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Agent-Based Modelling via Pedestrian Behaviour Elicitation in Virtual Reality

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Abstract

Pedestrian modelling and simulation play a fundamental role in reducing risks and implementation costs. Such models require a accurate representation of pedestrian behavior. However, to elicit human behaviour is not a trivial task. Virtual environments have been gaining notoriety as a behaviour elicitation tool, but it is still necessary to research the validity of this technique in the context of pedestrian studies, as well as to create guidelines for its use. This work proposes a methodology for pedestrian behavior elicitation using virtual environments, in conjunction with surveys or questionnaires. The methodology focuses on gathering data about the subject, the context and the action taken; analyzing the collected data, to finally output a behavioral model. The resulting model can be used to improve the original virtual environment, providing better conditions for future experiments. A concrete implementation was built based on this methodology, serving as an example for future studies. A virtual environment with several data collection mechanism was developed. The environment was used in conjunction with two surveys in a experiment in order to collected behavioral data about crossing. In the experiment the subjects controlled a virtual avatar through an HTC Vive and were tasked with traversing between two points of a city. The data collected during the experiment was analyzed and used to create a model for the pedestrians speed taking into account its actions and perceptions. The proposed methodology was successful in gathering the required data and make use of it to create behavioral models.

Resumo

A simulação e modelação de pedestres desempenha um papel fundamental na redução de riscos e custos de implementação. Estes modelos necessitam de representar de forma preciso o comportamento dos pedestres. Identificar e recolher comportamento humano não é, no entanto, uma tarefa trivial. A utilização de ambientes virtuais têm vindo a ganhar destaque como uma ferramenta para a recolha de comportamentos. No entanto, ainda é necessário estudar a validade desta técnica no contexto do estudo de pedestres, assim como criar precedimentos padrão para a sua utilização. Este trabalho propõe uma metodologia para idenficação e recolha de dados acerca do comportamento de pedestres, utilizando ambientes virtuais em conjnto com questionários. A metodologia é focada na recolha de dados sobre o sujeito, o contexto e a ação tomada, seguida da análise dos dados recolhidos, e finalmente da criação de um modelo comportamental. O modelo resultante pode posteriomente ser usado para melhorar o ambiente virtual, de modo a providenciar melhores condições para trabalhos futuros. Baseando-se nesta metodologia, uma implementação foi criada de modo a servir de exemplo para utilizações futuras. Um ambiente virtual repleto de mecanismos para a recolha de dados foi desenvolvido. O ambiente foi usado em conjunto com dois questionários para recolher dados acerca do processo de travessia das ruas. Durante a experiência os particpantes controlaram um avatar virtual através de um HTC Vive e cumpriram a missão de fazer a travessia entre dois pontos de uma cidade. Os dados recolhidos durante a experiência foram analizados e utilizados na criação de um modelo para velocidade dos pedestres, que tinha em atenção as suas ações e perceções. A metodologia proposta foi bem sucedidada na recolha dos dados pretendidos e na utilização desses dados para criar modelos comportamentais.

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Chapter 1

Introduction

This section serves as a preface to the dissertation proposal. It introduces the reader to the importance of pedestrian modelling and simulation while identifying its current issues. Virtual environments are introduced as a possible solution to these problems. The research questions are identified, and the main objectives and contributions are highlighted. Finally, an overview of the document structure is presented.

1.1 Context

Shibuya Crossing, a famous scramble crossing in Shibuya, Tokyo, is one of the busiest pedestrians crossings in the world, where it is estimated that up to 2500 pedestrians cross each time the traffic lights change during rush-hour[1]. While most crossings cannot reach such high numbers, the growing population and the trend for urbanization gives birth to new challenges in city planning and transportation. It is predicted that the human population will surpass eight billion in 2023[Uni17], with nearly 57% of them living in urban areas[Uni18]. Due to the rise of life expectancy and the median age[Uni17], the need to accommodate senior citizens becomes an important aspect to take into account. These emerging problems are present in our cities and can be observed in several domains.

According to the World Health Organization's report[Org18], road safety is a major concern in today's society. Worldwide, road traffic injuries are the eighth leading cause of death, with 1.35 million fatalities every year. The scenery is even more sinister in children and young adults were road fatalities are the main cause of death. The pedestrians sum 23% of all fatalities in traffic accidents.

Additionally, social problems are formed due to the automation trend and the introduction of new technologies. For instance, as the eventual implementation of fully automated vehicles[Lit17]

[1] https://www.worldatlas.com/articles/what-is-the-world-s-busiest-pedestrian-crossing.html, last accessed: July 3, 2019

nears, the receptivity of pedestrian towards these machines turns into a relevant research topic [DRSG18]. In sum, it is important to predict the impact of new policies before their implementation [Tek06].

These trends demand smarter and more efficient solutions, as well as new tools and techniques to assist designers and scientist in data collection and result forecasting. Modelling and simulation form an important domain of research as they can provide estimations of the behaviour and evolution of complex systems[Bat07]. Due to the nature of the context, these techniques are of utmost utility in reducing cost and risks, as, according to Batty, urban simulations allow for a hypothesis to be tested and applicable without concrete experimentation[Bat09]. Simulation plays a crucial role in improving urban conditions by facilitating the conduct of experiments that might have been impossible due to safety or monetary costs[AELJ04]. For this to be possible, accurate models are needed, especially those of pedestrians. Not only are they the most vulnerable group[Org18], but their interactions with vehicles are frequent crossings, the most dangerous one[AELJ04]. Pedestrians models are a contemporary and essential field of study, which has direct implications in urban settlements.

1.2 Motivation

The task of studying and modelling pedestrian behaviour is not trivial. Problems arise not only from the process of modelling but also from data collection.

In the context of modelling, models are defined as a representation of objects, behaviours, or systems[2], where the main objective is simplification[GK15]. As an inherent result, models are highly susceptible to bias, which can be introduced not only by the modeller's assumptions but also by the modelling methodology[Ste02]. This can raise uncertainties in the moment of evaluation.

According to Jian et al.[JLD05], when compared to other vehicles, pedestrians present a significantly more complex behaviour, not only because their range of actions is more flexible, but also due to not being restricted to lanes. Ronald[Ron07] added that pedestrian behaviour reflects both conscious and unconscious movement, which makes it more unpredictable.

Lastly, observing human behaviour is a laborious and expensive task. Most techniques not only carry high costs or require strenuous efforts, but are also often limited on both in the variety and accuracy of the information they can capture[MBR+09].

A possible solution to these problems might rest in the use of virtual environments. Virtual reality provides a sense of immersion by creating simulated environments that can recreate and transmit realistic sensory experiences to the users[Ste92]. By relying upon this sense of immersion it might be possible to elicit valid behavioural data while benefiting from the accuracy and variety provided by completely controlling the simulated environment.

While virtual reality has frequently seen use in the context of entertainment[Lin17] or training [SCG97], applications to behaviour research have been emerging. Almeida et al.[AJF+14] proposed a framework that relied on virtual environments to create agent-based models capable of

[2] https://www.iep.utm.edu/models/#H3

replicating pedestrian behaviour in evacuation situations. The project SIMUSAFE[3] contemplates the use of simulated environments to collect behavioural data of vehicles and pedestrians. Whether or not the data this technology can provide is valid is therefore pertinent to this context.

1.3 Research Questions

Assessing the validity of virtual reality as a tool for behaviour elicitation rises several problems. These problems include the determination of which data can and should be collected and the subsequent analysis and transformation into a working model. As such the following research questions were identified:

RQ1: How do modern behaviour elicitation techniques compare to traditional ones?

Modern approaches such as experiments in virtual environments and serious games make use of contemporary technology and devices to facilitate behaviour elicitation. This does not, however, uproots the validity of older methods such as observations and questionnaires. If so, then how do these techniques differ and what advantages they possess one over another?

RQ2: What metrics must be collected in order to understand pedestrian behaviour?

Pedestrian behaviour is not simple[JLD05]. One must first clarify what is pedestrian behaviour and then understand how can it be observed and recorded. Not only it is necessary to identify what metrics can be used to represent pedestrian behaviour, but a way to collect them must be found.

RQ3: How can the collected data can be effectively used to create realistic pedestrian agents?

After obtaining the aforementioned data, it can serve as a base to create pedestrians agents. One must first, however, understand how can this process be done, and if there is space for automation.

These three questions form the core of the literature review and methodology. It is expected that through this document and the proposed solution, these questions can be answered to a degree.

1.4 Objectives and Contributions

The main goal of this work is to demonstrate the suitability of simulated virtual environments as an auxiliary tool for behaviour elicitation and pedestrian simulation. Taking this goal and the previously defined research question, the following objectives were identified:

- Examine and compare the current behaviour elicitation approaches, identifying their main challenges.
- Identify common metrics and behaviours that can be captured through the use of virtual environments in the context of pedestrians.
- Examine the several approaches to pedestrian modelling, especially agent-based models.

[3] SIMUSAFE project official website, http://simusafe.eu, last accessed: July 3, 2019

- Build a simulated environment and implement the necessary mechanisms needed to extract the aforementioned metrics.
- Design an agent-based model using data retrieved from tests performed in the simulated environment with real pedestrians.
- Assess and verify the validity of the solution as a tool for behaviour elicitation.

By fulfilling these objectives it is expected that this work can offer some contributions and insights for future researches.

- **Virtual Environment suitable for behaviour elicitation.** The simulated environment will provide a set of mechanisms that can capture varied information about the behaviour of a pedestrian. It is aimed that this environment can be easily expanded to capture new metrics relevant in future experiments.
- **Guideline of Metrics that represent behaviour.** Through the development of this work, the metrics that can be used to represent behaviour will be identified. This process may serve as a guideline for future projects.
- **Pedestrian Model.** From this work will result a pedestrian model. One will be able to use this model in new experiments or simulations.
- **Validation process.** This work will use data captured in a virtual environment to create pedestrian models. The process of validation of this kind of data will probably offer challenges not seen in real data.
- **Assessment of virtual environments as a tool for behaviour elicitation.** The final result will be an assessment of the validity of the virtual environments as a tool for behaviour elicitation. On a positive result, this will open a path to facilitate future research in the context of pedestrians and road safety.

1.5 Document Structure

This document is structured in four chapters and their respective subdivisions. Each chapter begins with a short introduction of its contents and objectives. These chapters are:

Chapter 2 presents a literature review focused on the scientific background of the domains and concepts that are related to the problem in question or, while not directly related, present a significant relevance to the proposed solution. Each domain and concept is first defined and explained, followed by a presentation of some related works. Finally, an overview of the literature is presented as a comparison of the past works and the proposed solution.

Chapter 3 contains the authors proposal to the problem. A pipeline to elicit behavioral data in an virtual reality experiment is explained. Then, guidelines about how to build the virtual environment, what metrics to collect and how to collect them are provided. Matters concerning data storage, data analysis, modelling and utilization of the results in further experiments are also addressed.

Chapter 4 presents an implementation of an experiment which follows the methodology presented in **Chapter 3**. The material used is shown, and the virtual environment used is described. The mechanisms implemented to collect data are explained in detail. Finally, the experimental protocol is presented.

Chapter 5 addresses the results of the experiment. The subject population and the data collected are analyzed and discussed. An automatic analysis is performed on the some time series extracted from the collected data. The resulting prediction models are analyzed and discussed.

Chapter 6 closes the work by identifying and analyzing the main findings and conclusions.

Chapter 2

Related Work

This chapter aims to provide a literature review that summarizes and defines the key concepts and domains related to this dissertation problem and proposed solution. Through the specification of the problem's context and objectives, the following areas of research were identified: Pedestrian Modelling and Behaviour Elicitation. For each of the aforementioned areas, a review of their background and main works is done, followed by an in-depth research about how these areas are applied to this dissertation problem. Finally, the main findings are summarized and discussed.

2.1 Pedestrian Modelling

An introduction to pedestrian modelling is given is this section. First and foremost, the background is reviewed in order to contextualize the reader on this topic. In order to understand the several families of existing pedestrian models, a taxonomy is presented. Finally, an attempt at delving deeper into agent-based models and its applications to pedestrian modelling is given. For further reading on this topic, the reading of [MGLGFF17] is recommended.

2.1.1 Background

Studies on pedestrians and crows date back to the 19th century when concepts such as "crowd psychology" where first used[Gus95]. During the first two-thirds of the 20th century, scientists focused on understanding which factors induced pedestrians to take high-risk actions. Studies on the effect of reduced night visibility[Fer44], the relationship of accidents to the distance from their homes[Cha48], and the factors related to traffic violation[LBM55] are examples of such works. Only in the last third of the century that the number of pedestrian studies escalated. One of the most prominent works was Fruin's research on the comfort level of pedestrians[Fru71], which resulted in the definition of the concept "Level of Service". Gipps and Marksjö[GM85] developed one of the first pedestrian models used for simulation. The model was notably particular because it relied upon repelling forces originated from each pedestrian to move them over a grid. The simulation was computed using a microcomputer and it was one of the earliest to deliver a graphical display in this context.

Pedestrian modelling and simulation have historically been used in several contexts. Helbing et al.[HFV00] through the simulation of panic scenarios studied how different behaviours would affect the evacuation of individual pedestrians [ARF+14, ARJ+17] and crowds [ARAO15, ERFO09]. Other contexts included architecture[OM93], urban planning[JB99], and tourism[GCL+03]. It is especially important in the domains of road safety, traffic and transportation[OIF+05, KR07].

2.1.2 Taxonomy

A not small number of approaches to pedestrian modelling have proposed raising a need for some way to classify and differentiate them. Three criteria were identified.

A classic classification based on the scale is described by Lenner et al.[HPL+00]. This classification divides models into microscopic, mesoscopic and macroscopic.

- In *Microscopic Models* each individual is a treated as a separated entity with their own characteristics and dynamics, providing a view on local interactions and behaviours.
- *Mesoscopic Models* bridges Microscopic and Macroscopic Models. Individuals, while still present, are moved by group dynamics.
- Finally, *Macroscopic Models* erases any presence of individuals, instead of using representations based on density and flow.

Another approach was proposed by Michon[Mic85] in the context of vehicles and later adapted for pedestrians by Airault et al.[AELJ04] and Hoogendoorn and Bovy.[HB04], based on the level of the behaviours. This approach defined three levels for pedestrian behaviours and classifies the models according to the level they interact on: strategical, tactical and operational.

- *Strategical Level* corresponds to high-level decisions pertinent trip planning, such as goal, departure time and route choices.
- At the *Tactical Level* occurs the manoeuvres caused by the situational environment. This includes behaviours such as obstacle avoidance, turning and overtaking.
- The *Operational Level* reflects the most basic, automatic behaviours such as walking.

Martinez-Gil classified models according to the type of algorithms used[MGLGFF17]. Figure 2.1 represents the top two layers of Martinez-Gil classification. As can be observed in this figure, the author defined five categories: mechanics-based, cellular automata, stochastic, agency, and data-driven models.

Mechanics-based models are fundamentally inspired by mechanical systems. From a macroscopic point of view, pedestrian crowds can be interpreted as continuous, as described by their flow and density[MGLGFF17]. Henderson[Hen74] and Helbing[Hel92] proposed fluid dynamics model, based on the similarity between crowds and well-known fluid physics distributions. Later

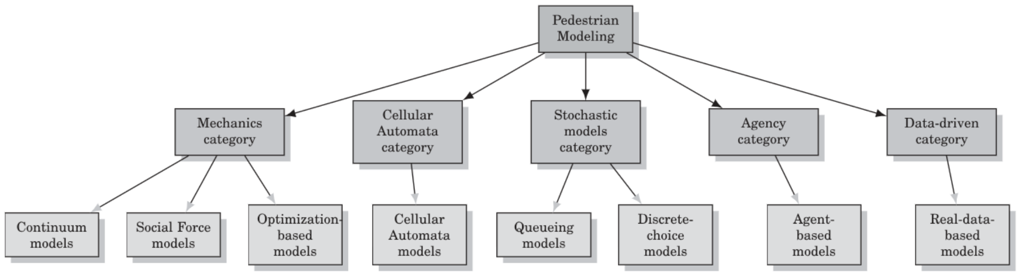

Figure 2.1: Martinez classification of pedestrian models(adapted).

works merged continuous distributions with potential fields based on crowd density[TCP06]and cost to reach goals[HWZ+09]. A variation of the fluid dynamics models is the flow tiles model [Che04], where the flow is applied to small spaces, forming a larger and more complex flow system.

Alternative approaches include the mass-conservation models based on the mass conservation equation[BBGP16]. Another alternative, based on a theory first proposed by Daganzo[Dag94, Dag95], where space is organized in cells that follow the principle of mass conservation prevails, is the cell transmission model[ASKT07]. While macroscopic continuum models are, in general, computationally lighter when compared to other approaches, a common characteristic in these approaches is the assumption that paradigms of continuum mechanics are valid for pedestrian crowds[BD11].

On a microscopic scale, Helbing proposed the Social Forces Model[HM95], where each "pedestrian acts as if he/she would be subject to external forces". These external forces represent both internal aspects such as the desired direction and external aspects such as the distance to other pedestrians or objects. Several implementations of the model have been successfully introduced[PAB07, HLTC10], inclusively in the context of emergency situations[WCM+12]. Chraibi identified several flaws in this kind of approach due to the fact that pedestrians movements don't always follow physics laws[CSSK11], such as unnatural oscillations or high speeds resulting from the superposition principle of forces.

Martinez-Gil also includes optimization-based models in the Mechanics category. Optimization based models, in general, try to minimize the effort and can be applied to several problems, including walking[HB03] and route selection[FSLL14]. Ramming proposed an alternative to the route finding problem by using maximization of utility instead of minimization of effort[Ram02].

Cellular automata based models represent the space with a grid, where each cell can be occupied by pedestrians. The first models, proposed by Blue and Adler. [BA98, BA01], limited the number of pedestrians in each cell to one, but later works started supporting multiple pedestrians in each cell[GHW12]. Each pedestrian moves according to a set of rules, generally dependent on the status of the surrounding environment.

A variant to this model is the field model[BKSZ01, Sch02], where each cell contains a probabilistic distribution of the movements the pedestrians can take. The methods and criteria for calculating the distribution vary from work to work[Har10, SK12].Other variants include Kretz's global distribution[KT09] and Leng's hexagonal tiles[LWZX14].

