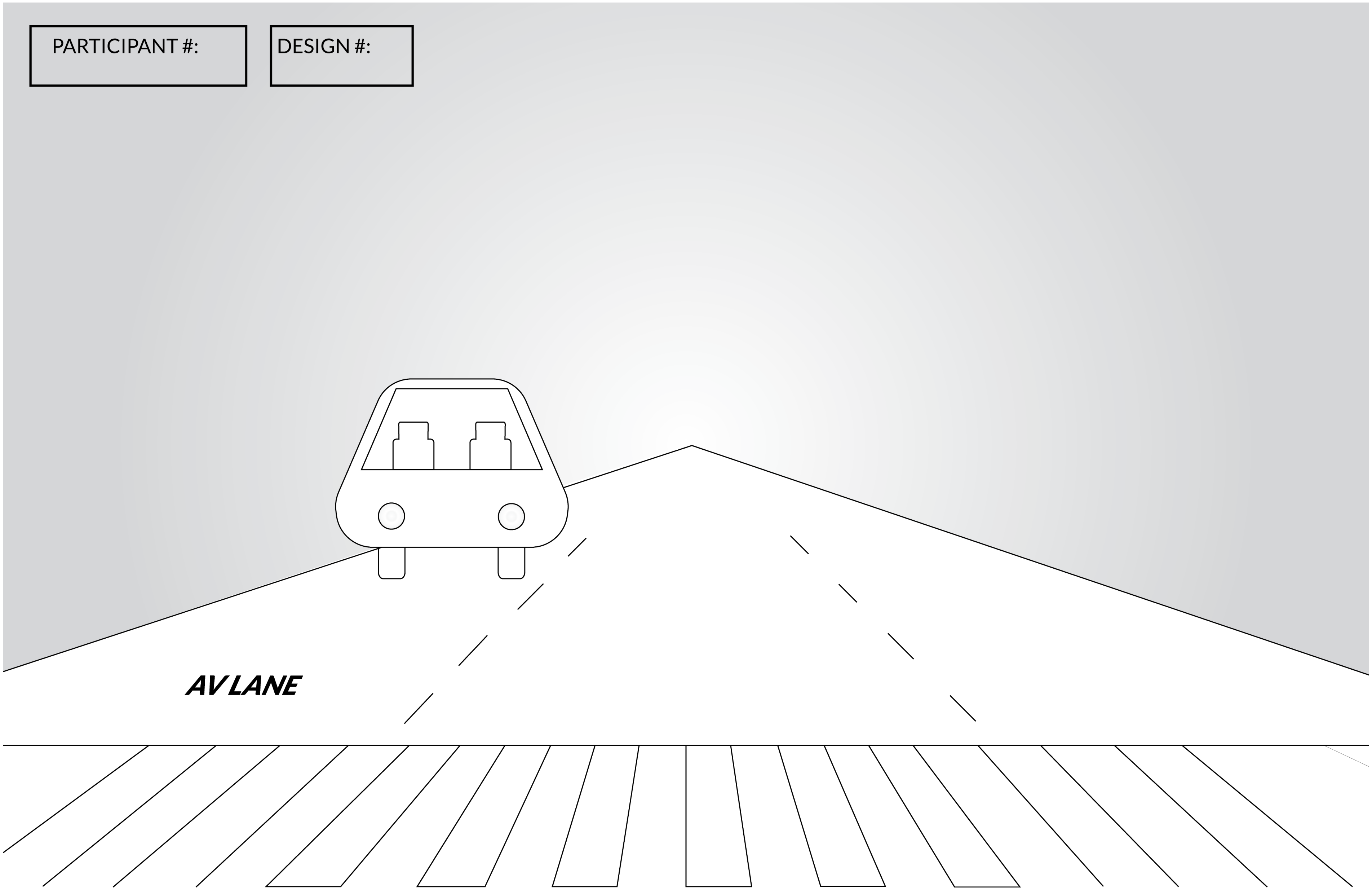
VEHICLE ONLY	VEHICLE ONLY	VEHICLE ONLY	VEHICLE ONLY
VEHICLE ONLY	VEHICLE ONLY	VEHICLE INFRA.	VEHICLE INFRA.

