

CARNEGIE MELLON UNIVERSITY

School of Architecture
College of Fine Arts

Thesis

Submitted in Partial Fulfillment of the requirements for the degree of

Master of Science in Computational Design

TITLE:

Pedestrian Futures

A VR and Biometric Simulation Framework to Explore Pedestrian
and Autonomous-Vehicles Interaction

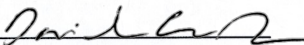
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Atefeh Mahdavi Goloujeh

Abstract

As autonomous vehicles enter the stage as a new form of transportation, researchers have developed theories and systems to understand their impact on cities. Autonomous Intersection Management (AIM), for example, rethinks urban intersection control systems when human drivers are replaced by autonomous driving agents. However, pedestrians are often ignored or insufficiently addressed in such systems. The main criteria for evaluating the success or failure of these systems are quantitative metrics such as speed of traffic. But, are these simulation platforms sufficient to represent the complex interactions of pedestrians in cities? This thesis takes a pedestrian-centered approach to this problem. The goal is to computationally identify and simulate the interaction between human and AV and propose a framework in which pedestrian experience in urban life can be studied. What I look for in this thesis is taking a new approach to explore and simulate pedestrians' experiences in urban environments.

I introduce an immersive experimental framework in Virtual Reality incorporating EEG scanners to identify how an individual interacts with autonomous vehicles in five different urban scenarios. My study investigates how our understanding of pedestrian's reactions such as excitement, stress, or concentration in conjunction with a qualitative study can foster a deeper understanding of (and design insight about) the new urban environments emerging in the age of autonomous technologies.

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1 Introduction

1.1 Research Area

The beginning of simulation models and tools can be traced back to eighty years ago in annual Meeting of the Highway Research Board in which Bruce Greenshields presented the first traffic flow model (Van Femke, Hoogendoorn, Vuik, & Lint, 2015). Since then different research groups began to develop models and software to simulate traffic (Lieberman, 2015). The purpose of simulation is mainly testing assumptions in a low-cost, low-risk environment (Duzevik, 2017).

Simulation of traffic was limited to vehicles at the beginning but simulation of pedestrians also received attention in recent years. Pedestrians are as important as vehicles in traffic simulations, if not more so. Even though years ago vehicles were considered as intruders in cities, it is now clear that these two entities (human and cars) have inseparable relations in real world. Accurate models of interaction between vehicles and pedestrians in transportation networks can inform the decision-making process in traffic safety and future development of urban environments (Chao, Deng, & Jin, 2008). In most cases, pedestrian movements' analyses are limited to "either route choice/activity scheduling models or crowd/evacuation models (Papadimitriou, Yannis, & Golias, 2009)."

1.2 What is the problem?

Pedestrian's movement models need to incorporate pedestrians' activity agenda, and their interaction with each other and their surrounding environment. Researchers have modeled pedestrians' activity as decision-making process consisting of several steps in which they perceive and evaluate the environment, come up with the best strategy and then act accordingly. However, pedestrian's movements do not only depend on a stimulus but also human factors and individual differences (Papadimitriou et al., 2009). In addition to that, vehicles are normally distributed along fixed paths in the environments, though pedestrian's movements are unique and "characterized by a significant degree of randomness. Consequently, pedestrians' behavior may be far more flexible and adaptable than motorists' (Papadimitriou et al., 2009)."

Two primary methods in traffic simulation are Macroscopic and Microscopic which differ in the degree of resolution. Macroscopic models use less-detailed models and represent the traffic as comprehensible fluid (Hueper et al., 2009). For example, assessing whether a transport system can handle the predicted passenger volumes in peak period (Mott & Beller, 2017). Studying pedestrians as groups and crowd in macroscopic simulations is primarily based on "traffic flow or queuing theory, or in fluid or continuum mechanic" which may result in losing details of the human behavior and thus over-simplification. In contrary, Microscopic models focus on the dynamics of individual entities (e.g. agent-based, social force models, cellular automata, multi-agent simulations) (Hueper et al., 2009). Looking at the same example mentioned above, microscopic models represent movements in a transfer station like the number of passengers currently waiting at the station for the train (Mott & Beller, 2017). Each agent behaves based on a set of rules that were derived from

observations or assumptions. However, there is always a certain level of abstraction in such models and the goal is mainly observing emergent behaviors among agents.

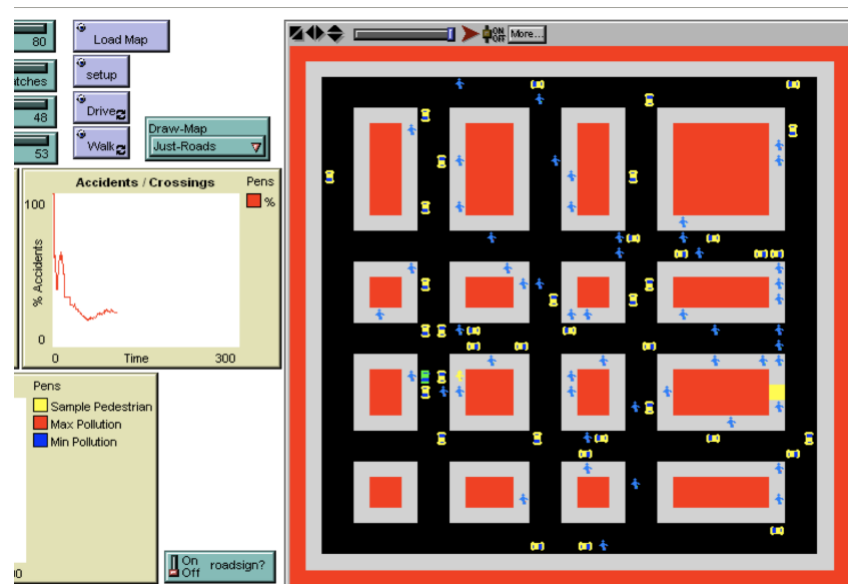


Figure 1 Net Logo interface, one of the popular simulation platforms

Additionally, current simulation models are based on previous studies on pedestrian behaviors in familiar situations. The question that can be raised is: What if we want to collect data through simulating specific conditions in urban environment which has not already happened or rarely happens? Autonomous vehicles are beginning to emerge as new forms of transportation in cities and the interaction between pedestrian and these cars is a not a previously identified situation in simulation models. Different research projects (which I explain in more details in the second chapter) are developing ideas for taking advantage of these cars for cities in near future. The primary tool for validating these new systems and scenarios are current simulation methods; however, these simulations are mostly focused on the efficiency of traffic flows and not the individual human experience. Thus, the main issues that I have identified in the aforementioned simulation models are:

- 1) Pedestrians are either not being considered and addressed or their behavior is assumed to be similar to vehicles. Specifically, in transportation simulations, pedestrians are mostly points moving on the screen, but do these simulations resemble the actual reality.
- 2) There is not much data available regarding pedestrians' behavior toward Autonomous vehicles.
- 3) Simulations are goal-based, meaning if the pedestrians satisfy a specific purpose (getting from point A to B) the simulation is successful. However, their struggles, fears and uncomfortable situations are being ignored.
- 4) As of yet, little is known about the pedestrians' reactions toward AV s mainly due to methodological challenges in obtaining empirical data about pedestrian interaction with autonomous vehicles.

5) Real people who inhabit cities cannot be strictly predicted, and are not merely the numbers and objects which appear in the initial simulation results, calculations or behavioral models (Vince, 2000). On the other hand, the ambiguity of human language may not be able to adequately represent the results (Atieno, 2009).

Based on the reasons mentioned above, a pedestrian-centered approach to the pedestrian simulation seems necessary.

1.3 Research Questions

My research questions are:

- In the wake of autonomous transportation, are we equipped with proper frameworks by which we learn their mode of interaction?
- How will the autonomous vehicles affect the pedestrian experience in urban environments?

2 Background

2.1 Historical Shift

Not many years ago, to the average city dweller, a city which is built around cars carrying groups of people, would not have been imaginable. Streets had been places for cars, horses and pedestrians but also “as playgrounds and gathering places”, says Brandon Keim in his article on *Did Cars Save Our Cities from Horses?* (2013). The traffic was moving only as fast as horses, and cars “had to compete with the many social and commercial functions of the city.” The modern idea of what we perceive as a street would have been unfamiliar (Wells, 2012).

Having such perception (streets are not for cars) would have caused many people to see motor vehicles as dangerous intruders. Consequently, blame for accidents was laid on drivers entirely and movements suggested that cars shouldn’t go faster than 25 miles per hour (Keim, 2013). Peter Norton in his book, *Fighting Traffic: The Dawn of the Motor Age in the American City* says “Today we learn that streets are for cars. That’s 100 percent opposed to the dominant view a century ago, ... It’s a different mental model of what a street is for (Keim, 2013; Norton, 2008)”

During the 1910s, many groups and syndicates including car dealers, manufacturers, associations of wealthy car owners and even motorists united as one group to promote a new model for streets in that way they can popularize cars. They started their campaign by informing people that for now on streets belong to cars and not pedestrians, teaching how residents should take safety measures when they want to cross the streets and etc. They went further by disparaging those people who didn’t respect this new model by labeling them a “jaywalker”. Actually, the modern use of the term “jaywalking,” which originally referred to rural visitors walking obliviously in big-city streets, dates to this propaganda campaign. The proponents of this new model found that the best way to discredit the streets-are-for-walking crowd was to make them look uncool (Keim, 2013).

As discussed above automobiles transformed cities. Since then, several movements began to react to the transformation. Many appreciated the presence of cars in cities and others started to fight for pedestrians’ rights. Architects, urban designer and urban planners took positions on this matter stating different opinions regarding how a street should look like and how future cities should be built in the age of the automobile.



Figure 2 Screenshot of a video from San Francisco in 1906 showing carriages, cars and pedestrian, source: https://www.youtube.com/watch?v=pEvB_ZIWtAg

Prominent architects even stepped further by depicting how a futuristic city should look like. Featuring in Popular Science Monthly magazine in August 1925, American architect Harvey W. Corbett described a city in 1950. He envisioned a layered urban landscape with four separate street levels for pedestrians, slow traffic, fast traffic, and underground trains. Three years earlier, Le Corbusier, a famous Swiss architect, proposed a similar city for the contemporary era. A city with a network of elevated highways with large green areas for pedestrians (Martinez, 2014).

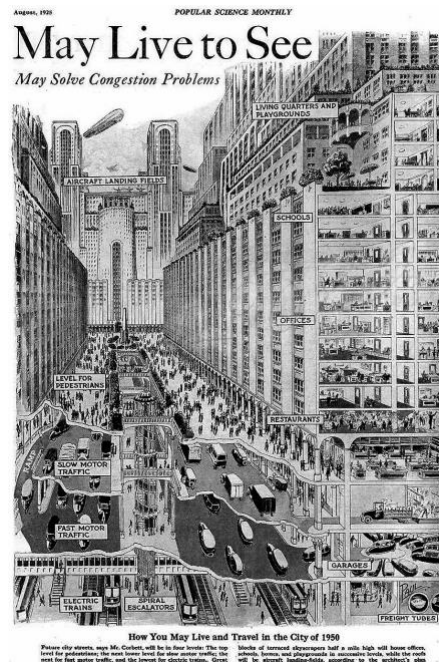


Figure 3 Corbett's idea of the future city published in Popular Science Monthly magazine

Le Corbusier, in his book *Four Routs* (1947) mentions that pedestrians are keeping cars reach to their true purpose of existence.

“We are faced with a major requirement of the machine age: the fate of the motor car must be decided. The present situation, in which pedestrian and cars are all tied up together, must go, once for all. Automobiles and

pedestrians must be kept apart... The present crossways are ridiculously close together: at every 60, 90, 120, 150 feet; rarely at 500. The normal pace of the foot-passenger or horse accounted for this arrangement, but for the automobile it is deadly. Such roads have indeed become a permanent menace to the very raison d'être of the car, which is speed (Le Corbusier, 1947)."

Architects of early 20th century including Corbett and Le Corbusier had this idea that one of the indispensable features of modern urban planning is physical separation of pedestrian and automotive traffic. But this peaceful coexistence of pedestrians and mechanical traffic in which each group commute in their own sphere of urban space, was not successful. Forcing pedestrians and vehicles ("with vehicles overwhelmingly winning the battle") to constantly compete over streets revealed that this idea was a failure (Martinez, 2014).

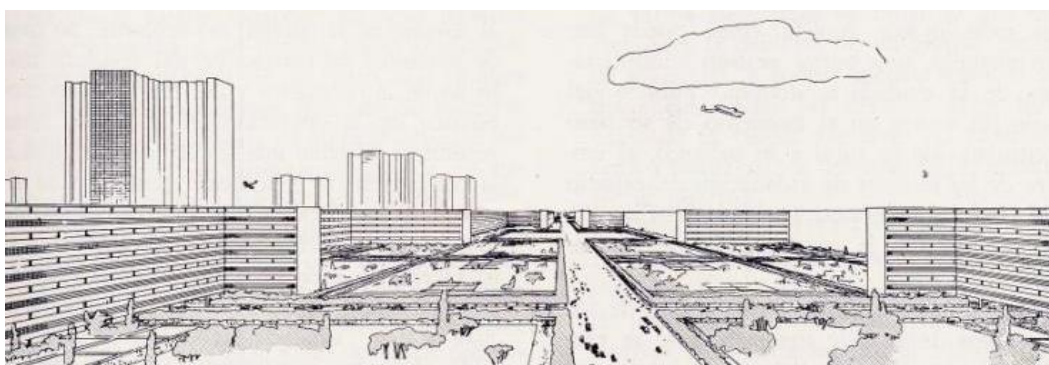


Figure 4 Le Corbusier's contemporary city 1992, source: <https://proyectos4etsa.wordpress.com/2013/07/02/6438/>

2.2 Driverless Cars

Building upon the discussion before there has been a shift in the meaning of street and its role as a place for pedestrians and possible communal activities to an artery for vehicles to pass. The shift happened based on the technological changes.

