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Diploma Thesis

Create a game in Unity for traffic education

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Thanks to

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Foreword

Technological advances in virtual reality (VR) and eye-tracking systems have opened up new horizons in research on human behaviour and interaction with the environment. In the context of modern urban centres and the development of smart cities, understanding pedestrian behaviour and improving pedestrian safety is a critical challenge. This study focuses on investigating pedestrians' reactions to various visual and auditory stimuli while crossing crosswalks, using advanced VR and eye-tracking technologies.

With this work, we seek to enhance the debate on the integration of advanced technologies in urban mobility and to highlight the importance of a multidisciplinary approach to addressing contemporary challenges. We hope that our findings will provide a basis for further research and development of solutions that will improve the quality of life and safety of citizens in the cities of the future.

Summary

This thesis focuses on the creation and analysis of a virtual reality game ,of a traffic education type, where the player assumes the role of a pedestrian and has to cross various road crossings under different conditions. The game includes scenarios with a variety of visual and auditory stimuli, such as crossings with or without traffic lights, obstacles, and different types of vehicles (e.g. electric). The main purpose of the thesis is to analyze the user's reactions, with a focus on eye movement recording and fixation points (fixations) during road crossings. Through the analysis of this data, the thesis aims to provide valuable insights into how users perceive and react to different traffic scenarios, as well as to explore the potential of applying smart city-type technologies to enhance pedestrian safety.

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Abstract

This thesis focuses on the development and analysis of a VR (Virtual Reality) traffic safety game, where the player takes on the role of a pedestrian and must navigate various road crossing scenarios under different conditions. The game includes scenarios with varying visual and auditory stimuli, such as crossings with or without traffic lights, obstacles, and different types of vehicles (e.g., The primary goal of this thesis is to analyze user reactions, with a particular emphasis on recording eye movement and fixation points during road crossings. By analyzing this data, the study aims to provide valuable insights into how users perceive and react to different traffic scenarios, as well as to explore the potential implementation of smart city technologies to enhance pedestrian safety.

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Abbreviations

VR	virtual reality
NPC	Non player Character
EV	electric vehicle
ITS	Intelligent Transportation Systems
HMD	Head Mounted Device

GLOSSARY or Term Rendering

virtual reality	Virtual Reality
Non-Player-Character	Non-truthful character
Checkpoint	Control point
electric vehicle	Electric Vehicle
Conventional car	Conventional vehicle
cognitive load	cognitive load
Intelligent Transportation Systems	intelligent transport systems
Eye-tracking	Ocular tracing

1

Introduction

1.1 Importance of the Road Traffic Problem from the Pedestrian's Point of View

Pedestrian safety is one of the most critical issues in road traffic, particularly in modern urban areas where pedestrians and vehicles coexist in an ever-evolving and complex environment. The coexistence of pedestrians and vehicles in urban traffic networks creates interactions that can lead to dangerous situations, resulting in serious injuries or even deaths. According to global statistics, a significant proportion of deaths from road accidents involve pedestrians, underlining the importance of safety and prevention in this context.

Pedestrians are the most vulnerable users of the road network, as they are not protected by the same safety mechanisms that vehicles provide for their drivers and passengers. The safety of pedestrians depends to a large extent on their ability to recognise and react appropriately to visual and auditory stimuli from their environment, such as traffic lights, traffic signs and noise from passing vehicles.

However, the rapid development of new technologies, such as electric and autonomous vehicles, has created new challenges for road safety. For example, electric cars, due to their silent operation, can make it difficult for pedestrians to detect them in time, which increases the risk of accidents in high-traffic areas. At the same time, road infrastructure is often not adequately designed to meet the needs of pedestrians, leading to confusion and dangerous decisions, especially when traffic signals are limited or unclear.

1.2 Objectives of the Work

In this paper we focus on investigating pedestrian behaviour in different road traffic scenarios through a virtual reality (VR) environment that simulates real road crossing situations. The goal is to analyze the user's reactions to different visual and auditory stimuli, such as crossings with or without traffic lights, obstacles and the presence or absence of noise from vehicles. In addition, by recording eye movements and fixations, the study aims to understand how pedestrians perceive their environment and to evaluate the effectiveness of smart city technologies to enhance their safety.

1.3 Contribution

This thesis makes a significant contribution to the field of road safety and the study of pedestrian behaviour through the development and evaluation of an innovative virtual simulation environment. Despite the existence of a number of studies examining road traffic, there is a notable gap in the literature in terms of approaching pedestrian behaviour from their perspective, particularly using Virtual Reality. This paper seeks to fill this gap by offering an innovative method to study and improve pedestrian safety in urban environments.

Specifically, the contribution of the work lies in the development of a detailed and realistic virtual environment, which represents the centre of a metropolis. To implement this environment, the Unity platform was used and code was written in C# programming language, which is embedded in Unity. The virtual environment includes scenarios of crossing streets in non-ideal conditions, as well as scenarios with innovative implementations of smart city-type technologies aimed at enhancing pedestrian safety. The paper analyses how pedestrians react to different stimuli(visual and auditory) and what are the effects on their safety. In addition, it evaluates the effectiveness of smart city type technologies, such as smart crossings with traffic lights, in enhancing pedestrian safety by identifying user acceptance and perception of these technological solutions.

The evaluation was carried out through an empirical study involving real users interacting with the virtual environment. Quantitative and qualitative data were collected through eye-tracking technologies, questionnaires and meta-experimental interviews. These data were analysed descriptively, leading to important conclusions on pedestrian behaviour and the effectiveness of the proposed technological solutions.

1.4 Structure of the Thesis

CHAPTER 1 presents the importance of the road traffic problem from the pedestrian's perspective, the objectives of the study and its contribution to the field of pedestrian safety.

CHAPTER 2 analyses the factors affecting pedestrian traffic. It examines pedestrian behaviour in urban environments and presents technological solutions and smart city initiatives aimed at improving safety.

CHAPTER 3 introduces the concept of virtual reality and eye-tracking and discusses their choice as tools for conducting research.

CHAPTER 4 presents the methodology followed for the implementation of the research. It describes the development of the virtual environment, the implementation of the world, the car and pedestrian traffic, as well as the player integration and the configuration of the VR equipment.