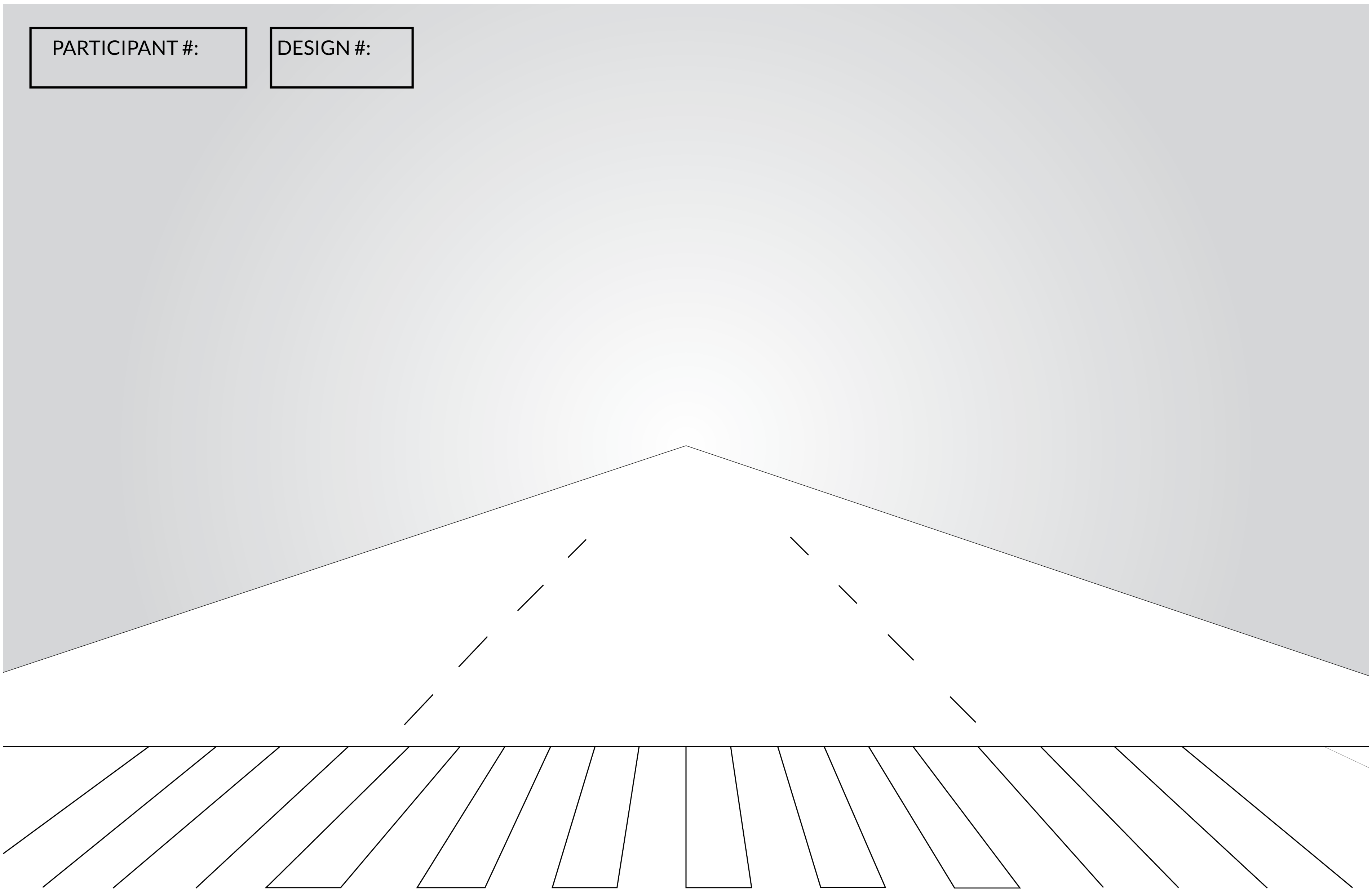
VEHICLE INFRA.	VEHICLE INFRA.	VEHICLE INFRA.	VEHICLE INFRA.
VEHICLE PEDES.	VEHICLE PEDES.	VEHICLE PEDES.	VEHICLE PEDES.