The idea of having a car which drives all by itself was very fascinating and it was only possible in Sci-fi; however, they are not fiction anymore. Admittedly, they are still in early stages of testing and they are not entirely ready to be used freely around cities. The undeniable fact now is many companies are working on the technology for Autonomous Vehicles¹ and many are testing their cars to prepare them

¹ According SAE International, an automotive standardization body, classifies autonomous vehicles into six different levels as follows (SAE, 2015):

- Level 0 — No automation: the driver is in control of the vehicle and responds to the automated systems in the vehicle.
- Level 1 — Driver assistance: the automated system and the driver share the driving responsibility. The driver is expected to take full control of the vehicle at any moment.

for actual road tests in the cities. A valid question could be: are city dwellers ready for these cars to come to the cities and among many ongoing studies are there any to show how pedestrians would respond to these changes?

On September 2016 Uber launched its fleet of 100 driverless cars in the city of Pittsburgh. Cecilia Kang in her article at New York Times on September 2016 announcing this news claimed that nothing much had been done to prepare the city for this change. According to New York Times “There have been no public service announcements or demonstrations of the technology. Except for the mayor and one police official, no other top city leader has seen a self-driving Uber vehicle operate up close (KANG, 2016).”



Figure 5 Uber's accident in Temple, Arizona which caused the death of 49 years old passenger Source:

<http://www.scmp.com/news/world/united-states-canada/article/2137938/woman-dies-arizona-after-being-hit-uber-self-driving>

-
- Level 2 — Partial automation: the system takes full control of the vehicle operation. The driver must monitor the driving at all times and be prepared to take control of the vehicle.
 - Level 3 — Conditional automation: The driver can disengage from driving tasks and the vehicle will inform the driver to take over the driving control in some limited time.
 - Level 4 — High automation: vehicles operate autonomously for entire trips and driver attention is not required. Human assistance is supported only in specific circumstances.
 - Level 5 — Full automation: fully autonomous system where the vehicle's performance is equal to human driver in any driving scenario. No driver assistance is required at any stage of the vehicle operation.

In this research, ‘driverless vehicles’ and ‘fully autonomous vehicles’ refer to Level 5 autonomous vehicles where a human is not required in the driving loop of the vehicle.

On March 18, an Uber SUV hit a 49-year-old passenger who was walking out of the pedestrian walkways which resulted in her death. Since the incident, Uber halted the self-driving study and NTSB² is investigating. The technical side of this incident should be carefully reviewed; however, the technical issues and the backup driver's careless behavior are not the only important factors to look at. The pedestrians' knowledge about self-driving cars, their possible reaction to such behavior from the car is also critical to study. Moreover, there was no way for the pedestrian if she noticed the car at all, to tell if the car was going to stop. The need for studying the pedestrians' view of this interaction is becoming apparent.



Figure 6 Screenshot of the YouTube video showing the accident

Autonomous Intersection Management (AIM) rethinks urban intersection control systems if human drivers were to be replaced by autonomous driving agents. According to Dresner and Stone (2008), when a vehicle approaches the intersection, a reservation request will be made by the agent, “which includes parameters such as time of arrival, velocity of arrival, as well as vehicle characteristics like size

² National Transportation Safety Board

and acceleration/deceleration capabilities”, to the intersection manager. Based on pre-determined policy, the intersection manager then passes this information, which determines if it is safe to let the vehicle cross the intersection or not. “If the policy deems it to be safe, the intersection manager responds to the driver agent with a message indicating the reservation has been accepted and including any supplemental restrictions the driver must observe in order to guarantee the safety of the traversal. Otherwise, the intersection manager sends a message indicating that the reservation request has been rejected, possibly including the grounds for rejection (Dresner & Stone, 2008).”

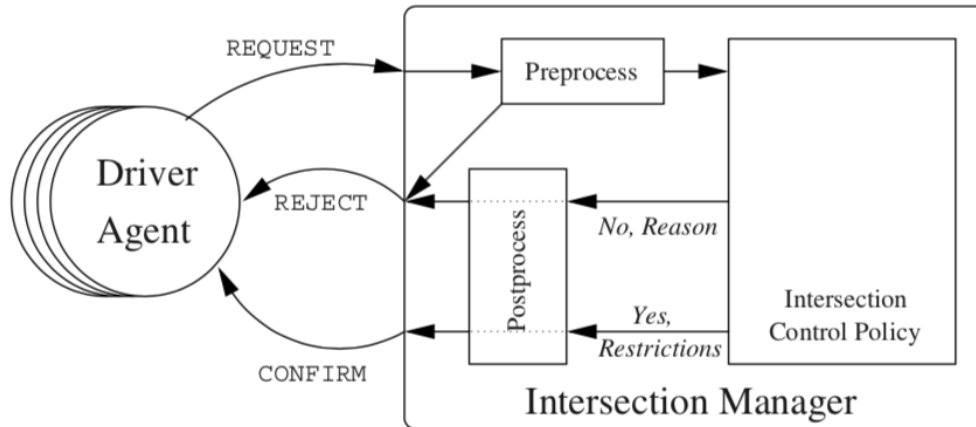


Figure 7 The procedure of making a reservation by driver agents, derived from A Multiagent Approach to Autonomous Intersection Management(Dresner & Stone, 2008)

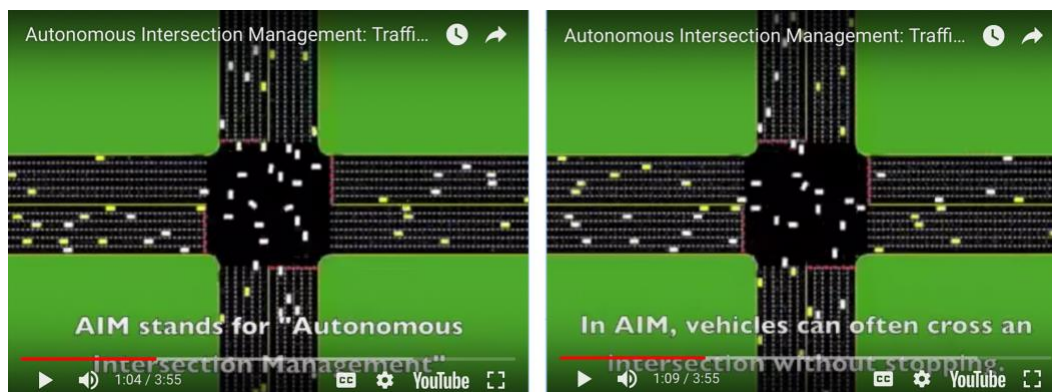


Figure 8 Screenshots from the project's video on YouTube, source:
https://www.youtube.com/watch?time_continue=69&v=4pbAI40dK0A

MIT's Senseable City Lab introduced Slot-based systems on 2016, which follows the same approach, derived from a commonly used approach in aerial traffic. (Remi Tachet et al., 2016)

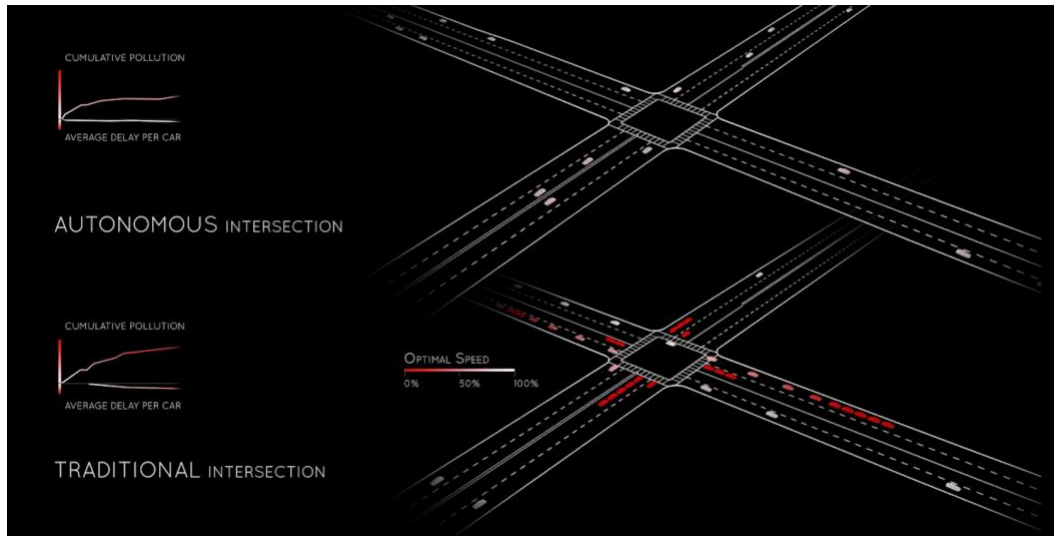


Figure 9 Screenshot from the project's video, Source: <http://senseable.mit.edu/light-traffic/>

The main idea is to imagine the most efficient way to let the cars pass the intersection and minimize their stop time or avoid stops if possible. Such systems envision that there are no traffic lights in intersections.

2.3 Precedents

With all the advancements in computer graphics and specifically virtual environments, these environments became one of the best ways to replicate and simulate the reality for different purposes. There are many cases that Virtual Reality (VR) tools have been used to better simulate traffic conditions creating a situation that is closer to reality for participants (Patterson, Darbani, Rezaei, Zacharias, & Yazdizadeh, 2017). Since participants can develop realistic spatial knowledge in the VR environment that is similar to actual physical environments, behavioral and safety studies will have more reliable and extensive results given (Sobhani, Farooq, & Zhong, 2017). Using human subjects in simulation will provide a more accurate result in comparison to agent-based or social forces simulations. Even though these simulations study different aspects of human behavior in their models, the process of human decision making is so complicated that any model would need to simplify it to some extent. By using human subjects instead of agents, we can also include real human differences such as social or cultural differences which are often ignored in other methods of simulation.

2.3.1 Virtual Reality based Study to Analyze Pedestrian attitude towards Autonomous Vehicles, Anantha Pillai (2017), Aalto University

This thesis is exploring the pedestrian attitudes towards Autonomous Vehicles in virtual reality. The author is looking for “How does lack of a human driver in a vehicle, influence pedestrians' interpretation of vehicle behavior under different visibility conditions?” The author believes that the

process of pedestrians crossing the street heavily relies on the eye-contact and body language that does not exist in the case of autonomous vehicles. Two environmental factors and three vehicle behaviors were experimented in this thesis. Three different vehicle behaviors were three different acceleration toward the pedestrian (Pillai & Virtual, 2017).



Figure 10 Two weather conditions were tested in this research, source: Anantha Pillai (2017)

There are five methods of analysis after collecting the data. Video recordings, VR situated recordings, semi-structured interviews, sketches on a whiteboard and Post-experiment semi-structured interviews. Based on the results of this research different vehicle accelerations, weather conditions, age, cultural differences were essential factors determining the difficulty of the process (Pillai & Virtual, 2017).

This research is a good starting point for VR simulations with human subjects. This research was published less than a year ago (October 2017) which reveals that current researchers are looking into the impacts of autonomous vehicles on pedestrians' life. However, this research is focused only on the weather conditions for generating different scenarios. Experimenting with more than one car will add more complexity to the experiment and will make the scenario more realistic because in urban environments we usually do not interact with only one car from one direction. Another important factor is the results are only based on the participants' responses and there are no other tools to measure their experience quantitatively.

2.3.2 Ghost Driver: A Field Study Investigating the Interaction Between Pedestrians and Driverless Vehicles

This research developed an innovative method to overcome limitations of conducting pedestrians and autonomous vehicles interactions. Their method involves field experiments to discover the interactions with driverless cars. They customized a car seat to conceal the driver in order to deceive people that the car is driverless. The driver was instructed to drive in a way to emulate autonomous system.

They observed 67 people and 30 people accepted to participate in the survey. The survey results can be subject to selection bias because people with a positive attitude towards the car are more likely to participate. Moreover, field experiments are less controlled because of the infinite factors that can affect the reaction of pedestrians (Rothenbucher, Li, Sirkin, Mok, & Ju, 2016).



Figure 11 Customized seat to conceal the driver, source: (Rothenbucher et al., 2016)

2.3.3 BikePGH

BikePGH is a non-profit organization which advocates within communities for bikeable/livable cities. On March 2017, BikePGH published the results of their survey, asking participants about “how they feel about being a fellow road user with AVs, either walking or biking.” They conducted the survey in two parts: BikePGH members and public and they 1119 responses in total. Figure 10 shows that less than 50% of the participants didn’t have any prior interaction with autonomous vehicles or wasn’t sure if they had. This result is not surprising because the survey was conducted almost one year after the time that Uber launched its autonomous cars (Eric Boerer, 2017).