While most cellular automata based models are of stochastic nature, hybrid approaches exist such as the forces/cellular automata model[WGYFBHWC06] and the agent/cellular automata models[DTJ00]. Cellular automata are computationally efficient but draw criticism due to being discrete models[MGLGFF17, VBD+16].

Stochastic models rely on probabilistic distributions. Two families of models exist in this category: queuing and discrete choice.

Queuing models originates from queuing theory, which defines the concepts of nodes and costumers. Each node represents a service provider that forms a queue if the costumers request a larger service the provided[RAA+13]. Lovas[Løv94] proposes a model where each section of a facility is represented by a node. Each pedestrian is then treated as an object that flows through a queueing network. Okazaki and Matsushita[OM93] proposes a forces-queuing hybrid approach. Pedestrians normally use a force model, but in designated spaces, a queue behaviour is applied.

Queuing models are more suited for optimization than descriptive tasks[VBD+16]. Their main drawback is the inability to capture complex behaviours like merging and intersecting[OM93]. According to Martinez-Gil et al.[MGLGFF17], this happens because queues are unidimensional.

Discrete choice models use a different approach. According to Robin et al.[RABC09], these models are based on random utility theory, where a decision-maker that is making a choice is considered. For each possible action, a utility function is calculated, with the highest value one being chosen. This utility function depends on a deterministic component, that results from the relevant attributes and a random error that follows a probabilistic distribution.

This kind of models can operate at several levels, including activity choice[DBAT+04], transportation mode choice[ESG04] and walking behaviour[ABW06]. A possible downside may lay on the fact that the choice is always the action with higher utility, which is not always the case with real pedestrians[MGLF15].

Agent-based models represent pedestrians through the use of agents. Woolridge and Jenning [WJ95] defined an agent as a software system that possesses the following characteristics: autonomy, social ability, reactivity and pro-activeness. Autonomy refers to the ability to act without the need for human intervention. Social ability refers to the ability to interact with other entities(agents or humans). Reactivity refers to the ability to perceive and react to an environment. Pro-activeness refers to the ability to choose and act on self-defined goals. The author identified that sometimes notions such as beliefs, knowledge, intention or emotional states used to characterize agents.

Due to their characteristics, there is a general consensus in the suitability of agent-based models to model microscopic pedestrian systems[PYG09].The most evident flaw with these approaches is the computational cost[MGLGFF17]. This is due to each agent being responsible for its own perception and decisions which severely affect the performance when the number of agents grows.

Data-driven models are based on real data instead of mathematical formulas or probabilistic distributions.

Lerner et al.[LCL07] proposed a crowd simulation technique that extracted trajectories from crowd videos to generate reactive rules. A similar approach was applied by Porzycki et al. [PLMW15], who used data obtained through a depth camera. Ju et al.[JCP+10] extracted data from several different samples and, through interpolation created new synthetic crowds. Pfeiffer et al.[PPS+18] used the data to train a neural network capable of simulating pedestrian-pedestrians interactions.

Some of these approaches create new models from data, while others just train an existing model. The main drawbacks of these techniques are the difficulty of obtaining data[MGLGFF17] and low explanatory power[PLMW15].

In table 2.1 an overview of the main characteristics identified in the mentioned models are presented. The characteristics taken into account are the scale, from macroscopic to microscopic; if space is represented as continuous or discrete; and the main merits or drawbacks typically associated with these models.

Table 2.1: Characteristics of Pedestrian Models

Model	**Scale**	**Space**	**Main Merits/Critics**
Continuum (Fluid/Gas)	Mac	Cont	Assumption of validity of continuum mechanics in pedestrian crowds.
Social Forces	Mic	Cont	Assumption that pedestrians follow physics laws.
Optimization	Any	Cont	Transformation between optimization and movement variables is not trivial.
Cellular Automata	Mic	Disc	Computationally efficient. Space is discrete.
Queuing	Any	Cont	Suitable for optimization tasks. Some crowd behaviours cannot be captured.
Discrete choice	Mic	Cont	Best option is always chosen.
Agency	Mic	Cont	Naturally suitable to reproduce pedestrian behaviours. Not easily scalable.
Data-driven	Mic	Cont	Data is hard to collect.

2.1.3 Agent-Based Models in Pedestrian Simulation

Agent-based models take the form of multi-agent systems, where each pedestrian is represented by an agent[MGLGFF17]. Papadimitrou et al.[PYG09] recognized that agent-based models are suitable to represent and simulate pedestrians at a microscopic scale. The author pointed out agents can be given certain capabilities, such as vision, cognition and learning, that can be used to incorporate complex rules and behaviours. Wooldrig and Jenningse[WJ95] mentioned that agents often conceptualized using humans as the base, integrating anthropomorphic notions such as intentions and emotional states.

In multi-agent systems, agents can present different levels of reasoning[SV97]: deliberative and reactive. Deliberative agents keep a representation of the world and are capable of planning and acting upon this representation, defining goals and expectations. Reactive agents lack any kind of memory, displaying behaviours that can be categorized as reflexes when the right conditions are met.

Agent-based simulations are not easily scalable[MGLGFF17]. Chen et al.[CWW+13] proposed the use of the Grid Simulation Architecture as a solution to support large scale simulations. Through the use of this technique, the author realized an evacuation simulation containing a huge crowd of deliberative pedestrian agents.

Reactive behaviour is not mandatorily simple. Paris et al.[PPD07] proposed a reactive agent model to simulate collision avoidance behaviours between pedestrians. Each agent was capable of predicting the trajectories of the other agents and calculate safe routes. While such a process is not trivial, it is merely a reaction to the world the agent perceives.

Ondřej et al.[OPO+10] applied cognitive science knowledge to formulate a rule-based model based on visual perception. Each pedestrian was capable of simulating a sense of vision. Locomotion was controlled through a set of reaction rules that changed direction and speed depending on the visual stimulus. The author approach was based on these rules on collision prediction and avoidance. Hughes at al.[HOD15] observed that crowd density affects pedestrian behaviour and built onto the original approach by incorporating this notion as the key element to determine the chosen reactions.

An agent-mechanics based hybrid architecture for pedestrian simulation was proposed by Crociani et al.[CPVB15]. The model operated on the tactical and operational level. The agents were responsible for tactical level decisions, such as obstacle avoidance and overtaking manoeuvres. The operational level actions were abstracted through the use of a floor-field.

An interesting approach to pedestrian modelling was proposed by Martinez-Gil et al.[MGLF14, MGLF15]. The author developed the MARL-Ped framework which applied reinforcement learning algorithms to generate the pedestrians behavioural policies. Four advantages of this approach were identified: each agent learns different policies, the learning phase is separated from the simulation, the existence of model-free techniques(such as Q-learning) that exempt the need of a model intervention, and the possibility of incorporating external knowledge using knowledge transfer techniques.

Casadiego and Pelechano[CP15] applied reinforcement learning techniques to solve obstacle avoidance problems. With this approach, one agent was trained to reach a goal, while avoiding static obstacles, and the resulting knowledge was then transferred to other agents. While the training phase was separated from the simulation phase, the author proposed its extension so that the agents could also learn during the simulation.

Several transport and traffic simulators based on multi-agent systems exist, of which a significant part supports pedestrians. Some of these simulators are the result of scientific research, while others are for commercial use, such as SimTread[1] and MassMotion[2].

[1] SimTread product page on Vectorworks official website, https://www.vectorworks.net/community/partner-community/industry-partners/simtread, last accessed: July 3, 2019

[2] MassMotion product page on Oasys official website, https://www.oasys-software.com/products/pedestrian-simulation/massmotion, last accessed: July 3, 2019

Research oriented simulators include ARCHISIM[DEV95] and MATES[Yos06]. The mentioned simulators were originally used for car simulation but have since then been expanded to include pedestrians. Airault et al.[AELJ04] expanded the ARCHISIM simulation tool to simulate pedestrians behaviour on zebra crossings. This behaviour was derived from the pedestrians perception of the environment, which was defined as the conjunction of an infrastructure(road and objects) and its users(pedestrians and vehicles). Fujii et al.[FUY17], achieved a mixed simulation framework by expanding the MATES simulator, which only contained cars, to include pedestrians and trams.

2.2 Behaviour Elicitation

An introduction to behaviour elicitation is given in this section. The concept of behaviour is defined and the background of behaviour elicitation is explored. Several techniques used in behaviour elicitation are reviewed and compared, and recent pedestrian behaviour elicitation works are presented.

2.2.1 Background

Before exploring behaviour elicitation, one must first answer the question: "What is behaviour?". Airault et al.[AELJ04] defined behaviour as "the set of the actor's reactions in front of what it detects of his environment". He further specified that these actions refer, not only to physicals actions but also to internal changes. This definition suggests the involvement of an actor, its perception of the environment and its actions.

According to Rossetti et al.[RAKG13], behaviour elicitation goes beyond simply monitoring and generating statistics. According to the authors, it also refers to implementing the mechanism needed to capture the semantics of decisional processes. This process carries great relevance as an auxiliary tool to understand how subjects interact with the environment, as well as how the level of comfort and safety affects their decisions[DMM05].

2.2.2 Techniques for Behaviour Elicitation

A large number of techniques and technologies have been developed for the purpose of eliciting behavioural data. Here five common types of approaches are analyzed and compared: direct observation, surveys, location tracking, video analysis and serious games.

Observation studies have been used for a long time to collect data about human behaviour. According to Bernard[Ber17], the first records of a systematic method for carrying out observation studies is credited to Malinowski[Mal22]. While this method carries no inherent monetary costs, it can take years to complete depending on the context the study is done.

Observation entails the need for an observer. Whether the presence of an observer is known by the subjects is an important factor in the validity of the findings, because it alters their behaviour, an effect called reactivity[BFZ79]. Hughes and Haynes[HH78] identified five other concerns about the direct observation's validity: excessive variances in observers and/or situations, erroneous sampling processes, bias introduced by the observer and inaccurate recordings.

Similar concerns appear when contrasting laboratory and real-world observation. According to Altmann[Alt74], laboratory research provides more accurate data, but the sampling and artificial environment can cause distorted behaviours. On the other hand, observations on the real-world are more generalizable but it is harder to get so accurate data due to the lack of laboratory equipment.

Despite these flaws, observation possesses an advantage in the scope of information it can obtain. Not only it captures the subject's behaviours, but it can also capture the context were they happen[GSW+97].

Survey Techniques include questionnaires and interviews. These techniques rely on subject descriptions and opinions, instead of using an external observer. When compared to other methods, they are relatively cheap and allow for the collection of varied data from large samples[MBR+09].

Questionnaires, as defined by Millonig et al.[MBR+09], provide a written set of questions and possible answers. Due to this strictness, standard questionnaires are capable of providing data that can be easily analyzed. This, however, can be a disadvantage because questions might be misinterpreted or the answer may be insufficient. Questionnaires are frequently used in conjunction with other methods[PLY15, AJF+14].

Interviews possess a higher degree of freedom because the answers are not a locked set. An interview can be structured, where only a standard set of questions is asked, or non-structured where the discussion just follows a general guideline[MBR+09]. While generally personal, interviews can be also applied to a group[SBF+15]. While more information can be collected through interviews than with questionnaires, they are harder to conduct and the information cannot be easily analyzed.[Cor03].

While survey techniques can capture a great range of information, there is no guaranty of its accuracy, because they depend on the on the subject interpretation of the questions. The validity of these techniques is also questionable because people tend to portray their "ideal-self" instead of their real one when knowingly being observed[MBR+09].

Location tracking refers to techniques that record the subject position over a period of time. While location tracking can be done using the aforementioned methods, recent technologies facilitate this process by providing accurate data and relieving the need for an observer[MBR+09]. This essentially due to the growing presence of mobile devices, which support this kind of technologies [MC13].

Several tracking technologies are currently available. The most typically used technology is the global positioning system (GPS)[Sho08]. This technology provides accurate positioning by relying on non-geostationary satellites. While fairly accurate outdoors, positioning becomes inaccurate or impossible indoors, due to signal obstruction. Yoshimura et al.[YSR+14, YAS+17] proposed the use of Bluetooth. While less accurate and shorter in range than GPS, it can be indoors. Other techniques include the use of cell-based positioning, laser range scanner, sensor mats, radio frequency identification tags and wireless local area network[MBR+09].

Although location tracking can only provide positioning information, these technologies are typically cheap and easily available. They are less invasive than direct confrontation methods and depending on the technology, can provide very precise data[MBR+09].

Video Recording and Analysis refer not only to surveillance but also to the use of computer vision algorithms as an auxiliary tool. Videos can be used to support other techniques as an integrating part of surveys[MGRB17] or for *a posteriori* observation[GLSY16].

The major advantage of videos, though, is the possibility of applying Computer Vision to automatically detect human behaviours. According to Millonig et al.[MBR+09], this process typically consists of three steps: object recognition, tracking and analysis. It can be applied both indoor or outdoors, but accuracy varies with the hardware setup, the context and the algorithms used.

Nowadays cameras are not restricted to collecting color images, as technologies like depth-imaging have been made more accessible. Computer vision is by itself an expansive research topic. Afsar et al.[ACS15] reviewed several computer vision algorithms that can be applied to human behaviour elicitation.

Virtual Environments and Serious Games are one of the most recent developments in this topic. Steuer[Ste92] defines virtual reality as a "real or simulated environment in which a perceiver experiences telepresence", where telepresence means to feel a sense of presence in an environment through the use of a medium. This medium can take the form of the popular headmounts or virtual reality glasses, Cave Automatic Virtual Environment or even a single monitor setup[FO15].

Kinateder et al.[KRN+14] identified several advantages of virtual reality, including precise measurements, safety, low costs and replication. While the author points out that are still not enough studies about the validation of these methods and not all senses can be reproduced yet, it is known that virtual environments are already realistic enough to be used for training in military and sports.

Serious games intrude in this context as a possible implementation of this technology. Zyda [Zyd05] pointed out that serious games behind the components of traditional games (story, art and software) by combining pedagogic activities. According to Rossetti et al.[RAKG13], the main purposes of serious games are behaviour assimilation, behaviour persuasion and behaviour elicitation. While serious games can take the form of virtual reality experiences to elicit behaviour[AJF+14], no works were found that proposed other forms of games as a behaviour elicitation tool.

When analyzing the validity of these techniques, it is useful to distinguish between internal and external validity.

- Internal Validity represents the extent to which the resulting statements, the identified cause-effect relations are correct[Mer98]. It expresses if the obtained conclusions are congruent with reality and how accurate they are. Low internal validity can result, for example, from inaccurate measurements, insufficient or meaningless data, and biases introduced by the method or researchers[Alt74].

- External Validity represents how generalizable the data is; if it can be applied to other situations[Mer98]. Low external validity is a common result of intrusive methods inducing unnatural behaviours. Such behaviours, while possibility internally valid, can only be applied to the testing conditions and cannot be generalized[Alt74].

In table 2.2 an overview of the mentioned techniques is presented. It the technique internal and external validity, whether its setting is on a laboratory or in the field, and what kind of behaviour information it can be captured.

Table 2.2: Characteristics of Behaviour Elicitation Techniques.

Method	Internal Validity (accuracy)	External Validity (generalization)	Setting	Data Captured
Observation (disguised)	Low	High	Field	Descriptions and statements
Observation (non-disguised)	Low	Low	Field	Descriptions and statements
Observation (in-lab)	High	Low	Laboratory	Descriptions and statements
Survey techniques	Low	High	Both	Descriptions and statements
Location Tracking	Varying	High	Field	Position
Video Analysis	Varying	Varying	Both	Any data
Virtual Environments	High	?	Laboratory	Any data

2.2.3 Pedestrian Behaviour Elicitation

Pedestrian behaviour is complex. Jian et al.[JLD05] pointed out that unlike vehicles, it is not restricted to lanes or by driving regulations. According to Haghani and Sarvi[HS18], it is dependent on the context, as a variety of factors can directly influence the range of behavioural responses observed[HS18]. Behaviour in dense crowds or lightly congested areas is different. The same applies when distinguishing panic and normal situations. Even in panic situations, different causes of panic can trigger completely different responses. From the elicitation perspective, this represents a high difficulty in capturing all these behaviours and their underlying semantics.

Studies on pedestrian behaviour typically fall in the contexts of evacuation and panic situations, crowd motion, or specific scenarios such as crossings.

Studies on evacuation and panic situations have been a long time challenge for scientists. Because these scenarios imply a considerable risk, they could not be naturally observed[DRSG18]. This kind of scenarios are typically investigated through the use of post-disaster surveys, evacuation drills, virtual environments and when available, video analysis[HS18].

Virtual reality experiments are particularly useful because they can be used to observe these scenarios with a minimal level of risk[DCS+17]. Almeida et al.[AJF+14] proposed the SPEED framework. This framework detailed a process of building agent-based models of pedestrians in evacuation situations. The agents were a result of data collected through the cross-validation of data obtained from questionnaires and serious games. The mentioned serious games were virtual reality experiments, that simulated several evacuation contexts. The data obtained through the questionnaires was related to subject characteristics and habits, while the virtual reality experiments evaluated the tendency to take certain actions. The advantages and disadvantages of using this technology were studied by Kinateder et al.[KRN+14].

Evacuation videos are a good source of data because they reflect real situations. Gu et al. [GLSY16] analyzed several videos of students evacuating during an earthquake. The author manually recorded how many students evacuate per second and compared it to a normal situation. It was, however, pointed out the scarcity of material of this nature.

The study of these situations is an important and growing research area. For further reading on study methods for evacuation scenarios, one can address [HS18].

Pedestrian crowds have been another important focus of study. According to Moussaid et al.[MPG+10] a large part of pedestrian traffic is made up of groups. Kok et al.[KLC16] identified three main characteristics of crowds: decentralization, collective motion and emergent behaviours.

The study of crowds can be performed from a macroscopic or microscopic perspective. Examples of macroscopic studies include Zhang et al.[ZWYC13] investigation of unidirectional crowd movements during a festival. People were counted through the use of infrared counters and image processing. Gorrini et al.[GVB16] analyzed the movements of older pedestrians in crowds. Data collection was performed through the use of a video tracking system. The system captured the trajectories and speed of older pedestrians, which was compared with the data obtained from younger ones. The author further compared singular pedestrian with groups, observing lower variability of speed in groups.

A Microscopic study was performed by Rio et al.[RDW18] who analyzed the effect of local interactions in the collective motion of crowds. The author used a virtual environment to study the effect of virtual pedestrians on the subject. Then the data was compared to an experiment performed with several groups of subjects.