CHAPTER 5 presents the results of the experiments conducted in the virtual environment. A descriptive analysis of the data is performed, with a focus on understanding pedestrian behaviour and evaluating the effectiveness of smart city technologies to enhance safety.

CHAPTER 6 summarises the main findings of the study and discusses the limitations of the research. Directions for future research are suggested to further improve pedestrian safety through technology and virtual reality.

2

Analysis of Pedestrian Traffic

2.1 Introduction to Pedestrian Traffic

Pedestrian traffic is a fundamental element of urban mobility and has a direct impact on the quality of life, health and safety of urban residents. Pedestrians are the most vulnerable users of the road network, as they do not have the same protective equipment as motorists. According to the World Health Organization (WHO), approximately 23% of road traffic fatalities worldwide involve pedestrians [1][29]. This highlights the need for a thorough understanding of pedestrian behaviour and the factors affecting their safety in order to design sustainable and safe urban environments.

2.2 Factors that Affecting on Traffic of Pedestrians

Pedestrian traffic is influenced by a number of factors that determine their choice to walk, their comfort and their safety in the urban environment. These factors can be categorised as physical and environmental, social and economic, as well as factors related to traffic flow and road infrastructure.

2.2.1 Natural AND Environmental Factors

Physical and environmental factors have a significant influence on people's decision to choose walking as a means of transport. Climatic conditions, such as temperature, humidity and rainfall can affect the comfort and willingness to walk. As noted in the study by Giles-Corti and Donovan, extreme temperatures discourage the use of sidewalks, particularly when conditions include extreme cold, heat or rain [25]. In addition, areas with poor air quality or increased air pollution often discourage walking, especially for people with sensitivities such as the elderly or children with respiratory problems.

Another important factor that positively influences the decision to walk is the availability of green spaces. Areas with parks, trees and generally high quality urban landscape attract pedestrians, providing pleasant walking conditions. The availability of green spaces is also associated with improved mental health and social interaction. As Sugiyama's research shows, neighborhoods with green spaces encourage physical activity and promote mental well-being among residents [26]. In contrast, environments with increased noise, poor aesthetics or lack of green spaces create less pedestrian-friendly conditions and reinforce the preference for other modes of transport.

2.2.2 Social AND Economic Factors

In addition to physical and environmental factors, socio-economic status, age and cultural habits play a key role in pedestrian travel. People with lower incomes often rely more on walking or public transport due to limited access to private vehicles. As stated in the Handy study, economic factors influence the use of available pedestrian infrastructure, as people living in areas with less developed sidewalk networks or degraded conditions may face more risks or barriers when moving around [27].

Population density and the variety of land uses in an area are also key factors that encourage walking. As Li notes, areas with increased accessibility to daily services such as shops, schools and public infrastructure promote walking by facilitating short, daily trips on foot [28]. Especially in areas with a mix of residential and commercial uses, pedestrians are more motivated to walk as distances are shorter and services are more accessible.

Finally, the feeling of safety is particularly important, as it has a strong influence on people's willingness to walk. Pedestrians are less likely to choose to walk in areas with high crime rates or poor lighting and policing. Handy highlights that the sense of safety and the quality of infrastructure are critical factors that influence the choice of walking as a daily activity [27].

2.2.3 Traffic Flow AND Road Infrastructure

Traffic flow and road infrastructure are fundamental factors affecting the experience and safety of pedestrians in urban environments [2]. As vulnerable users of the road network, pedestrians are highly dependent on the quality and design of infrastructure for their safe movement. The interaction between vehicle traffic and pedestrians is complex and is influenced by multiple variables such as signalling, vehicle speed, traffic volume and the quality of pavements.

2.2.3.1 Marking AND signalling

Adequate signposting and signalling is vital for guiding pedestrians and ensuring safe crossing of roads. According to Zegeer, the presence of signalized pedestrian crossings can significantly reduce the risk of accidents at uncontrolled intersections [2]. Clear and visible signage helps pedestrians identify safe crossing points and informs drivers of the potential presence of pedestrians.

Turner highlights that the quality of signage and signalling affects pedestrians' perception of safety and can influence their behaviour [3]. The use of traffic lights, signs and pavement markings facilitates communication between pedestrians and drivers, reducing uncertainty and the risk of collisions.

2.2.3.2 Speed AND Volume of Vehicles

The high speed of vehicles and the high volume of traffic create an environment that can be considered dangerous by pedestrians [4]. Fildes states that vehicle speed is one of the most determining factors for the severity of accidents [4]. The higher the speed, the less reaction time there is for drivers and pedestrians, increasing the likelihood of serious injury in the event of a collision.

Reducing vehicle speed in areas with high pedestrian traffic has been shown to reduce the number and severity of accidents. Aarts and Van Schagen point out that speed restricted areas, such as 30 km/h zones, can significantly improve pedestrian safety [5]. In addition, the adoption of traffic calming measures, such as speed bumps and road closures, can help to reduce vehicle speed.

The volume of traffic also affects the comfort and safety of pedestrians. On roads with high vehicle density, pedestrians may feel stressed and hesitate to cross the road, even at signalised crossings. The increase the volume of vehicles can lead to longer waiting times for pedestrians, encouraging them to break traffic rules and cross the road at unsafe places.

2.2.3.1 Quality AND width of pavements

Spacious and well-maintained pavements are essential for comfortable and safe pedestrian movement. According to Rosenbloom, the quality of sidewalks affects pedestrians' choice to walk and their sense of safety [6]. Spacious sidewalks allow for the unimpeded movement of many people at the same time, and are particularly accommodating for people with mobility problems, the elderly and parents with strollers.

Conversely, narrow or poorly maintained pavements can be a barrier to pedestrians. Obstacles such as poles, litter bins or poorly placed benches can reduce the space available and force pedestrians to step off onto the pavement, putting them at risk [6]. In addition, irregularities in the pavement surface, such as broken slabs or potholes, increase the risk of falls and injuries.

The maintenance and design of pavements must take into account the needs of all users. The application of accessibility design principles ensures that pavements are suitable for people with disabilities, encouraging their use and promoting social inclusion.

2.2.3.2 Combined effect on pedestrian behaviour

Traffic flow and road infrastructure interact and influence pedestrian behaviour in complex ways. When pedestrians feel that the environment is inhospitable or dangerous, they may choose to break the rules, such as crossing the road outside crossings or ignoring traffic signals. This can increase the risk of accidents and create a vicious circle of unsafe practices.

