AN INCLUSIVE DESIGN APPROACH TO INTEGRATING AN EXTERNAL HUMAN MACHINE INTERFACE WITH AUTONOMOUS VEHICLES

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ABSTRACT

An Inclusive Design Approach to Integrating an External Human Machine Interface with Autonomous Vehicles

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As autonomous vehicles become more prevalent in urban traffic settings, the safety of vulnerable road users, predominantly pedestrians, must be placed in high regard relative to the design of the autonomous vehicle's (AV's) external human machine interface (HMI). Traditionally, there exist communication methods between drivers and pedestrians, such as hand gestures, eye contact, and verbal cues that convey the driver's awareness of the pedestrian's presence. However, with autonomous vehicles, there is a shift in communicative responsibility from the driver to the vehicle itself. It is the vehicle's responsibility to intuitively and clearly indicate its actions to the pedestrian.

This research analyzes the factors contributing to AV skepticism and the ways in which the visual aspect of an AV's external HMI can be improved from traditional vehicle designs to accommodate visually impaired pedestrians. This was achieved by performing a study on 27 participants varying in age, gender, and vision impairment type. The study includes a survey and interview portion. Findings indicate that yellow and blue colors are viewed as most welcoming and memorable. It is suggested that these colors be used in the projected light system of the external HMI design. Quantitative results indicate that there is a moderate degree of correlation between the following: the use of cruise control and vision impairment severity (negative correlation), a participant's willingness to ride in an AV and vision impairment levels (positive correlation). The study also found a low degree of correlation in a participants willingness to ride in an AV and their trust in AVs.

Based on these findings and under the assumption than an external HMI is needed on the AV, it is recommended that the external HMI contain a light projection system on the vehicle's front body. Based on qualitative results, the light projection system should use a teal color light and project a directional arrow onto the ground when identifying a pedestrian in its path while turning. Intuitive signals such as these help ensure pedestrian safety and promote trust and acceptance of the use of autonomous vehicles on public roads.

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Chapter 1

INTRODUCTION

In a traditional traffic setting, the driver actively interacts with the pedestrian through eye contact, hand gestures, verbal cues, and the vehicle's turn signals [14] [15] [16] [17]. However, as autonomous vehicle technology evolves, cars are transforming from human-driven systems to fully-autonomous vehicles [18] [19]. The driver simply becomes a passenger in the AV, redirecting the pedestrian communication responsibility to the vehicle itself [20]. It is in this modern traffic setting that vehicle-to-pedestrian communication becomes critical for pedestrian and traffic safety [21].

This research, through an inclusive lens, focuses on two main components: a study on AV skepticism and a design recommendation of the external HMI of the autonomous vehicle.

This development of an external human-machine interface (HMI) aims to aid in AV-to-pedestrian communication in urban traffic settings. Using participant data, gathered via a survey and interview, this study analyzes the ways in which visually impaired pedestrians perceive AVs. Additionally, this study analyzes the importance of context relative to colors and visual signals that helps define the colors used in the external HMI design recommendation presented in this research [22].

This research has the potential to increase traffic safety with respect to pedestrians and the visually impaired community, in particular. Based on survey and interview results, this research provides insights into the factors contributing to AV skepticism. Additionally, this research provides a design recommendation for an external human-machine-interface with respect to AVs to promote an inclusive, safe, and refined vehicle-to-pedestrian communication method as it relates to user experience (UX). Using a diverse participant pool to ensure broader representation, this research provides insights into the visual limitations of communication methods between vehicles and pedestrians. Although vehicle-to-pedestrian communication includes non-visual forms of communication, such as sirens and other audio cues, this research focuses on visual communication methods. Additionally, this research focuses on the social skepticism associated with autonomous vehicles. Based on the results of this study, this thesis presents a design recommendation for an external AV HMI in an effort to promote pedestrian trust and safety relative to autonomous vehicles.

Although existing research addresses vehicle-to-pedestrian communication through external HMI design, there is a great need for additional research in the field with respect to autonomous vehicles and visually impaired pedestrians [23] [24] [25] [20]. This thesis aims to provide insights into the behavior, needs, and expectations of these vulnerable road users (VRUs) relative to their interactions with autonomous vehicles and various factors that impact the pedestrian's skepticism regarding AVs.

It is necessary to address user interface (UI) design relative to the user's behavior and expectations and adhere to the distinct needs of the general pedestrian population. The external HMI design of the autonomous vehicle needs to be acceptable by the general pedestrian population while ensuring the safety of vulnerable, visually impaired pedestrians who are more at-risk of automobile accidents in the urban traffic setting. This research focuses on the visually impaired pedestrian community and provides an external HMI design recommendation based on their unique needs and behaviors.

Vision impaired individuals, including those who are blind, colorblind, and individuals with moderate to severe single-vision prescription glasses, are vulnerable in traffic settings and require additional assistance to ensure their safety [26] [19] [27]. The main motivation for this research relates to the unique challenges faced by visually impaired pedestrians and the need for a more inclusive design approach to vehicle-to-pedestrian communication methods to promote traffic safety and the well-being of a more diverse pedestrian population.

Chapter 2

BACKGROUND

This chapter defines several key concepts and topics relating to AVs and various forms of vision impairments.

2.1 Autonomous Vehicles

A vehicle is considered to be fully self-driving if it is capable of performing all driving tasks with no human intervention. As shown in Figure 2.1, the Society of Automotive Engineers (SAE) categorizes vehicle automation based on the following criteria [1] [28]:

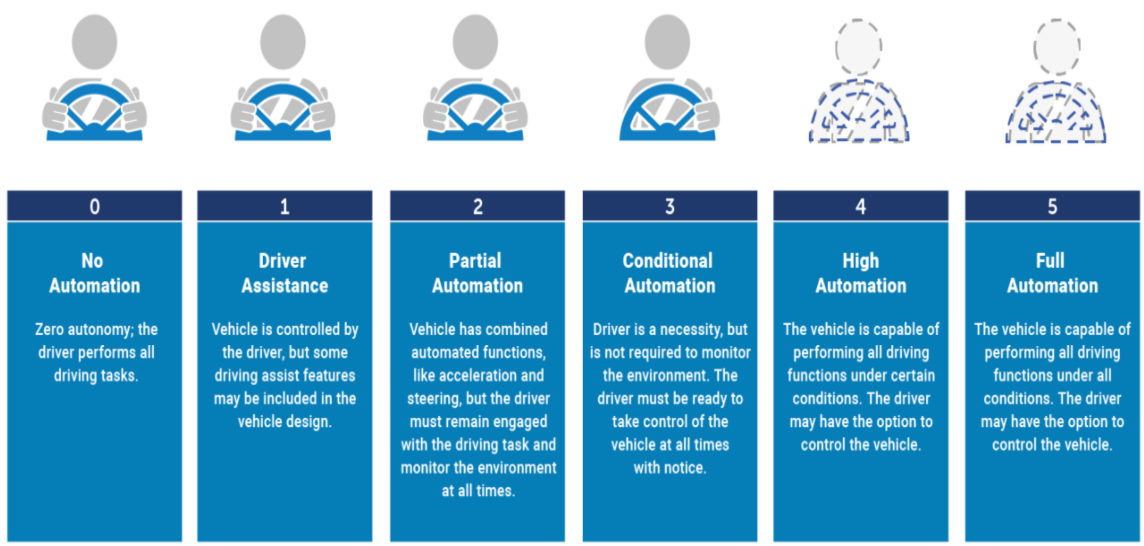

Figure 2.1: Society of Automotive Engineers (SAE) automation levels [1]

Level 0 - No Automation

The vehicle does not have any autonomy features. The driver is fully responsible in performing driving tasks and ensuring the integrity of the driving experience.

Level 1 - Driver Assistance

The driver is responsible for controlling the vehicle but there may exist certain driving assist features such as lane keep or lane assist that enhance the driving experience. Some examples of Level 1 automation include adaptive cruise control and dynamic brake support [1].

Level 2 - Partial Automation

The vehicle has enhancement features in place that allow for multiple automated controls at one time. A vehicle must have the ability to accelerate and steer automatically while the driver is still engaged. This can be observed in lane keep assistance technology in combination with adaptive cruise control that recognizes the necessary speed of the vehicle with respect other vehicles in its surrounding. The driver's engagement is assessed in various manners: capacitive touch or torque sensing steering wheels and eye monitoring systems ensure that the driver is still alert at the wheel and capable of taking over any automated tasks at any moment during the driving experience. The driver must be alert and actively partaking in the driving tasks in order to maintain these partial automation capabilities.

Level 3 - Conditional Automation

The driver is still necessary but is not required to maintain full engagement as in Level 2 automation. The driver does not need to monitor the environment during the driving experience but must still be ready to take over drive controls at any time with notice from the vehicle. The vehicle will notify the driver when they need to take over driver controls. This notification can be either a vibration in the steering wheel or driver's seat or an audio sound within the cabin accompanied with visual notifications in the instrument cluster.

Level 4 - High Automation

The vehicle is capable of performing all driving functions within certain environmental constraints. For example, the vehicle may only be capable of driving at 25 mph in clear weather conditions. The driver may be able to take over drive controls or have the option to disengage the automation feature.

Level 5 - Full Automation

Full automation enables the vehicle to perform all driving tasks under all environmental conditions. In this situation, the driver becomes a passenger and is not required or able to take over drive controls at any point during the driving experience. The vehicle does not allow the driver to take over and the steering wheel is non-existent in this level of automation. The driver does not need to be engaged with the vehicle and all responsibilities are shifted to the vehicle itself. In this research, Level 5 fully automated vehicles will be referred to as AVs [29].

Many vehicles on the road today have driver assistance in the form of adaptive cruise control or stop-and-go assistance which allows the vehicle to track and mimic the speed of the vehicle in front them [30]. Additionally, some cars have lane departure warnings which alert the driver if they exit the colored lines on the road through a manner of various audio and visual warnings signals in the driver's cabin [31]. These technologies are categorized as Level 1 or Level 2 according to the Society of Automotive Engineers (SAE) definitions [1].

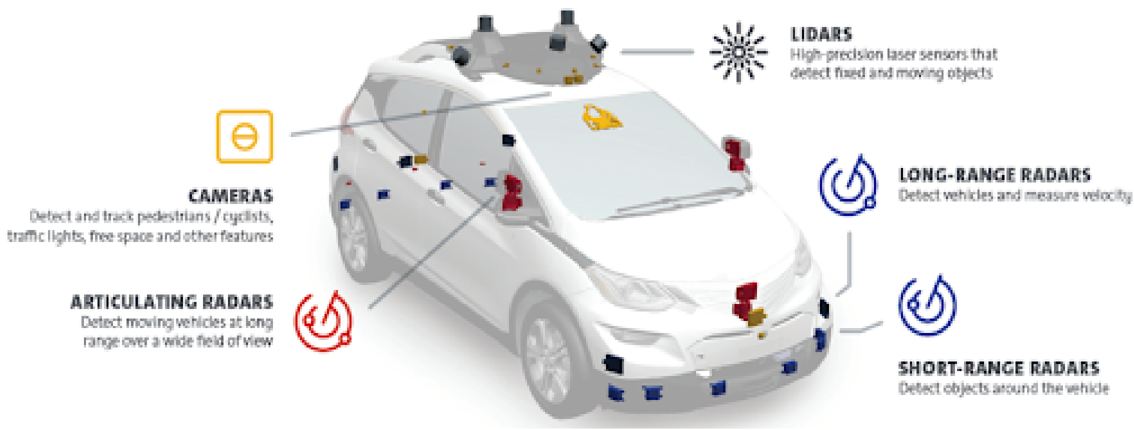

Figure 2.2: Orientation and positioning of various sensors on Cruise's autonomous vehicle [2]

As demonstrated in Figure 2.2, the Level 5 self-driving car design is considerably more complex than Level 1 or Level 2 automation levels with a significant number of sensors incorporated on the vehicle's exterior. Compared to Level 1 or Level 2 vehicles that rely on simple cameras and shorter range radars, Level 5 autonomous vehicles use multi-sensor fusion to gather complete data inputs and account for redundancy to a greater degree than in Level 1 and Level 2 vehicles which primarily rely on limited radar and camera sensors [29]. For the majority of AV companies in the U.S., Level 5 sensors include long-range LiDAR, short-range LiDAR, radar, near-field cameras, far-field cameras, and microphones (used for siren detection) that are all used in conjunction to allow the AV to accurately observe its environment.