Crowds are complex phenomena. For further literature in the subject, reading of [KLC16] is recommended.

Understanding pedestrian traffic also requires the elicitation of their behaviour in specific situations. The factors influencing crossing behaviour have been a recent focus of study.

Bernhoft and Carstensen[BC08] studied pedestrian and cyclists views on elements that affected their level of comfort and risk, as well as what influenced their route choices. The study was done through the use of an anonymous questionnaire. The collected information included age, gender, as well as a set of affirmations about what behaviours and the reasons why they were chosen.

Morrongiello et al.[MCSH15] used a virtual environment to study the effect of time pressure on crossing behaviour. The participants wore a virtual reality head-mount and had their movements captured through an optical-motion tracking system. The experiment scenario was a zebra-crossing which the subjects had to cross several times, both with and without time pressure. The collected information was about how many crossing opportunities had missed and how large the safe gap at the time of crossing. The same author later applied this process to further study kids perception of risk when crossing the road.

Papadimitriou et al.[PLY15] analyzed pedestrian behaviour with direct observation and questionnaires. The pedestrians were observed on a trip and confronted with a questionnaire that evaluated crossing habits. The subject actions and crossing conditions(road type, traffic flow, the presence of traffic control, infrastructure, obstacles and barriers) were registered by an observer.

Stefanova et al.[SBF+15] studied pedestrian risky behaviour at level crossings. The study was performed through the use of group discussion with regular users of a certain level crossing. Participants were tasked to discuss their habitual behaviour and unsafe crossing situations. Through this discussion, factors associated with safe crossing and violations were identified.

Another recent area of study lies in understanding pedestrian's focus of attention. This kind of works typically makes use of eye-tracking technologies to record what the subjects were looking at.

Zito et al.[ZCS+15] compared the crossing behavior of older and younger pedestrians. A virtual environment was presented through three monitors, and the subject movement was captured through a head and eye-tracking system. The experiment detected the subject direction of focus and recorded the number of missed opportunities to cross.

Meerhoff et al.[MBV+18] investigated the relationship between gaze behaviour and the trajectory of pedestrians in crowded places. The subjects were tasked to control a virtual pedestrian through a crowd, while their gaze direction was captured through an eye tracker. The results showed that most of the trajectory adjustments were preceded by a gaze behaviour.

Pedestrian display a large variety of behaviours. From the data collection perspective, this translates to the necessity of data collection and experimentation on a very large range of contexts.

2.3 Summary

In this chapter, the review of the literature was presented. The two identified topics (Pedestrian Modelling and Behaviour Elicitation) were discussed and the main techniques used for each one was identified. Here, a summary of the main findings will be given.

Several pedestrians models have been proposed over the years. Given Martinez-Gil classification, the five families of models(mechanics-based, cellular automata, stochastic, agent-based and data-based) were briefly described and compared. Agent-based models were recognized as the most suitable approach to model pedestrians. Several works and simulators using pedestrian agents were referred.

In the context of behaviour elicitation, it was identified that behaviour includes not only an action but also the subject and the perceived context. Several techniques were identified and analyzed: direct observation, surveys, location tracking, video analysis, serious games and virtual environments. Lastly, the main focus of recent researches has been presented.

Chapter 3

Methodology

In the previous chapters, the problem and its context were presented. Additionally, a literature review regarding the essentials aspects and variants of pedestrian models, as well as the major techniques used in behaviour elicitation studies, was presented. In this chapter, the methodology proposed by the researcher is described. Each of the steps will be detailed in the following sections.

3.1 Overview

Moving towards more realistic simulations and representation of pedestrians requires a better understanding of pedestrian's behaviour and decision making process. Reaching such understanding is, however, generally reliant on the study of real situations which, as previously mentioned, can potentially carry a risk for the subjects of the study. The studies can consequently raise ethical issues or be completely unfeasible. As such, it is important to find and study the feasibility of alternative methods to observe pedestrians. In this work, more specifically, the concept of Artificial Transportation Systems (ATS), relying on an artificial society of agents representing different actors in the urban setting, is of special interest [RLT11, RL15].

As previously mentioned, a potential alternative may rely on the use of virtual environments. In these environments, researchers can run realistic simulations of the world and its entities can be used to create situations that would be troublesome or impossible to produce in the real world. In the last chapter, several advantages of using virtual reality were identified, namely, the precision of measurements, safety, low cost and replication. Taking into account these characteristics, the importance of further analyzing this method becomes clear.

These characteristics are a defining trait of the use of virtual environments, which can be remarkably effective when properly applied to the pedestrian problem. In order to fully take advantage of this, a pipeline for the usage of virtual reality for pedestrian behaviour elicitation is presented here(see figure 3.1). The pipeline encompasses several processes, further explained in the following sections. These processes are simulation, data collection, data storage and transformation, data analysis and modelling.

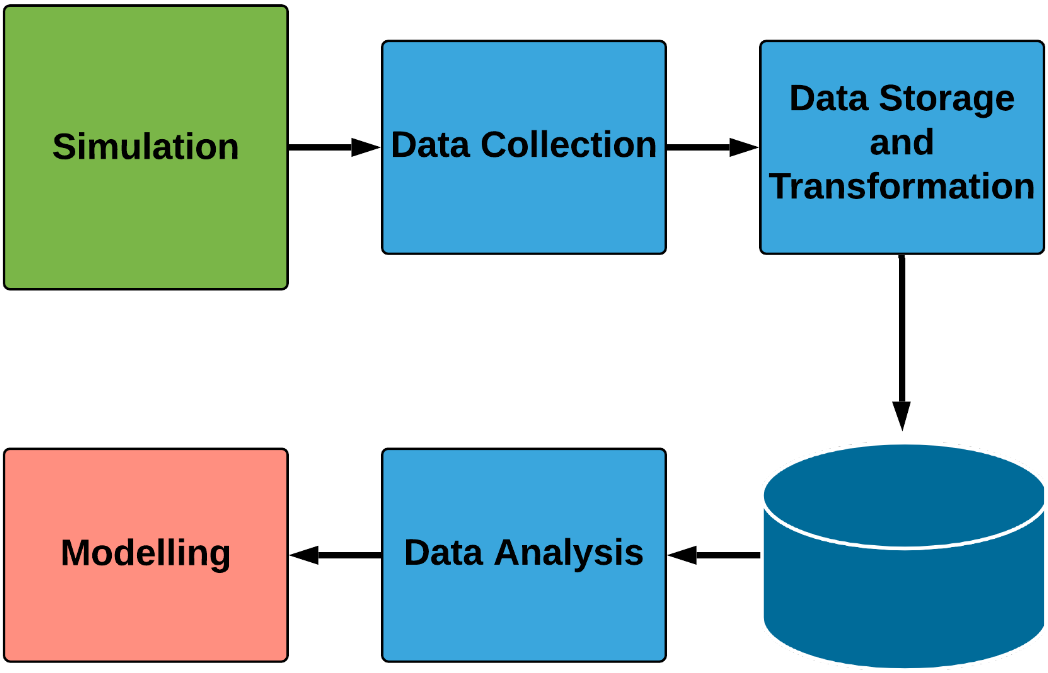

Figure 3.1: Pipeline for pedestrian behaviour elicitation.

3.2 Simulation

The most obvious and defining advantage of virtual reality lies in the ability to replicate an existing environment or creating a fictional one while still giving the user a sense of presence in that environment. Either way, this virtual environment is a simulation of reality which the user can interact with.

By simulating the various aspects of an urban environment, this virtual environment grows to become increasingly similar to the real world. The more complete, realistic and precise the simulation is, the less the subject will feel that it is fake. Subsequently, the subject's behaviour should be more natural and the validity of the data collected in this environment will rise. As such, one should aim to provide the best simulation possible in order to assure the collected data is valid.

Creating or improving a complete virtual environment is not a trivial task. Not only it is necessary to invest a large number of resources, but several aspects might not be yet fully understood or difficult to implement. One can, however, define a priority to which aspects are more important to the simulation. The author suggests a division in three layers(see figure 3.2).

The first layer is the world itself, as its presence is fundamental to perform any simulation. The roads, sidewalks, buildings and remaining objects form the base of the simulation. Not only

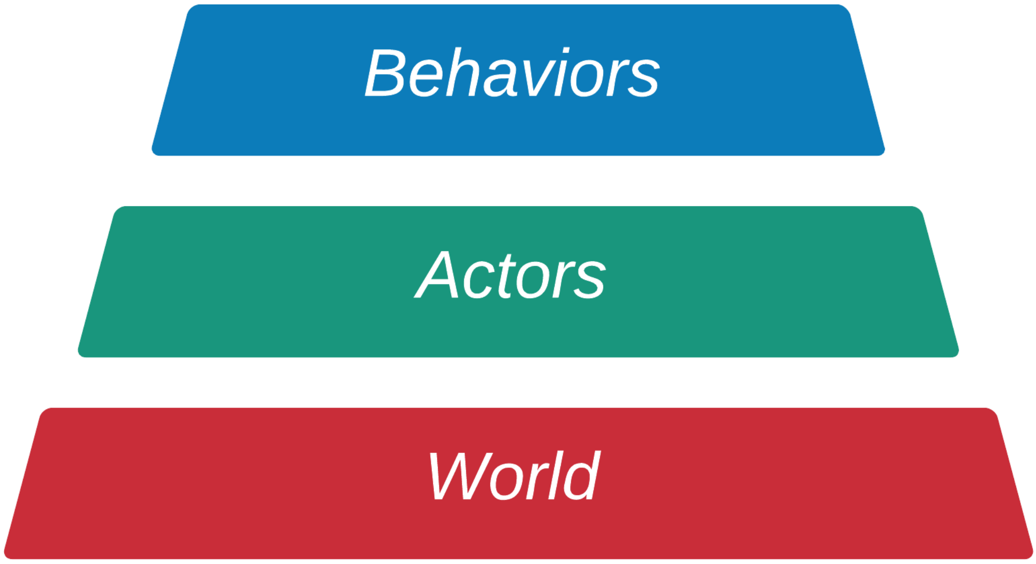

Figure 3.2: Aspects of simulation by level of priority and importance.

it is generally the first element observed by the subject, but it is also the only one that remains always present. As such, it can be said that the world is the element with the most impact on the subject's assessment of the authenticity of the virtual environment. It is important to create a world complete with many features. While simple studies can be performed with just a road and crosswalk; a more complete world, with buildings, weather, and other elements, will not only improve the subject's assessment but will also allow for testing with several different scenarios and conditions.

After the world is built, one can then start introducing the actors. Depending on the setting of the experiment, these actors can refer to other pedestrians, vehicles and even animals. Even if not directly related to the study, the introduction of these actors complements the world and augments the collection of possible scenarios available to the researchers.

The last step after creating the world and its actors is implementing, on them, realist behaviours. While their mere presence is enough to affect the simulation in a positive way, they should display some kind of behaviour. The most important element of their behaviour is perhaps the movement, but as more elements are added, the interactions between the actors and with the subject start to be relevant. By improving the behaviour of the actors, more complex scenarios, which take into account these interactions, can be studied.

Another factor to take into account when creating the virtual environment lies on improving the sense of presence. A defining characteristic of virtual reality is the creation of this sense of presence through physical immersion, which refers to synthetically stimulating the body senses through the use of technology[SC18]. As a result, it is important to simulate the human senses as close to reality as possible.

While in a perfect simulation all senses should be perfectly simulated, this is not currently possible. The most replicated sense is sight, which is perhaps the most important sense and thus a key component of any virtual reality simulation[MNB14b].Following it, the senses of hearing and touch are commonly replicated in most setups. While both are of significant importance to enhance the realism of the environment, devices to simulate the latter are still limited with most of them design solely for interaction with the hand[MNB14a].The other senses generally possess less impact and thus are generally not replicated in most systems yet. Aiming to provide a complete and precise sensory experience to the users improves their sense of immersion, and as such, impacts less on their behaviour.

3.3 Data Collection

The objective of the experiments is to gather data about pedestrians' behaviour. As identified by other authors[AELJ04, RAKG13], human behaviour amounts to more than a set of predetermined actions, but a result of a more complex interaction between an actor and the context (see equation 3.1).

$$Action = Actor \bigodot Context \tag{3.1}$$

The actor here mentioned refers to the subject which makes the decision and carries out, in this case, the pedestrian. Behaviour is dependent on the actor in the aspect that different actors can make different choices in identical situations. Several factors that influence the decision making process have been identified. Such factors include past experiences[JKG05], cognitive biases[WTS08], level of commitment[KJG05], and individual differences(age, socioeconomic status, etc)[DPF07].

Delving further into this concept, one can argue that even the same person can execute different responses in similar situations. Internal factors such as the emotional and physical state can impact the decision process, leading to different outcomes. It is then important to collect data about the actor, with the objective to understand not only its demographic characteristics but also to find some insight into its internal state and goals.

If the actor is the one responsible for making the decision, the context gives origin to the variables that serve as on input to that decision. The context includes not only the physical layout of the environment but also the entities there present and their interactions. One can go as further as to include all meaningful information available to the actor into this term. A relevant aspect lies in the fact that the actor itself, as well as its interactions with its surroundings, are an integrating part of the context(see equation 3.2). This is implied by the fact that the actor takes itself into account when making a decision.

$$Actor \in Context \tag{3.2}$$

It is, however, wrong to assume that all this information serves as a direct input to the decision making process. In fact, this input can be seen as the result of two different processes: perception and reasoning.

While the context might refer to all information available to the actor, it relevant to understand that not all this information is obtained by the actor. Humans rely on their sensory system to capture information about their surroundings. Different senses are able to capture different kinds of information. For example, a car horn's sound is captured by the sense of hearing or audition. Perception implies not only the capture of information, but also the transformation from low-level information, such as incoming light, to higher level information such as colour and shape, and further higher through the process of recognition(See figure 3.3). Perception is also affected by the actor itself, through several aspects such as learning, memory, expectation and attention. These processes can be seen as operational nodes that not only transform the incoming information but also work as filters.

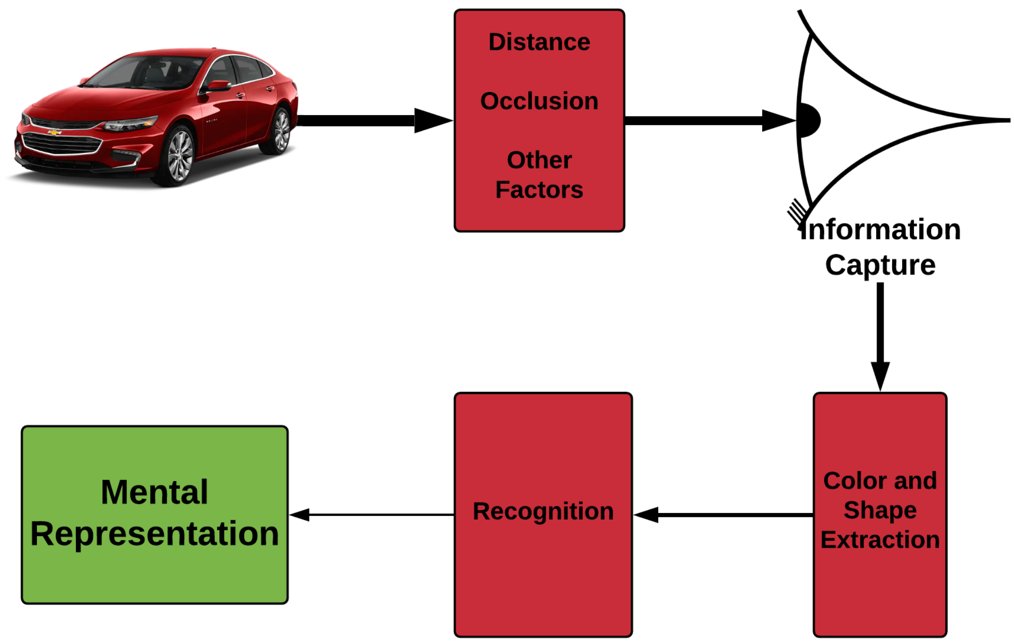

Figure 3.3: Representation of perception process.

While perception refers to the process of obtaining information through one's senses, there are other sources of information, namely memory. At a certain point in time, a pedestrian decisions do not rely only on new information, but also on previously acquired knowledge. The ability to recall this information is used not only in the process of recognition but also to obtain new information through reasoning. Reasoning uses new and old information to generate new beliefs and predictions about the surrounding world. For example, at a crossing with a traffic light, when perceiving that the light is red, one can reason that it will turn green in the future and that there should be one a green light for the vehicles somewhere near. Recalling and reasoning are also important steps to the selection of the itinerary.

Finally, the action, or inaction, represents the result of the decision process performed by the actor taking into account its perception of the context. Understanding the subject's action requires not only to learn what it does but also how, and hopefully, why. For every situation, the subject can choose between a set of actions. The first step lies in discovering the relationship between the subject, the context and the chosen action. Next, one must understand how the action itself is affected. Finally, one can try to understand the decision process that led the subject to take the action in that specific manner. A practical example where this difference can be observed is a crossing with traffic lights. The first level would be to research if the subject crosses or not, depending on the colour of the light. The next level would be to understand, for example, how quick the movement is on each situation. At last, one could try to recreate the decision process that leads to the taken action.

The use of virtual reality to insert the user in the simulated environment brings an advantage not available in other methods. This advantage lies in the precision and control of the collected data. While other methods try to collect data from a real pedestrian, and as such might be subjected to error; this method involves the user controlling an avatar through some kind of interface. The avatar is a virtual entity, and as such, all data is already available and can be easily extracted. While this trait does not eliminate the error in data, as the problem is outsourced to the interface; it indeed might the life of researchers by diminishing the required work to collect data.

The task of collecting data is facilitated by virtual reality, as it improves the quality and quantity of data that can be collected, mainly on the aspects of the action and context. A problem, however, remains on the fact that no suitable method was found to collect relevant data about the actor. Discerning the mental state of the person in real time is not a trivial task. Furthermore, no methods were found to acquire data about past experiences. As such it is not correct to rely only on virtual environment to study behaviour as it might lead to ignoring an important aspect of it.

The conjunction with other methods is advised and even required. Such methods should aim to complete and verify the data collected through the virtual environment, by capturing the relevant information on actor. Suitable methods for this task might include interviews and surveys, which are generally quick and easy to implement, diminishing the burden on both the subjects and the researchers.