An environment with well-designed infrastructure, controlled vehicle speed and clear signage encourages pedestrians to follow the rules and feel safe. Drivers, aware of the presence of pedestrians, are more likely to behave cautiously, reducing their speed and giving way where necessary.

2.3 Pedestrian Behaviour in Urban Environments

Pedestrian behaviour in urban environments is a multidimensional phenomenon influenced by a multitude of factors such as risk perception, interactions with other means of transport, technological developments and psychological parameters. A deeper understanding of these factors is critical to improving safety and quality of life in cities [7].

In modern megacities, where traffic density and the variety of transport modes are high, pedestrians are required to navigate in environments with increased complexity. Their interaction with the environment and other road users requires constant decision-making and adaptation to dynamic conditions.

2.3.1 Effect of Cognitive Load on Pedestrian Behaviour

Cognitive load refers to the amount of mental effort required to process information and make decisions in an environment. In urban environments, pedestrians are confronted with a multitude of stimuli, such as traffic noise, traffic lights and constant vehicle traffic. As the complexity of the environment increases, so does the cognitive load required to make correct decisions.

When the cognitive load is increased, pedestrians find it difficult to process all the information necessary to understand the risks and make safe decisions. For example, distractions such as using mobile phones or listening to music while moving increase cognitive load, reducing the pedestrian's attention to their surroundings. The use of mobile phones while crossing roads has been shown to increase reaction time and reduce pedestrians' ability to identify potential hazards [11].

In addition, the increased cognitive load affects the ability of pedestrians to correctly process traffic-related information, such as estimating the speed and distance of passing vehicles. Failure to correctly assess these parameters can lead to incorrect decisions, such as attempting to cross a road without sufficient time. According to Neider and Kramer, engaging in activities that increase cognitive load, such as chatting or using a telephone, significantly reduces pedestrians' ability to react to hazards in a timely manner [12]. This is particularly important on busy roads with high traffic speeds, where timely and correct perception of hazards can be crucial for pedestrian safety.

2.3.2 Risk perception

Risk perception is fundamental for safe pedestrian movement in urban environments. During their travel, pedestrians need to make decisions related to risk management, such as when it is safe to cross a road or which route is more appropriate. Their ability to recognise environmental stimuli, both visual and auditory, plays a key role in these decisions [8].

Pedestrians rely on visual stimuli such as traffic lights, traffic signs and crossings, as well as auditory stimuli such as the sounds of vehicles to assess the safety of the environment. However, the development of silent electric vehicles has reduced the reliability of auditory stimuli, making visual observation even more important. Harrell reported that visual observation o f pedestrians now plays a greater role in safety assessment, particularly in urban environments with increased traffic [9].

In addition, the ability of pedestrians to correctly judge the speed and distance of passing vehicles is crucial for decision-making. Pedestrians often find it difficult to make accurate estimates, especially on roads with high traffic speeds. Factors such as distance from the road, viewing angle and environmental conditions can affect risk perception. This inability can lead to decisions that increase the risk of accidents, such as underestimating the time required to cross a road [8].

2.3.3 Interaction with Vehicles AND Other Pedestrians

Interaction with vehicles and other pedestrians also affects pedestrian behaviour in urban environments. Pedestrians need to anticipate the intentions of drivers and communicate with them through eye contact or gestures to ensure safe passage. However, this is not always possible, especially in cases where drivers do not respect traffic rules or do not give priority to pedestrians. The absence of clear communication can lead to dangerous situations [10].

With the introduction of autonomous vehicles, this interaction becomes more complex. According to the United Nations Economic Commission for Europe [10], autonomous vehicles require new standards of communication with pedestrians, as the absence of a driver limits traditional visual communication.

Pedestrian behaviour is also affected by interaction with other pedestrians. In crowded areas, the flow of pedestrians and the movement of crowds influence their decisions. Social pressure may lead them to follow the crowd, even if it means breaking traffic rules, such as crossing a street at a red light. Rosenbloom [6] found that pedestrians are more likely to violate traffic signals when they are in a group.

Finally, pedestrian behaviour at unmarked crossings is a particular challenge. In the absence of clear signals for pedestrian crossings, pedestrians are forced to rely on their own personal judgement as to when it is safe to cross the road. This increases the risk of accidents, as the lack of signage can create uncertainty and insecurity. Pedestrians need to interact directly with drivers to ensure their safety, which can be particularly difficult on busy roads or in situations where drivers do not give way [7].

2.4 Security Issues and Challenges

Pedestrian safety is a critical issue in urban environments, as pedestrians are the most vulnerable users of the road network. Despite continuous efforts to improve infrastructure and traffic regulations, many challenges related to pedestrian safety remain. According to the World Health Organization, approximately **23% of road traffic fatalities** worldwide involve pedestrians, underlining the seriousness of the problem [29]. These challenges include accidents and injuries, inadequate signage and audible signals, and poor infrastructure design.

2.4.1 Accidents AND Injuries

Road accidents involving pedestrians usually have serious consequences due to the lack of protective equipment. According to the US National Highway Traffic Safety Administration [30], approximately 6,205 pedestrians died in traffic crashes in 2019, while the number of injured pedestrians exceeded 76,000. These accidents occur primarily in urban environments where traffic is heavy and crossing the streets without adequate protection is common.

Reducing pedestrian accidents requires multi-dimensional approaches involving education, infrastructure and strict enforcement of laws. Educating drivers about pedestrian rights, as well as educating pedestrians on how to cross the roads safely, can reduce the number of accidents. At the same time, strict enforcement of speed limits and the creation of special zones for pedestrians can enhance their safety [31]. At the international level, programmes such as Vision Zero aim to eliminate road traffic fatalities by focusing on the safety of vulnerable road users such as pedestrians.

2.4.2 Visual AND auditory stimuli

Failure to provide adequate visual and auditory stimuli can increase the risk of accidents. Pedestrians depend heavily on visual and auditory stimuli to perceive approaching vehicles and to make decisions about when it is safe to cross the road. The lack of adequate signage, traffic lights and audible signals can make this perception difficult. Studies have shown that unmarked road crossings significantly increase the risk of accidents, as drivers may not observe pedestrians in time [32].