VEHICLE PEDES.	VEHICLE PEDES.	MIXED	MIXED
MIXED	MIXED	MIXED	MIXED

STOP	**STOP**	**STOP**	**STOP**
STOP	**STOP**	**STOP**	**STOP**

SIGNAL	**SIGNAL**	**SIGNAL**	**SIGNAL**
SIGNAL	**SIGNAL**	**SIGNAL**	**SIGNAL**


PARTICIPANT #:
DESIGN #:
AV LANE



PARTICIPANT #:
DESIGN #:

UNIVERSITY OF CALGARY

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary
Sowmya Somanath, Assistant Professor – Faculty of Design, OCAD University

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

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What Will I Be Asked To Do?

- Participant will be introduced to a design prototyping technique called Design Charrettes.
- Participants will work in pairs to design scenarios featuring autonomous vehicles in mixed traffic environments.
- Participants will present their work and provide feedback on their designs as well as the designs of other groups.
- At the end of the session, participant will discuss their experience and ask questions.

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There is a small possibility of experiencing simulation sickness while wearing the headset for extended periods of time. If this is encountered at any point in the study, the simulation sickness protocol will be followed. Feel free to ask questions about this study at any time.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you. TCPS advises that data from participants who have chosen to withdraw from the study not be retained.

All data received from this study will be kept for five years in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project. Data will be destroyed once it is of no further use (e.g., by erasing files and shredding paper copies).

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures

Your signature on this form indicates that 1) you understand to your satisfaction the information provided to you about your participation in this research project, and 2) you agree to participate in the research project.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature: ____ Date: _____________

Researcher's Name: (please print) ____

Researcher's Signature: ______________________________________ Date: ______________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
ehud@ucalgary.ca

Sowmya Somanath
Assistant Professor – Faculty of Design
OCAD University
ssomanath@faculty.ocadu.ca

Karthik Mahadevan
Research Assistant & MSc Student – Department of Computer Science
University of Calgary
karthik.mahaedevan@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

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ADDITIONAL MATERIAL FOR THE MIXED TRAFFIC STUDY

Here, we include all the supplementary materials we used to conduct the mixed traffic study described in Chapter 7.

- Study protocol
- Pre-study questionnaire
- Mid-study questionnaires
- Post-study interview
- Consent form

<u>Mixed Traffic-Pedestrian Interaction Study Protocol</u>

Hello! First off, thank you very much for participating in this study. My name is Karthik. I am a researcher at the University of Calgary. For the sake of consistency across all our participants, I will read the details of the study from this sheet.

The goal of our study is to understand how pedestrians and autonomous vehicles interact. In the near future, we will see several of these cars on our street. Since they will likely not have a driver on board, we are trying to learn how they can effectively communicate to pedestrians so that they can make safe crossing decisions.

In this study, you will be wearing a Virtual Reality (VR) headset, the Oculus Rift and be immersed in a virtual environment.

Two terms to be familiar with:

Awareness: The car communicates that it is aware of the pedestrian's presence, to the pedestrian. Eg: human drivers show awareness with gaze.

Intent: The car communicates the next action it is about to take, to the pedestrian. Eg: human drivers slow down/use arm movements/etc. to show intent to stop/go.

The study should take between 75-90 minutes.

Does this make sense so far?

Since this study is being conducted in a VR environment, there is a small possibility of experiencing VR sickness. To make sure that you are not at a high risk of experiencing this sickness, here's a questionnaire that has to be filled out.

VR Sickness questionnaire

If the score is too high, recommend that the participant doesn't continue with the study.

Pre-Phase

Provide Consent Form to Sign

Begin video recording.

Next, we would like you to fill a short questionnaire about your background.

Pre-Study form

Participant will fill in short form about their background and some basics of crossing decision making.

Familiarization Phase

Tell them the goal - you will be interacting with an autonomous vehicle.