Having a wide range of sensors allows the AV to make informed decisions and lowers the risk of vehicle level failure [32]. If any sensor fails, there are other sensors in place that can allow the vehicle to lead itself to a safe location and ensure passenger safety. As shown in Figure 2.3, the position and placement of various sensors ensures that the fields of view overlap to confirm that all relevant objects are detected around the vehicle [32].

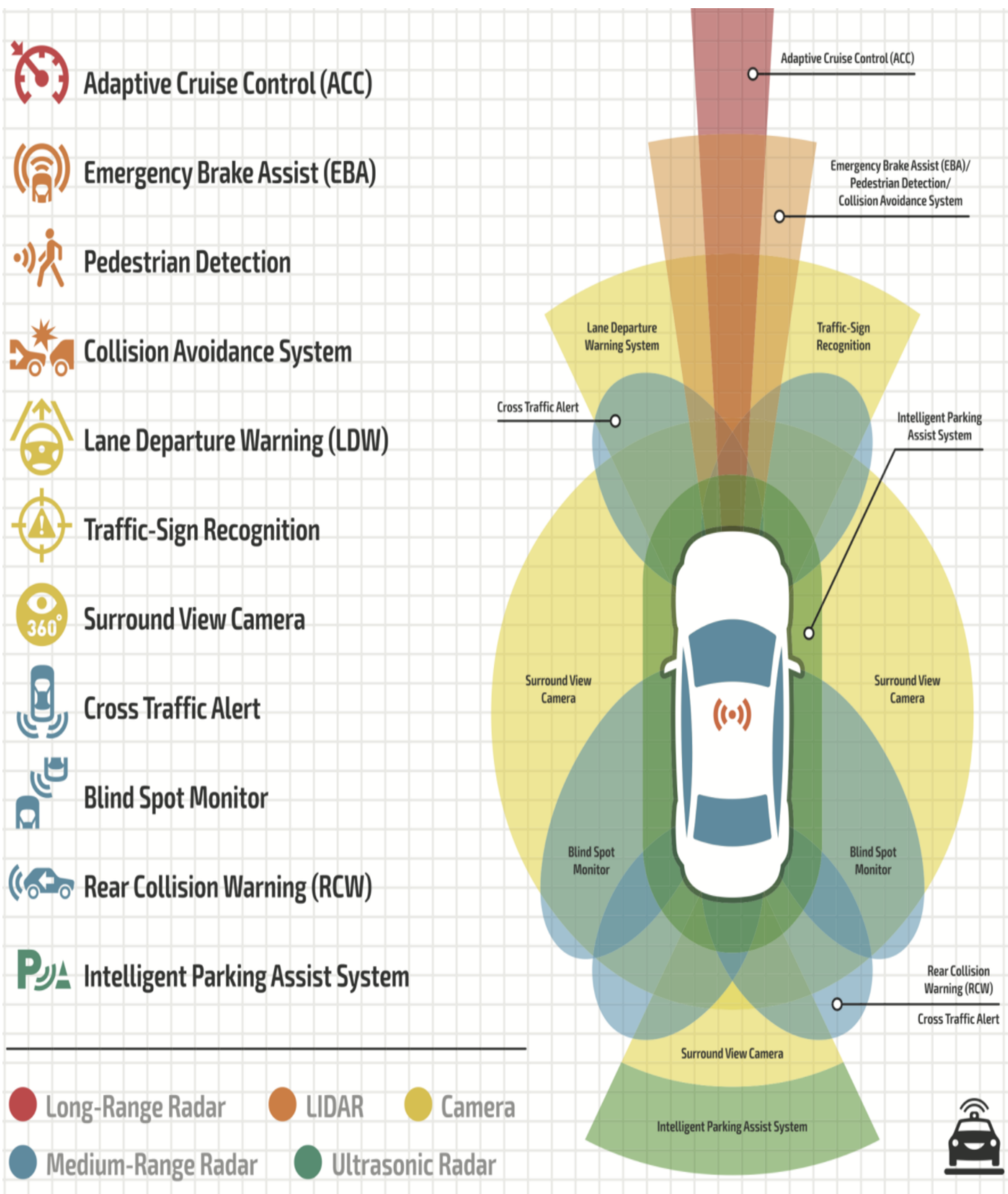

Figure 2.3: Autonomous vehicle sensor fields of view [3]

Autonomous vehicles are actively being researched and their full functionality is still under development. During these early stages, it is necessary to consider the vehicle design as it relates to pedestrians. Accounting for the design and external HMI of the AV early on can help ease the iterative design process as it relates to pedestrian safety.

2.2 Autonomous Vehicle Skepticism

As shown in Figure 2.4, the sensors and their housings act as key identifiers in categorizing autonomous vehicles relative to other vehicles on the road. With the multitude of sensors surrounding the exterior of the autonomous vehicle, these cars can seem threatening and foreign to pedestrians and other vulnerable road users (VRUs) [20] [25]. Regarding these sensors in addition to the public's general fear and discomfort of new technology, designers must balance the functional needs of the vehicle with the overall appearance [33]. The sensors play a key role in the overall vehicle design based on the unique physical requirements that each of them have.

Figure 2.4: Waymo AV with the exterior sensors [4]

People are uncertain about autonomous technologies. They do not yet trust autonomous vehicles due to lack of public presence and the disconnect in technical knowledge associated with understanding the complex inner workings of such vehicles [34].

This balancing act in the design of autonomous vehicles adheres to the American industrial designer, Raymond Loewy's, MAYA principle. MAYA stands for the "most advanced yet acceptable" design. This approach allows designers to deliver the most advanced product design to the user while ensuring that it is familiar and comfortable enough for the user to still embrace and accept [33]. When introducing novel products, such as autonomous vehicles, it is important to consider the MAYA design principle to promote its successful integration into existing traffic and pedestrian routines. Modern vehicle design has neglected the pedestrian and their safety and needs. Designers have been able to adhere to the driver's preferences and liking rather than adhering to pedestrian safety in today's vehicle design [35]. For example, over-sized front grills on pickup trucks appeal to the modern car consumer but are a danger to pedestrians and pose a higher risk of serious injury than the basic vehicle front body [36]. This design trend will need to change for autonomous vehicles as there is a larger need for pedestrian safety and high societal expectations regarding AV safety in the urban setting.

As of 2020, there are fewer than 2000 autonomous vehicles on U.S. roads [22]. The majority of these vehicles are operating under the San Francisco based company, Waymo and are used as a taxi service similar to popular ride haul apps like Uber and Lyft [37]. As more AVs begin operating on urban roads, the public perception of these vehicles may shift to be more positive once the vehicles have proven their effectiveness and safe operation. Designers can help expedite this shift in public perception by working to develop a more human-centric user experience utilizing UI and HMI for pedestrians who interact with these autonomous vehicles in traffic intersections and urban road settings.

Pedestrian fatality rates are increasing in the United States and it is necessary to counteract this statistic by designing future vehicles to adhere to pedestrian safety [38]. This is especially true for at-risk pedestrians who have visual impairments and may not be as attentive or aware of their surroundings in urban traffic settings. Due to the lack of pedestrian-centered vehicle design approaches typically seen in human-driven vehicles, this research focuses on defining the factors influencing AV skepticism in addition to the importance of the external HMI design for AVs. Transitioning to a more pedestrian-centered external vehicle design can promote pedestrian safety and minimize the skepticism associated with autonomous vehicles resulting from poor preexisting vehicle designs.

2.3 The Significance of Human Machine Interfaces on the User Experience

A user's experience interacting with a product heavily dictates their general satisfaction and perception [39]. The user's opinion is developed based on three key human factors: physiological/physical, sensory, and cognitive factors exemplified during the interaction between the user and a given product; in this instance the product is a vehicle.

2.3.1 Human Factors

Consider the human factors present in an interaction between a pedestrian crossing an intersection and a vehicle at a traffic light demonstrated in Figure 2.5. This figure is used to demonstrate the various human factors that should be accounted for when designing a vehicle to promote pedestrian safety.

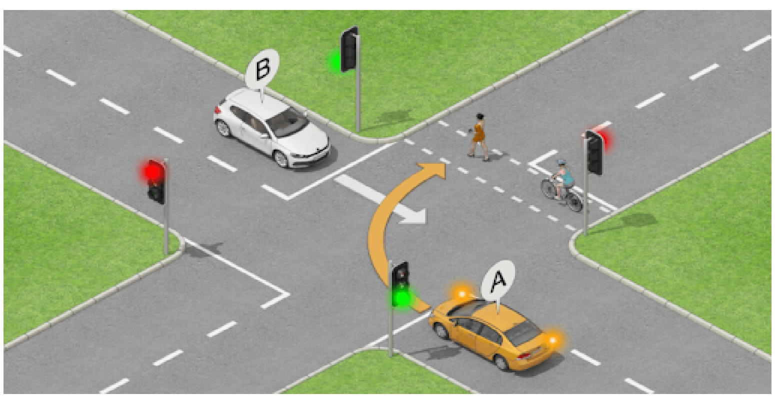

Figure 2.5: A traffic scenario with a vehicle at a traffic light and a pedestrian attempting to cross the street [5]

Physiological and Physical Human Factors

Physiological and physical human factors are concerned with the human anatomical, anthropometric, and bio-mechanical characteristics in relation to a physical activity [39] [40]. Anthropometrics focuses on the size and proportions of the human body and helps to define the design of products relevant to a human's reach, movements, and range of motion. For example, when designing a vehicle, the headlights must be positioned high enough to provide sufficient visibility for the driver while being low enough on the vehicle body to not directly interfere with the pedestrian's line of vision while crossing the street. The positioning of these headlights is determined by accounting for the mean adult anthropometrics and the relative bio-mechanical motion of the pedestrian as they cross the street [40].

Sensory Human Factors

Sensory human factors are concerned with sight, touch, sound, smell, taste, and movement in relation to the user and their interaction with a given product and environment. This explores the relationship between the product design and the user's comfort and satisfaction relative to the sensations and experiences they have while interacting with the product [40].

In busy intersections and heavily trafficked city roads, such as in Figure 2.6 , pedestrians may be more immune to the loud sounds of passing vehicles, horns honking, the many lights of lane change indicators, and the size of the large bus passing by. The concoction of these sensory inputs forces the pedestrian to blend certain sets of information together into one cohesive image of their environment. In comparison, in a more quiet street setting, pedestrians can be more attentive to the select few vehicles on the road. They can clearly distinguish one car's actions from the other's based on the lack of sensory overload as seen in city settings [24] [17]. A pedestrian can more confidently cross a street in this quiet setting than in a city setting due to the way in which they can process and react to the environment around them.

Figure 2.6: A busy traffic intersection in an urban city setting [6]

Cognitive Human Factors

Cognitive human factors account for the mental processes of the user during their interaction with the product: perception, memory, reasoning, and motor response. This is particularly significant with respect to the user's mental workload, decision-making, skilled performance, and human-computer interaction [40]. A common practice relative to cognitive human factors is the use of color psychology to exhibit certain emotions in the user [41].

For instance, pedestrians have learned to associate yellow lights on vehicles with construction, towing, or general traffic warning signals whereas red and blue lights are indicative of emergency vehicles such as ambulances, fire trucks, and police cars. In addition to the red and blue visual signals, pedestrians identify emergency vehicles by the siren sounds and vehicle body that distinguishes the emergency vehicle from commuter vehicles [41] [22].

The combination of these visual and audio cues, alongside the general fast transit speed of the emergency vehicle, triggers a learned response from drivers and pedestrians. Drivers and pedestrians are only able to distinguish an emergency response based on the active siren signal and flashing red and blue lights. If it were not for these cues, there would be no contrast between emergency responses and ordinary driving routine for these emergency vehicles. In emergencies, drivers are taught to move to the side of the road to let these emergency vehicles pass when they hear or see them driving. Pedestrians are instructed to yield to the emergency vehicle and only cross the street only once it is determined safe to do so by a crosswalk signal. This cognitive response is a result of the human factors integrated and developed for the emergency vehicle.