Electric vehicles, which are silent, may not be seen by pedestrians who rely on sound to tell when a vehicle is approaching. In such cases, incorporating LED lights along crosswalks or other pedestrian detection technologies can help improve safety. Pedestrian warning systems, which are activated by motion sensors and detect the location of pedestrians, have already been adopted in several smart cities to reduce accidents [33].

2.4.3 Infrastructure AND Design

The quality of infrastructure and the design of urban areas play an important role in pedestrian safety. Infrastructure that is not designed with the pedestrian in mind increases the risk of accidents. The absence of adequate pavements, inadequate traffic signals at intersections and poor road maintenance can put pedestrians at risk. According to Oxley, areas with well-developed pedestrian infrastructure have significantly lower accident rates, while areas with poor infrastructure record increased injury incidents [34].

Properly designing and improving infrastructure based on the needs of pedestrians is crucial to enhance safety. Pedestrian walkways, properly signposted crossings and low-traffic areas are some of the solutions that can be adopted to reduce accidents. This infrastructure should be designed with accessibility and safety for all road users in mind, including disabled people, the elderly and children [35].

2.5 Smart City Technology Solutions and Initiatives

The rapid evolution of technology and the emergence of Smart City initiatives have created new opportunities to improve the safety and experience of pedestrians in urban environments. Technological solutions integrated into urban infrastructure aim to address the challenges of urban mobility, promoting sustainability, efficiency and safety. Smart cities apply cutting-edge technologies to optimise traffic and ensure pedestrian safety through information and communication systems.

2.5.1 Smart Pedestrian Crossings

Smart pedestrian crossings are innovative solutions to increase pedestrian safety by incorporating technologies that improve visibility and safety when crossing roads. Traditional crossings often do not meet the needs of modern urban centres, where traffic is heavy and the speed of vehicles increases the risk of accidents.

One of the most widespread technologies in smart crossings is LED lights placed along the crossing. These indicators are activated when the presence of pedestrians is detected, warning drivers of the impending crossing. The visual cues provided by the lights increase driver awareness, particularly at night or in low visibility conditions, thus reducing the risk of accidents [24].

Figure 2.1: Smart crossing with LEDs along its length

In addition, the crossings are equipped with motion and heat sensors, which detect the presence of pedestrians and adjust the signalling accordingly. These technologies allow automatic activation of pedestrian lights, giving priority to those in the crossing and enhancing safety [16]. At the same time, interactive signs provide real-time information about traffic conditions and waiting time, allowing pedestrians to make more informed decisions about their movement [17].

2.5.2 Intelligent Transportation Systems (ITS)

Intelligent Transport Systems (ITS) are a critical aspect of smart cities initiatives, aiming to improve the efficiency and safety of road networks. ITS incorporate information and communication technologies that allow real-time traffic monitoring and management.

One example is adaptive signalling, which adjusts the timing of traffic lights based on actual traffic conditions. This adaptation allows for better traffic management, giving pedestrians priority at intersections when needed, thus reducing waiting time and increasing safety [18].

Driver warning systems also alert drivers to the presence of pedestrians via variable message signs or directly in vehicles, using Vehicle-to-Everything (V2X) communication technologies. This technology allows direct communication between the vehicle and the environment, ensuring that drivers are fully aware of the risks and can react in time [19].

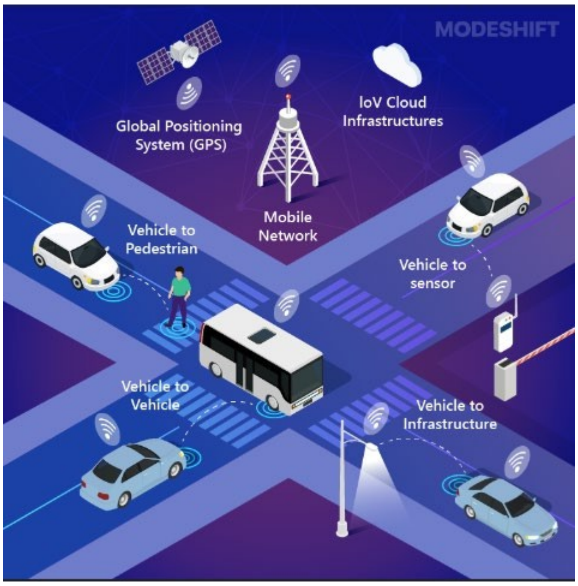


Figure 2.2: Vehicle-to-Everything example[45]

Another important element of ITS is real-time traffic management. The use of sensors, social media data and other sources allows real-time traffic monitoring. This technology reduces congestion and ensures that pedestrians are not exposed to dangerous traffic conditions [20].

2.5.3 Pedestrian Information AND Navigation Applications

Apps for smart devices have also become an integral part of smart city initiatives. They provide pedestrians with real-time information to improve their safety and experience while on the move.

One category of such applications is risk-avoidance applications, which warn pedestrians of dangerous intersections or areas with heavy traffic. These applications use data from sensors and traffic analytics to provide personalized alerts to pedestrians, enhancing their awareness of hazards [21].

Safe Routes navigation apps suggest routes to pedestrians that prioritise safety, avoiding areas with high vehicle speeds or lack of pedestrian infrastructure. In this way, pedestrians can move more safely in urban areas [22].

Finally, the integration of these applications with wearable devices offers additional possibilities to monitor the pedestrian's condition, such as fatigue or health status, and to adapt alerts according to their needs [23]. This technology allows a more personalized approach to pedestrian safety management, linking their physiological needs with traffic management.

3

Virtual Reality AND Eye-Tracking

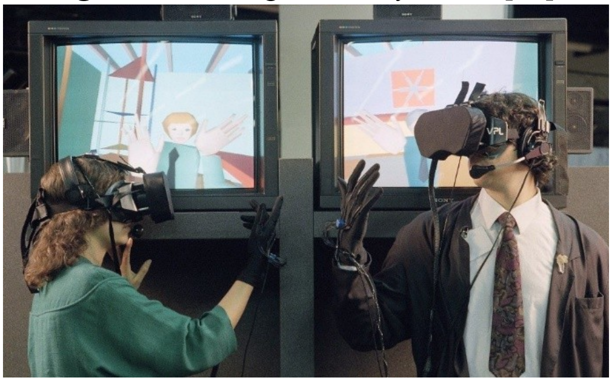
3.1 *Introduction to Virtual Reality*

3.1.1 History AND Evolution of Virtual Reality

Virtual Reality (VR) is a technology that allows the creation of a digital, three-dimensional environment in which users can interact with the world around them as if it were real. The history of VR goes back to the 1960s, with Morton Heilig's "Sensorama" prototype, which offered a multi-sensory experience of projecting images with a combination of sound, air and motion [13]. This system is considered as one of the first attempts to create immersive experiences.