We will track pedestrian comfort in making a crossing decision through a navigation bar on the Oculus Remote.

We will also track your level of comfort in crossing through a slider on the remote which you will see shortly. It will be out of 5. When the trial begins, it will be at a score of 3 and you can change it. At the end of the trial, it will reset back to 3.

Phase I
Put on the headset. Make sure it is comfortable and ask them to move around head.

A few trials to get you comfortable with what you will be doing in this study. Give the remote, explain it, and then let them try the 5 trials. Please pay attention to a few things: 1) Whether someone is inside the car, what they are doing, and also pay attention to the street.

For example, you may see a vehicle with a driver inside. Observe their behavior.

You may see multiple vehicles.

You may see people on the street.

You may see vehicles without drivers.

You may see vehicles that are communicating with you (not explaining right now how they are communicating but still.

After the 5 trials, ask them what they saw. Make sure they mention two driver types, a driverless type, crowd, and also an interface on the vehicle. Otherwise, give them another chance to see it.

Phase II

Participants will observe cars in different scenarios and will have to make crossing decisions accordingly. You will encounter different scenarios involving vehicles driving on a road with you standing on the sidewalk. There are 3 sets of trials. Between sets, you will be given a break.

Your task will always be the same. You will wear the headset, observe vehicles approaching you, and make a crossing decision (through a controller button press).

Show participants the interfaces they will encounter….. (the 5 categories).

Trials

- In the first set, we will complete trials 1-30. There is an indication in the simulation which will let you know when a trial begins and ends. Once this happens, your data will start being recorded.

Between-Sets

Short questionnaire and break.

Post-Study

Conduct an interview and ask questions as per the sheet. Try to gauge answers to the following questions:

- When we test these designs, we need to determine what factors contribute to making a design successful, if at all.
- Do interfaces help versus not having them versus having a driver?
- We want to figure out if awareness mattered at all or if intent mattered more, or both.
- We also want to explore the question of whether there is too much responsibility placed on one entity versus another to ensure the viability of that design. This would be a shift from the way we today think of intent and awareness, as the responsibility is mostly on the driver.
- Ask them to draw an interface out for you.

Pre-Study Questionnaire

* Required

1. **Participant Number** *

2. **1. Which country have you lived in for the majority of the last 10 years?**

3. **2. Age**

   Mark only one oval.

   - 18-25
   - 26-35
   - 36-45
   - 46-55
   - 55-65
   - 65+

4. **3. Gender**

   Mark only one oval.

   - Male
   - Female
   - Prefer not to say

5. **4. Area of study or work**

6. **5. How often do you cross the street?**

Mark only one oval.

- Once a day
- Two times a day
- Three times a day
- Multiple (4+) times a day
- Once a week
- Once a month
- Other: ______

7. **6. When making a street crossing decision, what information do you expect from the driver?**

______

8. **7. When making a street crossing decision, what information do you expect from the car?**

______

9. **8. Are you aware of autonomous vehicle driving technology?**

Mark only one oval.

- Yes
- No

10. **9. Are you color blind?**

Mark only one oval.

- Yes
- No

11. **10. If you answered yes to the above, please describe the type of color blindness you are affected by.**

______
______
______
______
______

Set 1 - Manually-Driven + Autonomous Vehicles

Mid-Study Set 1 (First)

* Required

1. **Participant Number** *

2. **1. Rank the following cues with respect to receiving awareness information (whether you have been noticed) from least to most useful:**

   Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Driver's actions (e.g. waving, eye gaze)	◯	◯	◯	◯	◯
Vehicle's motion (e.g. slowing down, speeding up)	◯	◯	◯	◯	◯
Interface cues on the vehicle (e.g. LED strip, animated hand)	◯	◯	◯	◯	◯
Interface cues on the street (e.g. street LED)	◯	◯	◯	◯	◯
Interface cues on the pedestrian (e.g. phone vibration)	◯	◯	◯	◯	◯
Other pedestrians' behavior (e.g. crossing the street)	◯	◯	◯	◯	◯

3. **Explain your reasoning for the above choice.**

4. **2. Rank the following cues with respect to receiving intent information (what the car's next actions are) from least to most useful:**

   Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Driver's actions (e.g. waving, eye gaze)					
Vehicle's motion (e.g. slowing down, speeding up)					
Interface cues on the vehicle (e.g. LED strip, animated hand)					
Interface cues on the street (e.g. street LED)					
Interface cues on the pedestrian (e.g. phone vibration)					
Other pedestrians' behavior (e.g. crossing the street)					

5. **Explain your reasoning for the above choices.**

6. **3. Between the interfaces on the vehicles without a driver, which ones helped you make a crossing decision?**

   Check all that apply.