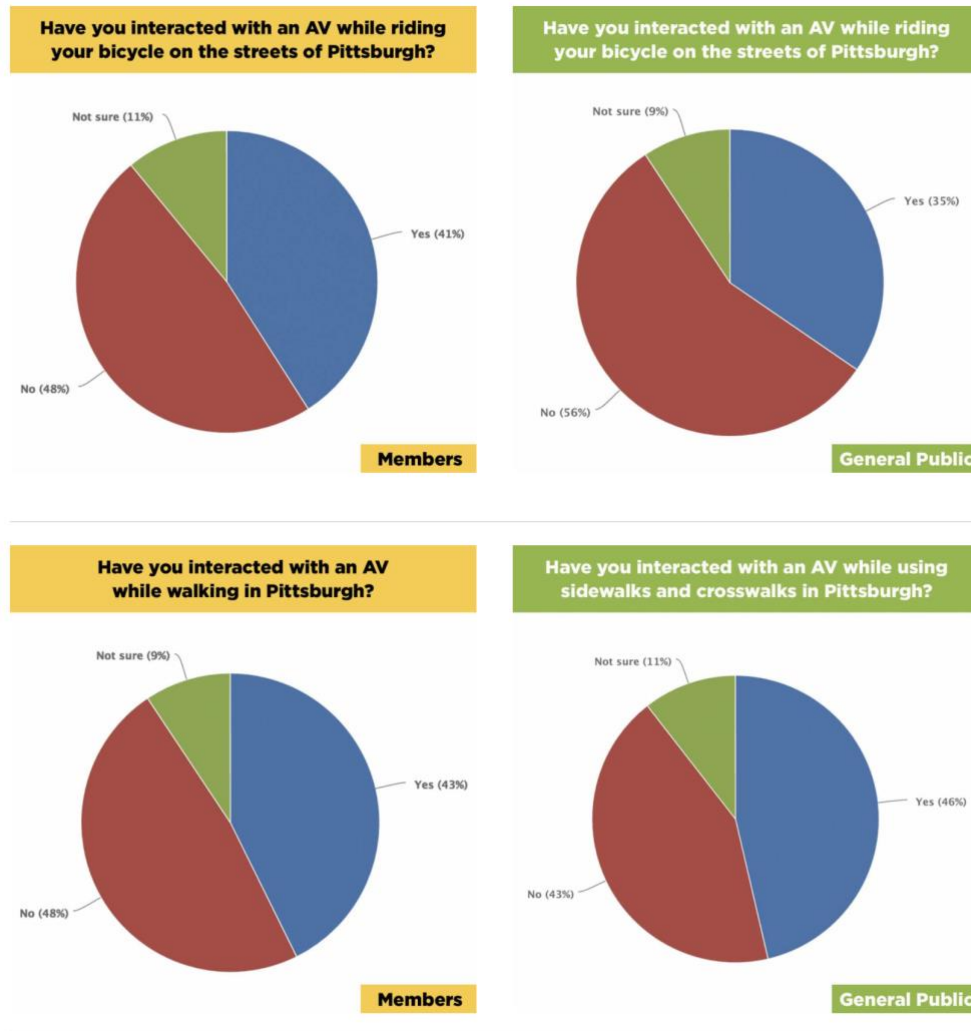


Figure 12 BikePGH results showing the percentage of participants who had prior interaction with autonomous vehicles, Source: <https://www.bikepg.org/our-work/advocacy/save/survey/>

Figure 12 illustrates the participants' feeling about Pittsburgh being the proving ground for autonomous vehicles. In contrast to AAA survey, BikePGH “only about 10% of those *with experience* sharing the road and 10% of those *without experience* sharing the road with AVs while riding a bicycle, disapprove of Pittsburgh as an AV test bed”. The results are revealing there is a positive opinion towards driverless cars in the Pittsburgh community, even though many didn't have any and the rest had limited interactions with these cars. For participants who didn't have any interaction before, their judgment can be based on what they on media. Therefore, the results can be biased. Additionally, more than 60% of the participants believed AVs have the potential to reduce injuries and they considered them to be safer than human drivers. These opinions may or may not change after time, particularly after the Arizona incident (Eric Boerer, 2017).

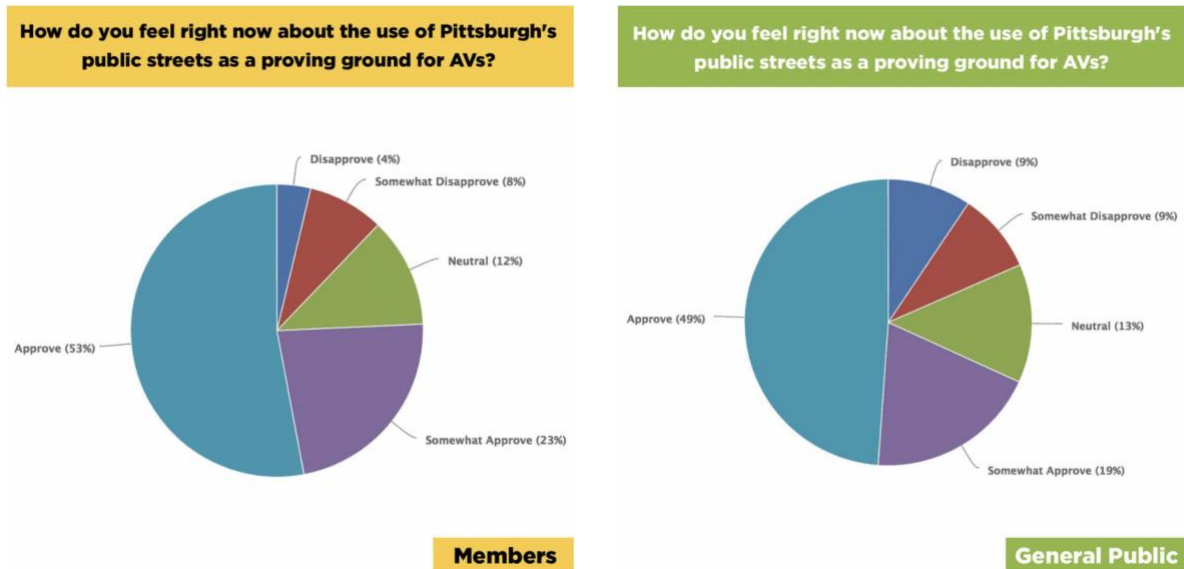


Figure 13 Charts showing the results of participants' feeling about testing autonomous vehicles in the streets of Pittsburgh. Source: <https://www.bikepgh.org/our-work/advocacy/save/survey/>

Overall this survey and similar ones have more penetration in the communities' due to the more straightforward process of obtaining the data in comparison to other methods. So, they are revealing the opinion of a bigger portion of the society. However, it is important to keep in mind many of these participants never interacted with an AV or their interaction was limited or they might not be able to clearly remember the experience. Therefore, their response may be biased based on what they see in the media or their assumptions.

2.4 Hypothesis

I premise that human experience in urban life is not goal-based and there are more factors involved in this experience. I hypothesize that having a simulation platform which is more focused on the quality of human experience rather than their purpose or goal of their movements can reveal more information about the quality of pedestrian experience in urban settings. Such simulation framework can also be used as a tool for collecting empirical data in less obvious or safe situations. I suppose measuring human reactions such as excitement, fear or concentration in conjunction with a qualitative study can help reveal a more comprehensive understanding of the human perception toward vehicles in the urban environment.

2.5 Goals

My goals in this research are:

- To create a framework in which actual human participants can explore different types of questions in urban setting.
- To computationally identify the interactions between human and Autonomous vehicles.
- To propose a framework to collect empirical data about pedestrian behavior toward autonomous vehicles

3 Methods

3.1 Methodology Overview

In this research, I am proposing a framework to collect data from pedestrians regarding their experience with autonomous vehicles. Since studying human behavior is often very complex and there are always aspects that are missing, I integrated Human Computer Interaction and Game User research methods to build a comprehensive understanding of the pedestrians. To do so, I am taking the following steps:

Experimental Research: I will conduct an experiment to collect empirical data about pedestrian's interaction with autonomous vehicles in controlled settings. The experimental method is one of the primary methodologies of various disciplines and of course Human-computer Interaction. The main purpose of this technique is "*To Collect Data and Build Scientific Knowledge*" (Olson, 2014).

Observations: I will observe the participants behavior through the experiment. Because moderating the session can get overwhelming, I will not do the observation during the experiment. The observation happens in two different levels:

- Audio and Video Recording the experiment environment for further review and analysis based on the metrics in the experiment
- Recording the virtual environment during the experiment to map the EEG results and check the participants' behavior based on the experiment analysis criteria

Biometric measures: Although observations and experimental research provide useful data for estimating the pedestrian behavior, they do not reveal much about the emotions experienced by the pedestrian during the experiment. One might argue that observations and body language can show emotions and this is very true. However, I cannot solely rely on that because determining the emotions based on observations is based on observer's interpretation of the behavior and also some participants might not to express their emotions in a self-evident way. Therefore, though I believe observations can provide beneficial and important information for me, complementing this information with a biometric method can show what is the participants actual experience to a great extent.

"Emotional signals equate to observable changes in the state of the human player, and are indicated by facial expressions, body posture, and physiological changes in the player's body. Physiological metrics consist of data representing the signals our body produces when it is in varying states of arousal or excitement, or when we experience emotions or mental activity (Drachen, Mirza-Babaei, & Nacke, 2018)."

The main methods are electroencephalography (EEG), electromyography (EMG), and galvanic skin response (GSR) recording systems (Drachen et al., 2018). I will use electroencephalography (EEG) for my research because it allows me to infer details of emotions in real-time.

Surveys: Surveys can be used as safety measures to make sure data coming from EEG matches the self-reported results from participants.

3.2 Scope

What I am looking for in this thesis is taking a new approach to explore and simulate pedestrians' experiences in urban environments. I will particularly study the interaction between pedestrian and autonomous vehicle as an example to show how the prototype and experiment structure work. My intention is not to provide an in-depth analysis of the human behavior or EEG results but to illustrate the advantages of such system over what I call goal-based simulations. This thesis is not about replacing other simulation methods but to propose a new avenue for simulation as a way to understand the quality of human experience.

3.3 Preliminary Results

With the fellow computational design researcher, Scott Donaldson, I co-hosted a workshop titled “Reimagining Urban Intersections through Systems Thinking”. This workshop was a part of Computational Design: Practices, Histories, Infrastructures symposium held by Daniel Cardoso Llach at Carnegie Mellon University. We framed the workshop to address our specific research questions. Participants were three female Carnegie Mellon University Students (two undergraduate and one graduate) Who were participants of the Computational Design: Practices, Histories, Infrastructures symposium. Based on the survey which was given to participants before the workshop their main way of commute was either biking or walking.

3.3.1 Stage1- Negotiation



Figure 14 Participants negotiating their way in the urban intersection

In the first stage of the workshop we created an abstracted urban intersection using teardrop cardboard pieces on the ground. This activity was designed to make the participants engaged in the workshop and make them think about the notion of negotiation³. Donaldson and I asked them to move in the intersection continuously assuming that participants are going to avoid collisions. We also asked them not to talk during the process to let them interact with non-verbal communication tools like body-language.

3.3.2 Stage2- Identification

Figure 15 Stage 2 in which participants came up with different influencing factors on urban intersections

³ The idea of negotiation by Hans Munderman suggests that if there were no traffic signs and stop signs vehicles and pedestrians would have learned to negotiate their way and be more responsible about the outcome of their actions in urban environment.

the workshop. Factors that participants decided to continue with were Smartphones, Accessibility, Regional habits and Signage.

3.3.3 Stage3- Imagination

We used Loopy⁴, an open source software to simulate the intersection in a macroscopic level (in contrast to the first stage) based the factors from last stage. Loopy is a high-level qualitative simulation to show the impacts of one factor on other ones and on the system as a whole. The process includes drawing circles as factors and connecting them to determine their relationship (e.g. predator and prey) (Donaldson, 2017).

Participants started by exploring the impacts of factors on each other and they ended up adding a sixth factor “safety” as the main goal for their simulation. They continued with revising the system in a way to minimize the problematic factors and maximizing safety. Some of the results seemed to be not desirable so they kept discussing and modifying the system to get a more stable and realistic result.

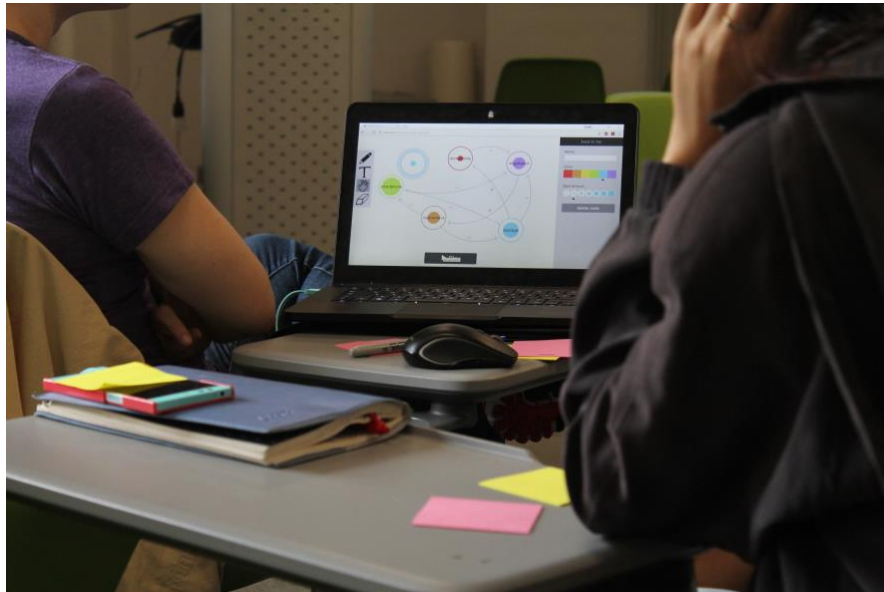


Figure 16 Using Loopy in stage 3, participants are observing the impact of different factors on each other

Stage4- Intervention

For the last stage of the workshop, we asked participants to propose design interventions based on their system. They had three ideas which they drew on the whiteboard. Their ideas were:

- Drawing people’s attention to the intersection

⁴ Case, Nicky. Loopy, <http://ncase.me/loopy>

- Finding the best path to cross
- Drawing driver's attention to pedestrian



Figure 17 Design interventions presented as storyboards

Findings

During the performance, we noticed that negotiation could happen without talking or even having eye contact with one another. There are certain types of body language which convey the path, direction or goal of a certain participant like “I am turning right” without explicitly saying it. It is essential to have proper set of tools to understand and determine other people’s intentions.