It is important to account for these human factors when developing an external HMI for autonomous vehicles. When designing the external HMI, lights or other communication methods on the vehicle should be designed to adhere to the pedestrian's movements and anthropometrics such that the pedestrian is able to safely and confidently walk in front of the vehicle when crossing an intersection. Similarly, the cognitive and sensory human factors need to be considered so that the pedestrian is able to understand the vehicle's intent with clear communication signals.

2.3.2 Human Machine Interfaces (HMI) and the Pedestrian Experience

Accounting for physiological, sensory, and cognitive human factors, vehicle designers can design the external HMI of a vehicle to adhere to the needs of pedestrians and their experiences. The pedestrian's user experience in traffic settings dictates the way in which they feel about and react to the vehicle. It is because of this experience that autonomous vehicle designs must ensure that the vehicle's appearance is welcoming, intuitive, and adheres to the pedestrian's specific traffic expectations and learned responses.

In urban settings, pedestrians have become reliant on driver-to-pedestrian communication in traffic settings. For example, when crossing an intersection, a pedestrian will often make eye contact with the driver to confirm that the driver is aware of their presence. The driver may even gesture with their hand to indicate that they are allowing the pedestrian to cross. These gestures and visual cues, through eye contact and various facial expressions, play a key role in pedestrian traffic safety [14] [16] [17]. A vehicle's external HMI, in this scenario, supports the driver in their communication with the pedestrian in various means such as lane change indicators, brake lights, and horn sounds. The pedestrian has learned that these combined signals from vehicle and the driver are indicative of the driver's awareness of the pedestrian and give them confidence in their maneuvers [42].

However, this driver-to-pedestrian communication does not exist with autonomous vehicles. The responsibility of the driver is entirely transferred to the vehicle itself, in this instance. This shift in responsibility from driver to vehicle in regards to pedestrian safety requires a more complex and human-centered design approach to the external HMI of these autonomous vehicles [23]. By implementing a more intuitive external HMI, the pedestrian will feel more safe and confident in their interaction with the AV. This positive user experience from the pedestrian enables them to slowly gain trust in the autonomous vehicle as more successful and safe interactions take place on urban roads.

2.4 Visual Impairments

According to the 2019 world report on vision from the World Health Organization, at least 2.2 billion people have some form of vision impairment [27]. There exists a variety of vision impairments with varying degrees of severity and impact to the individual's daily life.

This section provides context in regards to the categorization of eye conditions and the degrees to which various ailments impact the quality of sight. This section gives insights into the ways in which various vision impairments impact an individual's experience in urban traffic settings like the traffic intersection presented in this research. Additionally, understanding these vision impairments assists in the design of the survey and interview questions presented in this research study by ensuring images and questions are clear and large enough to be viewed by the participant.

2.4.1 Full Visual Capability and Near Normal Vision

An individual is considered to have normal or full visual capabilities if they have 20/20 vision [7]. In the U.S. this categorization is based on an eye exam in which the individual is asked to identify specific letters on an eye chart 20 feet away. The first number indicates the distance of the individual's feet relative to the eye chart. The second number is the distance at which a normal-vision person can read the same line. Both numbers are in units of feet. A standard eye chart, shown in Figure 2.7, measures visual acuity in regards to letter sharpness and clarity [7].

When taking an eye exam, the ophthalmologist will ask the patient to read the letters in each row of the eye chart from left to right with both eyes open, facing the chart. The patient then will be asked to close one eye and repeat the same process of identifying the letters. The same process is repeated for the second eye [7].

Figure 2.7: Example of a standard ophthalmological Snellen eye chart [7]

2.4.2 Single Vision Prescriptions

If, during the eye exam, the ophthalmologist determines that an individual does not have good or healthy vision, the patient may be given a single vision prescription, to correct their vision. Single vision prescriptions are given to individuals who have near-sightness, far-sightness, or minor to moderate forms of astigmatism [43].

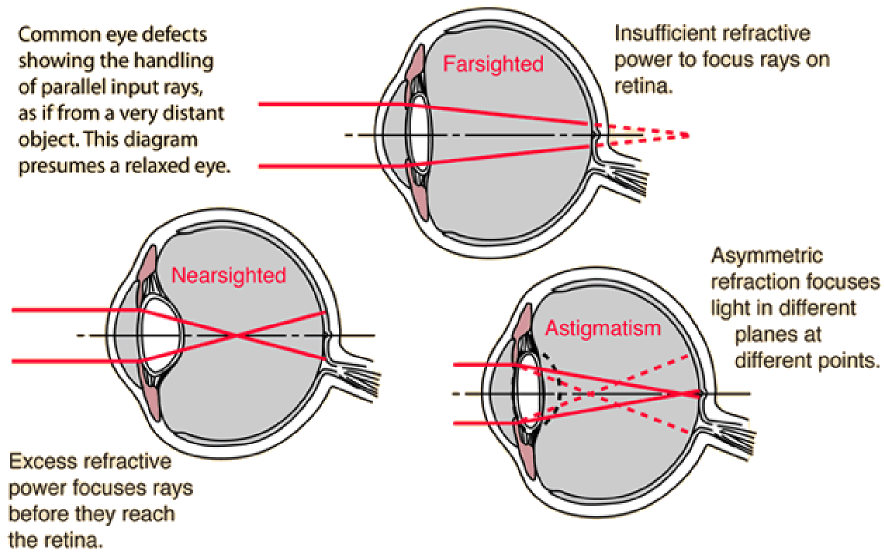

Figure 2.8: Common eye defects and the manner in which light refraction impacts vision [8]

Near-sighted vision, otherwise known as myopia, is the condition in which objects look blurry at far distances but appear normal close up [43]. As shown in Figure 2.8, this occurs when the eye shape forces the light to focus in front of the retina rather than directly on it. In contrast, far-sighted vision, or hyperopia, is the condition in which objects look blurry at close distances but normal far away [8]. These conditions can impact pedestrian interaction with the external HMI of the autonomous vehicle by limiting their ability to see the signals generated by the vehicle when attempting to make a turn in a traffic intersection.

Another common reason individuals get single-vision prescriptions is due to the development of astigmatism. This is a condition in which the cornea, the clear front membrane of the eye, or the lens, becomes deformed. As a result of this deformation, individuals may have blurry or distorted vision [8].

Understanding the process of vision tests and the differences between far-sightedness, near-sightedness, and astigmatism helps in the design of survey and interview questions in this research study. Additionally, understanding these vision impairments and their prevalence in the pedestrian population helps in defining the habits of single-vision prescriptions glasses wearers in relation to traffic intersections and autonomous vehicles.

2.4.3 Cataracts

A cataract is the clouding of the lens in the eye which causes blurred and limited vision [27] [44]. In Figure 2.9, the cataract eye experiences fewer light rays passing through the clouded lens onto the retina. This limitation on the amount of light passing through the lens results in darkened and blurred sight [44].

Cataracts are mainly related to age with more than half of all Americans over the age of 80 having experienced them [15]. Modern medicine has enabled the development of cataract removal surgeries which enable the cataract patient to regain their vision. Although cataracts may reappear, these surgeries enable patients to enjoy improved vision with a quick procedure and fairly minimal recovery time [44].

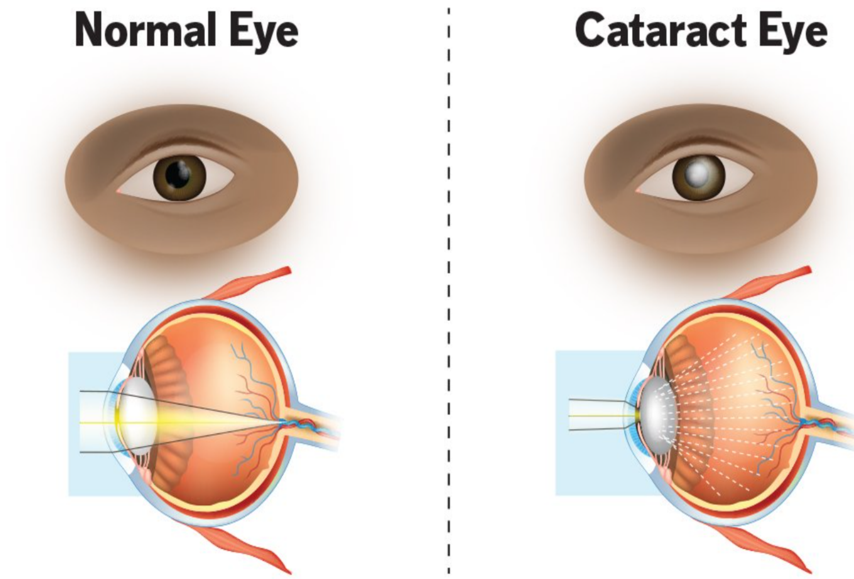

Figure 2.9: A comparative illustration of a normal eye and the refractive light penetrating the lens compared to a cataract eye with dispersed light rays [9]

This research focuses on participants who have untreated cataracts. Considering individuals with active cataracts in this research study helps to understand the constraints and special needs required for safe pedestrian behavior in traffic intersections by ensuring that their needs and behavioral preferences are considered in the design of the external HMI.

2.4.4 Color-blindness

Color-blindness is the condition in which an individual can not see the full spectrum of visible light colors. In severe cases, color-blind individuals may not be able to see color at all but view their surroundings in gray-scale [45].

The most common type of color-blindness is the inability to distinguish red and green hues. Other individuals may have difficulty seeing differences between blue and yellow hues. Variations in color-blindness include differences in the person's ability to identify the color itself, the brightness of the color, and the shade of color. In general, men are more likely to be color blind than women [46] [45] [47].

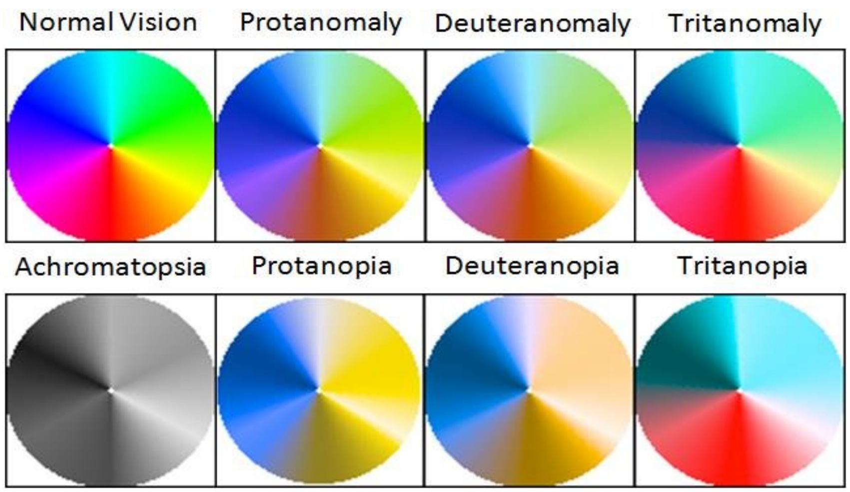

Figure 2.10: Color chart demonstrating different color-blindness categories [10]

Figure 2.10 demonstrates the various categorizations within color-blindness. There are four types of red-green color-blindness and two types of blue-yellow color-blindness [10].

The most common form of red-green color-blindness, deuteranomaly, impacts nearly 3 percent of the global population [46] [10]. In this case, individuals see green color as a red hue. With protanomaly color-blindness, individuals see red as a green hue with muted tone. Protanopia and deuteranopia, both impacting roughly 0.5 percent of the population respectively, make individuals unable to distinguish between red and green colors.

Individuals who have tritanomaly color-blindness cannot distinguish blue/green color from yellow/red color whereas individuals with tritanopia color-blindness are unable to distinguish between blue/green, purple/red, and yellow/pink colors. In the tritanomaly case, individuals see colors as more bright than in the tritanopia case [46].

In very rare cases, an individual can have achromatopsia, in which they are unable to distinguish between any color on the visible color spectrum. Individuals with this total color-blindness, or monochromacy, view everything on the grey-scale and may experience sensitivity to bright light [46].

Accounting for the impacts of colorblindness helps to define the interview questions developed in this research by ensuring that a broad spectrum of colors are displayed such that a broader range of participants are able to identify and interact with various colors.