   - [ ] Vehicle-Only (LED strip and voice)
   - [ ] Vehicle-Infrastructure (Street LED and voice)
   - [ ] Vehicle-Pedestrian (Haptic feedback and animated smile)
   - [ ] Mixed (Street LED, animated hand, and voice from headphones)
   - [ ] Vehicle motion was sufficient

7. **Explain your reasoning for the above choices.**

8. **4. On the vehicles without a driver, which of the following modalities of cues presented helped you make a crossing decision?**

Check all that apply.

- [ ] Visual cues (e.g. led strip)
- [ ] Auditory cues (e.g. voice from car or headphones)
- [ ] Physical cues (e.g. haptic feedback on phone, hand)

9. **Explain your reasoning for the above choices.**

Set 2 - Semi-Autonomous Vehicles + Autonomous Vehicles

Mid-Study Set 2

* Required

1. **Participant Number** *

2. **1. Rank the following cues with respect to receiving awareness information (whether you have been noticed) from least to most useful:**

   Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Driver cues (e.g. waving, eye gaze)					
Vehicle motion (e.g. slowing down, speeding up)					
Interface cues on the vehicle (e.g. LED strip, animated hand)					
Interface cues on the street (e.g. street LED)					
Interface cues on the pedestrian (e.g. phone vibration)					
Other pedestrians' behavior (e.g. crossing the street)					

3. **Explain your reasoning for the above choices.**

4. **2. Rank the following cues with respect to receiving intent information (what the car's next actions are) from least to most useful:**

Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Driver cues (e.g. waving, eye gaze)					
Vehicle motion (e.g. slowing down, speeding up)					
Interface cues on the vehicle (e.g. LED strip, animated hand)					
Interface cues on the street (e.g. street LED)					
Interface cues on the pedestrian (e.g. phone vibration)					
Other pedestrians' behavior (e.g. crossing the street)					

5. **Explain your reasoning for the above choice.**

6. **3. Between the interfaces on the vehicle without a driver, which ones helped you make a crossing decision?**

Check all that apply.

- [ ] Vehicle-Only (LED strip and voice)
- [ ] Vehicle-Infrastructure (Street LED and voice)
- [ ] Vehicle-Pedestrian (Haptic feedback and animated smile)
- [ ] Mixed (Street LED, animated hand, and voice from headphones)
- [ ] Vehicle motion was sufficient

7. **Explain your reasoning for the above choices.**

8. **4. On the vehicles without a driver, which of the following modalities of cues presented helped you make a crossing decision?**

   Check all that apply.

   - [ ] Visual cues (e.g. led strip)
   - [ ] Auditory cues (e.g. voice from car or headphones)
   - [ ] Physical cues (e.g. haptic feedback on phone, hand)

9. **Explain your reasoning for the above choices.**

Set 3 - Both Lanes with Autonomous Vehicles

Mid-Study Set 3 (Last)

* Required

1. **Participant Number ***

2. **1. Rank the following cues with respect to receiving awareness information (whether you have been noticed) from least to most useful:**
   Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Vehicle motion (e.g. slowing down, speeding up)					
Interface cues on the vehicle (e.g. LED strip, animated hand)					
Interface cues on the street (e.g. street LED)					
Interface cues on the pedestrian (e.g. phone vibration)					
Other pedestrians' behavior (e.g. crossing the street)					

3. **Explain your reasoning for the above choices.**

4. **2. Rank the following cues with respect to receiving intent information (what the car's next actions are) from least to most useful:**
   Mark only one oval per row.