Based on our observations in the first activity participants could negotiate their way and kept moving with all the constraints we introduced. An important factor that we should consider for future workshops is to have a set of instructions or goals for each participant. That is, making arbitrary choices while moving makes it easier to negotiate, however, in real urban life all the people have sets of goals and they want to go on a specific path.

Participants came up with variety of factors which were mainly related to pedestrians. We think this could be a result of their personal interest for walking and using public transportation (Based on their responses in the survey). In the process of categorizing individual factors as a group one of the participants pointed out that cars look dangerous because there is no way for us to communicate. We can see a relation to what we explained earlier about the presence of proper tools to communicate can let people negotiate.

Design interventions proposed by participants could be classified in different categories. From one perspective, they came up with ideas that put the responsibility on the pedestrians as opposed to one in which they saw drivers as the responsible agents. All the design interventions proposed by participants were aiming for informing the users of the intersection (both pedestrians and drivers). They explored different variations of information and different ways in which intersection users could be informed.

3.4 Prototype

3.4.1 Workflow

Figure 18 illustrates the workflow of the prototype. A scenario will be modeled in Unity 3d to recreate a specific situation in virtual reality. User wears VR and EEG headsets at the same time and goes through the scenario. A camera records the real world and EEG records the electric signals of the participant's brain. Signals will be classified with an Emotion Assessment Algorithm to determine emotional state of the user through the process.

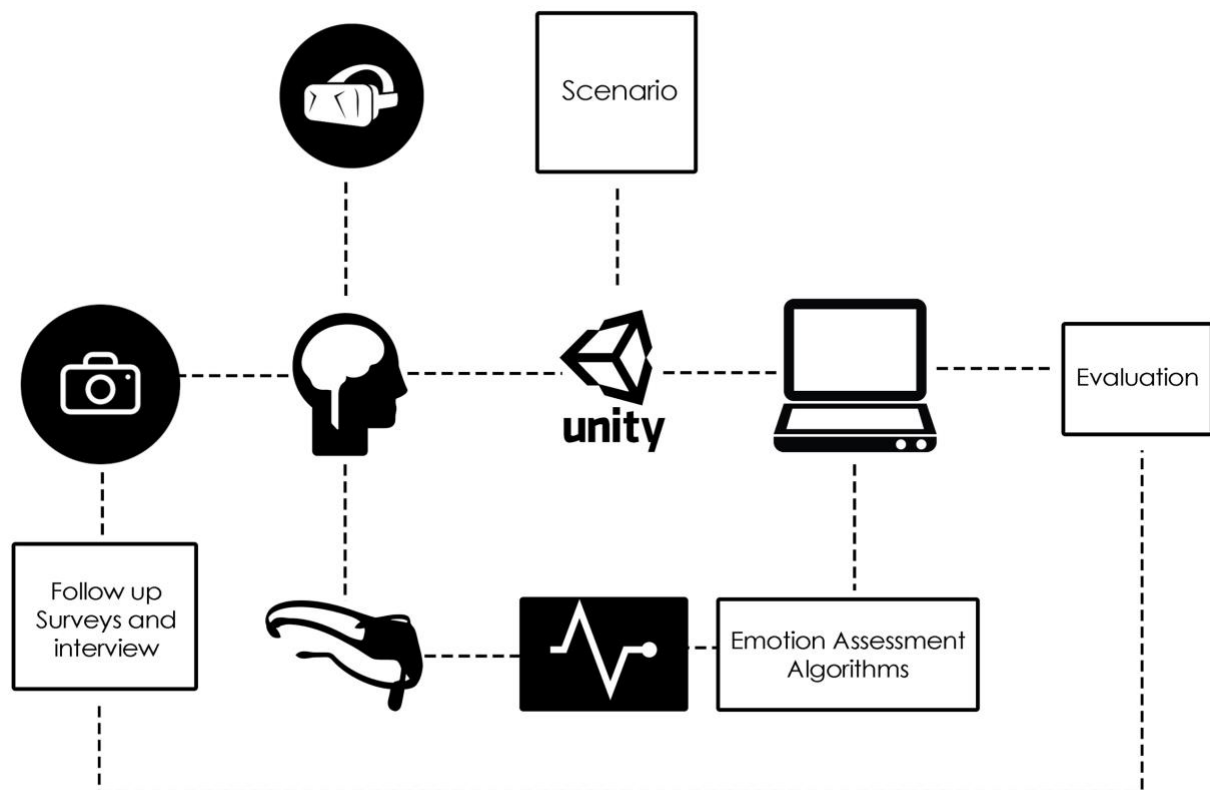


Figure 18 Diagram showing the workflow

3.4.2 Technology

There are different software and hardware components in the prototype. In this section, I briefly go over a general overview of the technology and the specifications.

- Virtual Reality

“Virtual reality is a term often used interchangeably for three different systems: “a virtual environment presented on a flat screen, a room-based system, or a head-mounted display

(HMD)⁵.” These systems seem to be very different; however, the common feature among them is the introduction of “stereoscopic depth” which lets the users to have the illusion of being in virtual space. Having a great control over many aspects of the environment like the appearance, stimulus representation in three dimensions and also the possibility of user input are the main advantages of virtual reality which led researchers to use VR as a research tool (Wilson & Soranzo, 2015).

Neuropsychological researchers, Rizzo et al. describe virtual environments as tool to create complex situations and stimulus conditions that would not be possible to be controlled in the real world and also allowing for both “cognitive processes (e.g., attention)” and “functional behaviors (e.g., planning and initiating a series of required actions)” examinations (Rizzo, Schultheis, Kerns, & Mateer, 2004; Wilson & Soranzo, 2015).

I used HTC Vive package for my VR prototype. HTC Vive is of the very popular options for people who are interested in virtual reality because of its fully immersive experience and Chaperone⁶ system which makes the user experience safer.

To set up the virtual environment. I used Unity 3D which is one of the main tools to produce virtual reality content, such as games. Most of the game developers rely on unity as their primary development tool. An excellent resource that comes with Unity is Unity Assets Store which included a significant number of previously developed assets and packages. These packages are helpful when there is a component of the project that needs specific knowledge.

- Electroencephalogram

Emotiv Insight EEG Headset is the Electroencephalogram device that I use to get the electrical activity of the brain. This EEG headset is a commercial product which is being produced and sold by Emotiv bioinformatics company. There are five channels to detect electrical brain activity which is not the most accurate option available, but it is the most affordable. Since the workflow is the same as other EEG headsets and the results were proved to be reliable (with a lower degree of accuracy), I decided to use this headset over the more expensive options (e.g. Emotive Epoc, Neurosky).

Emotiv Xavier Control Panel is the software which was developed by Emotiv Company to work with Emotiv headsets. The software enables the user to set up the headset and determine whether the signal quality is good, poor, bad or there is no signal at all. This software provides the user with four types of detection: mental commands, facial expressions, performance metrics, internal sensors.

⁵ Techopedia defines head-mounted display as a type of display that “is worn on the head or is built in as part of a helmet.” This type of display is very popular for a total immersion of the user in the virtual environment.

⁶ Showing the boundaries of real-world so that users can make sure they will not hit anything and the play area is safe.

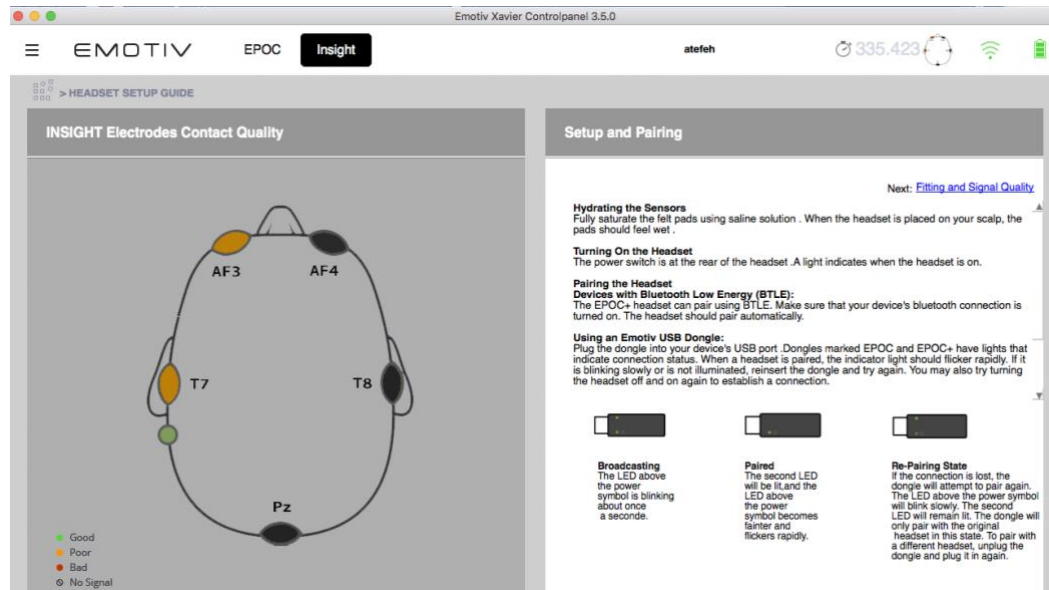


Figure 19 Setting up the Emotiv Insight headset

Cortex is Emotiv's API which lets the user communicate with the headset through web sockets. Although the API is not very well-documented, it is the only way of getting specific parameters that are not being provided by the Xavier Control Panel. Using Cortex API with Community SDK license enables the users to get the α , β , θ , γ and individual channels' values which are useful for further analysis.

3.4.3 Virtual Environment

The whole process consists of different steps: Setting up the urban environment, setting up the simulation in unity, setting up the cars and their movements, adjusting the camera and scale and adjust different tasks according to the experiment with Unity animation.

There are different approaches to setup urban environments. If certain environmental factors that needs to be included in the environment or the intersection needs to be an exact copy of a specific place, modeling is the best method. As an example, Urban Simulation Team at UCLA modeled 10,000 square miles of Los Angeles for their research purposes. There were certain limitations to this approach: First, getting all the necessary data to model a real urban environment was out of the scope of a master thesis and also seemed unnecessary. In addition to that, the similarity of virtual environment to actual places that people experience could have affected their behavior in the process. The other approach could be getting all the necessary separate components and build an urban environment. This is also a good approach for having specific environmental qualities that can be targeted in future research projects. The problem with this approach was introducing personal biases to the environment. Another approach is to use an urban environment from assets. In order to find a proper urban setting, I looked into Unity Asset Store which is a good source for pre-defined assets and building upon them.

I used Modern City Unity package by Ray Chezer from Unity Asset Store as my main environment because of the two main reasons. Because the environment itself can have a significant impact on the

participant's behavior I wanted a normal urban setting not to affect participants behavior. The environment was low-poly which is crucial in complicated and highly populated VR setups otherwise, there will be constant lags during the process.



Figure 20 Screenshot of the virtual environment

Testing the environment is one of the key steps in any VR. In order to be able to walk in the environment and test without wearing the Vive headsets I used Virtual Reality Toolkit. This toolkit works perfectly with steam VR and it covers several common solutions for building a virtual environment.

Setting up cars movement in the urban environment was the next step. I began with studying different methods of simulating car movements and implementing them. My first step was to write a script to make an object (e.g. car) move on a specific path in unity environment. I defined different nodes as simple targets in the unity environment which were connected by a visible line in unity and then made the car moved to these target points. I modified the code to make the car rotate when it was changing its direction but this attempt was a failure because of robot-like feeling that sudden rotations of the cars had. Observing the car movements made me realize that naturally simulating their behavior highly depends on physics and mechanics rules.

Then I decided to look for libraries to simulate cars movements based on physics and mechanic forces. There is a specific Unity Engine called Physics⁷ to handle physical simulation. There also several algorithms and libraries to simulate vehicles mostly for racing games in VR based on Physics engine. Unity Vehicles package is a package for creating realistic car movements which include physics and dynamic of the cars. Various parameters are involved in the car control algorithm like steer angle, speed, slip, brake torque, etc. This script is in charge of moving the car.



Figure 21 Using cubes to illustrate waypoints in each waypoint system

After setting up the basic movements I created a waypoint system to define specific targets for the cars. Waypoints are targets which can be visualized as game objects in unity and their connection will create a path. The default car in vehicle package was a race car, so I had to bring regular cars and adjust them with the library. Car models with separate wheels can be adjusted to the default car and library. Separate wheel colliders to create the effect of rotation in the play mode are necessary. They need to be adjusted to the new cars wheels position.

⁷ According to Unity documents description, to have convincing physical behavior, an object in a game must accelerate correctly and be affected by collisions, gravity and other forces. Unity's built-in physics engines provide components that handle the physical simulation for users. By controlling the physics from scripts, users can give an object the dynamics of a vehicle, a machine, or even a piece of fabric (Unity3D.com, n.d.)

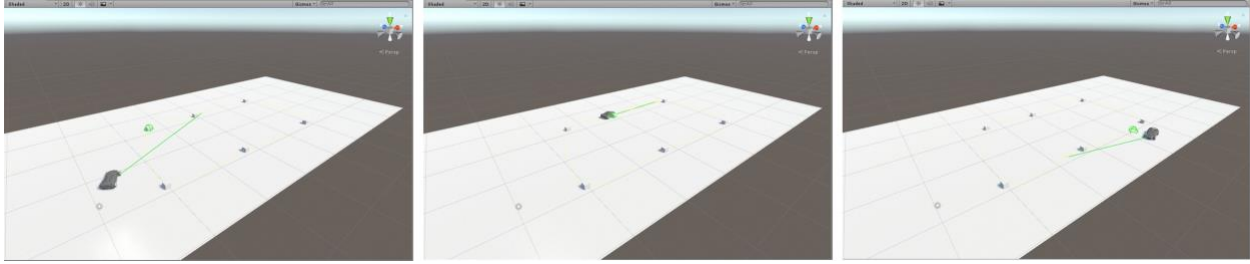


Figure 22 Car following a simple path using Unity Vehicles

Next step was to add Car AI script which controls the car while it is moving on a path, like steer sensitivity, brake sensitivity, acceleration sensitivity and how forgiving the path following process can be. Then I needed to make the car on my waypoints which can be done with waypoint progress tracker script. By using this script, the desired waypoints can be introduced to the car and then by pressing play car began to move. The first problem with the car was that all the pre-defined measures were based on a racing car behavior with a very high speed and a high steer angel. This is not normally the case for city cars because they have limitation in the lanes and they cannot suddenly go out of the lane. I then fine-tuned the parameters to make the car move in a more natural way. Then I created waypoints for different cars and integrated more cars into the environment.