The data collected to understand pedestrian behaviour encompasses information about the actor, the context and the action taken by the actor. While the latter two aspects can be efficiently obtained through the use of virtual environments, it is more suitable to gather data about the actor though alternative, complementing methods such as interviews or surveys. The researcher should then try to balance all three aspects according to the problem at hand and identify which information should be collected and how to collect it.

3.4 Data Storage and Transformation

After discerning what information to collect, and the methods to do it, one might find itself facing a different kind of challenge. This challenge lies in how to keep the data collected. The data can range from raw numerical values such as the position of an object to more complex and meaningful conclusions such as identification of an ongoing activity or the state of some entity. This discrepancy on the complexity of the data might cause a problem when one tries to store or analyze it. It is then important to find a coherent format to store the data so that while it can be easily stored and read, it retains all relevant information.

At this point, one generally has two possible solutions. The first is defining a structured format, such as spreadsheets or more complex relational models. Although this option will allow for relative ease when reading the data, it can become detrimental as it limits the kind of data that can be stored or require a heavy processing phase to format the data. The second option is using an unstructured format, which will allow for more freedom on the kind of collect data, as well as a possible increment in human readability. This option, however, might hinder the next phase as analyzing unstructured data is not a trivial task.

Another aspect to take into account when storing the data is accessibility. Not only the collected data must be easy to read, but also simple to access and filter. This can be easily achieved by creating an external database to hold the collected data, as shown in figure 3.4. Through this method, not only it becomes viable to hold several experiments at the same time, but it also facilitates the access and management of the data.

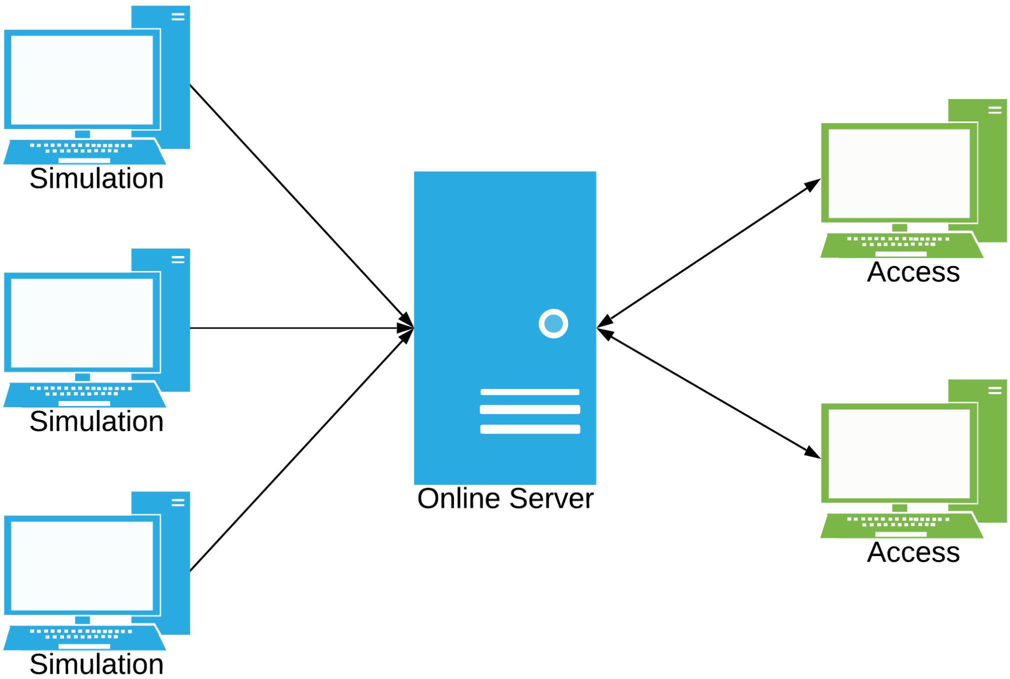

Figure 3.4: Example of data flow with an online database server infrastructure.

Finally, fusion with data external to the simulation must be also taken into account. As mentioned in the previous section, the data can come from different sources, such as the virtual reality simulation and interviews or surveys. When creating the infrastructure, one might need to implement methods to fuse the data from all sources. The specified infrastructure and data format should satisfy all these criteria, in order to maximize the usefulness of the collected data.

3.5 Data Analysis

After running the simulation with several subjects and storing the formatted data, one can finally start to work towards creating a model to represent pedestrian behaviour. For that purpose, the data must be analyzed in order to extract useful information, reach conclusions and confirm or dismiss the hypothesis. In section 3.3, behaviour was defined as a relation between the actor, the context and the action (see equation 3.1). During the experiment, data referring to all those elements has been gathered, so the objective now is to find this relation, or at least, try to present a close approximation.

The data analysis process is not a trivial step. The amount and variety of the collected data is not small. Furthermore, depending on the chosen format, automatic solutions to analyze the data might not be able to read the data. Thus, the first task is to process the data, transforming the data into a format compatible with the tools and analysis that will be performed. While this task might seem inconsistent with the previous process, one must note that both steps have different objectives. In the previous process, the objective was to keep the maximum amount of data, so that in this process multiple analysis can be performed, without the need to collect additional data. Aside from processing the data, it might be necessary to clean it, removing errors that might have been introduced during the collection or storage processes.

The next task lies in the analysis itself. By manipulating the data, with the support of automatic tools, researchers can try to find patterns and correlation in the values. These results must then be interpreted in order to reach clear conclusions that can be used to create models that represent the behaviour being studied.

3.6 Models

The final process is the creation of models to represent the studied behaviour. During the literature review in chapter 2 it was observed that agent-based models are recognized as the most suitable for pedestrian microscopic simulations. This fact makes this kind of model a prime candidate, not only for controlling the other pedestrian entities during the simulation if they exist; but also to be the model used for the result, as it can then be used in the simulation itself. This, however, is completely dependent on the kind of study being made.

As mentioned in section 3.3, the comprehension of an action can refer to diverse levels. Simpler approaches aim to find when certain actions are taken, taking into account the inputs from the actor and/or the context. Understanding why an action was chosen is fundamental to start understanding a pedestrian decision process. As one gets deeper into this topic, it becomes necessary to not only knowing when an action is chosen but also how it is performed. Even when the same action is chosen, slight variances can occur. For example, when a pedestrian crosses the street, whether it is crossing fast or not is also relevant. Information like how fast one is moving, what distance one maintains to the road, how big the head movement is to look around are examples of aspects of the behaviour that are outside of the scope of knowing what action what chosen, but are nevertheless important. Reaching the apex in this topic would mean completely understanding what and how a pedestrian thinks at all times, thus creating a complete and ever accurate model. This ideal model cannot be created at the present, aiming the efforts towards this goal can aid in the creation of more realistic and precise models.

3.7 Recursion

With the conclusion of the modelling process the study reaches the end, with the model being its output. This, however, might not be optimal, as there is space for improvement. This improvement might lie on the re-utilization of the model to improve the initial simulation. Taking into account the context of the problem, the initial simulation will presumably contain several components whose origin might not be completely certain and objective. The resulting models from this process might be capable of substituting or improving these components taking into account that they are the result of analysis of pedestrian, not in a controlled environment, but in an environment similar to reality. As previously mentioned, the subject behaviour might be affected by the intrusiveness of the used methods. As such, the more realistic the simulation is, the less the effect it should have on the behaviour of the subject. An improved pipeline would then assume the form seen in figure 3.5, in which the output models are reused to improve the simulation, so that better and more valid data can be collected.

3.8 Summary

This chapter presents the author's approach to pedestrian behaviour elicitation in virtual reality. The process pipeline is displayed and broken down, with each process being detailed in its respective section. These mentioned processes were simulation, data collection, data storage and transformation, data analysis and modelling. Heavy focus is given to the first two processes, as they relate to the focus of this thesis.

In the first process, simulation, the importance of the virtual environment is discussed. The aspects of the environment are ranked by order of importance and implementation, as follows: world, actors and behaviours. The impact of realistic sensory replication is also mentioned.

The next process, data collection, focuses on explaining what kind of data should be collected and the suitable methods to do so. This section also acts as an answer to research question RQ2.

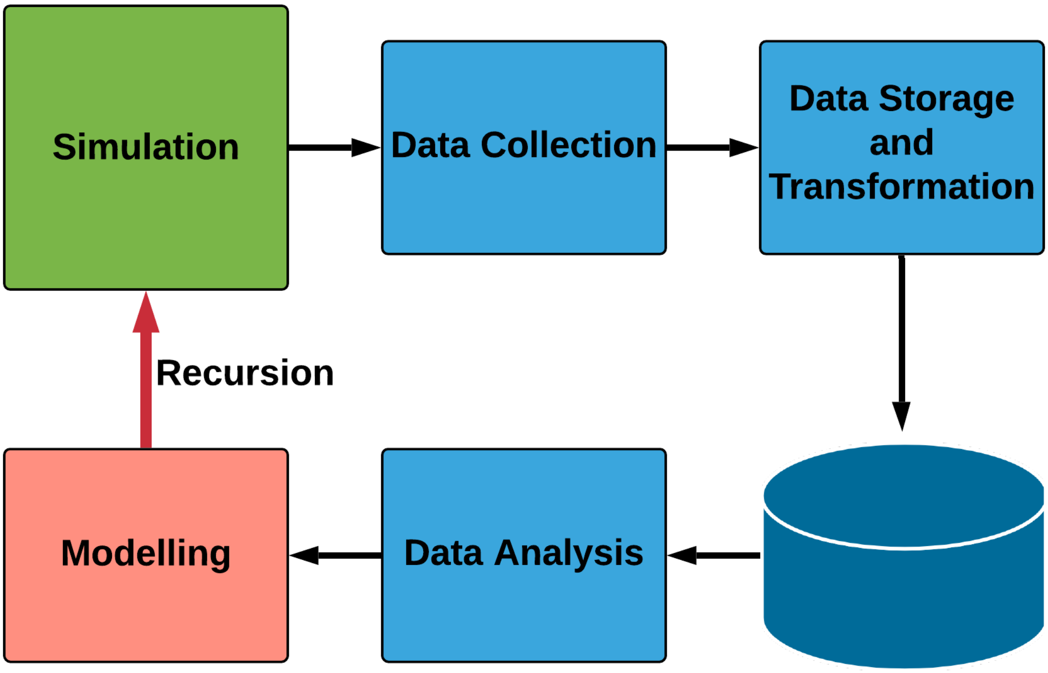

Figure 3.5: Improved pipeline for pedestrian behaviour elicitation.

Human behaviour is represented as a function between the subject and the context, that results in an action. Each of these elements is then explained.

After explaining each process, the whole pipeline is reviewed and a possible improvement is suggested. This improvement lies in feeding the simulation with the results of previous experiments, creating a loop that will increasingly improve the quality of the collected data.

Is this chapter, the process is explained from a theoretical viewpoint, with only the general design and concepts being explained. The following chapters will provide an example implementation of an experiment taking into account these concepts.

Chapter 4

Implementation

The previous chapter alluded to the usage and advantages of using virtual reality as a tool for pedestrian behaviour elicitation, as well as the pipeline suggested by the author to complete the task. Each step was explained and the possibility to reusing the results of the process to do new experiments was mentioned.

This chapter presents a possible implementation of the process, revealing an experiment performed by the author. The objective of this experiment is to collect data about pedestrian behaviour in an urban environment, through the use of virtual reality and it is designed taking into account the steps mentioned in the last chapter.

4.1 Material

This section details the material used in the experiment, referring not only to the setup used during the experiment but also to the theoretical minimum requirements of the machines used. The simulation was developed with Unity 3d, version 2018.1.8, using several assets which will be mentioned in the following sections. The virtual reality interface used was the HTC Vive headset, configured through SteamVR.

The hardware used during the experience is shown in figure 4.1. The used and minimum specifications are presented in table 4.1. The minimum specifications are based on the requirements of Unity3D, Steam VR and the HTC Vive headset. While the minimum specification might be enough to run the simulation, the experiment itself might be severely affected by low performance, more specifically low frame rates which not only impact the realism of the setting but can also cause more severe virtual reality sickness symptoms.

During the experiment, the subjects were given two questionnaires and a consent form to fill. The questionnaires were given to collect demographic data about the subject and to access if any symptoms of virtual reality sickness occurred. The Informed Consent Form informs the subject

Figure 4.1: HTC Vive.

Table 4.1: Hardware requirements.

Component	System Requirements	System Components Used
CPU	Intel Core™ i5-4590 AMD FX 8350 Equivalentor better	Intel® Core™ i7-7700K
GPU	NVIDIA GeForce GTX 970 AMD Radeon R9 290 Equivalent or better Requires support to DX10(shader model 4.0)	NVIDIA GeForce GTX 1080
Memory	4 GB RAM	16 GB RAM
Video Output	HDMI 1.4 DisplayPort 1.2 Or Newer	HDMI 1.4 DisplayPort 1.2
Ports	1x USB 2.0 Or Newer	USB 2.0
Network	Broadband Internet connection	Broadband Internet connection
Operating System	Windows 7 SP1, 8.1 or 10 (64-bit versions only)	Windows 10 (64 bit version)

of the objective of the experiment, as well as the potential symptoms they might feel. All of those documents are available in Annex Sections A to C.

4.2 Virtual Environment

The virtual environment used during the simulation was developed under the scope of SIMUSAFE project. Several of the assets were provided by the partners of the project, particularly the terrain and vehicles.

The simulation takes place on a virtual coastal city during the day. This environment was created and provided by ITCL, and later modified by the author. The city possesses several urban features, including buildings of varied size and architectural style, roads with crosswalks, roundabouts and underpasses. Other features include a highway, a beach, a train line, as well as several bus stops. The setting is significantly detailed with several objects such as light posts, trash bins, parked cars and benches. Figure 4.2 contains some of the scenarios there present.

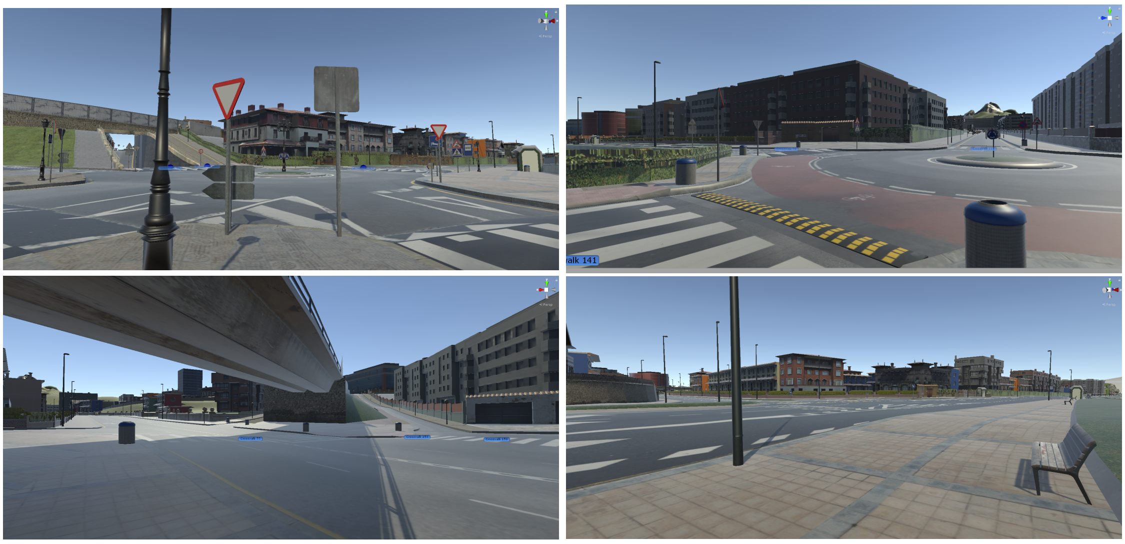

Figure 4.2: Example of scenarios in the virtual environment.

The city itself possesses enormous dimensions, so the experiment confines the subjects to a smaller section where the majority of the mentioned features are present. The setting is complemented by the introduction of pedestrian and vehicle agents that roam this section of the map. An aerial view of this section can be seen in figure 4.3.

The pedestrian agents present in the simulation were developed in conjunction with ITCL and UPorto. ITCL provided several different animated models which can be seen in fig 4.4), while the artificial intelligence behind the behaviour of the agents was developed in UPorto. The agents are created based on a previously generated population, assuming different aspects depending on age and gender.

The pedestrians behaviour implemented at the time of this writing is not too complex. Each agent is spawned randomly on one of several predetermined locations on the map(see figure 4.5) and selects at random one of the other locations as a goal. It then moves through the use of Unity3D navmeshes, showing some emergent behaviours such as collision avoidance. This movement takes

Figure 4.3: Aerial view of the virtual environment.

Figure 4.4: Pedestrian models used in the simulator (from the left to the right: young man, old man, young woman, old woman).

into account different weights for roads, crosswalks and sidewalks, adjusted through trial and error by the author.

The vehicles were the result of a preliminary integration effort with the ArchiSim simulator provided by Ifsttar[1]. ArchiSim is responsible for controlling all moving vehicles and sending their data to Unity3D, which displays to vehicle model on the setting (see figure 4.6).

The subjects interface with Unity was implemented using the Virtual Reality Toolkit (VRTK) package[2], which offers a set of scripts used to build VR projects. The package offers a solution to locomotion in a virtual environment, using the motion of the arms to compute the movement of a virtual avatar. The solution supports several devices including the used HTC Vive, thus

[1] Ifsttar official website, https://www.ifsttar.fr/accueil/, last accessed: July 3, 2019

[2] Virtual Reality Toolkit on Unity Asset Store, https://assetstore.unity.com/packages/tools/integration/vrtk-virtual-reality-toolkit-vr-toolkit-64131, last accessed: July 3, 2019

Figure 4.5: Pedestrian spawn points and goals(represented as green spheres).