2.4.5 Blindness

Although there are varying degrees of vision loss and blindness, individuals who have 20/80 visual acuity in the U.S. are considered to have moderate visual impairment whereas individuals who are considered to have profound visual impairment have 20/1000 visual acuity [48] [49].

Near to total blindness is categorized as the most severe form of blindness. At this level of vision impairment, individuals rely on audio aids and braille to take in information. They must use additional vision substitution aids such as guide dogs, and rely on their other senses such as touch, smell, and sound to process, react, and interact with their surroundings [50].

Although there are many other eye conditions and factors that contribute to vision impairments, this research will focus on the five categories described in an effort to better understand some of the most prevalent visual ailments and their impact and influence on pedestrian experiences in traffic settings. Understanding the visual constraints of each of these vision impairments helps in the development of the survey and interview questions of this research. With this understanding, the external HMI of the autonomous vehicle can better be designed to adhere to the unique needs and behaviors of the vision impaired pedestrian.

Chapter 3

DESIGN OF EXPERIMENTS AND SURVEY METHODOLOGY

This chapter describes the design of experiments, survey methodology, and the motivations for an experimental approach that allows for a user-centric analysis of pedestrian behavior and habits to aid in the development of an external HMI design for autonomous vehicles. This external HMI design is defined by the results of this study and in cooperation with the pre-existing lane-change indicators and signals of the vehicle body.

3.1 Experiment Overview

Table 3.1 includes the hypotheses made for this experiment. The experiment gives insights on the ways in which the external human machine interface of an autonomous vehicle can build a trust-driven relationship between AVs and pedestrians. The experiment contains two parts: a survey and an interview. The survey focuses on understanding pedestrian and driver habits and determines the relationship between knowledge and skepticism in regards to autonomous vehicles. This understanding helps to understand the factors influencing AV skepticism and helps to define the parameters of the external HMI design. Acknowledging the root cause of this skepticism and the preexisting knowledge on AVs during the external HMI design process can assist in optimizing the pedestrian experience in relation to the AV. The interview looks into the ways in which various colors and patterns evoke different feelings and emotions in the observer. Additionally, the interview is designed to give a better understanding of the significance of context and environment relative to these colors and patterns. The interview is designed to give a greater understanding of the most optimal color and pattern configuration that would ensure effective communication from the AV to the pedestrian.

Table 3.1: Table of research questions and hypotheses

Research Question	**Hypothesis**
How do visual impairments impact the processing rate of various colors and patterns?	• *H1* Individuals who have visual impairments respond at different rates to colors and patterns in their field of view based on the severity of their impairments • *H2* Legally blind individuals rely more on audible signals from vehicles in traffic than those who do not have any visual impairments
How does an individual's background knowledge about AVs impact their trust in AVs?	• *H3* Individuals who use cruise-control while driving are more likely to trust an AV than those who do not use cruise-control • *H4* Jay-walkers and individuals who use their cellphone while crossing the street are less likely to feel safe around AVs
How do various light patterns and colors relate to awareness, fear, anxiety, trust, and comfort?	• *H5* Short pulses of color and light are more alarming than longer pulses • *H6* Yellow is the most welcoming and engaging color aside from blue and red which are colors reserved for emergency vehicles • *H7* Individuals rely on intuitive patterns from vehicles in order to understand the vehicle's action. Autonomous vehicles will need more intuitive communication methods aside from traditional lane change indicators are rear brake lights.

3.2 Participants

The experiment categorizes participants by age, gender, and visual impairment. Participants range in age from 18 to 65 years old. All participants who partook in the interview or survey were required to sign an informed consent form. A total of participants took part in the survey. Of these 27 participants, a total of 21 participants also took part in the interview portion of this experiment.

Table 3.2 demonstrates the breakdown of the participant pool. This table includes all participant responses even in that case where a participant may have multiple vision impairments such as cataracts and colorblindness. These have been accounted for in the data processing portion of this research where only the more severe form of vision impairment was considered. Sub-categories for each visual impairment are based on the level of severity of the respective visual impairment ranging from light to severe. Severity sub-categories are not shown in table 3.2 but have been accounted for during data processing.

Table 3.2: Participant pool breakdown based on age, gender, and visual impairments

Age	18-24		25-34		35-44		45-54		55-65	
Gender	F	M	F	M	F	M	F	M	F	M
No vision issues	2	1								1
Single vision prescriptions	3	1	1	2	1	1	1	1	1	1
Cataracts									1	1
Color-blind	1	1		1		2		1		1
Blind				1		1		1		2

The sub-categorization of vision impairment levels in this study is defined as follows:

- Light severity is defined as the following:
  - Single-vision prescription participants: +/- 0.25 to +/- 2.00 diopters prescription strength for single prescription participants
  - Colorblind participants: Red-green or blue-yellow color blind
  - Blind participants: 20/200 vision in the better eye
- Moderate severity is defined as the following:
  - Single-vision prescription participants: +/- 2.25 to +/- 5.00 diopters prescription strength
  - Colorblind participants: Red-green and blue-yellow color blind
  - Blind participants: less than 20/1,000 vision
- Severe severity is defined as the following:
  - Single-vision prescription participants: +/- 5.25 and above diopters prescription strength
  - Colorblind participants: Complete color blindness. The participant sees only monochromatic tones in the black and white spectrum.
  - Blind participants: No light perception

The participant pool is reflective of the average and most abundant gender, age, and visual impairment types in the United States. According to the 2010 United States census, individuals between the ages of 18 and 65 make up more than 62 percent of the population [51]. It is significant to include this wide age range in participants within the experiment to better understand the traffic habits most prevalent on urban roads relative to both vehicle and pedestrian behaviors [39].

It is equally as important to consider gender relative to traffic safety [39]. It is known that gender plays a significant role in the differences in driver behaviors in traditional traffic settings [47]. It is important to consider driver behavior relative to gender in this research as it provides a better understanding into the nature of the pedestrian-to-driver relationship. This experiment expands on this knowledge and analyzes the impact of gender on pedestrian behavior, AV skepticism, and AV knowledge. The experiment focuses on the most common forms to accommodate for the mean of the user population. Participants who did not have any known form of visual impairment were selected in order to establish a baseline and reference relative to the norm. Individuals with single vision prescriptions were considered across the entire age range whereas participants with cataracts were only considered in the last age bracket based on the significantly higher probability of cataracts in older populations relative to those below the age of 55 [27].

Select visually impaired individuals, especially those in the “severe” sub-categories require additional assistance in completing the survey. In the case where a participant needed assistance, the investigator verbalized the survey questions and noted the participant’s responses. The interview was not performed on any individuals who are in the “blind” category based on their inability to see the images presented in the interview material. Blind participants were asked to take the survey exclusively and independently of the interview with assistance from the investigator [25].

Participants were informally recruited through word-of-mouth and online forums. Severely visually impaired participants, such as those who are blind, were initially sought from California-based clubs, groups, and organizations focusing on the visually impaired. These include: the Braille Institute of San Diego, the Braille Institute of Santa Barbara, Guide Dogs for the Blind of San Luis Obispo, the Palo Alto Vista Center for the Blind and Visually Impaired, and the Cal Poly Disability Resource Center. Due to lack of response, or unwillingness to participate, no participants from these organizations were included in this study. All participants were informally recruited outside of these organizations.

If an individual informally agreed to take part in the research, they were sent an email containing a formal participation request and the informed consent form. The informed consent form is included in Appendix A. Each participant was given the informed consent form prior to the beginning of any experiment. All participation was voluntary and performed under the conditions of the informed consent.

3.3 Survey Design and Questions

The survey for this research was developed in an effort to gain more insights regarding AV skepticism and the influence of driver traffic behaviors, pedestrian traffic behaviors, and general participant knowledge on autonomous vehicle technology on the participant's trust of autonomous vehicles.

Participants completed the survey via Google Forms. All questions were labelled as not required. Blind participants were given the option of assistance in completing the survey as they may have had difficulty in viewing the questions asked. All participants included in this experiment completed all survey questions.

Appendix B contains the survey used and distributed to qualifying and voluntary participants in this study. The survey content is divided into three main sections. The first portion contains questions relative to the participants' demographics and asks participants to self report their age, gender, and visual impairment(s). The second section focuses on defining the user's typical behavior in traffic settings as a driver and a pedestrian to identify a relationship between caution, trust, and skepticism in regards to vehicles and traffic safety. Together, this survey defines the user population and presents quantitative and qualitative data for analysis.

Questions relating to participants' demographics were given in multiple choice form to better identify each individual within the constraints of the experimental categories of age, gender, and visual impairment type and severity. For example:

- When driving, do you ever use cruise control?
  - Yes
  - No
  - I do not drive

Questions regarding emotions, walking and driving frequency and habits were all given in a rank format so that the participant is best able to self identify within a given range and scale. Allowing for this ranking diversifies the data set and accommodates for a wider range of responses. An example ranking question is shown below:

- Rank your trust in autonomous vehicles
  1. I do not trust autonomous vehicles at all. They should not exist
  2. Autonomous vehicles are not safe on public streets but I would take a ride in a controlled environment if I had the ability to take over the driving if needed
  3. I am indifferent
  4. I believe autonomous vehicles are safe on public streets and would take a ride in one
  5. Autonomous vehicles are entirely trustworthy and safe for both passengers and pedestrians

Select survey questions contain a free response section. This question style gives a better understanding of the participant's unfiltered responses without the guidance or bias typically associated with multiple choice questions [52]. An example free response question is shown below:

- Please list three words that best describe your feelings towards autonomous vehicles.

The questions were arranged in the same order for all participants and distributed via the web. If a participant agreed and qualified for the interview portion, the survey was distributed prior to any interview appointment to map participant demographics and corresponding identifiers with their interview question responses.

3.4 Interview Design and Questions

The second portion of this study involves a virtual interview where participants respond to a series of questions relating to various images and two short videos. These images and videos help define the ways in which emotion is influenced by both color and context and the importance of clear and intuitive HMI design.

The interview was designed to take approximately 10 minutes but each participant was given as much time as needed to respond and the freedom to withdraw or skip questions at any time. The experimenter was responsible for identifying possible distractions for the participant such as pets, electronic devices, and children and creating a calm, welcoming, and non-intimidating virtual research environment over Zoom. Enabling this welcoming and calm environment can minimize the impact of the participant's environment of their responses.

Each participant was given the opportunity to ask questions prior to the start of the interview. To maintain uniformity amongst interview administration, each participant was read a script throughout the interview process which minimized any potential biases, notions, or subconscious influences from the experimenter. This script is contained within Appendix C.

In total, there are 9 core questions in the interview. The order of the questions was randomized for each participant such that no two consecutive questions regarding an image or video were asked. A sample interview with pseudo-randomized question order is contained within Appendix D. Partially randomizing the order of the interview questions, shown in Table 3.3, minimizes the order effect within the collected data sets where one participant's question order negates the learning impact of another since multiple questions are repeated across different images and videos [53]. The order effect occurs when participants are asked a series of similar questions and subsequently learn the predictability and expectations of each of the questions. In this instance, participants could subconsciously produce biased responses as they complete more of the questions such that the first question is unbiased and last question is influenced by what the participant learned during the interview process and questions.

Repeated measures throughout the various interview questions are taken to define and compare means across one or more variables from repeated observation. Assignment of question arrangement is based on the participant's age and gender categorization relative to other participants in the same categories. This ensures that no two participants have an identical question order in any given age or gender category and minimizes the probability of biased or skewed data sets.

Table 3.3: Randomized interview questions and question arrangement options

Arrangement Option	Order of Questions		Question Number	Question
A	1-3-5-7-2-4-6-8-9		1	What colors make you feel happy in this image?
B	2-4-6-8-1-3-5-7-9		2	What colors make you feel sad, scared, or any other negative emotions in this image?
C	8-1-4-7-3-6-2-5-9		3	What colors make you feel happy in this image?
D	3-6-7-2-4-5-1-8-9		4	What colors make you feel sad, scared, or any other negative emotions in this image?
E	7-5-2-4-1-6-8-3-9		5	What colors make you feel happy in this image?
F	4-1-5-7-3-6-8-2-9		6	What colors make you feel sad, scared, or any other negative emotions in this image?
G	5-2-8-4-6-7-3-1-9		7	Watch this short video once. What color was present? What color was not present? (slow blink)
H	6-7-1-3-5-8-2-4-9		8	Watch this short video once. What color was present? What color was not present? (fast blink)
I	3-8-5-2-4-7-6-1-9		9	What direction is the red car going to go next? What direction is the yellow car going to go next?