	1 (least useful)	2	3	4	5 (most useful)
Vehicle motion (e.g. slowing down, speeding up)					
Interface cues on the vehicle (e.g. LED strip, animated hand)					
Interface cues on the street (e.g. street LED)					
Interface cues on the pedestrian (e.g. phone vibration)					
Other pedestrians' behavior (e.g. crossing the street)					

5. **Explain your reasoning for the above choices.**

6. **3. Between the interfaces, which ones helped you make a crossing decision?**
Check all that apply.

- [ ] Vehicle-Only (LED strip and voice)
- [ ] Vehicle-Infrastructure (Street LED and voice)
- [ ] Vehicle-Pedestrian (Haptic feedback and animated smile)
- [ ] Mixed (Street LED, animated hand, and voice from headphones)
- [ ] Vehicle motion was sufficient

7. **Explain your reasoning for the above choices.**

8. **4. On the vehicles without a driver, which of the following modalities of cues presented helped you make a crossing decision?**
Check all that apply.

- [ ] Visual cues (e.g. led strip)
- [ ] Auditory cues (e.g. voice from car or headphones)
- [ ] Physical cues (e.g. haptic feedback on phone, hand)

9. **Explain your reasoning for the above choices.**

Post-Study Interview Form

General

* Required

1. **Participant Number ***

2. **1. Would you say that the decisions you took in this simulation environment are similar to the decisions you make at a crosswalk every day or would have made at a crosswalk? Why is it similar? Why is it dissimilar? How well does your decision map to real life?**

3. **2. How important was it to get awareness cues in making your crossing decision?**

4. **3. How important was it to get intent cues in making your crossing decision?**

Crossing Strategy

5. **4. Did you develop a crossing strategy over the course of the experiment? For example, one strategy would be to wait until the vehicle completely stops and then make the decision to cross.**

6. **4a. Follow up: Did your strategy change when you faced vehicles that had a driver on board + no driver**

7. **4b. Follow up: Did your strategy change when you faced vehicles that had a distracted driver + no driver?**

8. **4c. Follow up: Did your strategy change when you faced vehicles that had no driver in both lanes?**

Communication

9. **5. Did you notice that the lane order of the different vehicles was fixed? For example, the driver attentive car came on the left lane, same with distracted driver, and driverless came from the other lane. Did this affect your crossing decision in some way?**

10. **6. Do you think communication with cues on the AV makes sense? Why?**

11. **7. Do you think communication with cues on the street makes sense? Why?**

12. **8. Do you think communication with cues on the pedestrian (yourself) makes sense? Why?**

13. **9. Did you think a specific modality helped you make crossing decisions more than others? Why? Why not?**

14. **10. What about the treatment of pedestrians beyond this? Would the interfaces you saw today help those with different requirements? Those who are visually or hearing impaired, those who are older or younger, etc. Why or why not?**

15. **11. Did you feel that you had to be more alert and spend more time processing the awareness cues on the vehicle without a driver?**

16. **12. Did you feel that you had to be more alert and spend more time processing the intent cues on the vehicle without a driver?**

Trust

17. **13. Did you trust the vehicles without a driver on board when there were other vehicles with a driver paying attention? When and why?**

18. **13b. Did you trust the vehicles without a driver on board when there were other vehicles with a distracted driver? When and why?**

19. **13c. Did you trust the vehicles without a driver on board when all vehicles on the street did not have a driver on board? When and why?**

20. **13d. Did the trust the vehicle without a driver on board when there were other pedestrians crossing?**

21. **14. Does the trust come from the fact that autonomous vehicles have been engineered to be precise and perfect or does it come from having an interface on board the vehicle?**

Other Questions

22. **15. Do you think any of the interfaces prototyped here could be applied to a real self-driving car?**

23. **16. Which factors beyond what you saw here may affect your crossing decision? We tested pedestrian behavior, interfaces (or lack thereof), and the vehicle stopping/not stopping.**

24. **17. What do you think the responsibility distribution is like when you cross today? Between the car and yourself.**