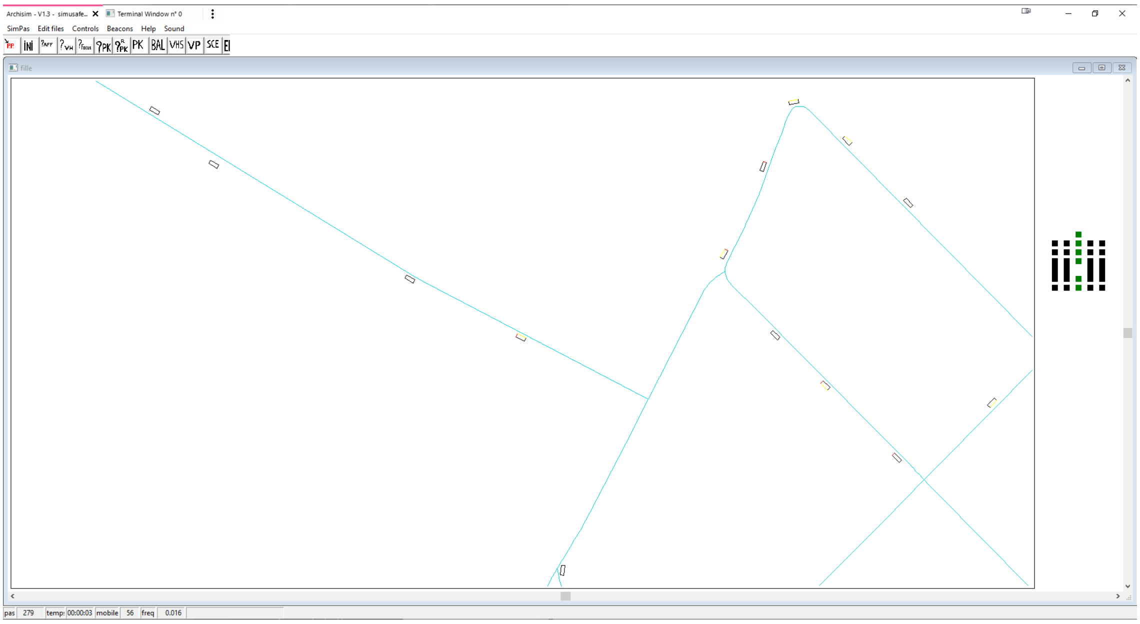

Figure 4.6: Archisim simulator.

could be directly implemented in the project. The avatar uses a generic model (see figure 4.7), whose animation is computed using inverse kinematics. While the movement is controlled by the package, the speed and height of the avatar are adjusted using the height of each subject.

4.3 Data Collection Mechanisms

The objective of this experiment is to collect data about pedestrian behaviour in an urban environment. As identified in the previous chapter this implies trying to understand the action, the actor

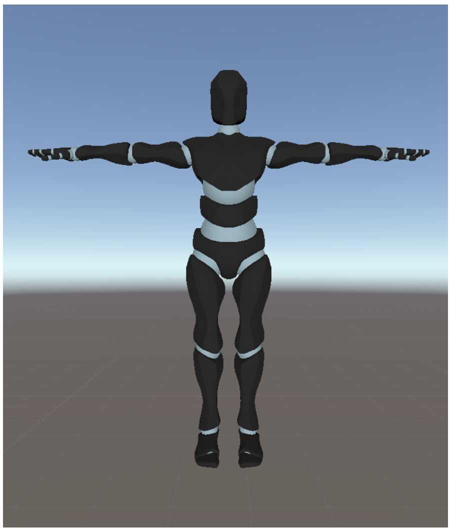

Figure 4.7: Subject's avatar.

and the context. The actor, unlike the action and context, is more suitable to be researched using other methods. In this experiment, the chosen method was a set of two surveys.

The first questionnaire, denominated the User Profile and Demographics, will be given at the beginning of the experiment. The presented questions will concern the subject's demographic information(age, gender, height) and general transportation habits. The information gathered will be used to adjust the subject avatar height and stride during the simulation experiment. The complete questionnaire can be found in Annex B.

As previously explained, the avatar movement is controlled by the VRTK package. This package defines a "speedScale" variable that affects the maximum speed one can achieve. The default value for this variable is one, but such value heavily restricts the speed, impending action nuances such as walking fast. In fact, the movement felt slow even when walking normally. Through trial and error, the author found out that the most suitable value for this variable was two. At this value, it was possible to move faster and the arm movement needed to walk normally was closer to the natural. In order to adjust this value for the subject, this value was multiplied by the subject's height, relative to the height used during the trials (see equation 4.1).

$$SpeedScale = 2 * Subject'sHeight/BaseHeight \tag{4.1}$$

, where the base height is 175 centimeters.

The second questionnaire, known as Virtual Reality Sickness Questionnaire, will be given after the experiment. The presented questions will concern the subject's feedback about the experiment, focusing on any symptoms felt during or after the experiment. The question follows a four-point Likert scale schema. A space for informal feedback will be available. The questionnaire is based on Kim et al.[KPCC18] work which adapts the Simulation Sickness Questionnairy[KLBL93] to be used in a virtual reality setting. The complete questionnaire can be found in Annex C.

As explained in the previous chapter, these questionnaires serve the purpose of complementing the data gathered during the simulation. This data pertains to the subject's perceptions and actions. Before explaining the implemented mechanisms and collected metrics it is relevant to explain the format used.

The used format is based on Experience API (or xAPI)[3], which aims to collect data about an experience a subject has. This specification predicts the use of format statements containing a noun, a verb and an object. Through the use of these statements, almost any activity can be described and stored, while still being human-readable.

For this experiment, a variation of this structure was defined. This structure contains five key elements: an actor, a verb, an array of objects(which may or not contain objects), a time stamp and session identifier. The actor identifies the entity about which information is being collected. The verb defines the performed activity and the objects identify the entities affect by the activity if there are any. Finally, the timestamp holds the time at which the activity occurred or at last, when it was registered, and the session identifier is used to keep track of which simulation session the whole statement occurred in. This structure still predicts the use of an additional field called a modifier, which is contained both in the verb and in each object. This field can contain a whole object and is used to record any additional information aside from the identification of the verb or object itself.

This structure lays on JSON format and is used to record both the actions and perceptions. The distinction between the two is based on the defined verbs. A example containing an statement about a visual perception of a car be observed on listing 4.1.

```
{
    "actor": "pedestrian/...",
    "verb": {
        "id": "saw"
    },
    "objects": [
        {
            "id": "car/...",
            "modifier": {
                ...
            }
        }
    ],
    "timestamp": ...,
    "sessionId": ...
}
```

Listing 4.1: Example statement

As observed in the example, each entity is identified by a set of words, divided by slashes, which end in an integer. This structure allows for the identification of the type of entity, as well

[3]Experiencia API official website, https://xapi.com/overview/, last accessed: July 3, 2019

as some room for creating a hierarchy of types. For asserting the use of this structure, a JSON schema, which can be seen on Annex E, was created.

On the virtual environment, these entities refer not only to moving agents but any object about which it is relevant to keep information. All entities are registered on an Entity Manager which provides the methods to search them. when an entity is created, its first task is to register itself in this manager, which assigns to the entity the integer found on the identifier. The manager keeps the entities in a dictionary of lists, whose keys are the types of the entities there present. Though this method it is possible to filter entities by type, diminishing the number of operations needed on certain procedures. Each of these objects keeps track of his own information, possessing the task of updating its values regularly. Depending on the nature of these values, these values may be updated at different rates. The types of entities considered in this scene are pedestrians, cars, traffic lights, crosswalks and weather.

Pedestrians are the most detailed and expansive group of entities. Each pedestrian keeps track of several metrics: position, rotation, apparentGender, apparentAge, activity, speed, area, nearestCrosswalk, nearestCrosswalkDistance, onCrosswalk and for the pedestrian controlled by the subject, direction. Position and rotation are obtained from the object transform and are updated in each physics cycle. ApparentGender and apparentAge are initialized when the pedestrian is generated and never changed during the simulation. ApparentGender can assume the values of male or female, and apparentAge can be child, adult or old, though the former is not observed in any pedestrian due to the lack of suitable models. Speed, nearestCrosswalk and nearestCrosswalkDistance are calculated in each physics cycle. Area is obtained by sampling the current position into a navmesh present in the scenario, and onCrosswalk takes uses this value to check if the current area is a crosswalk. Activity takes all these aspects to describe the pedestrian state in a simple sentence. Finally, the direction metric corresponds to the head rotation, assuming the values of front, right or left, depending on if the y-value of the rotation is bigger than 30^{o} to either side or not.

Cars are much simpler, containing only three metrics: position, rotation and state. Position and rotation, similarly to the pedestrians, are obtained from the object transform and updated each physics cycle. State keeps track of whether the car is moving or stopped.

Similarly to cars, crosswalks contain few metrics. In fact, they only keep track of the position and rotation, which is not updated since they are static entities.

Traffic lights are a bit more complicated. They do not keep track of position and rotation as it was deemed unnecessary. Instead, they maintain three other metrics: carState, pedestrianState and crosswalk. CarState and pedestrianState refer to the colour of the lights for the vehicles and pedestrians, respectively. The crosswalk value is an identifier of crosswalk controlled by the traffic lights if any.

Finally, the weather entity is used as an example of how can general features of the context be recorded. This entity keeps track of two metrics: state and time. The state metric refers to the state of the weather, as in "cloudy" or "sunny". The time refers to the time of day, as in "noon", "dusk" or "night". These values are static not only in a simulation session but also between all sessions, once again, reinforcing the idea that this is just an example.

Aside from storing these metrics, each entity is also responsible for creating methods to share them in a formatted structure. These methods are generally related to the verbs that use these metrics to fill the modifier field. Each one of the methods corresponds to one or more verbs, that work as key to reach the desired information. Though this method is possible for different information to be returned when the same entity is questioned with different verbs. Figure 4.8 illustrates the general structure of an entity.

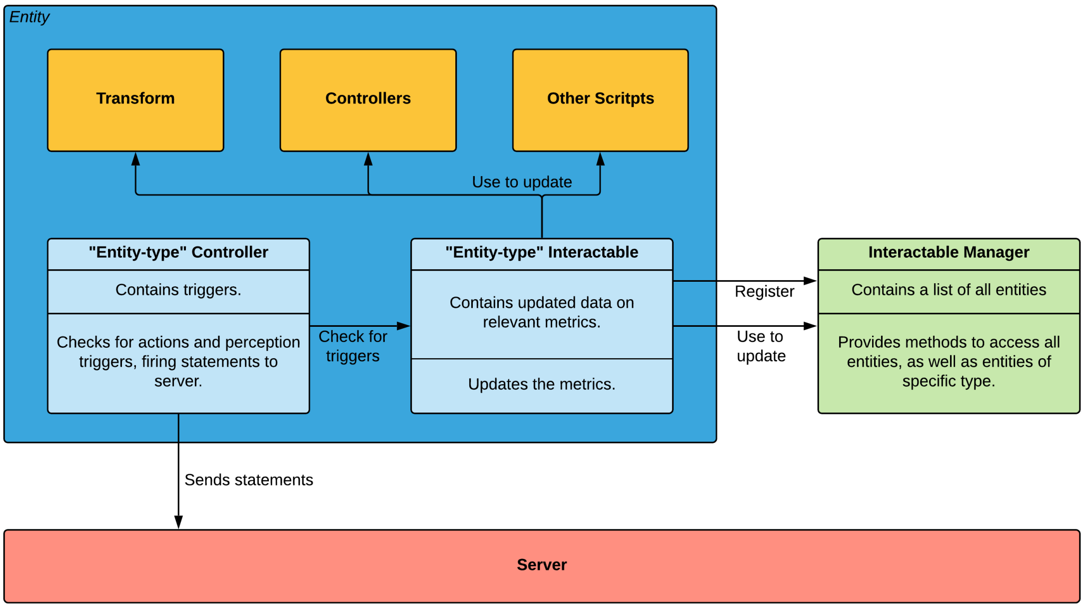

Figure 4.8: Structure of an entity.

During this experiment, five verbs were defined, with some corresponding to action verbs and other perception verbs. Action verbs include "walked", "crossed" and "lookedAround". The verbs corresponding to perception are "saw" and "is".

The "walked" verb (see listing 4.2) corresponds to the action of walking, as well as its variations, such as running or stopping. This verb requires a modifier which is retrieved from the same entity that performs the action. This modifier filters the pedestrian metrics retrieving only the speed and area. Due to the nature of this only pedestrian entities define a modifier for the "walked". This verb corresponds to a continuous action so a complete registering would need one statement per physics cycle. This, however, is a large workload for the simulation, so the rate as set to one statement each half of a second.

```
{
    "actor": "pedestrian/50",
    "verb": {
    "id": "walked",
    "modifier": {
        "speed": 1.47216427,
        "area": "sidewalk"
    }
    "objects": [],
    "timestamp": 17.12,
    "sessionId": "30/04/2019 11:26:41"
}
```

Listing 4.2: Example of "walked" statement

The "crossed" verb (see listing 4.3) represents the action of crossing the road. Unlike the "walked" verb this action is not a constant event, so a different trigger mechanism had to be defined. This trigger was defined as the change in the area metric, which represents what surface the subjects are walking on. Through this definition, and by comparing with the information retrieved by the "walked" verb's statements, it is possible to understand when the crossing started, which is represented by a crossing event where the last area was "Sidewalk"; when it finished, which is represented by a crossing event where the new area is "Sidewalk"; and even if the subject changed between walking on the crosswalk and in the road, which is represented by a crossing event where the new and last areas are not "Sidewalk". Aside from this information, the modifier also retrieves the metrics that relate to the nearest crosswalk, which are the identifier and the distance to the subject.

```
{
    "actor": "pedestrian/50",
    "verb": {
        "id": "crossed",
        "modifier": {
            "nearestCrosswalk": "crosswalk/108",
            "nearestCrosswalkDistance": 3.71473765,
            "onCrosswalk": true
        }
    },
    "objects": [],
    "timestamp": 23.9644451,
    "sessionId": "30/04/2019 11:26:41"
}
```

Listing 4.3: Example of "crossed" statement

The last action verb, "lookedAround" (see listing 4.4) holds information about the head movement, this is, about the action of turning the head to see in a different direction. Once again a different approach was used with this verb. Obtaining information about the current rotation of the head in relation to the body is not as meaningful as directly understanding which direction the actor is currently facing. As such, the trigger for this action was defined as the breaching of a 30º threshold to either side, this is when the direction metric of the pedestrian changed. When the new angle is contained between -30º and 30º, the returned direction is front. Otherwise, either left or right are chosen. Whenever this value changes the statement is created, so at any point in time, the current direction can be known by checking the last statement.

```
{
    "actor": "pedestrian/50",
    "verb": {
    "id": "lookedAround",
        "modifier": {
            "direction": "front"
        }
    },
    "objects": [],
    "timestamp": 22.586668,
    "sessionId": "30/04/2019 11:26:41"
}
```

Listing 4.4: Example of "lookedAround" statement

The "saw" verb (see listing 4.5) corresponds to visual perception, this is, to the sense of sight. As mentioned previously, the most important human sense is believed to be sight. Thus recording which entities the pedestrian is seeing, as well as the characteristics of these entities that can be observed through this sense is an important aspect that should be recorded. While this verb does not define any modifier, it may take several objects which represent the seen entities, such as other pedestrians or vehicles. Each of these objects, on the other hand, will have associated a modifier which contains the information discernible with sight, such as position, rotation and other state-related metrics depending on the kind of entity. Because sight is activated at nearly all times, similarly to the "walked" verb, statements are only recorded every half of a second. Furthermore, taking into account that the perception process is not perfect, with a significant amount of information being lost, a mechanism that works as a filter for which objects are seen was defined. This filter tries to simulate the information loss that occurs due to distance and occlusion. To face this problem, a naive solution based on a threshold distance between the actor and the entities, as well as the angle was defined. As long as the object is within this range and the angle between head direction and the object is lesser than 90º, the object is recognized as seen. This solution is extremely simple and fails when objects can be observed from long distances or when at a small distance it is occluded due to other objects being in front. This solution, however, was chosen due to a better solution requiring more processing power, thus affecting the quality of the simulation when the tests would take place.

```
{
    "actor": "pedestrian/50",
    "verb": {
        "id": "saw"
    },
    "objects": [
        {
            "id": "crosswalk/122",
            "modifier": {
                "position": {
                    "x": -170.015228,
                    "y": 18.3461914,
                    "z": -700.572266},
                "rotation": {
                    "x": 1.33402134e-08,
                    "y": 26.211832,
                    "z": 0.622161746}
            }
        },
        {
            "id": "car/19",
            "modifier": {
                "position": {
                    "x": -175.828,
                    "y": 18.85,
                    "z": -691.988
                },
                "rotation": {
                    "x": 0.3,
                    "y": 342.99,
                    "z": 3.335099e-09
                },
                "state": "stopped"
            }
        }
    ],
    "timestamp": 25.12,
    "sessionId": "10/05/2019 15:25:35"
}
```

Listing 4.5: Example of "saw" statement

Finally, the "is" verb (see listing 4.6) can be seen as an outlier because, while it is treated as a perception verb, it does not represent a sense. What this verb represents is the spatial perception, this is the ability to perceive the spatial relationships between oneself, the environment and the others. This translates to being able to record the position and rotation of oneself. Once again, the statements concerning this verb are only recorded each half of a second.

```json
{
    "actor": "pedestrian/50",
    "verb": {
        "id": "is",
        "modifier": {
            "position": {
                "x": -210.219971,
                "y": 18.7081318,
                "z": -677.501038
            },
            "rotation": {
                "x": 0,
                "y": 180.0,
                "z": 0
            },
            "apparentGender": "male",
            "apparentAge": "adult",
            "activity": "waiting on sidewalk"
        }
    },
    "objects": [],
    "timestamp": 3.55,
    "sessionId": "30/04/2019 11:26:41"
}
```


Listing 4.6: Example of "is" statement

Through the simulation, these five kinds of statements are collected when their respective trigger occurs. Table 4.2 summarizes the metrics of each kind of entity, as well as what verbs can collect them as well as the origin of the data there contained. These statements are created in Unity and sent to a Python server which stores them in a MongoDB database (see Annex D).

Table 4.2: Summary of metrics collect by entity and verb.

Actor	Measure	Verb	Definition	Computation
Car	position	saw	The car current position in the world.	Retrieved from the object transform.
Car	rotation	saw	The car current rotation.	Retrieved from the object transform.
Car	state	saw	Whether the car is parked or moving.	Static field as only moving cars are recognized as entities.

Table 4.2: Summary of metrics collect by entity and verb.