After the initial setup, I tested the environment with HTC Vive. One of the main challenges in virtual reality is the dimensions of play area⁸ in comparison to the virtual world. Base stations⁹ can cover a 5m diagonal distance in real world. The solutions for this limitation vary depending on the goals and purposes of the project or game. The most popular way of moving in virtual reality is teleporting¹⁰. This method is very reliable but it is not very intuitive for the users. “Another option to give a user a walking-like experience is the walking-in-place approach that uses walk-like gestures to travel through virtual environment, while the physical location does not change (Vasylevska, Podkosova, & Kaufmann, 2015).” Different devices have been prototyped to keep the user in one place or limit their movements in real world while they are moving around in VR. There are specific shoes or treadmills which gives the users the feeling of walking. This is a very good method to solve the issue; however,

⁸ The play area is the play area a VR game or application is guaranteed user can move within (“How To Maximize HTC Vive Play Area,” n.d.)

⁹ Powers the presence and immersion of room-scale virtual reality by helping the Vive headset and controllers track their exact locations.

¹⁰ Teleporting means using the controllers to specify points on further locations in virtual reality and get to those locations directly without moving your body. In teleporting user can sit in real world but moving in the virtual space.

these devices are not very affordable specially for smaller projects. Another approach is to accelerate the movement in virtual reality so that when the user moves they traverse a longer distance in VR. This is a good approach for giving users the feeling of walking without the necessity of having extra devices in the play area.

I used VRTK_RoomExtender script to adjust the movements of participants in virtual reality. Movements of each participant is being multiplied by 1.1 in virtual reality. I tested this feature of the environment on a couple of volunteers to determine whether it feels disturbing or not. According to their opinion the movements are continuous and smooth. One of the participants mentioned “I was thinking this is a VR effect. I can feel the speed but it does not feel strange and I am comfortable.” I also realized that I had to adjust the height of the camera rig for each participant to let them have a more natural feeling about their height and scale in the virtual city.

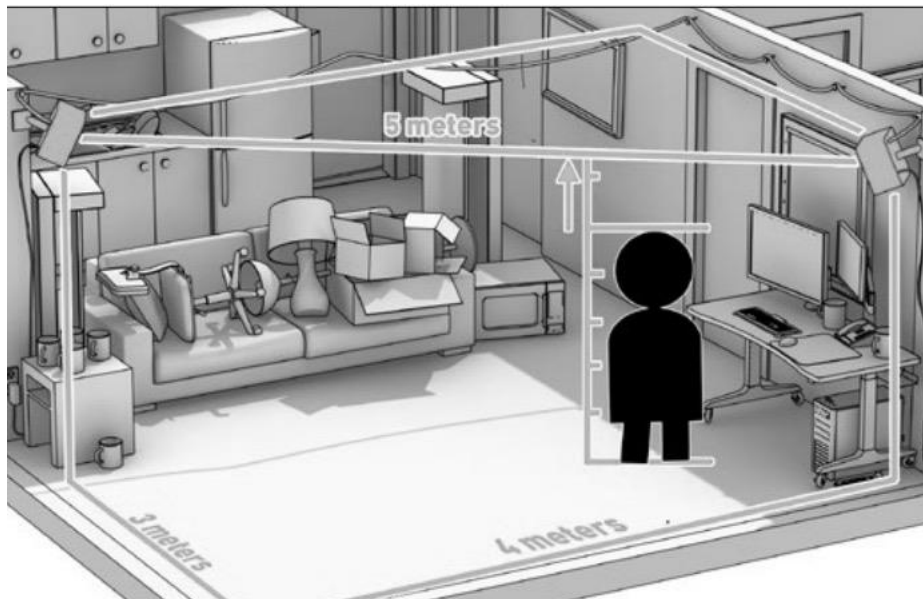


Figure 23 Virtual Reality play area dimensions, source: <https://medium.com/@dariony/room-scale-vr-using-unity3d-da39919d1063>



Figure 24 Showing the teleporting process using controllers, source: <https://goo.gl/images/xHeHL2>

To ensure that there are specific numbers of cars passing by the participant at the same time and having substantial control over the sequence of events, I used Unity animation. Unity animation is a great tool to control different parameters in different prefabs and game object. I created a timeline for the animation and set the cars to be activated at specific moments in the timeline and deactivated after a certain amount of time. I tailored the timing based on my observations in the environment and timing the cars' presence in the scene. Figures 17 and 18 show the paths and animations in unity.

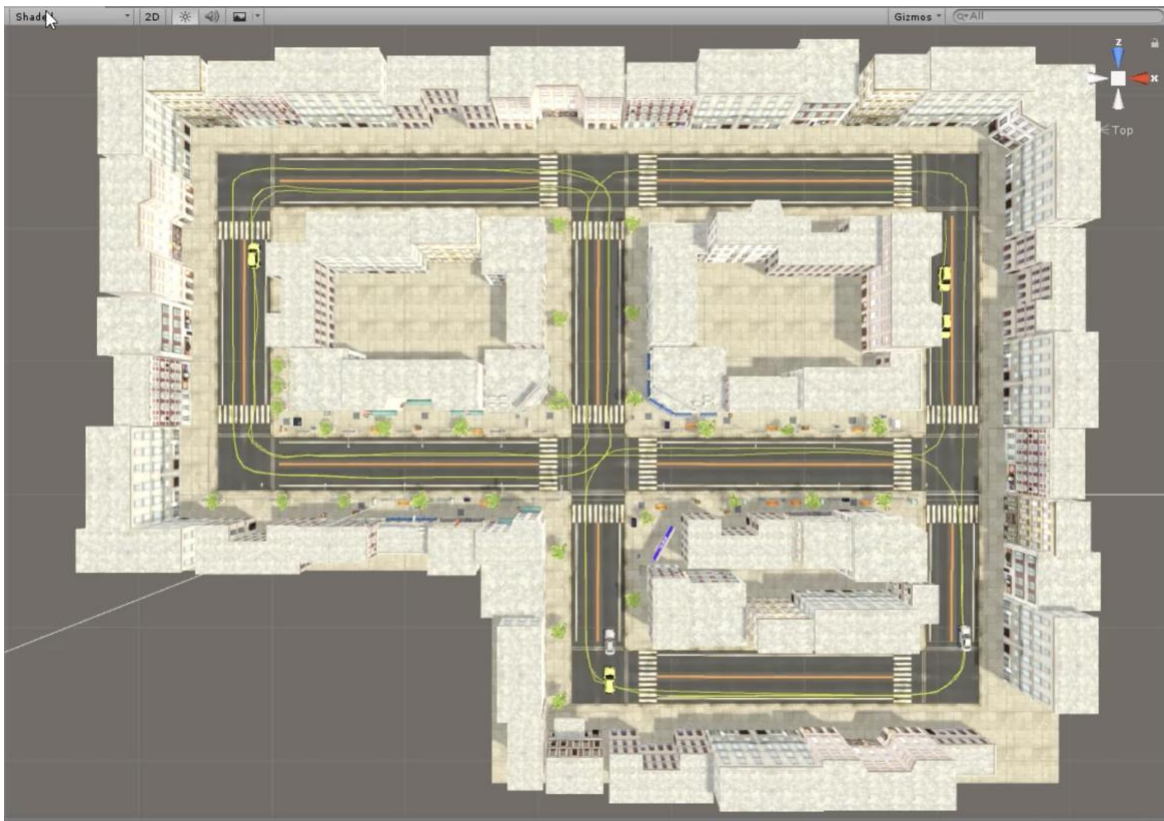


Figure 25 Screenshot from the Unity with toolpaths and initial car generations.

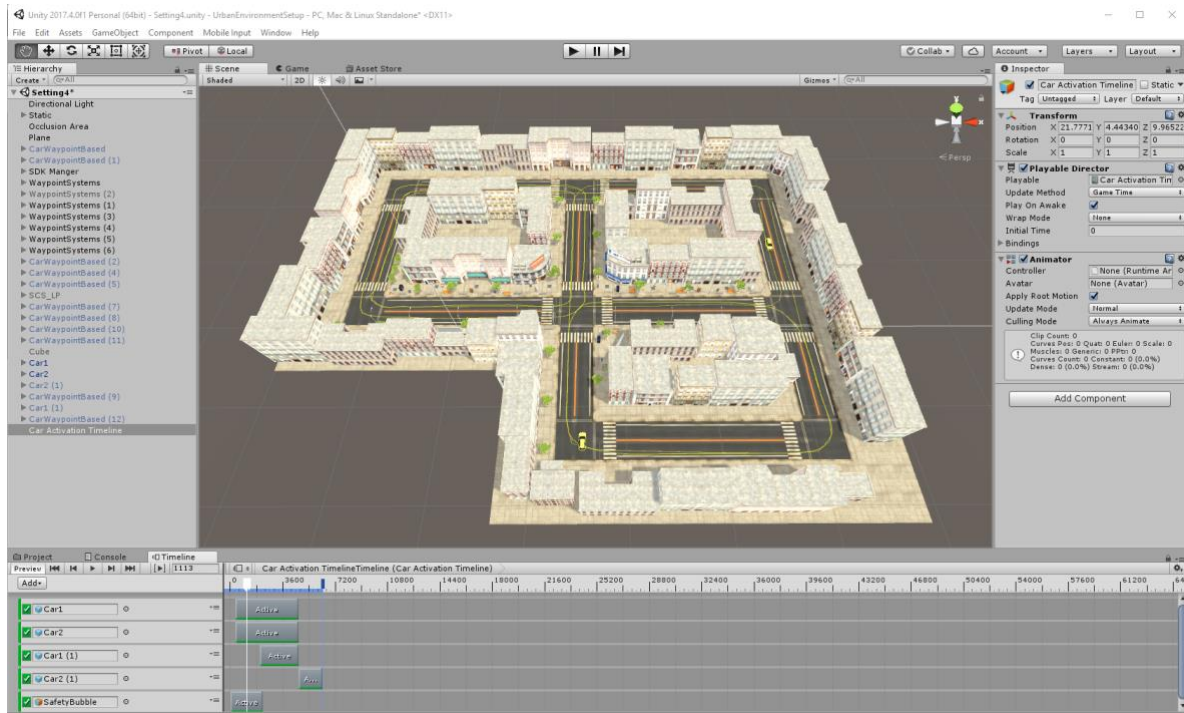


Figure 26 Screenshot from unity with animation setup

To make the car yield in setting 4, I created a cube (i.e. SafetyBubble) as the child of Camera Rig in VRTK SDK Manager. I made the cube activate and deactivate at a certain time so that the car collides with the cube and then continues its way. To prevent some cars from yielding and passing I added the car to another layer (CarIgnorePlayer) and unchecked the collision with the SafetyBubble in the Layer Collision Matrix. Figure 20 shows the Layer Collision Matrix in setting 4.

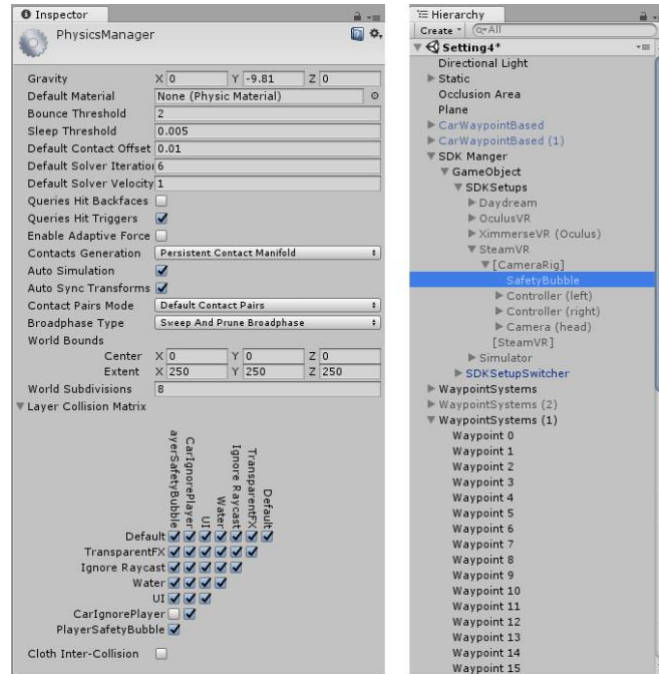


Figure 27 Layer Collision Matrix and hierarchy of VRTK SDK Manager Game object in Unity

Table 1 shows detailed specifications for each setting.

Table 1 Specifications of each setting

Settings	Number of cars	Steer Angle	Speed	Signal	Yield	Description
Familiarity	0	NA	NA	NA	NA	-
Setting 1	6	50	10-15	No	No	Max 4 cars at the same time
Setting 2	6	50	15-35	No	No	Max 3 cars at the same time
Setting 3	4	40	10-15	Yes	Yes	Max 2 cars at the same time, blue and red signaling

3.4.4 Biometrics

Biometric measures can provide real-time assessment of users' physiological state using signal-recording technologies. This method is being used in many different disciplines as well as Game User Research to evaluate player's physiologically when they are engaged in a game (Drachen et al., 2018). Brain waves affect the entire system of each person's body, that is, they can determine the emotional state of a person. As emotions are very important in the interaction between individuals, their surrounding environment and also events occurring around them. Brainwave is physiological signal and is known as electroencephalography (EEG) (Candra et al., 2015).