25. **17a. Follow up: What do you think the responsibility distribution was like in the scenarios you saw? Did the interfaces drop that or increase that level of responsibility you felt towards crossing?**

26. **18. Did any aspects of the driver affect your crossing decision? Their appearance, gender, ethnicity, age? Do these things affect the way you perceive the situation?**

27. **19. Did you feel information overload during interface trials when in the presence of vehicles with a driver? Meaning, was there already enough information or did you need the interfaces to also communicate with you? Did any interfaces add to this overload or was it evenly distributed?**

28. **Optional. Your thoughts on the following variables that may affect crossing decisions? Print Rasouli survey factors and ask those?**

UNIVERSITY OF CALGARY

Name of Researcher, Faculty, Department, Telephone & Email:

Karthik Mahadevan, Research Associate - Department of Computer Science, University of Calgary
Dr. Ehud Sharlin, Associate Professor – Department of Computer Science, University of Calgary
Sowmya Somanath, Assistant Professor – Faculty of Design, OCAD University

Supervisor:

Ehud Sharlin, Associate Professor - Department of Computer Science, University of Calgary

Title of Project:

Designing for Smart Machine-Human Interactions

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study

The goals of this study are to better understand how pedestrians envision awareness and intent to be communicated by autonomous vehicles (AV) in street crossing scenarios.

What Will I Be Asked To Do?

- Participant will be introduced to a Virtual Reality (VR) Headset (HTC Vive, Oculus Rift).
- Participant will wear the headset and interact with vehicles while standing at a crosswalk.
- Participant will take part in a study where they will evaluate the intent and awareness cues attached autonomous vehicles in a virtual environment. Participants will make crossing decisions in different trials.
- At the end of the session, participant will discuss their experience and ask questions.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers. You will receive a remuneration (value $20) for your participation.

This study should take approximately 60 minutes.

What Type of Personal Information Will Be Collected?

Should you consent to the participation, we will collect demographics information, i.e. gender and age.

There are several options for you to consider if you decide to take part in this research. You can choose all, some, or none of them. Please review each of these options and choose Yes or No after carefully reviewing the information below:

I agree to let whole or parts of recordings from the study to be used, for presentation of the research results:	Yes: ___ No: ___
I agree to let audio and video recordings or parts of it from the session to be used, for data analysis only:	Yes: ___ No: ___
I agree to let my conversations during the study be quoted, in presentation of the research results:	Yes: ___ No: ___
I wish to remain anonymous, but you may refer to me by a pseudonym:	Yes: ___ No: ___

The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use video recordings or parts of it in presentations or other electronic media, but this can only happen with your consent. Please, indicate above if you grant us permission to use video clips or pictures from this interview. Any video clips or pictures will **not** be associated with your name or contact information. If consent is given to present identifiable video clips and/or photographs (see table above), then no anonymity can be provided and you will be clearly recognizable as a participant in this study.

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

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In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video pictures of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

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In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this

research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ______________________________________

Participant's Signature: ____________________________________ Date: ____________

Researcher's Name: (please print) ____

Researcher's Signature: __________________________________ Date: _____________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Dr. Ehud Sharlin
Associate Professor - Department of Computer Science
University of Calgary
ehud@ucalgary.ca

Sowmya Somanath
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OCAD University
ssomanath@faculty.ocadu.ca

Karthik Mahadevan
Research Assistant & MSc Student – Department of Computer Science
University of Calgary
karthik.mahaedevan@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact an Ethics Resource Officer, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

H

COPYRIGHT PERMISSION

Here, we include copyright permissions from co-authors and ACM.

Re: Regarding use of materials from papers we co-authored

Ehud Sharlin <ehud@cpsc.ucalgary.ca>

Wed 9/11/2019 9:25 AM

To: Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>

Dear Karthik,

I hereby formally grant you permission to include the five paper titles I co-authored with you, listed below, in your thesis.