Actor	**Measure**	**Verb**	**Definition**	**Computation**
Crosswalk	position	saw	The crosswalk current position in the world.	Retrieved from the object transform.
Crosswalk	rotation	saw	The crosswalk current rotation.	Retrieved from the object transform.
Pedestrian	activity	saw\is	The pedestrian current activity(e.g. walking on sidewalk, crossing on road, stopped).	Calculated based on current area and speed.
Pedestrian	apparentAge	saw\is	The pedestrian apparent age, whether young, adult or old.	Static field defined during generation.
Pedestrian	apparentGender	saw\is	The pedestrian apparent gender, whether male or female.	Static field defined during generation.
Pedestrian	area	walked	Whether the pedestrian is standing on the road, crosswalk or sidewalk.	Obtained through sampling the current position in the navmesh.
Pedestrian	onCrosswalk	crossed	Whether the pedestrian is crossing on the crosswalk or not.	Reuse area.
Pedestrian	nearestCrosswalk	crossed	The identifier of the closest crosswalk.	Squared distance to every crosswalk is calculated and the id of the closest one is kept.

Table 4.2: Summary of metrics collect by entity and verb.

Actor	Measure	Verb	Definition	Computation
Pedestrian	nearestCrosswalk Distance	crossed	The distance to the nearest crosswalk.	Squared distance to every crosswalk is calculated and the distance of the closest one is kept.
Pedestrian	position	saw\is	The pedestrian current position in the world.	Retrieved from the object transform.
Pedestrian	rotation	saw\is	The pedestrian current rotation.	Retrieved from the object transform.
Pedestrian	speed	walked	How fast the pedestrian is moving.	Magnitude of the diference between the current and last positions.
Pedestrian (Cockpit only)	direction	lookedAround	Which direction the player is facing, in relation to the body.	Between -30 and 30 degrees, returns front, otherwise either left or right.
TrafficLight	carState	saw	Traffic light current light color for vehicles.	Each traffic light keeps it state which changes after a set time.
TrafficLight	crosswalk	saw	Crosswalk id, if any.	Static information stored in the trafficlight.
TrafficLight	pedestrianState	saw	Traffic light current light color for pedestrians.	Each traffic light keeps it state which changes after a set time.
Weather	state	saw	The state of the weather (e.g. sunny, rainy, snowing)	Static field as only sunny weather is present.
Weather	time	saw	The time of the day (e.g. noon, evening, night)	Static field as only noon time is present.

In addition to all the previously mentioned data, the view of the subject inside the simulator will also be recorded for the duration of the experiment. The videos are recorded using the Unity Recorder tool[4]. Unlike the 3D presented by the HTC Vive to the subjects, those videos only contain the 2D view.

4.4 Experimental Protocol

The experimental protocol was designed with the desire that the subjects felt the maximum amount of freedom possible. The experiment itself consists of making the subject travel between two points in a virtual environment. The route is not specified so that the subjects can choose freely. The experiment was designed as follows:

- The experience is presented to the test subject as an experiment to collect data on pedestrian behaviour. It is asked to the subject to behave as they normally would in a real situation, in order to avoid bias. The risk and symptoms associated with virtual reality are explained.
- Subject signs the Informed Consent Form if willing to participate in the experiment.
- An internal ID is assigned to the subject used to link the given questionnaire answers to the data collected during their session.
- The subject fills the first questionnaire: User Profile and Demographics.
- The subject's virtual avatar is adjusted to match the subject's height and stride.
- The subject tries a short tutorial in which no data is recorded.
- A map of the environment is presented to the subject, signalling the origin and target points(see fig 4.9).
- The subject performs the first round of the experiment. While the subject is free to choose any path, directions can be given shall the subject finds itself lost.
- The subject can rest for 1-2 minutes, with the possibility of reviewing the map.
- The subject performs the second round of the experiment. One more time, directions can be given shall the need arise.
- The subject fills the second questionnaire: Virtual Reality Sickness Questionnaire.
- Informal and unstructured feedback are collected.

[4]Unity Recorder on Unity Asset Store, https://assetstore.unity.com/packages/essentials/unity-recorder-94079, last accessed: July 3, 2019

Figure 4.9: Map shown to subjects before the session.

4.5 Summary

Throughout this chapter, the experiment designed by the author was explained. The experiment took the subject to a virtual city which must be traversed following a path the subject itself could choose. The required material during the experiment, as well as a detailed explanation of the environment, was given on their respective sections.

Through their journey, several measurements are taken and a video is recorded. A data format, based on the Experience API was specified, in order to organize the collected data. This format predicted the existence of five types of statements: "walked", "crossed", "lookedAround", "saw" and "is".

Finally, the entire experimental protocol was displayed, giving an overall impression of the tasks performed during the experiments.

Chapter 5

Results and Discussion

The previous chapter presented an experimental protocol for a simple experiment following the methodology presented in chapter 3. This protocol covers the first three phases of the presented methodology, simulation, data collection, data transformation and storage.

This chapter will cover the next steps, data analysis and model. The results of the experiment will be analyzed and discussed. Next, they will be used to create some models that describe pedestrian behaviour.

5.1 Data Sample

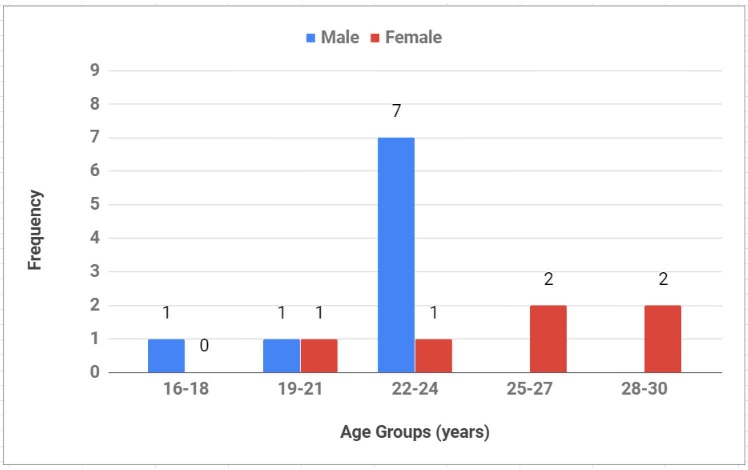

Figure 5.1: Distribution of subjects by gender and age.

Fifteen subjects aged between 16 and 30 years (mean age = 23.2 years, standard deviation = 3.47) participated in the experiment by completing two rounds of simulation and completing the two surveys ("User Profile and Demographics" and "Virtual Reality Sickness Questionnaire"). The subjects were contacted directly by the researcher. Nine of the subjects were male, while the remaining six were female. As observed in figure 5.1, the most represented group are males in their early 20's. Female participants were on average older than their male counterparts(females mean age = 25.5, males mean age = 21.6). The subjects height varied between 160 and 187 cm (mean height = 173.9 cm, standard deviation = 7.65), as shown in figure 5.2.

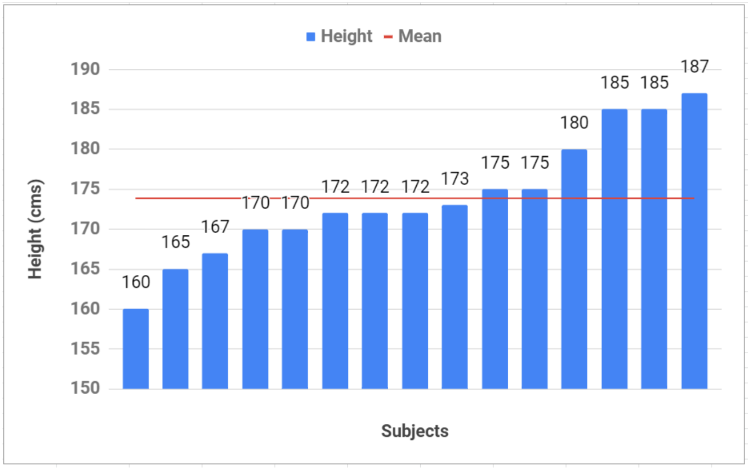

Figure 5.2: Distribution of heights in centimeters of each user.

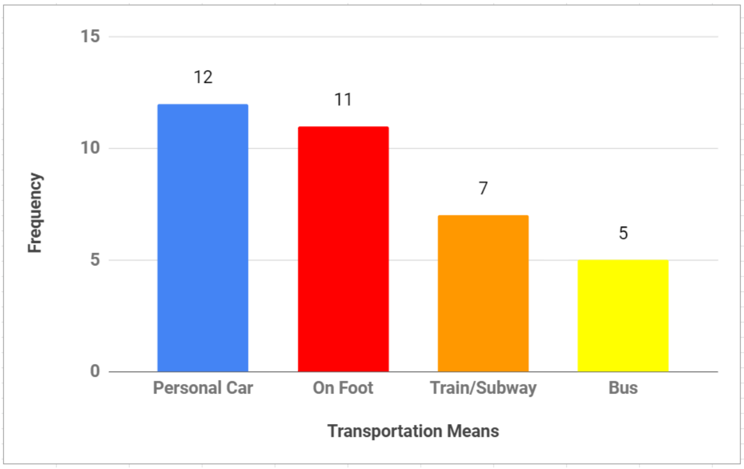

Figure 5.3: Absolute frequency of means of transports used by the subjects.

All but one subject possessed a driver license and none reported any kind of mobility issues. When asked about which means of transport the subjects generally used, the most frequent answer was a personal car, with 12 out of 15 (80%) giving this answer (see figure 5.3). The next most frequent answer was walking, with 11 (73%); followed by train or subway, with 7 (47%); and finally, bus, with 5 (33%) subjects. No other mean of transport was reported.

Each experiment took around thirty minutes and each subject recorded two sessions, for a total of thirty sessions. The total recorded video time was four hours, six minutes and fifteen seconds. The average time of each session was eight minutes and thirteen seconds (standard deviation = 2m05s). Figure 5.4 presents the distribution of times.

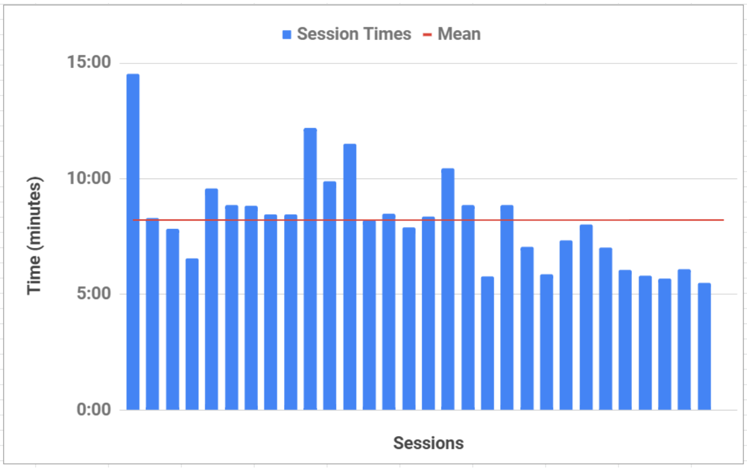

Figure 5.4: Distribution of session times in seconds for each subject.

Some subjects displayed big discrepancies in duration between the first and the second session, with an average of one minute and thirty-two seconds. Nevertheless, no significant tendency for one session to be quicker than the other was found. As can be observed in figure 5.5, the first session was a small tendency to take more time (mean = 13s; standard deviation = 2m17s), but such time only accounts for 2.5% of the average time of a session.

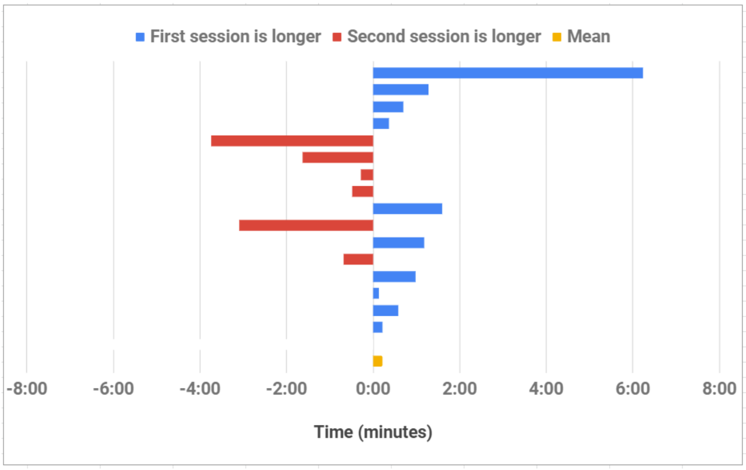

Figure 5.5: Difference in time in seconds between first and second session for each subject.

After terminating the experiment, the subjects gave their report about the symptoms of virtual reality sickness (see table 5.1). The questions were presented using a 4-point Likert scale. The most frequently reported symptom was Fatigue (mean = 1.1 out of 3; standard deviation = 0.80), while the less reported one was Dizziness with closed eyes (mean = 0 out of 3; standard deviation = 0.00) without any positive reports.

Computing the VRSQ score requires the calculation of two components, Oculomotor and Disorientation. The results (see figure 5.6) reveals that the Oculomotor component's symptoms display an higher degree of intensity (mean = 21.1; standard deviation = 14.49), in comparison

Table 5.1: VRSQ symptons mean and standard deviation following a 5-point Likert scale.

VRSQ Symptom	Mean (out of 3)	Standard Deviation
General discomfort	0.5	0.64
Fatigue	1.1	0.80
Eyestrain	0.5	0.74
Difficulty focusing	0.4	0.51
Headache	0.2	0.41
Fullness of head	0.4	0.63
Blurred vision	0.5	0.74
Dizzy (eyes closed)	0.0	0.00
Vertigo	0.2	0.56

with the Disorientation component (mean = 8.4; standard deviation = 9.29).

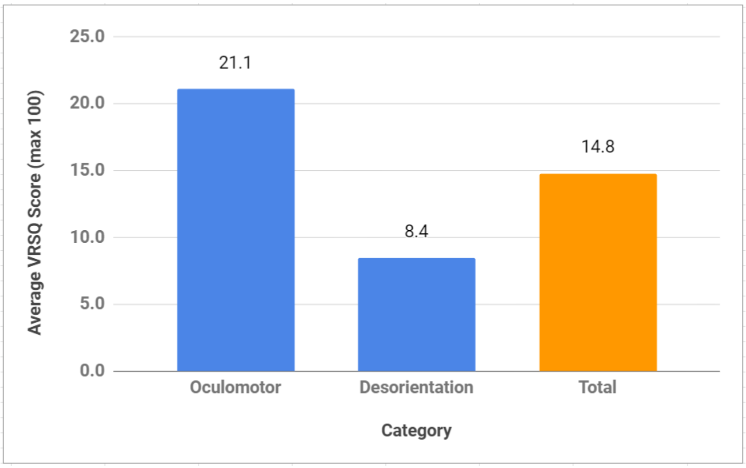

Figure 5.6: VRSQ component scores.

These results imply that the experiment was somewhat physically strenuous, to the point of causing fatigue. This was corroborated by some verbal comments from the subjects. The main cause to this fact is attributed to the movement control mechanics during the simulation which required significant arm movements, which, over the not short duration of the experiment could naturally cause fatigue.

Questions regarding the realism of the environment were presented using a 5-point Likert scale. Regarding this topic, subjects reported fairly positive results (mean = 3.9 out of 5; standard deviation = 0.52). Streets were identified as the most realistic component (mean = 4.5 out of 5; standard deviation = 0.74), while cars where reported as the less realistic (mean = 2.8 out of 5; standard deviation = 1.08). Verbal reports and written responses corroborated these results. The results point out to a problem with cars, namely with the car's model and behaviour. Figure 5.7 displays the results for each component.

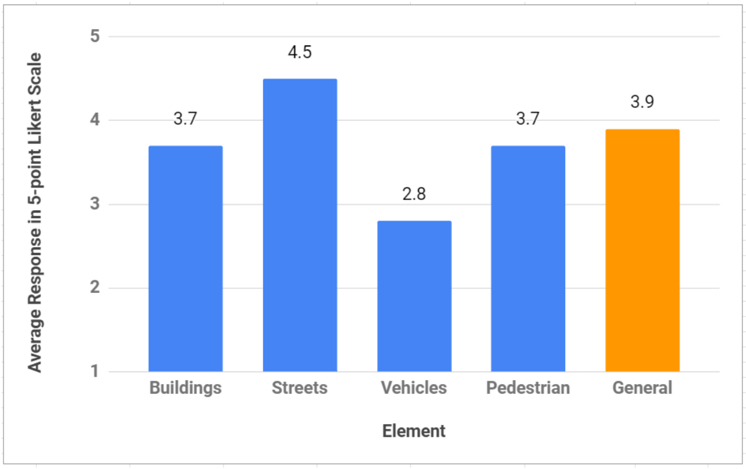

Figure 5.7: Realism scores following a 5-point Likert scale.

5.2 Behaviour Analysis

While the format used to store the data collected during the simulation promotes its readability, it makes the task of analyzing it not so trivial. While seeking to maintain the maximum amount of information, the defined data structure contains more information than needed to perform some automatic analysis. As such, it is convenient to transform the collected data into another format.

Thus, the collected data was transformed in order to create a set of time series that represented the speed of the subject, whether it was looking left or right and if it was seeing cars. These time series concern only the time of crossing, so before extracting them, the moments of crossing need to be found. While this could be achieved using the "crossed" statements, in order to obtain an aligned timestamp, the "walked" statement was used. Using these statements, a crossing event is defined as the time gap between two detached "walked" statements where the area is "sidewalk". Algorithm 1 is used to perform this task.

Algorithm 1 Crossing event search algorithm.

Data: statements
Result: crossingEvents
crossing = False init, end **foreach** *statement* $\in$ *statements* **do**
    if *statement verb is walked* **then**
        if *not crossing AND walked area not "sidewalk"* **then**
            init = statement time crossing = true
        else
            if *crossing And walked area is "sidewalk"* **then**
                end = statement time crossing = false add [init, end] to crossingEvents
            end
        end
    end
end

To analyze the crossing event, however, this is not enough. It is necessary to to analyze each event, not only during the duration of the crossing but also the preceding moments. As such, when extracting the mentioned time series, the relevant statements will be filtered by time stamp, beginning at the time of the start of the crossing minus a defined time value of five seconds, and finishing at the time of the end of the crossing.

The first time series is speed. The most common activity of a pedestrian is walking, thus investigating the speed at a crossing is naturally a relevant topic. The speed time series can be directly extracted from the "walked" statements (see algorithm 2), as the speed metric is stored there and the records where done at a constant rate.

Algorithm 2 Data conversion to "Speed" time series.