In the 1980s, Jaron Lanier introduced the term "Virtual Reality" and founded the company VPL Research, which developed some of the first commercial VR systems, such as "Dataglove" and "EyePhone" [13]. These devices allowed users to interact with virtual objects through gestures and head movements.

Figure 3.1: Dataglove & EyePhone[46]



With the advances in computer and graphics technology, VR saw a significant development in the 1990s. The first handheld VR devices began to be used in training and simulation applications, such as in the military and medical fields [13]. The development of Head-Mounted Displays (HMDs) improved the quality of the visual display and allowed more natural interaction with the virtual environment.

3.1.2 Modern Applications of Virtual Reality

Modern VR devices, such as the Oculus Rift, HTC Vive and PlayStation VR, have significantly improved the quality of the experience, offering high resolution, accurate motion sensors and the ability to interact with virtual world objects [13]. VR has found applications in many fields:

- **Education AND Training**: used to simulate situations that are difficult or dangerous to reproduce in real life, such as training pilots or surgeons [13].
- **Entertainment AND Games**: It offers immersive experiences for users, allowing them to explore imaginary worlds and interact with the environment in a natural way.
- **Architecture AND Design**: allows for presentation and exploration architectural drawings in 3D space, facilitating understanding and decision-making.
- **MEDICINE AND Psychology**: used in treatments such as the treatment of phobias through exposure to controlled virtual environments [13].

3.1.3 Immersion AND Sense of Presence

The main goal of virtual reality is to create an environment that immerses the user and makes them feel like they are really there. The concept of immersion is central to a successful VR experience, as it is linked to the user's sense of presence in the virtual world. According to Slater (2017) [14], immersion refers to the objective level of technology offered by the system, while presence is the subjective experience of the user.

The more realistic the visual, auditory and tactile stimuli, the greater the sense of immersion. The quality of graphics, accuracy of motion detection and low latency are factors that contribute to creating a realistic experience [13]. In addition, the ability to interact with the environment enhances the sense of control and presence.

3.2 Eye-Tracking: Technology and Applications

3.2.1 History AND Development of Eye-Tracking Technology

Eye-Tracking is the technology that allows the recording of a person's eye movements in order to analyse their attention, perception and interaction with the environment. The history of eye-tracking dates back to the early 20th century, when early researchers became interested in how people read and perceive visual information. In 1908, Edmund Huey developed a mechanical system to record eye movement during reading [15].

Over the decades, eye-tracking technology has evolved significantly. In the 1970s and 1980s, the first electronic eye-tracking devices appeared, using techniques such as electro-ophthalmography (EOG) and video-ophthalmography (VOG). The development of high-speed digital cameras and improvements in eye-tracking algorithms allowed for more accurate and faster recording of eye movements [15].

3.2.2 Modern Applications of Eye-Tracking

Today, eye-tracking is used in various fields:

- **Research in Psychology AND Neuroscience**: Allows understanding of cognitive processes, attention and perception.
- **ADVERTISING AND Marketing**: used to evaluate the effectiveness of advertising and product placement by analysing where consumers focus.
- **Human-Computer Interaction (HCI)**: helps design more user-friendly interfaces by understanding how users interact with applications and websites.
- **MEDICAL Diagnosis**: Used for the diagnosis of ocular and neurological disorders.

3.2.3 Eye-Tracking technology in combination with VR

Although historically used in areas such as medical research and human-computer interaction, it is now becoming an integral part of VR. Companies leading the way with HTC in 2017 and Apple's Vision Pro platform in 2024 have incorporated eye tracking into their VR products, with other manufacturers such as Sony and Pico following suit using the specialist eye tracking hardware of Tobii, an innovator in the field and specifically in video games. Eye movements are among the fastest and most complex movements of of the human body, including various types, such as smooth tracking movements and sudden movements. Eye tracking in VR typically uses cameras and lights to detect these movements, with machine learning algorithms analyzing the data in real time. This feature allows the VR system to respond to the movements of the user's gaze, head and hands, creating a more direct experience[43].

The integration of eye-tracking into VR devices has opened up new possibilities in research and application development. By recording the focus points of the gaze within the virtual environment, researchers can analyze the attention and behavior of users more accurately [16]. This enables the creation of more customized and dynamic experiences, as the environment can react directly to the user's eye movements.