Sincerely,
Ehud

> 1. Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James. E. Young, and Ehud Sharlin. (2019). AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. In Proceedings of the ACM Conference on Designing Interactive Systems (DIS).
> 2. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI).
> 3. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Enabling Pedestrian Communication with Autonomous Vehicles. In CHI 2018 Workshop - Interacting with Autonomous Vehicles: Learning from other Domains.
> 4. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Can Interfaces Facilitate Communication in Autonomous Vehicle-Pedestrian Interaction? In Companion Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction Pioneers Workshop (HRI).
> 5. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). “Fight-or-Flight”: Leveraging Instinctive Human Defensive Behaviors for Safe Human-Robot Interaction. In Companion Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI).

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Ehud Sharlin
uTouch Research Group, Interactions laboratory, Department of Computer Science, University of Calgary
2500 University Drive NW, Calgary, Alberta, Canada, T2N 1N4
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Mobile: +1.403.836.4240
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http://ilab.cpsc.ucalgary.ca/

Re: Regarding use of materials from papers we co-authored

Somanath, Sowmya <ssomanath@faculty.ocadu.ca>
Sun 9/8/2019 11:26 PM
To: Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>

Hello Karthik,

I grant you permission to include all the below listed papers we have co-authored.

Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James. E. Young, and Ehud Sharlin. (2019). AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. In Proceedings of the ACM Conference on Designing Interactive Systems (DIS).

Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI).

Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Enabling Pedestrian Communication with Autonomous Vehicles. In CHI 2018 Workshop - Interacting with Autonomous Vehicles: Learning from other Domains.

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Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). "Fight-or-Flight": Leveraging Instinctive Human Defensive Behaviors for Safe Human-Robot Interaction. In Companion Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI).

Thanks,
Sowmya

This email is sent from my mobile device.

From: Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>
Sent: Sunday, September 8, 2019 11:21 PM
To: ehud Cpsc; Somanath, Sowmya
Subject: Regarding use of materials from papers we co-authored

Hello Everyone,

Faculty of Graduate Studies requires that I get permission from my co-authors to include our publications in my thesis. If you could please respond to this email stating that: *you grant me permission to include the paper title <name of the paper(s) in which you are a co-author> in my thesis*, I would appreciate it.

1. Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James. E. Young, and Ehud Sharlin. (2019). AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. In Proceedings of the ACM Conference on Designing Interactive Systems (DIS).
2. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. In Proceedings of the CHI Conference on

Human Factors in Computing Systems (CHI).

3. Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. (2018). Enabling Pedestrian Communication with Autonomous Vehicles. In CHI 2018 Workshop - Interacting with Autonomous Vehicles: Learning from other Domains.
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Regards,
Karthik

Re: Regarding use of materials from paper we co-authored

James Young <young@cs.umanitoba.ca>
Mon 9/9/2019 10:11 AM
To: Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>

Hi Karthik,

I grant me permission to include the paper title AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator in yourthesis.

Best
Jim

2019/09/08 午後10:25 Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>:

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>
> Regards,
> Karthik

Re: Regarding use of materials from paper we co-authored

Ellie Sanoubari <elaheh.sanoubari@gmail.com>
Sun 9/8/2019 11:29 PM

To: Karthik Mahadevan <karthik.mahadevan@ucalgary.ca>
Cc: Jim Young <young@cs.umanitoba.ca>

Dear Karthik,

You have my permission to include our paper titled "AV-pedestrian interaction design using a pedestrian mixed traffic simulator" in your thesis.

Cheers,

On Sun., Sep. 8, 2019, 11:25 p.m. Karthik Mahadevan, <karthik.mahadevan@ucalgary.ca> wrote:

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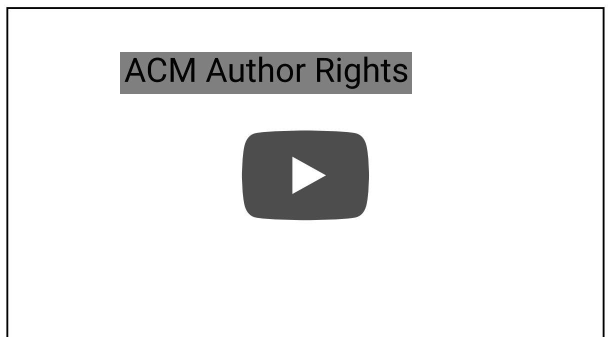

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