Data: statements
Result: speedTimeSeries
foreach *statement* $\in$ *statements* **do**
  if *statement verb is walked* **then**
    add speed value to speedTimeSeries
  end
end

The time series which explains if there are any cars on sight cannot be so easily obtained, because it is not a numerical value, but a boolean. As such, for this time series, it was defined that at a point, the value must be either one or zero, to represent if cars are being seen or not, respectively (see algorithm 3). The objects field of the "saw" statements contains all seen entities at the moment. To discover the value, one only needs to check if any of the objects are of the type "car/*".

Algorithm 3 Data conversion to "Car" time series.

Data: statements
Result: carsTimeSeries
foreach *statement* $\in$ *statements* **do**
  if *statement verb is saw* **then**
    sawCar = False **foreach** *object* $\in$ *statementobjects* **do**
      if *object type is car* **then**
        sawCar = True break
      end
    end
    if *sawCar* **then**
      add 1 to carsTimeSeries
    else
      add 0 to carsTimeSeries
    end
  end
end

The left and right time series are by far the most complicated to obtain. They are boolean values, so an approach similar to the time series related to seen cars must be followed. There is not, however, any constant rate statement that holds this information. Instead, there is the "lookedAround" statement, which, while containing the direction of the head, is only triggered when this changes. In order to obtain a time series matching the two previous ones, for every point in time, a value must be kept containing the value found from the last "lookedAround" statement (see algorithm 4).

Algorithm 4 Data conversion to "left" and "right" time series.

```
Data: statements
Result: leftTimeSeries, rightTimeSeries
lastDirection = "front" lastTime = -1 foreach statement ∈ statements do
    if statement verb is saw then
        lastTime = statement time if lastDirection is "right" then
            add 1 to rightTimeSeries add 0 to leftTimeSeries continue
        end
        if lastDirection is "left" then
            add 1 to rightTimeSeries add 0 to leftTimeSeries continue
        end
        add 1 to rightTimeSeries add 0 to leftTimeSeries continue
    end
    if statement verb is lookedAround then
        lastDirection = lookedAround direction if statement time - lastTime < 0.25s AND
         lookedAround direction not "front" then
            if lookedAround direction is "left" then
                last value on leftTimeSeries = 1
            else
                last value on rightTimeSeries = 1
            end
        end
    end
end
```

By visualizing these time series some interesting patterns were found in the form of seemingly random troughs (see figure 5.8) in the speed time series. These troughs are relatively short in duration, which signifies that there was a really short stop or speed decrease. The short duration and relatively high frequency, however, raises some doubts about why these patterns occur.

Comparing to the recorded videos, it was observed that, more often than not, the decrease is very slight or not apparent at all. The speed metric is obtained by calculating the difference of the position between the current and the last physics cycles, divided then by the time gap between them. The position of the subject's avatar is controlled through the VRTK package, which computes the movement using the motion of the arms. The movement of the arms is based on the position of the HTC Vive controllers hold in each of the player's hands. It is believed that this speed loses are a result of some unknown error in this process. This is corroborated by some verbal reports about the arm motion sometimes not being detected. Taking this into consideration these patterns were classified as noise introduced by the system or the hardware, though it cannot be removed as there is no certainty nor obvious method to remove it.

After the initial analysis, these time series were joined into a table and loaded into Rapidminer,

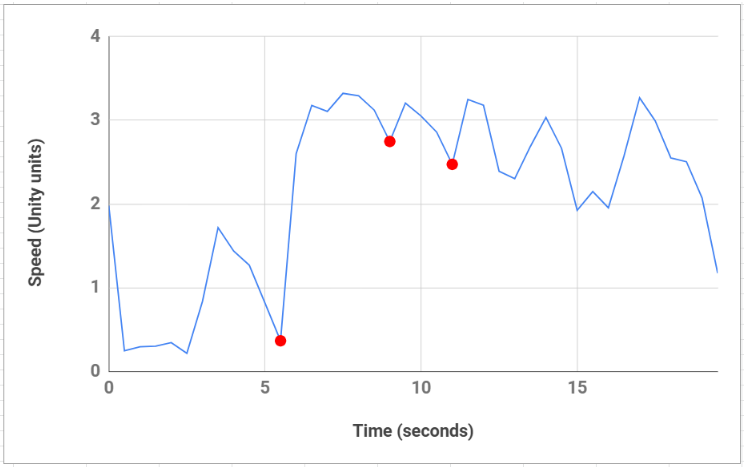

Figure 5.8: Example of speed time series.

a data science software platform that provides an integrated environment with methods for data preparation, machine learning and predictive analytics. This environment provides a method, nominated "Auto Model", which permits a quick analysis and modelling of data, using several different algorithms. This method allows the user to choose what kind of problem should be solved (Prediction, Classification and Clusters), and what variables to use. Then several algorithms are applied in parallel. The results are evaluated and displayed in a table so that the user can compare them.

Before conducting any tests, however, one more transformation must be performed. Raw speed is not very useful, because it is known that walking speed depends on certain factors such as height. Thus, instead of directly using the computed speed, the values are divided by the maximum speed set during the simulation, which results on representation of how fast a subject is walking in comparison to his maximum speed.

The initial test was to try to predict speed based on the remaining variables. After running the "Auto Model" process, the best algorithms displayed a root mean squared error of 0.304. To better understand these results one of the best models was applied to one crossing event (see figure 5.9). As it can be observed, the predicted speed is limited to certain values. While the limited variety of results is logical, due to the variables all being booleans. The proximity of the values, however, points outs that these variables are not enough to obtain a close prediction of speed.

Taking into account that these variables were not enough to predict speed, the addition of these variables values on the last frame was performed (see algorithm 5). For each of these variables a new column, named last_"variable_name" was created, in which its value is the value of the original variable in the last frame.

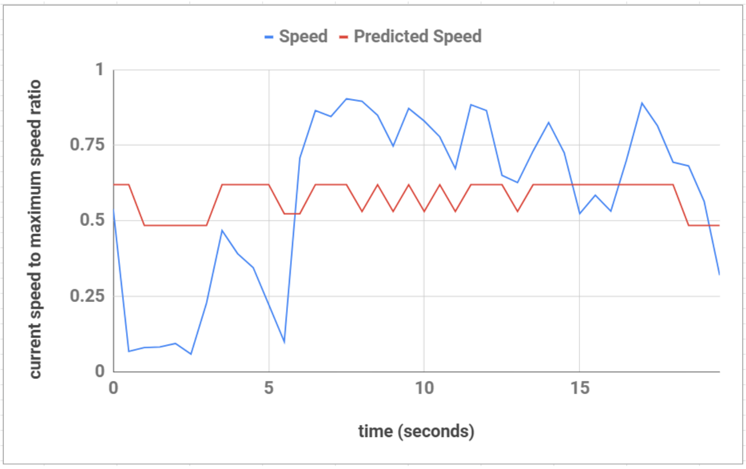

Figure 5.9: Speed prediction.

Algorithm 5 Obtaining the previous values for each variable.

Data: last_speed, last_right, last_left, last_cars

Result: speed, right, left, cars

for *t in time* **do**

    last_speed[t] = speed[t-1]

    last_right[t] = right[t-1]

    last_left[t] = left[t-1]

    last_cars[t] = cars[t-1]

end

With these new columns, the same process was followed. The root means squared error diminished to 0.207. While it still isn't a low value, the improvement is certainly present. Once more, comparing the results with the original values on the same event provides additional insight. As seen if figure 5.10, the prediction are closer to the original but they mostly depend on the previous value of speed, leading to a delay between when the speed changes abruptly change.

The obtained results show that these variables are still not enough to obtain a precise prediction of speed. While there is a significant relationship between the previous speed value and the next it is not enough to predict abrupt changes. Trying to peek further in the past does not show promising results, as the improvements when experimenting with the last two values display insignificant improvements (root mean squared error = 0.203). The prediction graph can be observed in Annex 5.11. While the remaining variables remain seemingly unrelated to the speed value, some of the algorithms give significant weight to the "left" and "right" values. While not comparable to previous speed value, this seems to point out to an existing, yet superficial, decay in speed when looking around.

As previously mentioned, the speed value possesses some noise, which might have had an effect on the obtained results. It is also important to recall that the time between each set of values is half of a second. While not large, experimentation with smaller values might reveal new

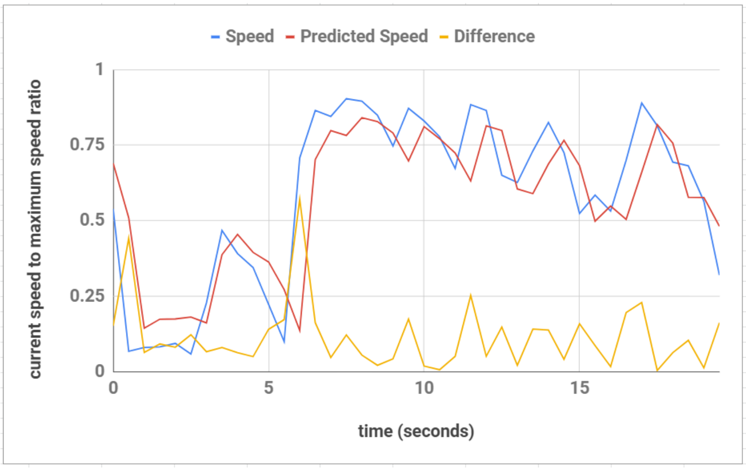

Figure 5.10: Speed prediction using previous values.

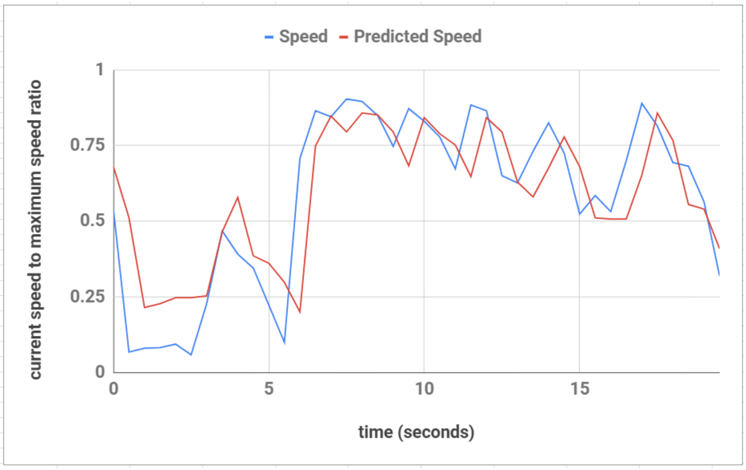

Figure 5.11: Speed prediction using the two previous values.

findings, or diminish the impact of the noise. Further analysis of this matter, taking into account these factors, and using additional variables, is needed to corroborate these conclusions.

Aside from predicting the value of speed, it is possible to try to predict whether the pedestrian will look right or left. This prediction takes into account the current and last value of speed, as well as the last right and left values.

For the left prediction, the best results display an accuracy of 84.7%. As observed in figure 5.12, the same pattern observed in the speed prediction, where the prediction relies mostly on the last value, is present. There are however cases when this change is successfully predicted, which corroborates with the previously mentioned idea that looking to the left is associated with a superficial decay in speed.

For the right prediction, the results were similar with an accuracy of 87.0%. Once more, the same delay pattern is observed (see figure 5.13), and some successful predictions that do not follow the last value are present.

Overall, the analysis using these four variables was less successful than initially predicted. It

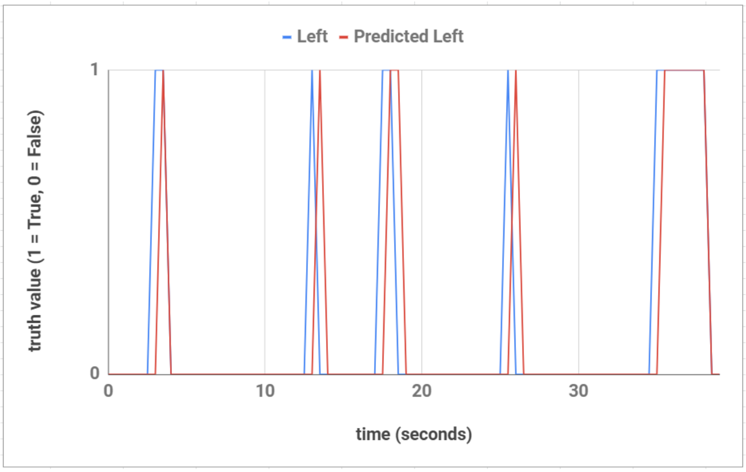

Figure 5.12: Left prediction.

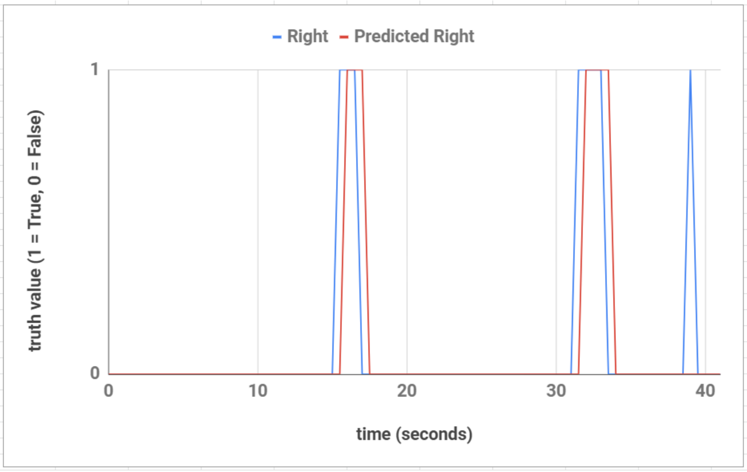

Figure 5.13: Right prediction.

was expected that the act of looking around and the presence of cars in the field of vision would have a greater impact on a person speed. The results, however, show that these activities do not interfere with the pedestrian movement in a significant way. The selected metrics for analysis seem to be insufficient for an accurate prediction, as such additional analysis will be needed.

5.3 Summary

This chapter delved into the analysis of the data collected in the experiment discussed in chapter 4. The subjects' answers to the surveys were analyzed and discussed. The results showed that the experiment was fairly realistic, but it was tiring for the subjects.

Time series representing speed, the existence of cars in the field of vision, and looking direction were extracted from the collected data. The time series were analyzed using Rapidminer, where the data was prepared and used to build predictive models. The resulting models were compared with the original data, which revealed that while the prediction was not much different, it was mostly based on the previous value, which resulted in the inability to predict abrupt changes. The results showed that the analysis of other collected metrics or even the collection of additional metrics might be needed.

Chapter 6

Conclusion

Through this document, the possibility of using virtual reality as a tool for pedestrian behaviour elicitation was studied. In chapter 1, the context and motivation behind this problem were explained, and some research questions were raised. Additionally, the structure of this document itself was also explained. In the literature review, presented in 2, several approaches to pedestrian modelling were found and analyzed. Of these, it was observed that agent-based models are recognized by the scientific community as the most suitable approach to model pedestrians in a microscopic simulation. Different behaviour elicitation methods were also studied and compared, exposing some of their flaws and qualities. Chapter 3 presented the author approach to the problem, by presenting a pipeline for pedestrian behaviour elicitation studies. Several aspects to take into account were identified, such as the key elements to the simulation, what kind of metrics to collect, how to store them, and reusing the resulting models in new experiments. In Chapter 4 an experiment following these principles was presented. This implementation focused on showing how could some fundamental metrics be collected. Finally, in chapter 5, the data collected in the experiments as analyzed and discussed.

In all these chapters, answers to the research questions defined in 1.3 can found:

RQ1: How do modern behaviour elicitation techniques compare to traditional ones?

Traditional behaviour elicitation techniques, such as direct observation and survey techniques generally provide data in the form of descriptions and statements, collected by the researchers themselves. Numerical data can also be collected but it might either be inaccurate or demand a large number of resources. This kind of approaches generally lack validity, either internal or external due to being intrusive or inaccurate.

Modern approaches, on the other hand, make use of technology to alleviate the researcher's workload. The collected data is numerical by nature, but other kinds of data can be extrapolated. The latter task, however, might not be trivial or accurate enough. These approaches display the capacity to hold both high internal and external validity, as they are more precise and generally less intrusive than traditional methods and, depending on the devices used, several times more precise.

While modern approaches show a tendency to hold more validity than traditional ones, all approaches show some kind of advantages and disadvantages depending on the objective of studies. As such, using multiple approaches to complement each other might also be a solution to take into account

RQ2: What metrics must be collected in order to understand pedestrian behaviour?

Pedestrian behaviour can be represented as a relation between the actor, the perceived context and the taken actions. For the subject, one must try to understand its thought process so metrics related to past experiences and demographics should be collected. Most current virtual reality lack the capacity to collect this kind of metrics, so making use of alternative methods such as surveys is recommended. Metrics about the context represent the sensory information that the actor receives. As such, a standard should include at least what objects are perceived. Further metrics include the state of the perceived objects and relative location. Finally, the actions are completely dependent on the setting of the experiment. Even then metrics such as whether and when an action is taken are, for the most part, fundamental. The latter two elements require the capture of several metrics whose methods of capture are relatively easy to implement in a virtual environment and thus suitable to be collected in it.

RQ3: How can the collected data can be effectively used to create realistic pedestrian agents?

The data collected in virtual reality environment can represent several different aspects of behaviour, and be kept in different formats. Thus there might be a need to transform the data before performing any meaningful analysis. After this step however one can try to discover rules or probabilistic distributions for a pedestrian to perform certain actions on each situation. Furthermore, one can try to discover how each action is affected by the context, in order to obtain finer details. The models that result from this process can then be used to control pedestrian agents. The agents can then be used in a new simulation, to collect new data, subsequently giving birth to new agents. Through this cycle, the accuracy and realism of the pedestrian agents should incrementally rise. This process is mostly manual, as no tools were found or created in order to aid the creation of these agents, except for those which automate the analysis process, such as Rapidminer.

6.1 Limitations

Several limitations, both design and technical, were identified. These limitations are present mostly on the implementation, but some can also be identified in the proposed methodology.

The processes explained in the methodology propose to aim for an ideal study where all needed resources are available. Even though the minimum requirements for the simulation are touched upon, it is a reality that even those might not be possible to achieve in some situation. Success, when the situation nears this lower limit, is also not guaranteed. As such, whether or not this methodology can be applied when there a lack of resource is still an open question.

Another limitation of this methodology lies in data processing. As mentioned, virtual environments allow for a variety of data to be collected, but this gives birth to a huge amount of data which might be hard to process. Organization issues might also arise due to this variety.