Often the classification algorithms are not disclosed because of "their status as industrial intellectual property (Mavros, Austwick, & Smith, 2016)". To make it clear how the emotional states are being extracted from raw EEG data, I briefly go over the classification methods for classifying EEG data. Circumplex model of emotion was proposed by Psychologist James Russell in 1980. "The circumplex model is a conceptualized 2-dimensional continuous space where the horizontal and vertical axes correspond to the degree of valence (pleasure) and arousal, respectively. Discrete emotional states such as 'happy', 'sad', 'angry', and 'relaxed' can be inferred from the degree of valence and arousal as illustrated in Fig. 28. Using this model, the degree of any of the aforementioned discrete emotional state can be measured (Candra et al., 2015)."

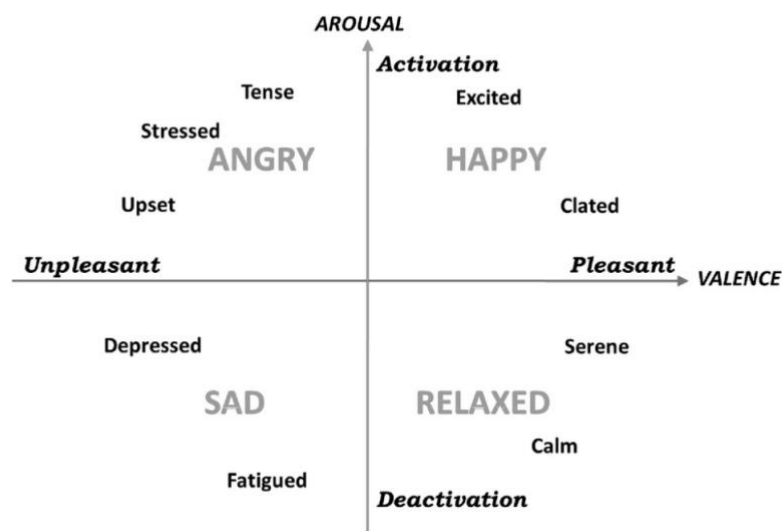


Figure 28 Russell's circumplex model of affect , source: (Candra et al., 2015)

In order to get a higher quality signals, I saturated the felt pads with Saline Solution. All the sensors should make contact with the scalp. Emotiv description for the setup process suggests that users can make adjustments by holding and pressing my hands against the scalp for 3-4 seconds. According to EmotivXavierControlPanel the majority of the indicators should be green; however, the detections

usually tolerate input if the indicators show orange. The whole set up process usually takes 30 minutes to an hour depending on the form of head and hair of the user.

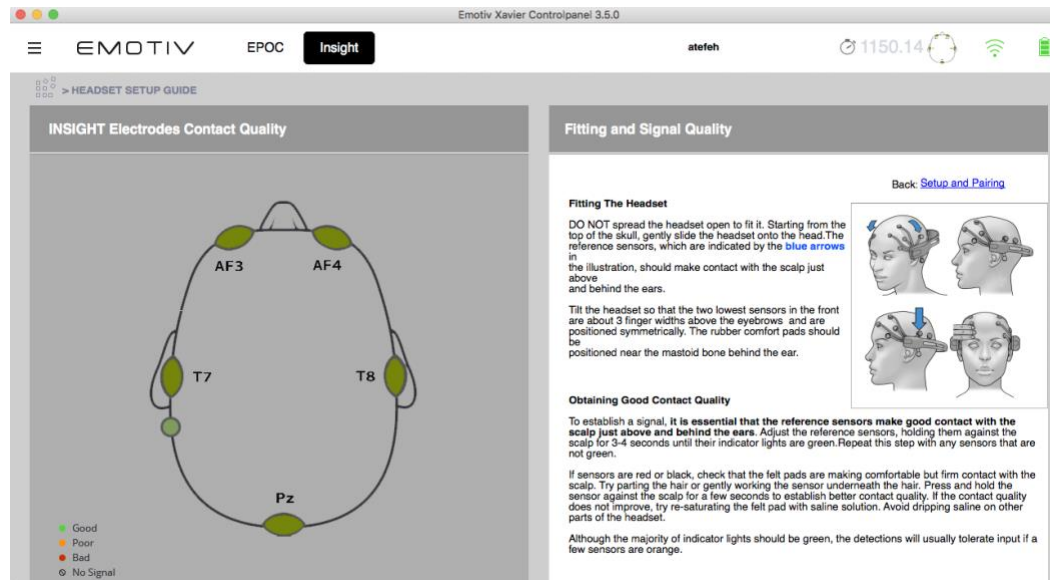


Figure 29 EmotivXavierControlPanel, indicators are showing all green which means participant can start the process

Although the Xavier interface shows the performance metrics live, it does not provide any numbers or statistics. Emotiv provided developers with its Cortex API documentation and how to get specific data from the headset in several programming languages. The Node.js directory includes examples of obtaining data from headset. I used the Numbers.js file which is useful for streaming band power, performance metric and motion data.

3.5 Experiment

To clarify this is a proposal for experiment approved by IRB which I only conducted once on one participant. In next steps, the experiment will be conducted on 15 participants.

3.5.1 Aim

This experiment aims at exploring the pedestrian and autonomous vehicles' interaction in different scenarios. Although there are many factors involved in this interaction, this experiment is testing just a few because of the limited time and scope of the project. The methodology and process can be applied to other factors, as well.

In this experiment four main factors in this interaction will be tested:

- The impacts of proposed methods of signaling
- The impacts of speed
- The impacts of the degree of automation

3.5.2 Participants

Participant underwent Screening based on the following criteria. People with any kind of disabilities, cognitively impaired, neonates, children (less than 18), pregnant women, and people who wear glasses are excluded. Participants wasn't affiliated with companies promoting autonomous vehicles. Participants was at least 18 years of age.

3.5.3 Procedure

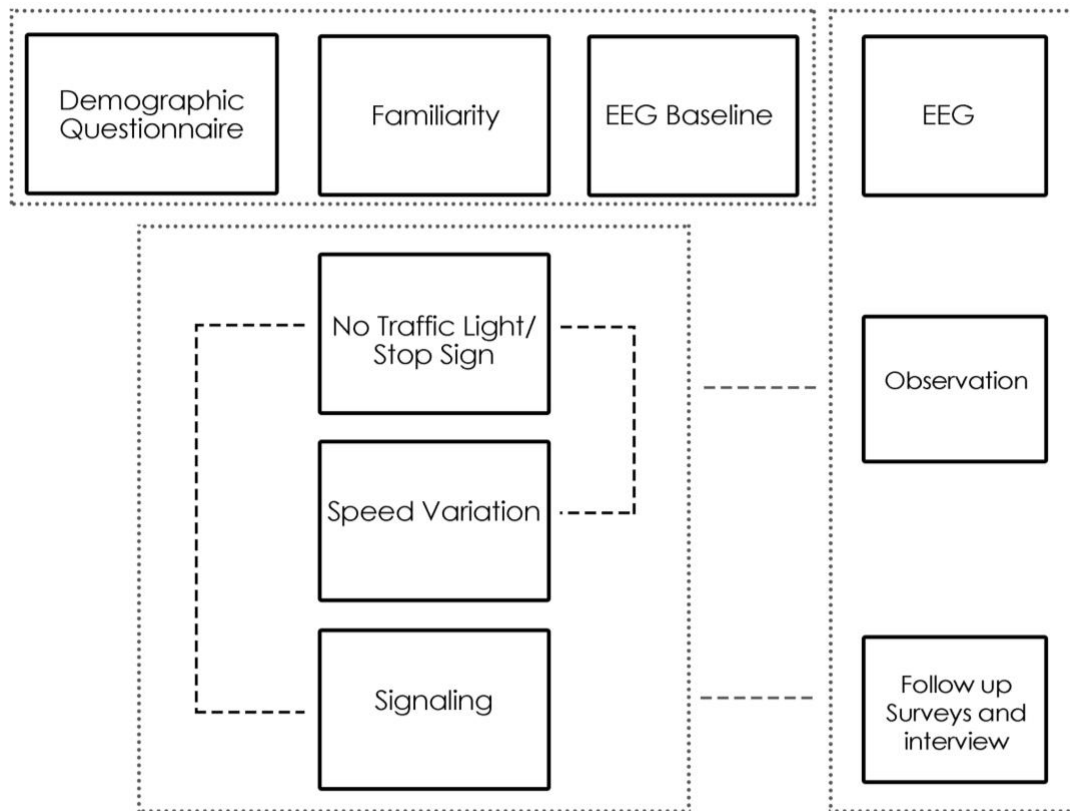


Figure 30 Diagram showing the experiment design

The procedure is a single 1-hour session. The participants are first given a background questionnaire to collect demographic information. They get directions and explanation of what they are going to do in this study. I provided them with the consent forms to sign. Each participant was first given a background questionnaire to collect demographic information. They also read a brief description of the procedure, what they are going to see in the virtual environment and what they are supposed to do. Facts about virtual reality were explained for example, they cannot get killed or injured by a car and if they feel uncomfortable about anything through the process they can terminate the task. Participants were informed that the virtual environment is being recorded.

Participants are supposed to cross the street in 3 settings in virtual reality. An EEG Insight headset is going to be put on participants head while they are completing the tasks in order to keep track of their brain electrical signals. Independent variables are different for each task and details are provided in task descriptions. Dependent variable is the pedestrian's "reaction" to this scenario. Switching between virtual and real environments can affect the results, therefore participants should not take the headsets off in the middle of the experiment and the process should be done at once.

In all the tasks participant were asked to proceed in a way that they feel comfortable. There is time slot called "start time" through the process in which participant is expected to begin crossing the street. The participant has 3 minutes to finish the task and if they are not done by that time the task will be stopped. Participant was informed about the "start time" after finishing all the tasks in order to avoid any behavioral change or to put any pressure on them to act quickly. The experiment has a fractal and within the subject design. For future experiments tasks should be randomly ordered in order to avoid introducing biases, because participants can learn from each task and the prior task can affect the emotional state of the next one.

Setting 0 (Baseline)

In task 0 participant in all three blocks became familiar with the environment. They were asked to cross the street in an urban intersection with no cars. This is also useful for them to reach a more stable emotional state. This task was used as a baseline for other tasks and to get information about their individual characteristics, for instance their walking speed or emotional state.

Setting 1 (Not Yield)

In setting 1 participant was asked to go to a desired point in the intersection in a shared space setting. The desired point will be diagonal to the participants' initial location. In this task, independent variable is "no traffic light or stop signs and cars will not yield". Participant could cross the street when they felt comfortable. The speed of cars was considered to be slow.

Setting 2 (Signaling)

In this setting participant was asked to go to a cross the street in a shared space setting. This setting is the same as previous setting. The speed of cars was considered to be slow. The independent variable in this task is "signaling" by autonomous vehicles. Participant was instructed on what each signaling color means. The proposed way of signaling is as follows:

There are two colors for the signaling:

- Blue: AV is stopping
- Red: AV is continuing at a constant speed

Setting 3 (Speed)

In setting 3, participant was asked to cross the street in an "Autonomous Intersection" setting. The independent variable in this task is the speed. In this setting cars want to pass as fast as they could.

Evaluating participants' "reaction" is based on these criteria:

Table 2 Factors and methodology

Factor	Method	Source
Challenge	Qualitative	Observation + Questionnaire
Comfort	Qualitative	Questionnaire
Duration	Quantitative	Each Task's duration
Intensity	Quantitative	EEG Headset

3.5.4 Qualitative and quantitative measures

Qualitative:

Participant was observed during the process and all the tasks was recorded from the VR environment for further evaluation. I observed participants and their behavior from three aspects:

- In-game events
- Spontaneous player comments
- Anatomy of observation

For next steps, I will create the below table for events for each participant and then I will aggregate all the tables to find similar patterns. Players' body language, facial expression, and posture are also very hidden important factors to look at.

Table 3 Questions to look for during the observation, source:

Question	Description
<i>What</i> happened?	Player behavior/decision/comment/expression
<i>Where</i> did it happen?	In a specific area of the game, the map, or the screen.
<i>When</i> did it happen?	At a specific time or a specific step in a sequence of events.
<i>Why</i> did it happen?	What was the cause or the rationale behind the action?

Another measure for computing the level of challenge based on the observation are based on two events.

Table 4 Observation measures

Behavior	Grade
Sudden Movements	-1
Walking speed variations	-1

The participant's initial grade is 10. Grade 0 or lower means very challenging and grade 10 means not challenging. Moreover, participants were asked to fill a questionnaire to provide more information about their experience.

Quantitative:

The duration of each task was measured based on the VR recordings and it can be an indicator of how easy or challenging was the task for pedestrians. More importantly, Intensity of the participants' electrical brain behavior was measured with and EEG Insight headset through the process. Seven outputs can be retrieved from the headset during the process, Interest value, Stress value, Relaxation value, Excitement value, Engagement value, Focus value. Stress value will be recorded.

3.6 Results

I did one experiment to test my workflow and test my hypothesis. The virtual reality situated recordings show the decision-making process and the nuances in the participant's behavior. To be more specific, the participant looked around, recognized a car and then waited even though there were plenty of time before the car gets to their location. My assumption is that participant decided to wait because it was their first interaction with the car and they didn't have prior knowledge regarding the car. After waiting for two cars to pass, participant looked around for several times and made sure that no car is coming. Then the participant decided to cross the street. During the crossing, participant was constantly checking the street till they get to the other side of the street. For the second setting participant acted quicker and decided to cross even though they saw the car, then they realized that the car was moving faster. "Oh! The car is coming so fast" the participant said and started to run to reach the other side of the street.