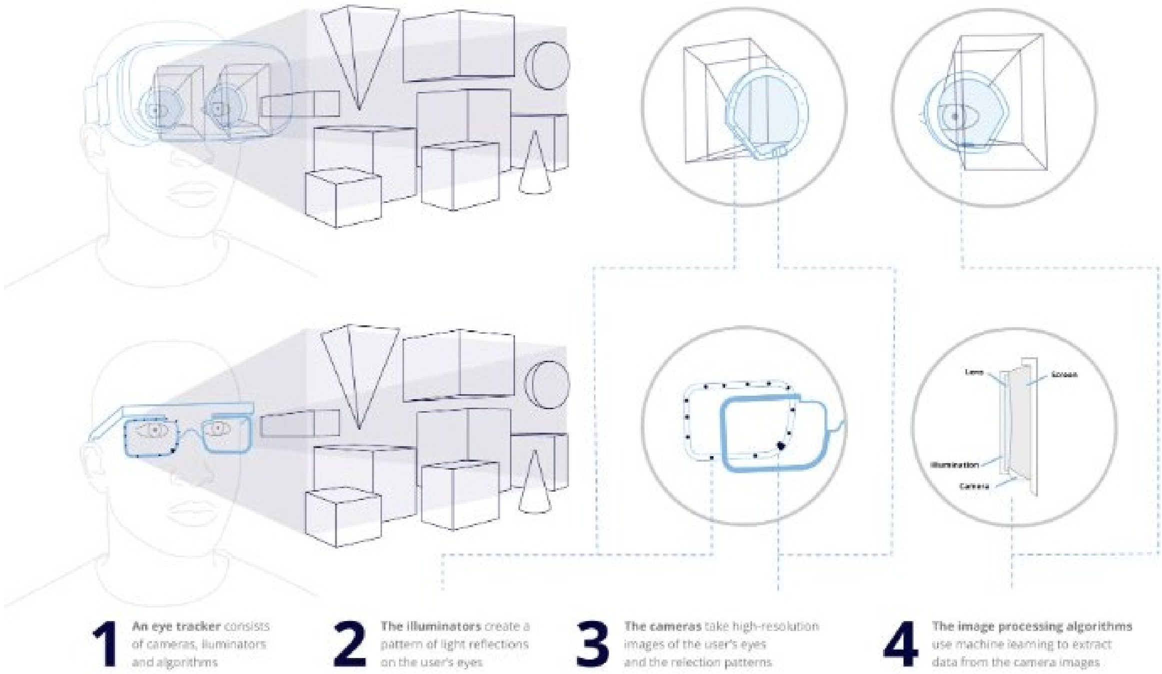


Figure 3.2: How eye-tracking works in VR.[47]

3.3 Using Virtual Reality and Eye-Tracking as Study Tools

3.3.1 Study of Behaviour of Pedestrians at VIRTUAL Environments

Studying pedestrian behaviour in real-life settings often comes with challenges, such as difficulty in controlling variables and risks to the safety of participants. In this context, VR combined with eye-tracking offer a reliable alternative, allowing the simulation of realistic urban environments and the safe investigation of pedestrian behaviour [15].

Deb and Carruth [15] present a review of studies that have used VR to investigate pedestrian behaviour. Through VR, researchers can simulate various scenarios, such as road crossings with different traffic levels, the presence of autonomous vehicles, and the influence of environmental factors.

3.3.2 Applications in Attention AND Perception Analysis

Eye-Tracking allows recording the points on which pedestrians focus when crossing roads. This provides valuable information on how they perceive risks and how they make decisions when walking in urban environments [17]. Analysis of eye-tracking data can reveal patterns of behaviour, such as the priority pedestrians give to specific visual stimuli, such as traffic lights or passing vehicles.

3.3.3 Improving Technological Interventions AND Infrastructure

The use of VR and eye-tracking allows the evaluation of the effectiveness of various technological interventions, such as smart pedestrian crossings, signage and traffic lights [16][17]. By simulating different scenarios and analysing pedestrian behaviour, designers can improve infrastructure and develop more effective systems to increase safety.

3.4 Advantages of Virtual Reality and Eye-Tracking in Pedestrian Behaviour Study

- **Realistic Simulation AND Control of Variables:** VR enables creating detailed and realistic models of urban environments, where researchers can fully test experimental conditions. This allows isolating the effects of specific factors, such as traffic density or the presence of technological interventions [13][15].
- **Safety AND Ethical Issues:** In contrast to field studies, where the participants are exposed to real risks, VR offers a safe environment where even dangerous situations can be simulated without risk to the safety of the participants [15]. This facilitates research in scenarios that would be difficult or impossible to explore in real life.
- **Collecting RICH AND ACCURATE Data:** the combination of VR with Eye- Tracking allows the collection of detailed data on pedestrian behaviour and perception. Analysis of eye movements provides information about attention and decision-making, while VR data can capture body movement and reactions [16][17].
- **Flexibility AND REPEATABILITY:** VR allows for easy customization of experimental conditions and repeating the experiments with different parameters. This contributes to the reliability of the results and facilitates the investigation of multiple scenarios [13].
- **Improving the User EXPERIENCE:** The use of immersive technologies can lead to a better understanding of how pedestrians perceive and interact with the urban environment. This can contribute to the development of more user-friendly infrastructure and technologies, improving the overall pedestrian experience [14].

4

Virtual World Development

4.1 Research objectives and scenario design

For the creation of the virtual world of the research, the game development engine Unity Engine was chosen. This choice was based on the flexibility of the tool, the extensive literature and the support offered by the game and virtual reality (VR) development community. All assets used to create the environments came from the Unity Asset Store and were available for free [42].

First, the scenarios to be tested were defined, with the aim of analysing the behaviour of users in different pedestrian crossing conditions. The scenarios were designed to examine users' reactions to different visual and auditory stimuli, as well as the effectiveness of smart city implementations in enhancing pedestrian safety.

The scenarios can be divided into two main categories:

4.1.1 Stimulus scenarios

In this category, the user passes through pedestrian crossings with various combinations of visual and auditory stimuli. Four scenarios were developed:

- **Crossing with visual but no auditory stimulus (A.1)**

The user is crossing a typical pedestrian crossing without traffic lights, where only electric vehicles (EVs), which do not produce noise, pass. This scenario offers only visual stimuli and aims to evaluate the user's ability to perceive vehicles despite the absence of auditory signals.

- **Crossing with visual AND auditory stimuli (A.2)**

The user crosses a typical pedestrian crossing without traffic lights, where both conventional vehicles (with internal combustion engines) and electric vehicles are moving. This scenario provides both visual and auditory stimuli and seeks to ascertain the user's reaction to the presence of vehicles and his/her timely or delayed response.