The implemented experiment revealed some difficulties in the motion capture mechanisms and subsequent movement computation. While it is not obvious whether these problems are the fault of the hardware itself or the VRTK package, they introduce noise into the collected data. A more concerning problem, however, is the fact that the system relies on the arms motion to control the virtual avatar. Not only is this restrictive, but it is unnatural, constituting a source of bias by forcing altered behaviours.

During the experiment, several metrics were collected. While most were only used as proof of concept or example to the implementation, it is clear that other metrics could still be collected. These metrics might not be useful at all but there is a significant chance that new findings could be made. The same limitation occurs when talking about the sample and the setting. The sample itself was small so not all possible scenarios could be observed. Even if there was a bigger sample, the urban setting itself did not contain all possible situations that could happen, as, for example, the only present vehicles were cars. Amending these limitations requires expanding the experiment with more data collection mechanisms, a larger sample and even a more detailed simulation.

6.2 Contributions

The main contribution of this work is the methodology presented in chapter 3, which provides a guideline to how to elicit pedestrian behaviour through the use of virtual environments. This methodology does not only address the sequence of tasks to perform but in each step, highlights the key elements to take into account for maximizing the value of the experiment.

As a byproduct of the implemented experiment, this work yields several contributions to pedestrian behaviour research. A whole simulation environment was created, complete with several data collection mechanisms. While the environment itself cannot be shared, the implemented mechanisms can serve as inspiration for future projects, which might not be necessarily tied to pedestrians. These mechanisms might be applied to other topics which make use of virtual reality to elicit behaviour. Furthermore, aside from the mechanisms, the kind of metrics collected can also act as a guideline for other experiments on this topic.

In order to store the collected data, a specific format was defined. This format supports a natural division of data according to the verbs and objects used, thus enforcing human-readability. While the format enforces a general structure, it foresees the need for variation, thus providing a field to insert semi-unstructured data. The format definition, along with the provided examples, can be directly used or adapted by other experiments.

Finally, the result analysis and subsequent model creation provided some models to represent pedestrian behaviour. While the application of these models remains to be completed and the results are not much precise, they still constitute a valid representation of pedestrian behaviour.

6.3 Future Work

While this work yields several contributions to pedestrian behaviour research, there is still room for further work. As mentioned previously, after finishing the model creation step, that model should be fed to the simulation in order to improve it, and the process should start anew leading the collection of more valuable data. Ideally, this recursive step would be implemented and tested.

Experiments with a larger and more diverse sample are also being considered. As previously mentioned, the sample was limited this time, so further consolidating the current results is imperative. Additionally, this might lead to new findings as new situations might occur.

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Appendix A

Informed Consent Form

DECLARAÇÃO DE CONSENTIMENTO

(Baseada na declaração de Helsínquia)

No âmbito da realização da tese de Mestrado do Mestrado Integrado em Engenharia Informática e Computação da Faculdade de Engenharia da Universidade do Porto, intitulada **Agent-Based Modelling via Pedestrian Behaviour Elicitation in Virtual Reality**, realizada pelo estudante **João Filipe Pereira da Costa**, orientada pelo Prof. João Jacob e sob a co-orientação do Prof. Rosaldo Rossetti, eu abaixo assinado, ______________, declaro que compreendi a explicação que me foi fornecida acerca do estudo em que irei participar, nomeadamente o carácter voluntário dessa participação, tendo-me sido dada a oportunidade de fazer as perguntas que julguei necessárias.

Tomei conhecimento de que a informação ou explicação que me foi prestada versou os objectivos, os métodos, o eventual desconforto e a ausência de riscos para a minha saúde, e que será assegurada a máxima confidencialidade dos dados.

Explicaram-me, ainda, que poderei abandonar o estudo em qualquer momento, sem que daí advenham quaisquer desvantagens.

Por isso, consinto participar no estudo e na recolha de imagens necessárias, respondendo a todas as questões propostas.

Porto, 29 de Abril de 2019

____

(Participante ou seu representante)

Appendix B

Virtual Reality Sickness Questionnaire

Perfil

*Required

ID *

Your answer

Género *

- Masculino
- Feminino

Idade *

Your answer

Altura (cm) *

Your answer

NEXT

Never submit passwords through Google Forms.

Perfil

*Required

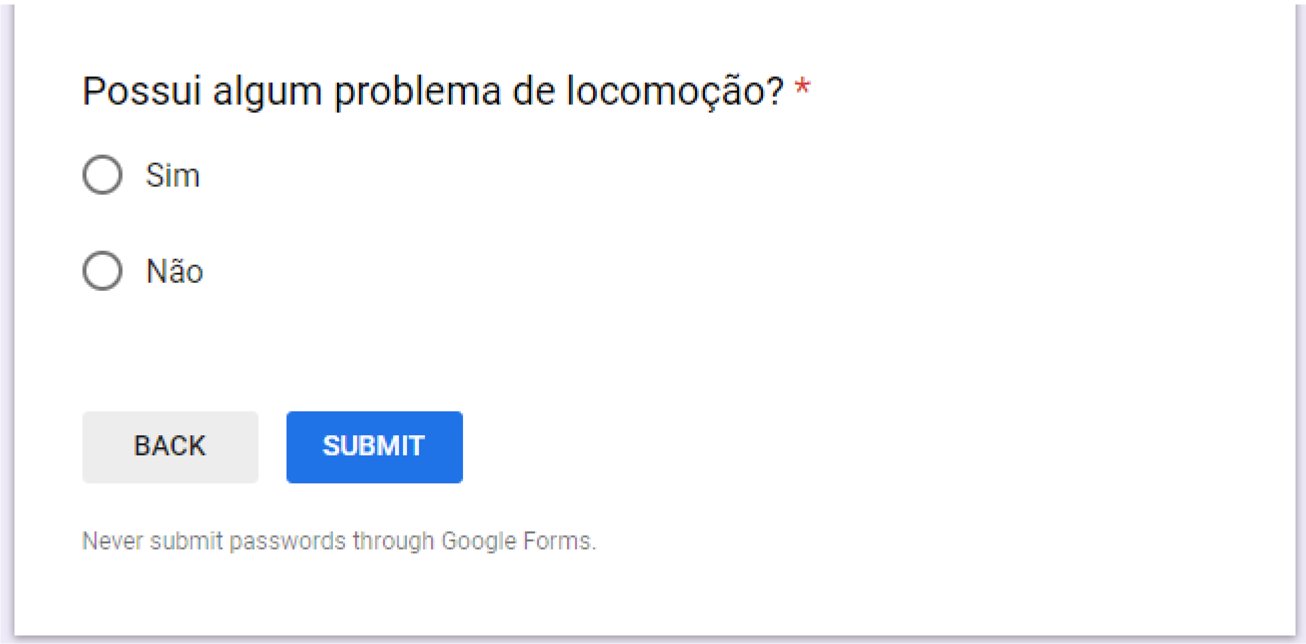
Hábitos

Possui carta de condução? *

- ◯ Sim
- ◯ Não

Quais dos seguintes métodos de transporte usa frequentemente?

- ☐ Carro Pessoal
- ☐ Autocarro/Camioneta
- ☐ Motociclo
- ☐ Comboio/Metro
- ☐ A pé
- ☐ Other: ____________________



Possui algum problema de locomoção? *

- Sim
- Não

BACK SUBMIT

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Appendix C

User Profile and Demographics

VRSQ

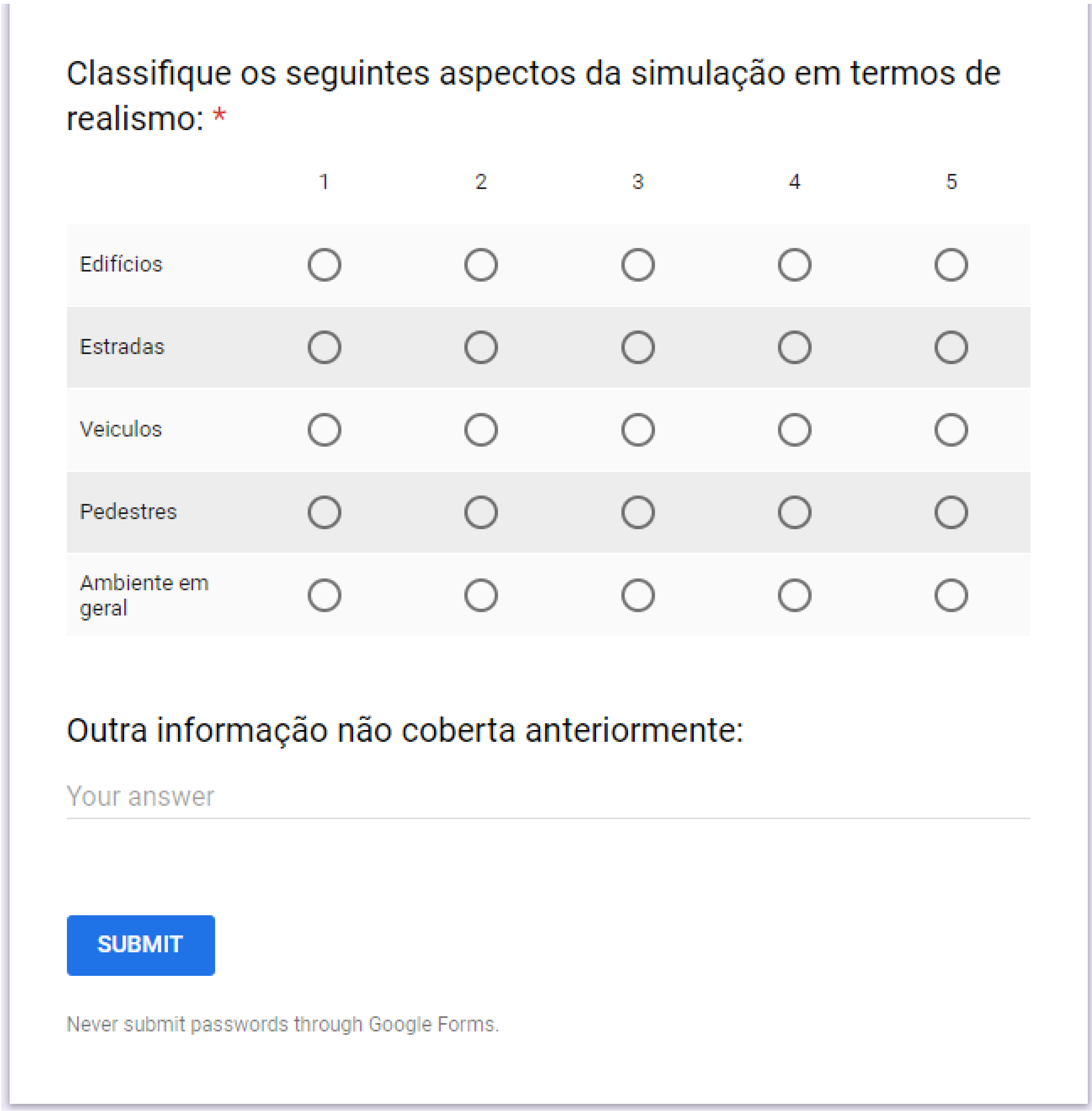
*Required

ID:

Your answer

Indique se sentiu algum dos seguintes sintomas: *

	Não senti	Ligeiramente	Moderamente	Intensamente
Desconforto	○	○	○	○
Fatiga	○	○	○	○
Olhos cansados.	○	○	○	○
Dificuldade em focar	○	○	○	○
Dores de cabeça	○	○	○	○
Cabeça cheia	○	○	○	○
Visão turva	○	○	○	○
Tonturas (com olhos fechados)	○	○	○	○
Sensação de vertigem	○	○	○	○



Classifique os seguintes aspectos da simulação em termos de realismo: *

	1	2	3	4	5
Edifícios	○	○	○	○	○
Estradas	○	○	○	○	○
Veiculos	○	○	○	○	○
Pedestres	○	○	○	○	○
Ambiente em geral	○	○	○	○	○

Outra informação não coberta anteriormente:

Your answer

SUBMIT

Never submit passwords through Google Forms.

Appendix D

Data Storage Server Code

```

import pymongo
import socket
import json
import jsonschema

myclient = pymongo.MongoClient("mongodb://localhost:27017/")

mydb = myclient["simusafe_experience_registry"]
mycol = mydb["jfc_test_db"]

#-------------------------------------------
# Schema
#-------------------------------------------
#Settings
check_schema = True
schema_file_path = "./Registry/schema.json"
exceptions = []

#Script
schemaFile = open(schema_file_path,'r')
schema = json.load(schemaFile)
schemaFile.close()

#-------------------------------------------
# Socket
#-------------------------------------------
server_address = ('localhost', 10001)
sock = socket.socket(socket.AF_INET, socket.SOCK_DGRAM)
sock.bind(server_address)

#-------------------------------------------
# Core
```

```
#------------------------------------------

print('Simusafe Experience Registry is up.')

while True:
    data, address = sock.recvfrom(4096)
    data = json.loads(data.decode())
    if data:
        try:
            jsonschema.validate(data, schema)
            mycol.insert_one(data)
            print("Nice")
        except Exception as e:
            exceptions.append(e)
            print(e)
            continue
        #print(data)
```

Listing D.1: Server code

Appendix E

Data Storage Schema

```
{
  "definitions": {
    "vector3" : {
      "$id": "#/definitions/vector3",
      "type": "object",
      "title": "The Vector3 Schema",
      "required": [
        "x",
        "y",
        "z"
      ],
      "properties": {
        "x": {
          "$id": "#/properties/x",
          "type": "number",
          "title": "The X Schema",
          "default": 0.0,
          "examples": [
            3.32313
          ]
        },
        "y": {
          "$id": "#/properties/y",
          "type": "number",
          "title": "The Y Schema",
          "default": 0.0,
          "examples": [
            2.3231
          ]
        },
        "z": {
          "$id": "#/properties/z",
          "type": "number",
```

```
          "title": "The Z Schema",
          "default": 0.0,
          "examples": [
            213.2
          ]
        }
      }
    },
    "enum": {
      "$id": "#/definitions/enum",
      "type": "string",
      "title": "The Enum Schema"
    },
    "id": {
      "$id": "#/definitions/id",
      "type": "string",
      "title": "The Id Schema"
    },
    "boolean": {
      "$id": "#/definitions/boolean",
      "type": "boolean",
      "title": "The Boolean Schema"
    },
    "float": {
      "$id": "#/definitions/float",
      "type": "number",
      "title": "The Number Schema"
    }
  },
  "$schema": "http://json-schema.org/draft-07/schema#",
  "$id": "http://example.com/root.json",
  "type": "object",
  "title": "The Root Schema",
  "required": [
    "actor",
    "verb",
    "objects",
    "timestamp"
  ],
  "additionalProperties": false,
  "properties": {
    "actor": {
      "$id": "#/properties/actor",
      "type": "string",
      "title": "The Id Schema",
      "examples": [
        "pedestrians/1", "vehicles/cars/3"
      ]
    },
```

```
    "verb": {
      "$id": "#/properties/verb",
      "type": "object",
      "title": "The Verb Schema",
      "required": [
        "id"
      ],
      "additionalProperties": false,
      "properties": {
        "id": {
          "$id": "#/properties/verb/properties/id",
          "type": "string",
          "title": "The Id Schema",
          "default": "",
          "examples": [
            "action/stopped", "perception/saw"
          ],
          "format": "json-pointer"
        },
        "modifier": {
          "$id": "#/properties/verb/properties/modifier",
          "type": "object",
          "title": "The Modifier Schema",
          "properties": {
            "position": {
              "$ref": "#/definitions/vector3"
            },
            "rotation": {
              "$ref": "#/definitions/vector3"
            },
            "headRotation": {
              "$ref": "#/definitions/vector3"
            },
            "rightHandPosition": {
              "$ref": "#/definitions/vector3"
            },
            "rightHandRotation": {
              "$ref": "#/definitions/vector3"
            },
            "leftHandPosition": {
              "$ref": "#/definitions/vector3"
            },
            "leftHandRotation": {
              "$ref": "#/definitions/vector3"
            },
            "gender": {
              "$ref": "#/definitions/enum"
            },
            "apparentAge": {
```

```
              "$ref": "#/definitions/enum"
            },
            "speed": {
              "$ref": "#/definitions/float"
            },
            "direction": {
              "$ref": "#/definitions/enum"
            },
            "onCrosswalk": {
              "$ref": "#/definitions/boolean"
            }
          }
        }
      }
    },
    "objects": {
      "$id": "#/properties/objects",
      "type": "array",
      "title": "The Objects Schema",
      "items": {
        "$id": "#/properties/objects/items",
        "type": "object",
        "title": "The Object Schema",
        "required": [
          "id"
        ],
        "additionalProperties": false,
        "properties": {
          "id": {
            "$id": "#/properties/objects/items/properties/id",
            "type": "string",
            "title": "The Id Schema",
            "default": "",
            "examples": [
              "pedestrians/1", "vehicles/cars/3"
            ],
            "format": "json-pointer"
          },
          "modifier": {
            "$id": "#/properties/objects/items/properties/modifier",
            "type": "object",
            "title": "The Modifier Schema",
            "properties": {
              "position": {
                "$ref": "#/definitions/vector3"
              },
              "rotation": {
                "$ref": "#/definitions/vector3"
              },
```

```
              "headRotation": {
                "$ref": "#/definitions/vector3"
              },
              "rightHandPosition": {
                "$ref": "#/definitions/vector3"
              },
              "rightHandRotation": {
                "$ref": "#/definitions/vector3"
              },
              "leftHandPosition": {
                "$ref": "#/definitions/vector3"
              },
              "leftHandRotation": {
                "$ref": "#/definitions/vector3"
              },
              "gender": {
                "$ref": "#/definitions/enum"
              },
              "apparentAge": {
                "$ref": "#/definitions/enum"
              },
              "crosswalk": {
                "$ref": "#/definitions/id"
              },
              "trafficLight": {
                "$ref": "#/definitions/id"
              },
              "state": {
                "$ref": "#/definitions/enum"
              },
              "material": {
                "$ref": "#/definitions/enum"
              }
            }
          }
        }
      }

    },
    "timestamp": {
      "$id": "#/properties/timestamp",
      "type": "number",
      "title": "The Timestamp Schema"
    },
    "sessionId": {
      "$id": "#/properties/sessionId",
      "type": "string",
      "title": "The SessionId Schema"
    }
```

```
  }
}
```

Listing E.1: Data storage JSON schema