Figure 31 The process of experiment, mapping real-world actions to virtual world experiment

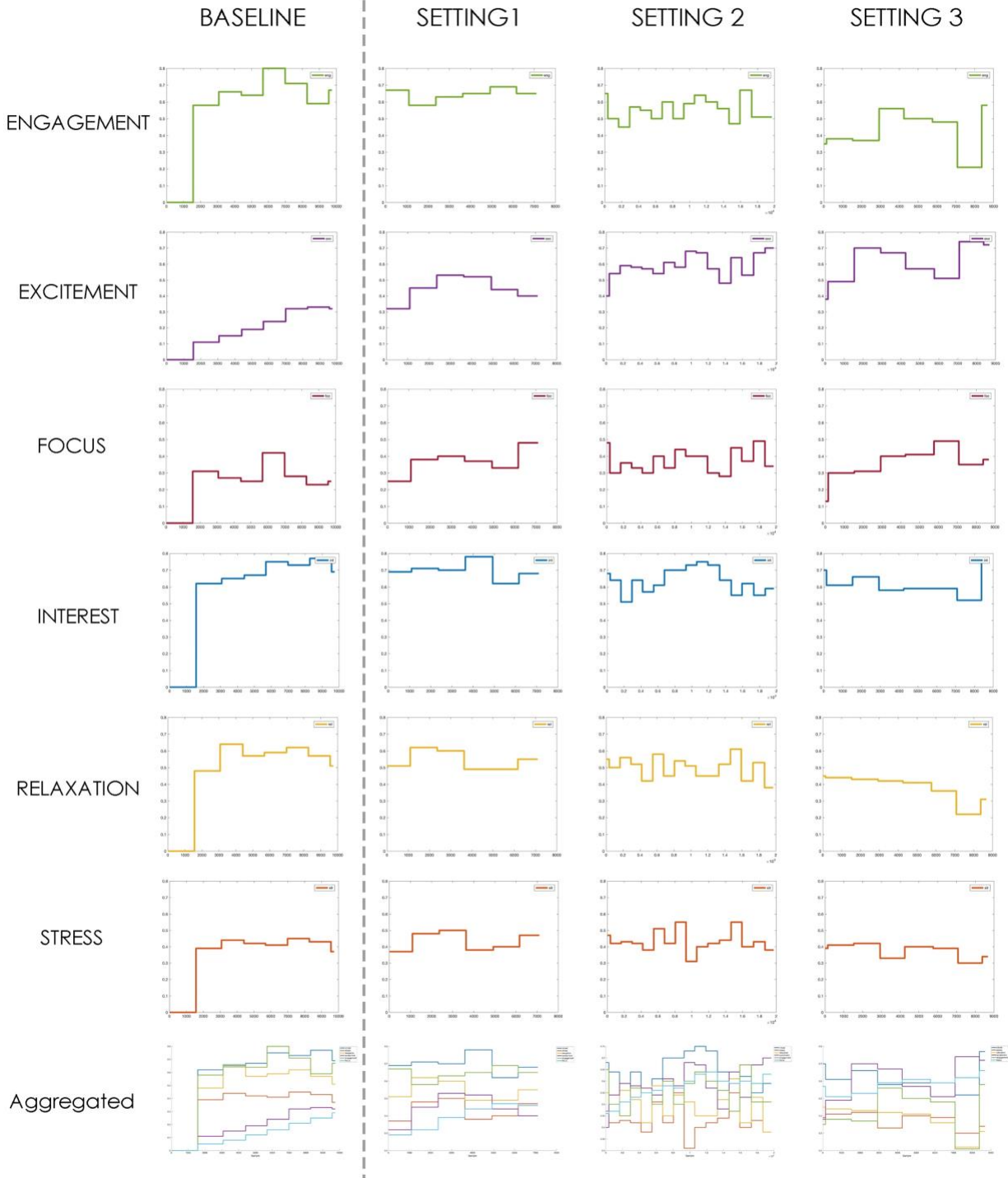


Figure 32 Experiment results on one participant

Figure 31 illustrates the results of one experiment with one participant. As previously discussed the experiment included a familiarity setting as the baseline and three other settings. During the

experiment, the participants spent approximately 4 minutes in the familiarity setting to get familiar with the virtual environment. Also, the baseline shows the importance of comparing the values of each task with the baseline, for example participant had a high interest value from the beginning and after the familiarity setting it began to decrease through the process. This can correspond to the fact that this experiment was the very first virtual reality experience of the participant which could cause the interest value and excitement value to be very high.

There are clear differences between each setting's results. For instance, according to the participant, setting2 was the most challenging "*Last one felt the safest, the second one was the hardest.*" Correspondingly, the results presented in Figure 29 shows many fluctuations in the participant's emotional state in setting2. Whereas in setting 3 in which vehicles yield and signal for the pedestrian there are fewer fluctuations and consequently a flatter chart. Moreover, among the three settings, setting2 had the highest stress value sample and highest average.

I was expecting to find a correlation between the relaxation value and stress value but results do not show a meaningful correlation between them. However, the average of the relaxation value in setting 2 is lower than the average in setting1 and the baseline. I can relate the lower relaxation values in the Baseline and Setting 3 as the start and end of the process which could have introduced biases because of getting not being familiar with the environment and getting used to it after a while. Engagement values confirm that the participant was not as engaged in the last setting in comparison to the last setting. To make sure that the order of settings does not introduce biases in the results, I need to randomize the order for future experiments. Table 6 shows averages of each emotional state through each task.

Table 5 The averages of each emotion through different settings

Emotional States	Baseline Average	Setting1 Average	Setting2 Average	Setting3 Average
Interest	0.5839	0.6982	0.6368	0.6007
Stress	0.3535	0.4317	0.4331	0.3755
Relaxation	0.4820	0.5439	0.4979	0.3808
Excitement	0.1863	0.4486	0.5910	0.6116
Engagement	0.5552	0.6440	0.5514	0.4230
Focus	0.2460	0.3661	0.3682	0.3722

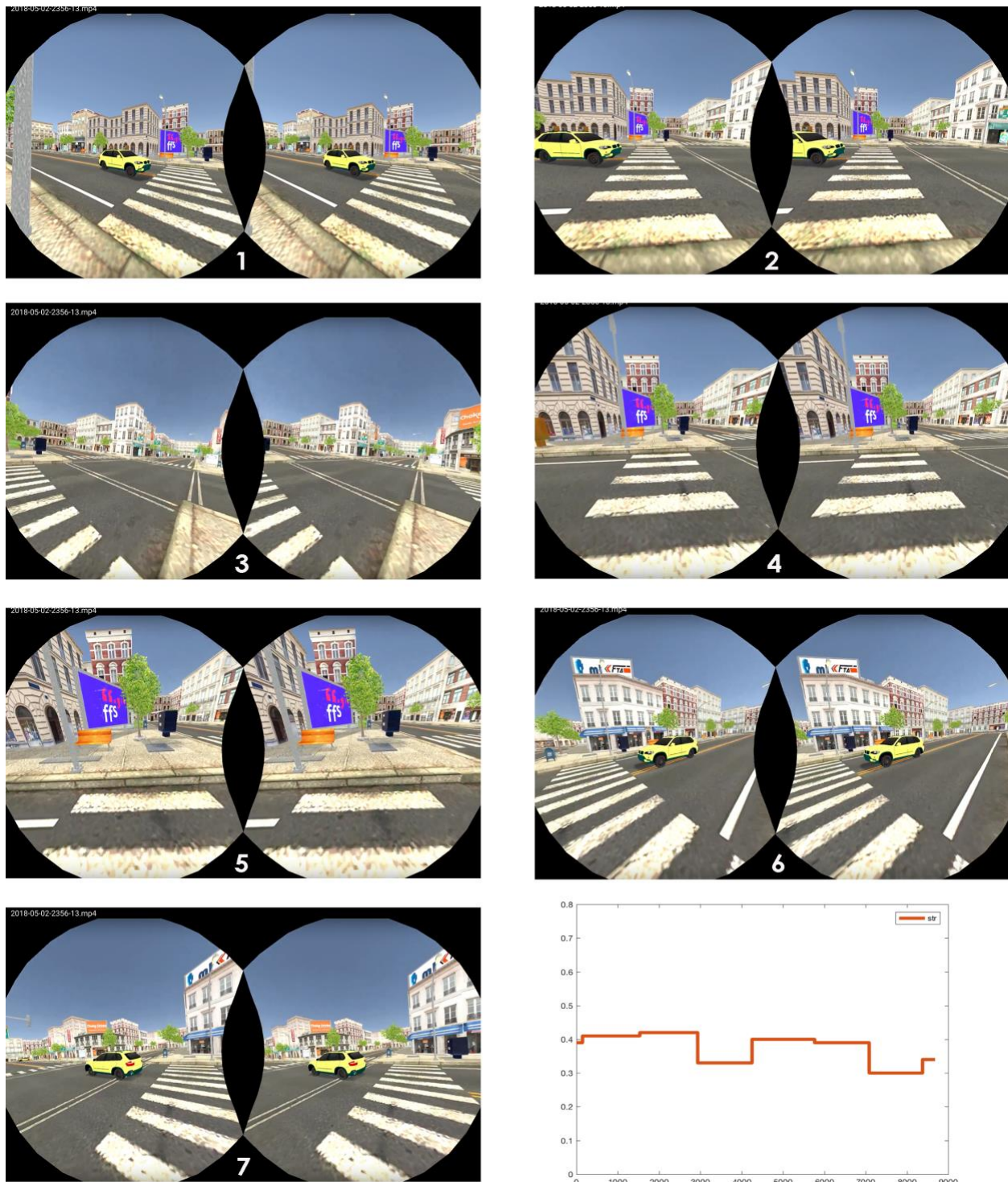


Figure 33 Participant's behavior in Setting 3

To open up more on the analysis, I go through my observations in setting 3 where the cars were signaling and yielding for pedestrians. Figure 33 illustrates the process. The participant saw the vehicle

that is approaching and the car was signaling blue, meaning that the car was going to yield for the participant. Surprisingly, the participant didn't show any intention to cross the street (1). The car yielded for the participant, but participant didn't move and stayed in the same place (2). It took a while for the participant to start crossing the street and based on the virtual environment video, there was still a bit of hesitation in the participant's behavior (3,4). The participant crossed the street and immediately looked back to the car (5, 6) and saw that the car is still waiting. Then the car started moving (7). Mapping the EEG data to the observations are showing promising correlations. As an example, the stress value during the process is shown in figure 33. By observing the car, the stress value increased slightly, and by the time the participant crosses the street it reached to its maximum value, and it dropped when the participant reached the other side of the road and waited for the second round to pass.

Table 6 Results of the survey done by participant

Question	How challenging did you find the task?	Do you think the presence of AVs make it more difficult for you to complete the task?	What was making it more difficult to complete the task in this scene?	Did you feel comfortable crossing the street in this task
Answer	Slightly challenging	Moderately	AV's way of signaling	Comfortable

After the experiment, I asked the participant to answer 5 questions in the survey. Table 7 shows the result of the survey after the experiment. For the last question of the survey in which the participant was asked to provide a comment about their experience, the participant responded: "I was confused when the vehicle stopped and waited for me to cross the street. Not sure how long it will stay put and if it will notice me when it starts to move again." This statement explains the participant's behavior during the process and provides more information about the hesitation. The focus value also increased when the pedestrian started to cross the street. Observing the step by step behavior, mapping the observations to the EEG data and interviewing the participant after the experiment led to the following conclusions:

The autonomous vehicles themselves had an impact on the difficulty of tasks not because of their specific behavior, but the fact that the participant didn't have any prior experience with them. The participant explicitly stated during the interview that "People need to get used to them." I can relate the hesitation of the participant in crossing the street to the lack of knowledge they were mentioning. Although the EEG data shows many fluctuations, the participant chose the "slightly challenging" option in response to the question of "How challenging did you find the task?" I speculate that participant was used to a certain degree of stress as a pedestrian in the city; thus, they may not call a specific situation challenging anymore. The participant was amazed by the fluctuations in the level of stress after seeing the results.

4 Discussions and next steps

4.1 Conclusion

Simulation methods, platforms, and models have been wildly studied to recreate and examine the real situations. In my thesis, I took a different approach to the subject of simulation, to show that simulation can be more than a tool to prove the correctness or efficiency of a decision. I should emphasize that this thesis was not looking for a final answer, but to propose a pedestrian-centered approach for exploring qualitative aspects of human experience in the urban environment.

I proposed a workflow combining different methodologies to reveal the nuances of pedestrian's interaction with autonomous cars and designed an experiment to test the workflow. The results of the experiment show that a simple task (e.g., crossing the street) which is often (in other simulation platforms) assumed to be a simple movement from point A to B can actually be emotionally very involved. The workflow is not deterministic, but it can inform design, planning, transportation or policy-related decisions.

Virtual Reality has excellent potential as a tool to recreate real situations; however, a lot of effort is needed to recreate different scenarios with high fidelity. The subtle difference between autonomous vehicles and regular cars can be further studied and models in the virtual environment. Moreover, prior experience in virtual reality can have an impact on the participant's emotional state (excited or bored) which can introduce less meaningful or biased results. In order to minimize the effects of virtual reality, participants should spend enough time in the virtual environment before the experiment.

EEG data show promising results, but further experiments are necessary to help us understand and analyze human experience in urban environments. The results suggest that the workflow can reveal the nuances of pedestrians' interaction with autonomous cars. That is, the fluctuations in participant's emotional state during the experiment confirms the hypothesis that human experience cannot simply be abstracted to movements and set of goals.