To help assess the effects of situational context on the emotional interpretation of color, there are three different paintings used in this interview. Paintings were selected in this research in an effort to maintain a uniform medium when depicting images. The first painting, shown in Figure 3.1, named *Yellow-Red-Blue* by Wassily Kandinsky, is abstract and is intended to be a neutral test case in the interview given the lack of natural scenery and presence of nonrepresentational figures [11]. The second painting, shown in Figure 3.2, named *Girl with Death Mask* by Frida Kahlo, is typically observed to be more ominous and evokes negative emotions in the viewer [12]. The third painting, shown in Figure 3.3, named *Happy Days* by Edward Henry Potthast is intended to be the more positive test case with a positive and inviting setting [13]. Accounting for the pseudo-randomized question order, each participant is asked to define the happy and sad colors within the respective paintings. This question series is implemented to help understand how colors may be viewed and felt differently given the context in which they are presented. One color may be seen as more positive in one painting and more negative in the next given the environment and scene presented to the viewer. This dependency on context and color psychology plays a key role in defining the colors used in autonomous vehicle external HMI designs. An AV must have clear light signals that are alerting yet welcoming enough to promote a safe and intuitive relationship between the vehicle and pedestrian [23] [33].

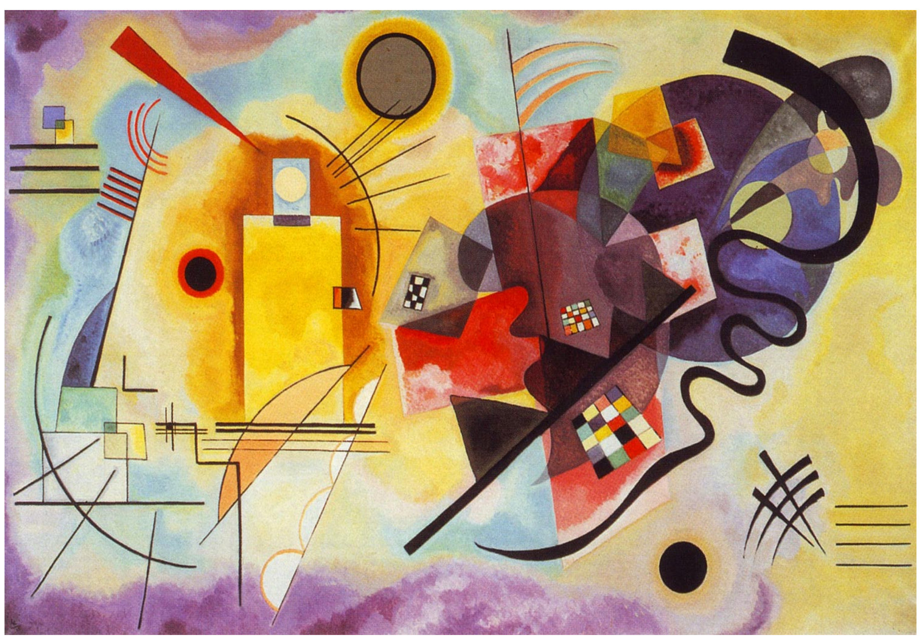

Figure 3.1: Kandinsky: *Yellow-Red-Blue* [11]

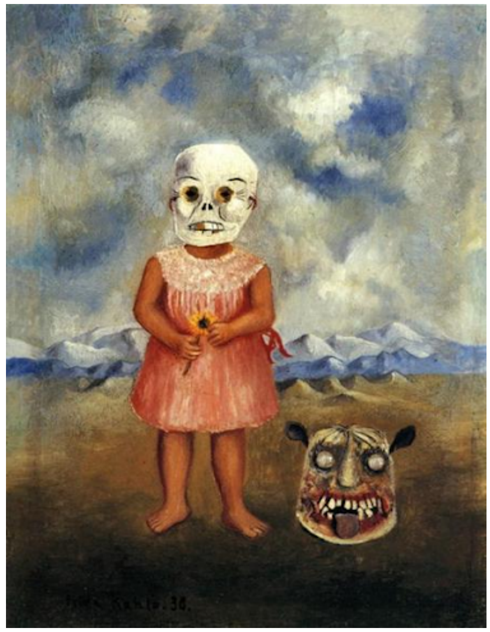

Figure 3.2: Kahlo: *Girl with Death Mask* [12]

Figure 3.3: Potthast: *Happy Days* [13]

In an effort to better understand the significance patterns and light impulse frequency relative to memory, the interview also contains two videos. Questions relating to these videos containing were developed to understand how frequency and duration of light signals relate to alertness and attentiveness in the participant. One video contained a slower blinking frequency of a color changing circle and the other was the same color arrangement but with a faster blinking frequency. The circles presented in these videos were consistent is size, shape, and color order for both videos. The color arrangement of the circles for both videos is as follows: purple, red, blue, green, white, orange, pink, purple. The order of videos was pseudo-randomized in accordance with Table 3.3 to counteract the learning that occurred during the experiment. These videos are presented to the participant only once. Following each video, the participant is asked to recall the color of the circles that were presented. Then, the participant is asked to recall the color(s) that were not present in the video. For data processing, the following colors were noted for these responses: red, orange, yellow, green, blue, purple, pink/fuchsia, grey, brown, black, and white. These two questions help to define what colors are most memorable and alerting to the viewer.

Each interview session ends with a final image and two questions. This final image, shown in Figure 3.4 is always left last in the randomized question arrangement options to coincide with the learning gained from all prior questions. Participants are asked to identify the direction of the red and yellow vehicles. The red vehicle contains a projected directional arrow used to indicate its next direction whereas the yellow vehicle projects only a gradient of light showing its intended next direction. The purpose of these two different projected indicators is to better understand participant's intuition when it comes to vehicle communication methods and the manner in which urban traffic settings have shaped pedestrian knowledge and expectations.

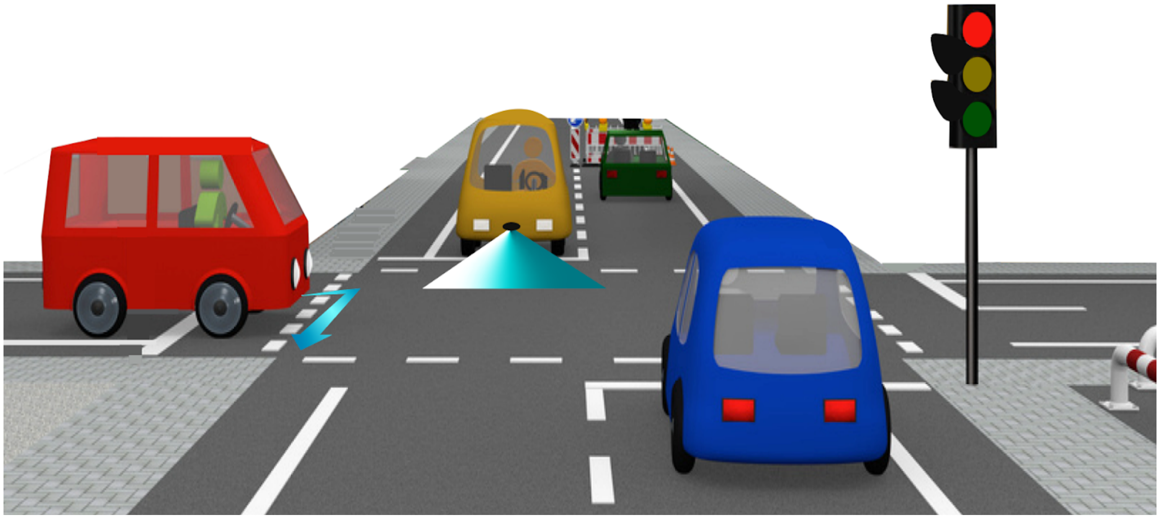

Figure 3.4: An urban traffic scenario in which two different autonomous vehicles are projecting visual indicators onto the street to communicate their next intended directional path.

Chapter 4

KEY RESULTS AND FINDINGS

This chapter discusses the key results and finding from the survey and interview. The results are derived from participant responses. The design recommendations for the AV's external HMI are made based on the survey and interview results.

4.1 Survey Results

The survey section of this study focuses on participant demographics, driving habits, pedestrian habits, and autonomous vehicle knowledge and trust. A total of 27 participants took part in the survey varying in gender and age as demonstrated in Figure 4.1. There were 13 females and 14 males in this study ranging in age between 18 and 65 years. In addition, each participant had the opportunity to self identify multiple visual impairments. If a participant had multiple visual impairments, the most severe form of visual impairment took precedence in data analysis. For example, if a participant identified themselves as colorblind and required light single-vision prescription glasses, responses were mapped relative to colorblindness only if it was ranked more severe relative to the other visual impairment. If an individual had light single-vision prescription glasses and had a light severity of colorblindness, the colorblindness took precedence.

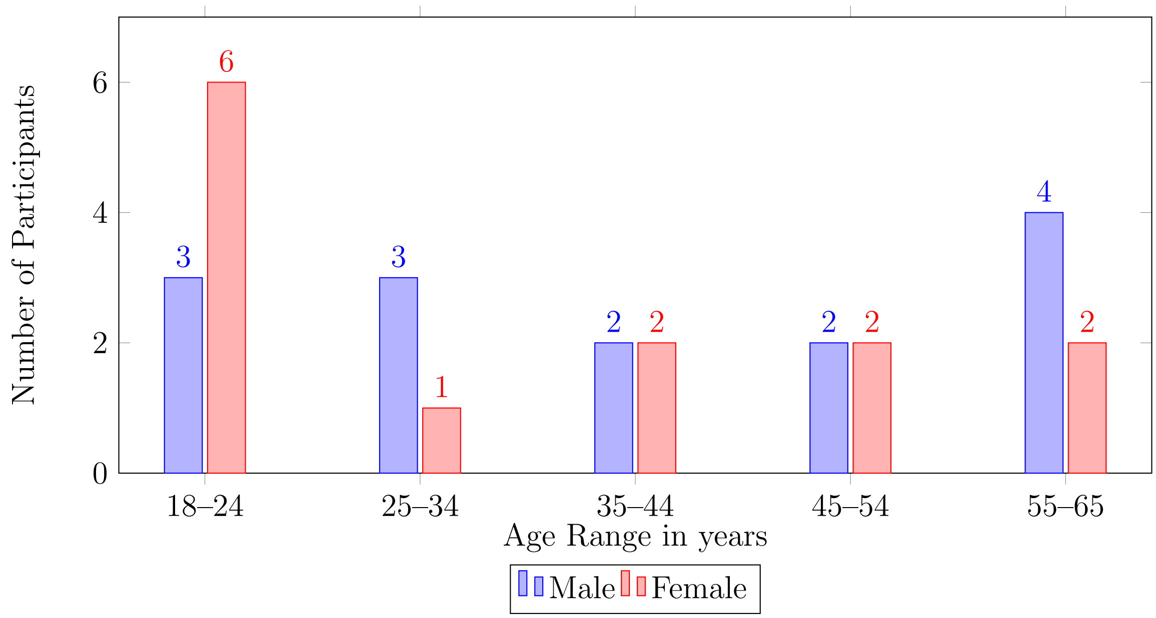

Figure 4.1: Age and gender demographics of the participant pool

All data processing for the survey responses was completed in Minitab [54]. This study looks at the Spearman rho correlation coefficients and the respective p-values based on the ranking system used in participant responses [55]. Therefore, this study assumes that the scores on one variable are monotonically related to the other variable for all 9 variables analyzed in these results. Additionally, this study assumes that the data relating to the results shown in Table 4.1 is ordinal in accordance to the ranked response values.

Figure 4.2 demonstrates the types of visual impairments present in the participant pool and the number of participants relative to each type. In total: 4 participants had no visual impairment, 13 participants had single-vision prescription glasses, 2 participants had cataracts, 7 participants were colorblind, and 5 participants were blind.