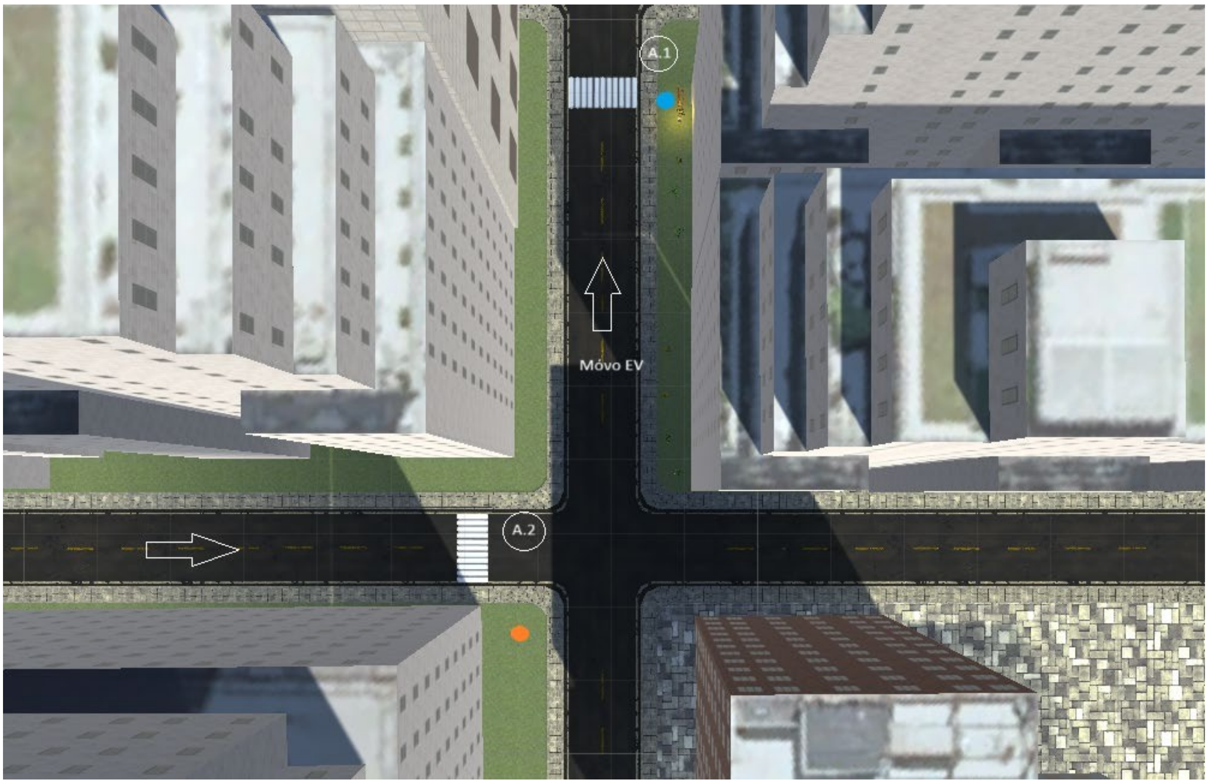


Figure 4.1: Scenarios A.1 and A.2, Blue dot is the player, orange is the checkpoint he has to go to

- **Crossing without visual but with auditory stimulus (A.3)**

The user is crossing a typical pedestrian crossing without traffic lights, while a parked bus limits his field of vision. Only conventional vehicles cross, which produce noise, providing only auditory stimuli. The scenario considers whether the user will react to the auditory stimulus and whether he will proactively check the area behind the obstacle before crossing the road.

- **Crossing without visual or auditory stimulus (A.4)**

The user is crossing a typical pedestrian crossing without traffic lights, where a parked truck restricts the field of vision and generates noise, masking any sounds from passing vehicles. Passing vehicles are only electric vehicles (EVs), which do not produce noise, exacerbating the absence of stimuli. The scenario seeks to determine whether the user will take precautionary measures despite the absence of visual and auditory stimuli.

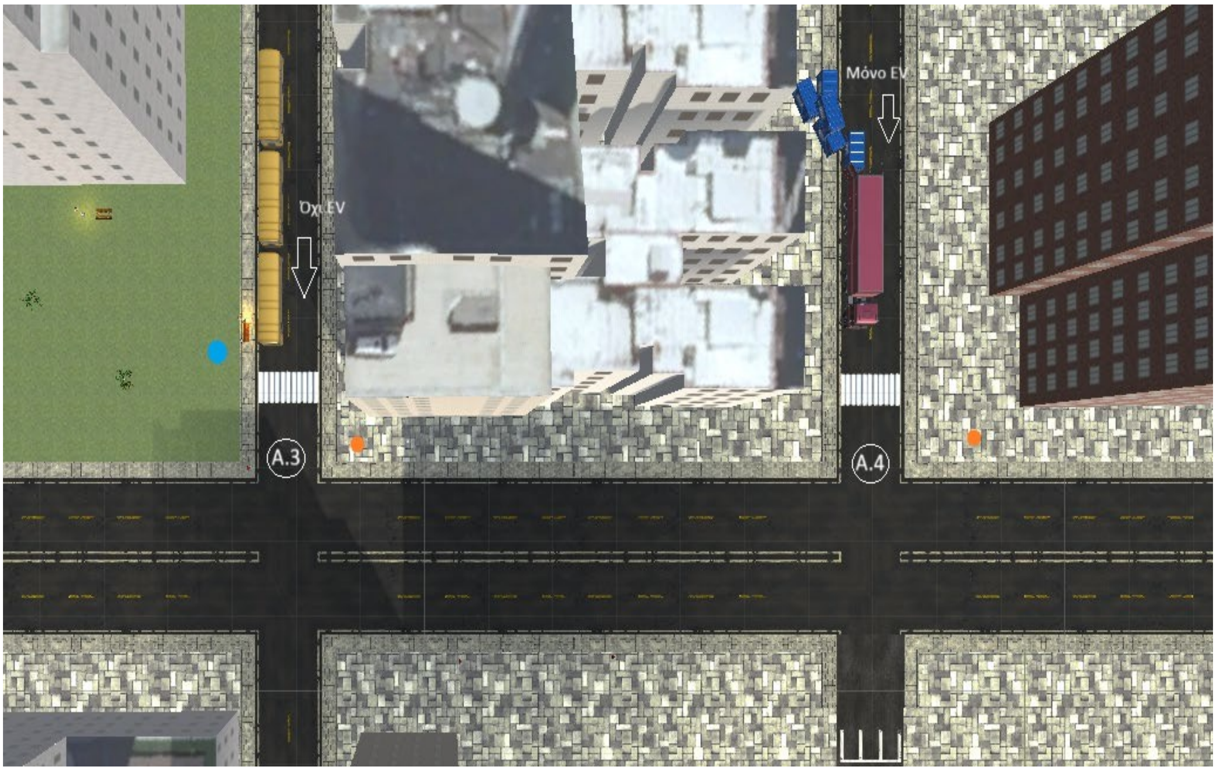


Figure 4.2: Scenarios A.3 and A.4.