4.2 Limitations

Virtual reality is a great tool to create real-life situations for simulation and a high-fidelity VR environment can get very similar to reality. However, there are certain limitations and constraints that needs to be considered in the simulation process. Modeling and simulating naturally in virtual reality can take a lot of time. Not having a prior experience can affect the participants emotional state during the process

One of the main challenges in the virtual experiment is scale. As previously discussed there is a limited play area (world limit bounds) in virtual reality. Cameras which are detecting controllers and the headset can only have 5m diagonal distance which is a very limited space in comparison to the infinite world. Crossing the intersection which is more than 8 meters is not possible with regular walking with the headset. Therefore, walking freely in a virtual urban environment needs careful consideration and additional tools for the users to have a natural experience. As discussed before the VRTK package was used to let the participants move further than what they actually can in VR by multiplying their

speed to a certain number. This method which was more natural but still different from the actual walking.

Issues mentioned in the last two paragraphs can introduce certain biases into the simulation. For example, a different walking experience (Faster walking or teleporting) may not be the most intuitive way to move in comparison to reality. Such differences (even though small) can affect their decision-making process or their feeling and experience in the environment. In addition to that, the virtual environment is being designed by a researcher or group of researchers so there is the possibility of introducing biases based on researcher's own preferences in the virtual environment (from the appearance to functionality). To some extent having biases are inevitable but reducing them and being aware of them during the analysis is crucial.

Motion sickness¹¹ is one of the major concerns regarding VR headsets. Companies and VR researchers are working to improve the experience; however, there are still problems with people get sick after a long time using VR headsets. This research had limitations in this regard and needed to consider the sickness. So, the tasks for the experiments had to be designed in a way to be as short as possible. Also, there were breaks in between tasks to help the participants feel comfortable. It is true that the more time we spend in the environment the more data and insight we can get but for now there are certain limitations to that.

Working with EEG headsets has its own limitations. Getting good quality signals can get very tedious and keeping the signals while participant is moving around the room is a challenge. This limitation can be minimized by making a portable package (e.g. backpack) to let the participants move with the headset and laptop at the same time.

Finally, knowing that in the virtual environment pedestrians cannot get killed by cars may affect the participant's decisions. Participants may be more willing to take risks in virtual environment that they will not necessarily in real world.

4.3 Next steps

The current workflow provides us with the opportunity to study subtle differences between individuals. There is no doubt that culture influences individual behaviors in cities. Further studies can be conducted to identify the correlation between cultural differences on pedestrian behavior in cities.

¹¹ According to Stevan To in Bright Developers, motion sickness in simple terms is when what a person sees and what their body is experiencing is does not match. Factors that cause motion sickness in VR are, latency, Sensory conflict and eye strain. Latency means there is a delay between moving the body and the effect of that being drawn in virtual environment. Latency is the most common result of motion sickness. Another factor is sensory conflict which happens when a user is moving in the virtual environment but they are actually sitting in reality. Another cause of the motion sickness is not adjusting the headset to the user's eyes which can be solved. (To, 2017).

The results of such study can have impacts on policy making, urban planning and gives communities the opportunity of tailoring their transportations system to their culture.

Adding pedestrians to the simulation can reveal more interesting aspects of pedestrian experience in cities. For example, the idea of social cascade and how other people's decision affect our personal decision can be explored in such system.

Companies that promoting and testing autonomous vehicles are collecting a huge amount of data with their cars going around the city. However, this data is not public and it is not available for research purposes. The proposed system in this thesis can be used to create a public dataset related to pedestrian behavior. Such dataset has certain advantages over other vehicle-based data collection methods. The data is being collected by vehicles could "lead to reliance on driving as the primary mode of transportation"(Cattaneo, 2018). Additionally, these cars often move between certain areas of the cities and "are very likely imbued with demographic biases"(Cattaneo, 2018).

4.4 Contributions

I discuss the applications and contributions of my thesis within three different diciplines: design, public policy and planning, and transportation. However, the applications are not limited to these areas.

This framework can contribute the field of design in several ways. In a higher level, it can be used for testing specific modifications in the built environment and analyze how those changes are affecting the user (participant) of the environment. That is, the framework can be utilized as a tool for different "what if" scenarios. More specifically. It can inform urban design for various purposes, from signage design to very detailed changes like the curb height for the pedestrian to move in the sidewalk or crossing the street. It can also lead to better and more pedestrian-oriented design of Autonomous Vehicles and their signaling mechanisms. The modifications and scenarios can be prototyped in the virtual environment and be tested quickly so that the design team can know how their design decisions can affect the pedestrians" experience.

Public policy can also benefit from such framework for decision-making processes. For example, changes in public transportations systems, timing traffic lights can be tested through this framework. More importantly, the framework can be used for educating people regarding the new technologies in cities. The education can happen in two steps: Volunteers can use the system, and their experience can be observed. Then the government can use the data to identify the criteria that education or more information is necessary. For instance, regarding the autonomous vehicles, perhaps pedestrians should be informed about the subtle differences between regular and automated systems so that they do not feel scared if an Autonomous Car moves so close to them.

From the transportation point of view, the information can be used to inform companies that are promoting driverless cars to understand what are the features for pedestrians to feel safe sharing the road with self-driving cars. For example, an autonomous vehicle moves on a certain distance from a pedestrian which is safe based on the safety measures of the car. However, regular drivers are intended

to drive away from the pedestrian. Even though the situation is safe based on the safety measures, pedestrians may feel uncomfortable around the driverless car because it is moving so close. These nuances can be tested using this framework. Additionally, the empirical data collected using this framework can be used for autonomous vehicles training in future. Acknowledging the differences between pedestrians as human beings and the fact that their behavior may not be the same in similar situations will be crucial in autonomous vehicles training processes.

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Appendix 1: Experiment's consent form

Carnegie Mellon University

Consent Form for Participation in Research Study Title: Possible Socio-Technological Futures of Pedestrian Life

An Empirical Exploration of Pedestrian life in Urban Intersections

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Purpose of this Study

The purpose of the study is to explore the interaction between pedestrian and autonomous vehicles. This is important because any shift in forms of transportation may shift our paradigms toward a city and the meaning of the street.

Summary

I am studying a new method of studying pedestrians' experience in urban intersections. I will particularly be focused on the interaction between pedestrian and autonomous vehicles. I will conduct an immersive experiment in Virtual Reality (Using HTC Vive) incorporating EEG scanners (Emotiv Insight) to identify how an individual would interact with autonomous vehicles in urban context. I will get the stress and relaxation value from the EEG scanner that you will wear during the process

The experiment consists of 5 tasks and a familiarity task. In each task, you will cross the street while cars are moving. You get to choose when you want to cross the street and you shouldn't expect that the cars will yield for you. However, in the virtual environment there is no chance that you get hit by a car. When you cross the street, the task is finished. The process will be 1-hour long. Each task will take 5 minutes and then you will have another 5 minutes to rest and fill in a questionnaire about the task.

Procedures

The procedure is a single 1-hour session. If you participate in this study, first you would get directions about the virtual environment. Then you will be first given a background. Then you would go on a trial round to familiarize yourselves with the virtual environment. You can terminate the task at any point if they feel tired or uncomfortable about anything.

The virtual environment will be video recorded through the process from your eye-view in the pc. You will also be video and audio recorded in each task. The recording will start at the moment your wear the headsets

and will be stopped before you take them off. The virtual reality headset that I am using is HTC Vive and the EEG headset is Emotive Insight headset and you will put them on your head while you are completing the tasks. Each task will take 5 minutes. After each task, you will have 5 minutes to rest and complete a questionnaire about the task you have completed.

Familiarity Task: You will wear both headsets. You will cross the street when you want. I will make sure that the video recording and EEG headsets are working properly and you can ask any questions that you might have.

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Consent Form for Participation in Research

Task 0 In this task, you will cross a normal urban intersection with pre-timed traffic lights and 30% portion of AVs. The setting is exactly the same as trial. AVs are yellow and the rest of the cars are grey. Then You will have 5 minutes break and filling the questionnaire.

Task 1 (Shared space) In this task, you will to go to a desired point in the intersection in a shared space setting (“no traffic light or stop signs”). The desired point will be diagonal to the participants’ initial location. participant can cross the street when they feel comfortable. 30% of the cars will be AVs.

Task 2 (Signaling) In this task, you will go to a desired point in the intersection in the same setting. The desired point will be diagonal to the participants’ initial location. You will see different colors when autonomous vehicles are signaling. There will be three colors for the signaling: - Purple: AV is stopping - Blue: AV is reducing its speed - Orange: AV is continuing with a constant speed

Task 3 (Portion) In this task, you will go to a desired point in the intersection in a shared space setting. The desired point will be diagonal to the participants’ initial location. You will see more autonomous vehicles in this task. The ratio of autonomous vehicles to normal cars will be 70%.

Task 4 (AIM) In this task, participant cross the street in an “Autonomous Intersection” setting. In this setting cars will move quicker that previous ones but no more than 50 m/h.

Participant Requirements

Your age should not be less than 18. You shouldn’t be pregnant, physically or cognitively impaired and wearing glasses.

Risks

According to Emotiv website EEG or brainwave recording procedures are quite safe and has been in use for over 30 years; it is used routinely in hospitals to test brain function and to diagnose illness such as temporal epilepsy. There are no known major risks associated with this procedure other than a mild discomfort for some people who have sensitive skin when wearing the headset. This is not permanent and is of no serious

consequence. EEG Emotive insight headsets are lightweight and they can be adjusted to the participant's head. It detects brain activity with 5 sensors. The felt pads should be saturated with saline solution.

There is a potential risk of breach of confidentiality by participating in this study.

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There were reports of motion sickness because of using VR for more than 30 minutes without the break in the past.

Benefits

There may be no personal benefit from your participation in the study but the knowledge received may be of value to humanity

Compensation & Costs

Participant will get a 5\$ cash after completing the study. There will be no cost to you if you participate in this study.

Confidentiality

By participating in the study, you understand and agree that Carnegie Mellon may be required to disclose your consent form, data and other personally identifiable information as required by law, regulation, subpoena or court order. Otherwise, your confidentiality will be maintained in the following manner:

Your data and consent form will be kept separate. Your research data will be stored in a secure location on Carnegie Mellon property. By participating, you understand and agree that the data and information gathered during this study may be used by Carnegie Mellon and published and/or disclosed by Carnegie Mellon to others outside of Carnegie Mellon. However, your name, contact information and other direct personal identifiers will not be mentioned in any such publication or dissemination of the research data and/or results by Carnegie Mellon. Note that per regulation all research data must be kept for a minimum of 3 years.

Each participant will be assigned a number and the data will be identified during the study by that number. All the data (age, education, EEG values and screen recordings) will be stored in on a secure SMU server.

Optional Permission

I understand that the researchers may want to use a short portion of any video for illustrative reasons in presentations of this work for scientific or educational purposes. I give my permission to do so provided that my name and face will not appear.

Please initial here: _____YES _____NO

Rights

Your participation is voluntary. You are free to stop your participation at any point. Refusal to participate or withdrawal of your consent or discontinued participation in the study will not result in any penalty or loss of benefits or rights to which you might otherwise be entitled. The Principal Investigator may at his/her discretion remove you from the study for any of a number of reasons. In such an event, you will not suffer any penalty or loss of benefits or rights which you might otherwise be entitled.

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Consent Form for Participation in Research

Right to Ask Questions & Contact Information

If you have any questions about this study, you should feel free to ask them now. If you have questions later, desire additional information, or wish to withdraw your participation please contact the Principal Investigator by mail, phone or e-mail in accordance with the contact information listed on the first page of this consent.

If you have questions pertaining to your rights as a research participant; or to report concerns to this study, you should contact the Office of Research Integrity and Compliance at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu . Phone: 412-268-1901 or 412-268-5460.

Conflict of Interest

There is no conflict of interest.

Voluntary Consent

By signing below, you agree that the above information has been explained to you and all your current questions have been answered. You are encouraged ask questions about any aspect of this research study during the course of the study and in the future. By signing this form, you agree to participate in this research study. A copy of the consent form will be given to you.

PRINT PARTICIPANT'S NAME

PARTICIPANT SIGNATURE DATE

I certify that I have explained the nature and purpose of this research study to the above individual and I have discussed the potential benefits and possible risks of participation in the study. Any questions the individual has about this study have been answered and any future questions will be answered as they arise.

SIGNATURE OF PERSON OBTAINING CONSENT DATE

Version 1.2018

Appendix 2: Demographic Questionnaire

Thank you for your time. Please answer the following questions.

To which gender identity do you most identify?

- ☐ Female
- ☐ Male
- ☐ Prefer not to answer

What is your age?

- ☐ 18-24 years old
- ☐ 25-34 years old
- ☐ 35-44 years old
- ☐ 45-54 years old
- ☐ 55 years old or more

What is the highest degree or level of school you have completed? *If currently enrolled, highest degree received.*

- ☐ High school graduate, diploma or the equivalent (for example: GED)
- ☐ Some college credit, no degree
- ☐ Trade/technical/vocational training
- ☐ Associate degree
- ☐ Bachelor's degree
- ☐ Master's degree
- ☐ Professional degree
- ☐ Doctorate degree

How do you think autonomous vehicles can change pedestrian life in cities?

Easy	1	2	3	4	5	Hard
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Appendix 2: Survey

How challenging did you find the task?

- ☐ Very challenging
- ☐ Challenging
- ☐ Fairly challenging
- ☐ Slightly challenging
- ☐ Not challenging

Do you think the presence of AVs make it more difficult for you to complete the task?

- ☐ Extremely
- ☐ Very
- ☐ Moderately
- ☐ Slightly
- ☐ Not at all

What was making it more difficult to complete the task in this scene?

- ☐ AV's speed
- ☐ AV's way of signaling
- ☐ AV's to normal cars ratio
- ☐ Other _____

Did you feel comfortable crossing the street in this task?

- ☐ Very comfortable
- ☐ Comfortable
- ☐ Fairly comfortable
- ☐ Slightly comfortable
- ☐ Not comfortable

Please add comments about your experience.