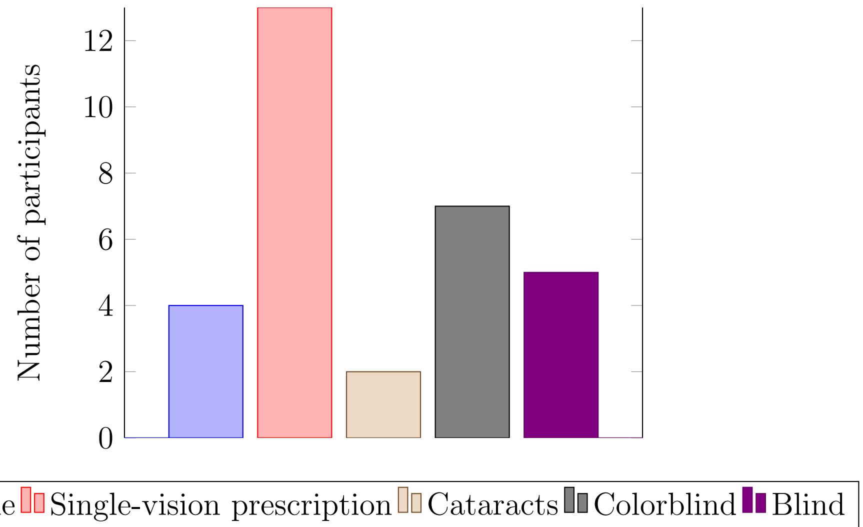

Figure 4.2: Types of visual impairments in the participant pool

Based on survey responses shown in Figure 4.3, 44.4% of participants labeled *blue* as their favorite color. The second most popular colors were *green* and *yellow*. 14.8% of participants labeled *green* as their favorite color and 14.8% of participants labeled *yellow* as their favorite color. This result is important to note when developing the design recommendations for the external HMI. Appealing and popular colors should be used in the light display of the AV in an effort to accommodate for the *MAYA* principle [33].

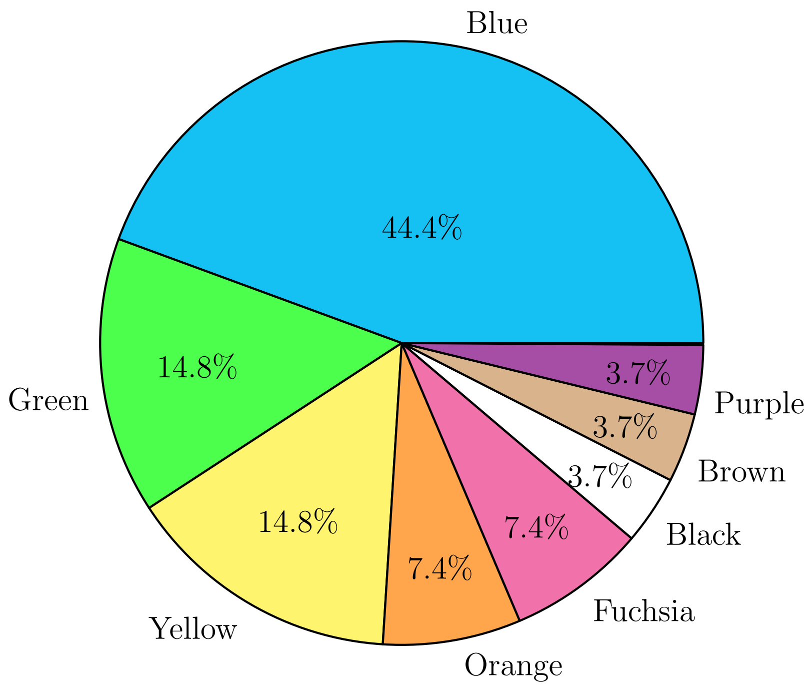

Figure 4.3: Participants' favorite colors

One of the survey questions asked participants to identify how often they use their mobile phones when walking across the street. 48.1% of participants stated that they *never* use their mobile phone while crossing the street. 100% of the blind participants were included in this pool because of their ability to provide valuable data while being assisted in the completion of the survey questions. Of the 40.7% of participants who claimed to *rarely* use their mobile phones while crossing the street, 36.36% had a moderate severity of single-vision prescription glasses. Only 11.1% (3) of participants stated that they *frequently* use their phone when crossing the street. These participants were all females in the 18-24 age bracket, 2 of whom had light severity single vision prescription glasses and 1 who had no vision impairments. As shown in Table 4.1, there is a low degree of correlation ($|r| < 0.39$) between vision impairment and phone usage while crossing the street with a Spearman rho correlation coefficient of $r = -0.353$ and $p = 0.071$ [55]. There is a weak relationship between individuals with more severe forms of visual impairments and their lack of mobile phone usage in this traffic setting than those who have light to no vision impairment. Due to the large p-value ($p = 0.071$) which exceeds the p-threshold of $p < 0.049$, this finding is not statistically significant.

Table 4.1: Spearman rho correlation coefficients and p-values for the 9 variables addressed in the survey

	Vision impairment	2.	3.	4.	5.	6.	7.	8.
2. Mobile	-0.353							
phone usage	0.071							
3. Jaywalking	-0.108	0.322						
	0.593	0.102						
4. Using	**-0.644**	0.354	0.161					
cruise control	**0.000**	0.070	0.420					
5. Prior AV	-0.083	**-0.435**	-0.107	0.152				
knowledge	0.682	**0.023**	0.596	0.449				
6. Willingness	**0.613**	-0.111	0.234	-0.259	0.115			
to ride	**0.001**	0.583	0.240	0.192	0.567			
7. Trust in AV	0.047	0.068	0.258	0.102	0.076	**0.482**		
	0.815	0.738	0.194	0.631	0.708	**0.011**		
8. Age	0.337	**-0.689**	-0.331	-0.232	0.132	-0.074	-0.291	
	0.086	**0.000**	0.092	0.243	0.510	0.714	0.141	
9. Gender	0.271	-0.147	0.355	0.011	0.081	0.189	0.030	0.211
	0.171	0.464	0.069	0.958	0.687	0.346	0.881	0.292

The survey results indicate that more individuals jaywalk than they use their mobile phones while crossing the street. 63% of participants indicated that they *rarely* jaywalk and 22.2% stated that they *frequently* jaywalk. 52% of jaywalkers in this study also use their mobile device while crossing the street. As shown in Table 4.1, despite having the majority of the participant pool self identify as jaywalkers, this study found no statistically significant correlation between jaywalking and a participants willingness to ride in an AV or a participants trust in an AV.

There is a moderate degree ($0.40 < |r| < 0.69$) of correlation ($r = 0.482$ with $p = 0.011$) between a participant's willingness to ride in an autonomous vehicle and their trust in AVs [55]. Additionally, there is a moderate degree of correlation ($r = 0.613$

with $p = 0.001$) between a participant's vision impairment level and their willingness to ride in an autonomous vehicle.

Survey results show that there is also a moderate degree correlation ($r = -0.644$ with $p < 0.001$) between a participants level of vision impairment and their use of cruise control. Additionally, there is a moderate degree correlation ($r = -0.689$ with $p < 0.001$) between a participants age and their use of mobile phones while crossing the street.

An unexpected, yet weaker, finding in this survey is the moderate degree of negative correlation ($r = -0.435$ with $p = 0.023$) between participants who look at their mobile phones while crossing the street and their prior knowledge on AV technology and functionality. There may be additional variables in a cross correlation that have contributed to this relationship that were not addressed in this study.

These statistical analysis results do not show any high degree ($|r| > 0.70$) of correlation between any of the 9 variables of Table 4.1 [55]. This could be the result of a small sample population or multi-variable impacts that were not accounted for in this study such as: ethnic background, education level, and income level of the participant. Further research can be conducted to explore these potential impacts.

The correlations found in this study help to identify the factors influencing AV skepticism through the lens of the vision impaired pedestrian. Finding these relationships between the 9 factors addressed in this research helps determine the root causes of AV skepticism and the impacts that this may have on pedestrian behaviors.

The last portion of the survey asked participants 3 free responses questions about their emotions towards autonomous vehicles and their suggestions on AV design improvements. Table 4.2 shows the most common emotions that participants identified regarding their feelings towards AVs. Emotions are listed based on the number of times they appeared in the data. Only the most prevalent and common emotions are included in this table, other emotions seen in the data include: *eager*, *impatient*, and *drained*. These emotions are significant to consider and note when designing the external HMI of the autonomous vehicle and have been accounted for in Section 4.3. Emotions can play a key role in the pedestrian's experience when interacting with the autonomous vehicle and it is important to maintain a welcoming and engaging relationship between the pedestrian and vehicle to promote the pedestrian's trust.

Table 4.2: Most commonly associated emotions relative to autonomous vehicles based on participant free response answers

Emotion	**# of Occurrences**
Nervous or Skeptical	19
Hopeful	17
Excited	12
Scared or Fearful	12
Comfortable or Safe	7

Aside from these emotions, participants also had the opportunity to provide feedback regarding the factors that would help improve their trust in autonomous vehicles. The majority of participants (14) stated that they wanted road data and vehicle safety reports readily available to the public. It should be noted that many autonomous vehicles already make their test and safety reports public [56]. Many participants were unaware that this resource is already available to them. This suggests that there is a gap in knowledge and awareness of AV technology and the current state of the AV's development.

Overall, these survey results are helpful in defining some parameters of the external HMI design of the autonomous vehicle. Identifying these correlation coefficients is key to gaining a greater understanding of the relationship between vision impairments and the ways in which pedestrians interact with vehicles in the urban traffic settings.

4.2 Interview Results

The interview portion of this study focused on understanding the impact that colors and context have on emotions as well as the ways in which individuals process Visual cues. Blind participants did not take part in the interview portion of this study. Thus, there were a total of 21 interview participants (22 of the original survey participant pool, 27).

Participants were asked to identify the happy and negative colors in Figures 3.1, 3.2, and 3.3 in an effort to define a relationship between color, context, and emotions. Across all 3 paintings, *yellow* was the most common happy color with 95,24% of participants choosing it in the Kandinsky painting, 42.86% of participants choosing it in the Kahlo painting, and 77.19% of participants choosing it in the Potthast painting.

On the other hand, *blue*, *red*, and *purple* colors were commonly associated with both happy and negative emotions depending on the context of the image. For example, 47.62% of participants identified *purple* as being a negative color in the "Happy Days" painting by Potthast. Of these participants, 70% claimed that *purple* was a happy color in the abstract painting by Kandinsky. Similarly, 57.14% of participants identified *red* as being a negative color in the painting by Kahlo. Of the participants who found *red* to be a negative color in in the Kahlo painting, 58.33% claimed that *red* was a happy color in the "Happy Days" painting by Potthast. This demonstrates the impact that context has on the ways in which participants associate color with emotions. One color may be seen as *happy* given a more positive context. If the context were changed to a scary setting, such as in the painting by Kahlo in Figure 3.2, that same color would be observed in association with more negative emotions.

The second portion of the interview focused on the ways in which flashing frequency impacted the alertness and memory of the participant. Each participant was asked to identify the colors present in a fast blinking and slow blinking video. Both videos displayed the same color pattern but one was faster than the other. This experiment was designed to observe the optimal speed of flashing light signals needed to best alert the participant. Participants recalled colors better at slower blinking rates than at faster ones. With the slow blinking video, 47.62% participants correctly recalled at least five colors. With the fast blinking video, 33.33% participants correctly recalled at least five colors.

In the slow blinking video, *blue* was the most commonly recalled color (aside from the color *purple* which was used as an indicator for the start and end of the video) with 90% of correct responses containing this color choice. This was true for the fast blinking video as well, with 90% of participants correctly recalling the color *blue*. This suggests that blue is a memorable color for participants.

In the last question of the interview portion, when asked what direction the *red* car was going to turn in Figure 3.4, 100% of participants stated that the vehicle would be turning right. When asked what direction the *yellow* car was going to turn, 95.24% of participants stated that the vehicle would not be turning at all, when, in fact, it was turning right too. This demonstrates the need for intuitive directional indicators from autonomous vehicles. The projected gradient of blue light was not sufficiently communicative to the pedestrian of the direction it was going to take next. With a distinctly projected blue arrow, such as the one displayed from the *red* car, the pedestrian is able to more confidently and intuitively interpret the intended next direction of the vehicle.

Overall, the interview section of this study provided significant insights into the ways in which participants take in and process visual cues. Participants prefer slower blinking signals which are alerting and informative in a non emergency setting such as in the standard traffic intersection considered in this research. Additionally, participants preferred the color *yellow* in conjunction with happy and welcoming emotions. These results indicate that intermittent signaling mechanisms should use a slower blink with welcoming and memorable colors such as yellows and blues.

4.3 External HMI Design Recommendations based on Key Results

Based on the results found in the survey and interview that indicate a lack of trust in AV technology and assuming that an external HMI is needed, the design on the AV should include an external HMI in addition to the standard headlights and lane change indicators present on the front body of the vehicle [23]. Adding an external HMI helps to bridge the gap between pedestrian and AV communication methods.

It is recommended that the external HMI should include a light projection system on the front portion of the vehicle. Additional communication methods from AVs to pedestrians, such as those provided with an external HMI, may help diminish the skepticism revolved around AVs. This design recommendation is developed in an effort to help resolve the degree of skepticism that individuals have regarding AV traffic safety performance found in the survey portion of this study. Additionally, this light projection system should be implemented to help produce a more intuitive and clear communication method to the visually impaired pedestrian who may have difficulty viewing lane change indicators. This suggestion is based on the video-based interview results demonstrating a preference towards slower blinking signals. Light projection should be displayed large enough on the ground so that light to moderately severe vision impaired pedestrians may be able to clearly identify it. Having a large projected arrow from the AV on the ground would assist the visually impaired pedestrian in their interaction between the AV while crossing a traffic intersection by giving a clearly visible, bright, and alerting signal to the pedestrian.

Survey results found that the most popular favorite colors were blue, green, and yellow. Additionally, interview results found that yellow is the color most associated with happiness and openness while blue is the most memorable color. Blue lights (in combination with red lights) are reserved for emergency vehicles whereas yellow lights are reserved for construction and labor vehicles [57]. Based on these findings and preexisting California vehicle codes, the light projection system of the external HMI should include a teal to light blue colored light from the front center of the vehicle body.

The light projection system of this external HMI, as shown in Figure 4.4 should project a clear directional design whenever a pedestrian is present while the vehicle is attempting to complete a turn at a traffic intersection. This directional design does not need to be an arrow but should be intuitively displayed for the pedestrian such that no additional training or learning is required from the pedestrian to understand its intentions. Having a clear and intuitive signal such as this gives the pedestrian confidence in the AV's performance and indicates to the pedestrian that the AV is aware of their presence in this traffic scenario.

Figure 4.4: A recommendation on the visual aspect of the AV's external HMI based on study results

Details regarding the distance required to project the light from the AV onto the ground were not assessed in this research. This research and design recommendation focused on the visual aspect of the AV's external HMI relative to the needs and behaviors of the participant pool which varied in age, gender, and level and type of vision impairment.

Chapter 5

FUTURE WORKS

This chapter identifies various additions and extensions to the study performed under this thesis in an effort to optimize the external HMI of autonomous vehicles to be more inclusive and communicative.

5.1 An Extension of the Participant Pool in the Experimental Study

This study can be extended to account for a broader, larger, and diverse participant pool. This study can be extended to account for regional and ethnic demographics. This can help understand participant interview responses regarding color and context that can be influenced by culture and regional identities. Secondly, this study can be extended to a greater range of visual impairments such as glaucoma, loss of peripheral vision, extreme light sensitivity, and night blindness. Accounting for this broader range can identify the unique challenges faced by visually impaired pedestrians and assist in the design of the external HMI such that it adheres to their specific needs.

Similarly, the participant pool can be expanded to hearing impaired individuals and individuals who are on the autism spectrum that would allow for a more comprehensive external HMI design based on visual and audio signaling that adhere to vision and audio impaired pedestrians. Accounting for additional disabilities, such as these, aids in the definition of the external HMI parameters in accordance to the needs of the pedestrian. It is necessary to develop the external HMI to be as impactful and communicative as possible while considering the consequences of over-stimulation to at-risk pedestrians such as those who are autistic.

5.2 A Development of a Rear-facing External HMI on Autonomous Vehicles

This study focuses on the forward-facing external HMI design. To better communicate with pedestrians, the autonomous vehicle can contain a 360 degree external HMI. This design development would require an additional study. The study should analyze the needs of AV pedestrian communication methods from various traffic settings such as reverse moving AVs and intersection instances where the AV may not be directly in front of the pedestrian. Gathering this data, in addition to the results found in this thesis, would enable the development of a more complex external HMI that adheres to the needs of pedestrians in a more diverse range of traffic scenarios.

This design recommendation can be viewed as a first iteration with future design iterations focusing on detailed parameters such as the specifics of the color hues, the positioning of the 360 degree external HMI on the vehicle body, and the implementation of audio signals to best improve and promote the pedestrian experience with AVs.

Chapter 6

CONCLUSION

This research analyzes AV skepticism and focuses on developing a design recommendation for an autonomous vehicle's external HMI. The lack of pedestrian safety considerations in modern vehicle design inspired this research and aided in the development of the external HMI design recommendation. Survey results show multiple cases of moderate degrees of correlation relative to the 9 variables addressed in this research study that help in defining the skepticism associated with autonomous vehicles and the need for AV external HMI integration. In addition to these quantitative results, findings from both the survey and interview portion helped to define the ways in which color and context evoke different emotions. These results are necessary to better understanding the preferences of visually impaired pedestrians and help to develop a more trusting and welcoming interaction between autonomous vehicles and pedestrians.

Prior to this research, visually impaired pedestrians did not have the consideration and attention needed to help ensure pedestrian safety relative to autonomous vehicle road operations. It is especially critical to do further research in this field and draw stronger research conclusions to ensure the safety of these vulnerable road users as more autonomous vehicles become prevalent on urban roads.

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APPENDICES

Appendix A

INFORMED CONSENT FORM

INTRODUCTION

This form asks for your agreement to participate in a research project on the effect different colors and patterns may have on perceptions. Your participation involves attending a virtual research session at over Zoom in which you will be asked to view some images and short videos and complete a couple of short questionnaires. The Zoom research session will not be recorded. It is expected that your participation will take approximately thirty minutes. The potential risks from this project are considered minimal. You may personally benefit from this study and others may benefit from your participation. If you are interested in participating, please review the following information:

PURPOSE OF THE STUDY AND PROPOSED BENEFITS

- The purpose of the study is to conduct a student's master's thesis research on the extent to which a person's visual perceptions may influence their interactions with traffic and vehicles.
- Potential benefits associated with the study include increased understanding of the effect of visual perception on pedestrian behaviors relative to autonomous vehicles. The findings from this study could potentially increase traffic and pedestrian safety.

YOUR PARTICIPATION

- If you agree to participate, you will be asked to attend one virtual research session over Zoom. At this session, you will need to view images and short videos associated with respective questions. After completing these questions via Zoom, you will complete a voluntary survey via Google Forms at your own time prior to the start of any potential interview questions. The images and short videos presented will be simple and large enough to view for most participants
- The investigator leading the research session will be available to assist you in reading the questions in the Google Forms survey if you are having difficulty viewing the questions on your own. If you choose, you can have an aid assist you in filling out the Google Forms.
- If you have severe vision impairments such as total blindness, or near total blindness, you will only be asked to voluntarily complete the Google Forms survey and the research session with images and short videos will be skipped.
- Your participation will take approximately 30 minutes.

PROTECTIONS AND POTENTIAL RISKS

- Please be aware that you are not required to participate in this research, refusal to participate will not involve any penalty and you may discontinue your participation at any time. You may omit responses to any questions you choose not to answer. If you choose to withdraw from the study, you must indicate this to the researcher in either verbal or written form at which point all collected responses will be removed from the data pool.

- There is a slight risk of emotional distress, but it is not anticipated to be more than that experienced in daily life. Specifically, if you have visual impairments, you might have difficulty seeing some of the images presented during the research session. This may result in emotional distress but no physical harm will take place as a result of this research.

- Your confidentiality will be protected as your name and other identifying information will not be used in reports of this research. The Zoom research session will not be recorded in order to protect personal information. All data associated with your participation will be stripped of identifiers and coded alphanumerically. This informed consent form, with your signature and name, and all related records will be stored in a locked file that only project personnel will have access to.

- In any written or oral presentation of this research, your identity will be kept private. Records that identify you may be inspected by authorized individuals such as the Cal Poly Institutional Review Board or employees conducting peer review activities. Your agreement to participate indicates consent to such inspections and to the copying of excerpts of your records, if required by any of these representatives. There is a minimal risk to you as a participant if your responses are accidentally disclosed along with your identifiers such as your age and gender.

- Identifying data will be removed from your private information and that, after such removal, the information could be used for future research studies or distributed to another researcher for future studies without additional informed consent.

RESOURCES AND CONTACT INFORMATION

- This research is being conducted by Sandra Roksic, a student in the Department of Electrical Engineering at Cal Poly, San Luis Obispo, under the supervision of Dr. Andrew Danowitz. If you have questions regarding this study or would like to be informed of the results when the study is completed, please contact the researcher.
- If you have concerns regarding the manner in which the study is conducted, you may contact the Chair of the Cal Poly Institutional Review Board, or the Director of Research Compliance

AGREEMENT TO PARTICIPATE

If you are 18 years or older and agree to voluntarily participate in this research project as described, please indicate your agreement by initialing on the line and signing below.

I have read the information provided and have had all my questions related to my participation answered. I understand that I may ask additional questions during the study if I need any other information.

Signature of Volunteer / Date

Signature of Researcher / Date

Please keep a copy of this form for your reference, and thank you for your participation in this research.

Note: All contact information and dates have been excluded from this appendix document in an effort to maintain experimenter and participant privacy. Proper contact information and necessary dates were provided to each participant

Appendix B

SURVEY QUESTIONS

The following questions are extracted from the Google Forms research survey used for a portion of this study. This does not include the virtual interview questions that are in fulfillment of the secondary part of this study.

1. Is anyone assisting you in completing this survey?
    (a) Yes
    (b) No
2. What is your gender?
    (a) Female
    (b) Male
    (c) Other
    (d) Prefer not to say
3. What is your age?
    (a) 18-24
    (b) 25-34
    (c) 35-44
    (d) 45-54
    (e) 55-65
    (f) 66+

4. What is your favorite color?
    (a) Red
    (b) Orange
    (c) Yellow
    (d) Green
    (e) Blue
    (f) Fuchsia
    (g) Purple
    (h) Brown
    (i) Black
    (j) White
5. Do you have any visual impairments? Check all that apply.
    (a) No
    (b) Single vision prescriptions (near-sighted, far-sighted, astigmatism)
    (c) Cataracts
    (d) Color-blindness
    (e) Blindness

6. Based on your response on the previous question, rank the severity of your visual impairment(s):
   (a) Light
   (b) Moderate
   (c) Severe
   (d) N/A
7. Prior to COVID-19 social-distancing regulations, how often do you walk outside in public roads with vehicle traffic?
   (a) Multiple times a day
   (b) Once a day
   (c) Every few days
   (d) Once a week
   (e) Less than once a week
8. How often do you look at your phone when walking across the street?
   (a) Frequently
   (b) Rarely
   (c) Never
9. How often do you jaywalk?
   (a) Frequently
   (b) Rarely
   (c) Never

10. How often do you drive in urban settings with intersections? An urban setting includes: cities, towns, suburbs.
    (a) Daily
    (b) Weekly
    (c) Monthly
    (d) Yearly
    (e) Never
11. When driving, do you ever use cruise control?
    (a) Yes
    (b) No
    (c) I do not drive
12. Rank your knowledge on autonomous vehicles
    (a) Don't know
    (b) I have heard of autonomous vehicles but don't know what they really are
    (c) I have a basic understanding of autonomous vehicles
    (d) I understand their performance on a broad level but don't know how they technically work
    (e) I fully understand the high level performance and technical details of autonomous vehicles
13. Please list three words that best describe your feelings towards autonomous vehicles.

14. Would you take a ride in an autonomous vehicle?

    (a) No, never

    (b) Only if it is absolutely necessary

    (c) Only if I had the ability to take over and drive the car at any time

    (d) Maybe eventually when the technology has evolved more and it is safer to do so

    (e) I would prefer to regularly ride in autonomous vehicles

15. Rank your trust in autonomous vehicles

    (a) I do not trust autonomous vehicles at all. They should not exist

    (b) Autonomous vehicles are not safe on public streets but I would take a ride in a controlled environment if I had the ability to take over the driving if needed

    (c) I am indifferent

    (d) I believe autonomous vehicles are safe on public streets and would take a ride in one

    (e) Autonomous vehicles are entirely trustworthy and safe for both passengers and pedestrians

16. In your opinion, what factors would make you trust an autonomous vehicle more?

17. When will autonomous vehicles be on public roads?

    (a) They already are

    (b) This year (2021)

    (c) Within the next few years

    (d) Within the next decade

    (e) Within the next few decades

    (f) Within the next century

    (g) Never

18. Do you have any suggestions on how to improve the autonomous vehicle?

Appendix C

INTERVIEW SCRIPT AND QUESTIONS

The following questions are extracted as an example research interview given the pseudo-randomization of questions used for a portion of this study. This does not include the survey questions that are in fulfillment of the primary part of this study. The interview script remained constant and independent of the randomized question arrangement options.

Randomized question arrangement option G of A through I:

Interview script:

Thank you for taking the time to participate in this research study today. My name is Sandra. I am a graduate student in the Department of Electrical Engineering at Cal Poly and I will be conducting today's interview session with you. *After checking that the informed consent form has been signed and emailed back to the researcher.* I would like to confirm that I have received your signed informed consent form and am looking forward to taking part in this interview with you.

Today I will be asking you a series of questions. Each question will have a visual aid in the form of a picture or video which will correspond to the question asked. There may be flashing lights in these videos. There is minimal risk associated with these questions. This Zoom meeting is not being recorded to maintain your privacy but your responses may be stored in accordance to your signed informed consent form.

Please ensure that your phone is silenced and that you are in a room with minimal distractions from others or pets. This interview should take approximately 10 minutes but you are free to take as much time as you need. As a reminder, this interview is entirely voluntary. Please note that you can stop this interview and research study at any time for any reason. You may also skip any question during this interview.

Your time and effort is greatly appreciated and your responses today may provide further insights into how we can better design cars and traffic communication systems. Before we begin, do you have any questions? *Answer any questions the participant may have.*

If there are no further questions, we can begin.

1. What colors make you feel happy in this image?

Figure C.1: Potthast: *Happy Days* [13]

2. What colors make you feel sad, scared, or any other negative emotions in this image?

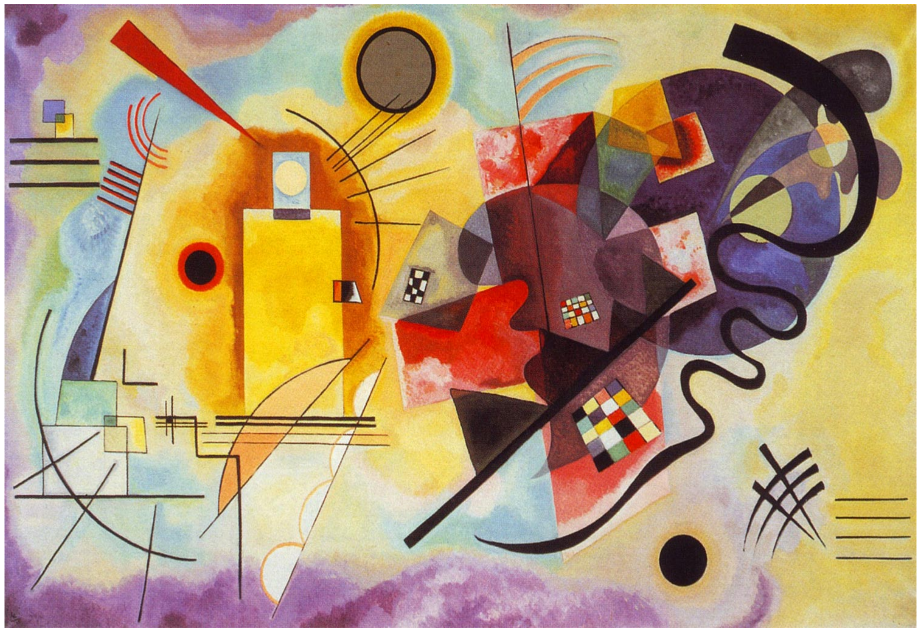

Figure C.2: Kandinsky: *Yellow-Red-Blue* [11]

3. This video will be played once. *play video*

   Link to video here: https://youtu.be/v2bawjl39xI

   (a) In the previous video, which color(s) were present?

   (b) In the previous video, which color(s) did not appear?

4. What colors make you feel sad, scared, or any other negative emotions in this image?

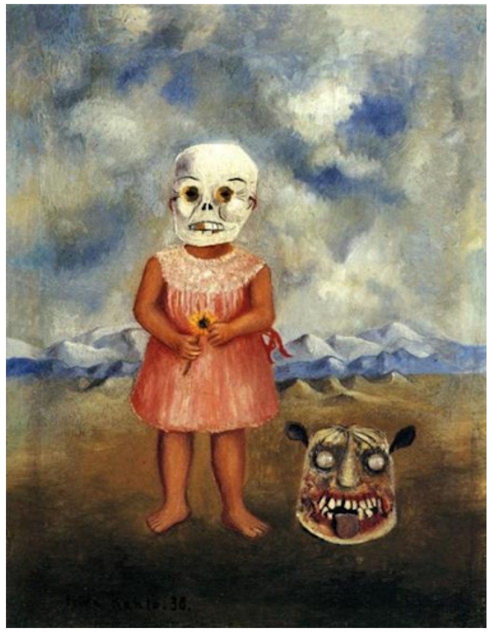

Figure C.3: Kahlo: *Girl with Death Mask* [12]

5. What colors make you feel sad, scared, or any other negative emotions in this image?

Figure C.4: Potthast: *Happy Days* [13]

6. This video will be played once. *play video*

   Link to video here: https://youtu.be/ZZOGeDn4phE

   (a) In the previous video, which color(s) were present?

   (b) In the previous video, which color(s) did not appear?

7. What colors make you feel happy in this image?

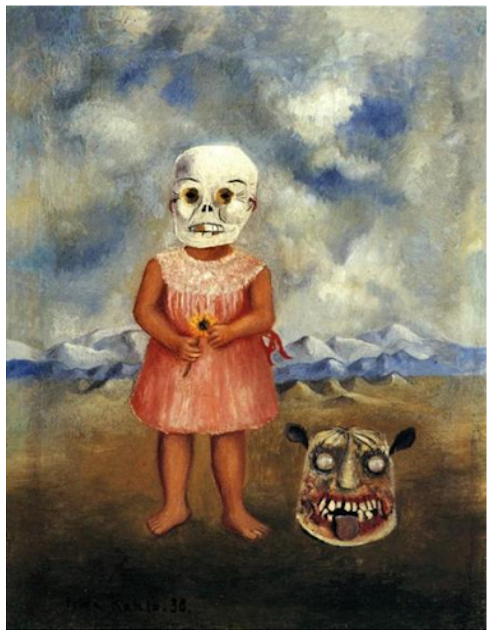

Figure C.5: Khalo: *Girl with Death Mask* [12]

8. What colors make you feel happy in this image?

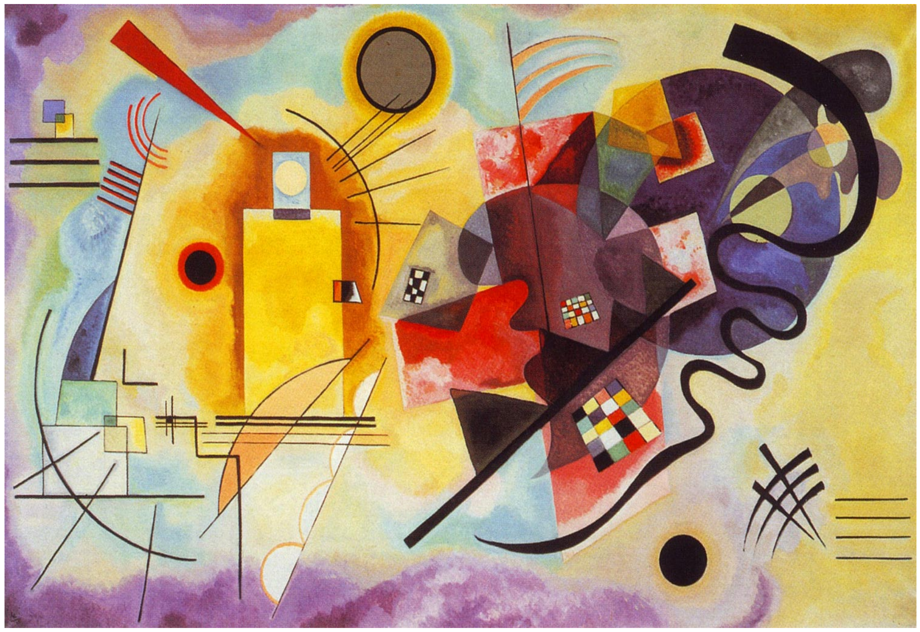

Figure C.6: Kandinsky: *Yellow-Red-Blue* [11]

9. There are two questions regarding this final image.

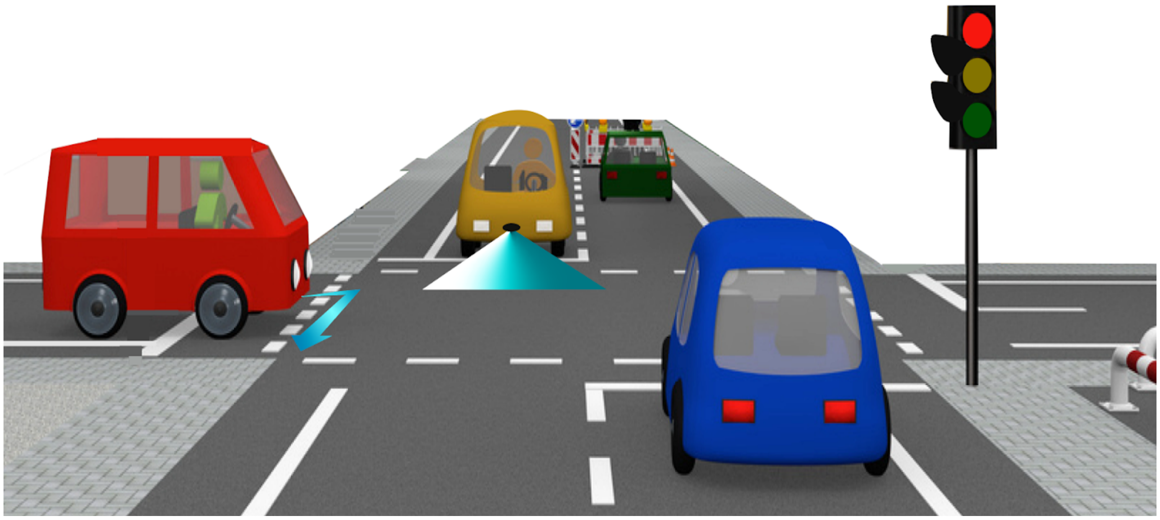

Figure C.7: An urban traffic scenario in which two different autonomous vehicles are projecting visual indicators onto the street to communicate their next intended directional path.

(a) With respect to itself, what direction is the red car going to go next?

(b) With respect to itself, what direction is the yellow car going to go next?

This concludes our interview session. Thank you again for your time and active participation in this research study. It has been an honor to take part in this with you. As a reminder, your name will not be linked to any of your responses today and your privacy is secured and maintained in accordance to the informed consent form. If you are interested in getting a copy of the key findings and conclusions from this study once it is finalized or if you have any follow-up questions from today's interview please email the experimenter. Thank you again and I hope you have a great rest of your day.

Note: All contact information and dates have been excluded from this script in an effort to maintain experimenter and participant privacy. Proper contact information and necessary dates were provided to each participant