4.1.2 Scenarios Implementations "Smart City" AND Landmarks Analysis

In this category, the user is taken through scenarios that include implementations of innovative smart city solutions. The aim is to evaluate the effectiveness of these implementations in enhancing pedestrian safety, and to understand user attention to critical elements of the environment through the analysis of fixations. Two scenarios were developed:

- **Crossing with traffic lights along the crossing (B.1)**

The user is asked to cross a two-way street where, in addition to the classic traffic light, there are also lights placed along the pedestrian crossing. These indicators act as additional visual information. The scenario aims:

1. **Preference ASSESSMENT**: to determine whether the user finds this implementation useful and whether he prefers it to conventional traffic lights.
2. **Focus analysis**: by recording the points of focus, it examines which type of signalling device the user first observes and the duration of focus on each one, helping to evaluate the effectiveness of the new technology.

Figure 4.3: Scenario B.1, The traffic light along the crossing is circled in blue.

- **Road with red LEDs prohibiting pedestrians from CROSSING the road (B.2)**

The user arrives at a point where the shortest route to the destination involves crossing a two-way road, which is equipped with red LED strips indicating that crossing is prohibited. The user must seek an alternative, safer route, which is significantly longer. Should the user attempt to cross the road and step on the LED lanes, an audible warning signal is activated. The scenario considers:

1. **Preventing Illegal Transit**: If the light and audible signal prevent the user from crossing the road from the prohibited place.
2. **Perception AND Compliance**: If the user notices the light and chooses to seek the safe route.
3. **Bias analysis**: The user's focus on the traffic light, the correct crossings when searching for the alternative route, and attention to passing vehicles is recorded.
4. **Reaction to SOUND Signals**: The user's reaction to the activation of the audible warning signal in the event of an illegal crossing shall be examined.

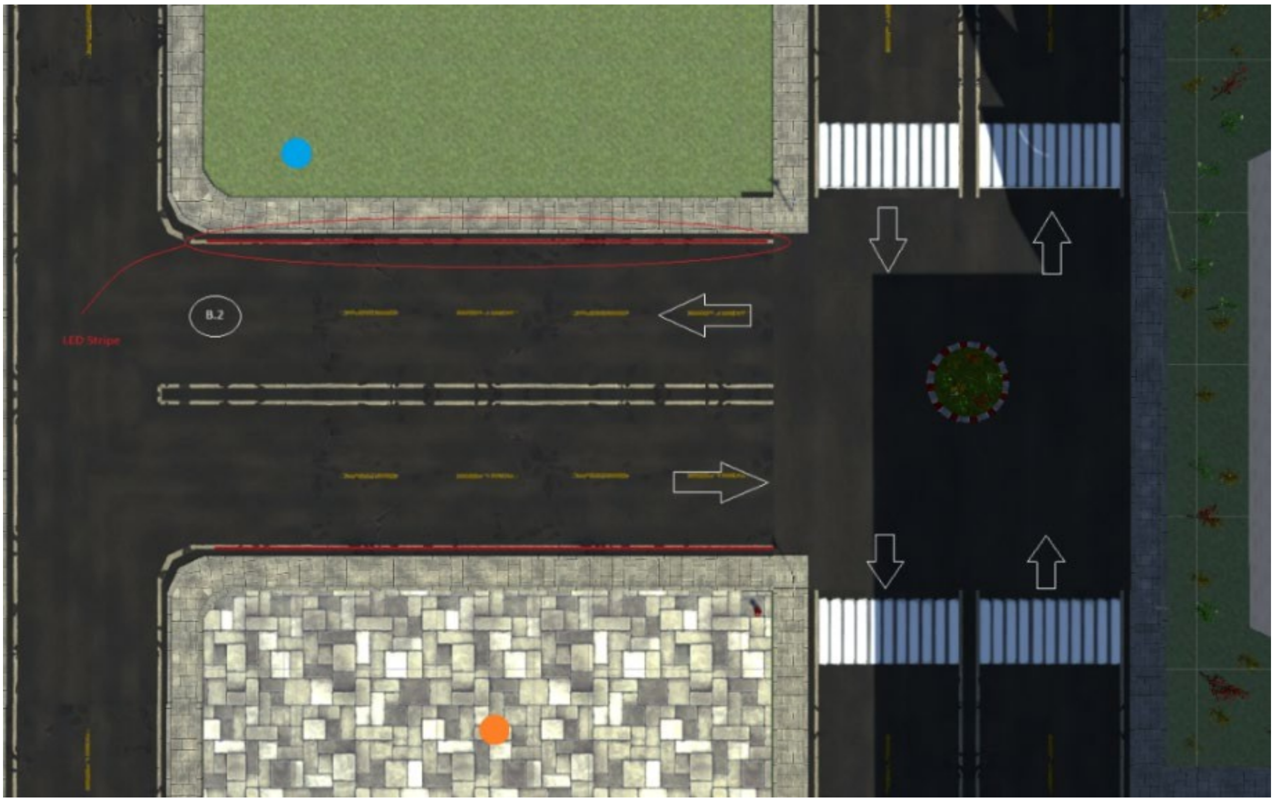


Figure 4.4: Scenario B.2, with the LEDs circled red that prohibit the crossing of the road.

In addition, the survey includes the analysis of users' attachment points in all other scenarios, in order to understand their perception of the elements of the environment that affect their security. The following were examined:

- **Observation of Crossings AND Signalling**: If users observe and focus on crossings and traffic lights before crossing.
- **Effects of VISUAL AND AUDITORY stimuli**: How the presence or absence of visual and auditory stimuli affects users' attention and behaviour.
- **Beware of Passing Vehicles AND Obstructions**: If users focus on passing vehicles and proactively check areas with limited visibility due to obstructions.

With this analysis, the research seeks to provide a comprehensive picture of user behaviour in different urban environments, contributing to the development of safer and more pedestrian-friendly urban infrastructure.

4.2 Car Traffic Implementation

The simulation of vehicle traffic was performed using the Gley Traffic System[44], a 3rd party asset from the Unity Asset Store. This system allows the creation of an integrated traffic network, including priority intersections and traffic lights. It provides a car model in ten different colors, with functional lights (flash) and acceleration sound, adding realism to the simulation. In addition, it gives the programmer the possibility to set multiple parameters, allowing the traffic system to be configured according to the requirements of the experiment.

In the context of this work, the following configurations were carried out:

- **Vehicle Lanes**: two categories of vehicles were created, conventional and electric (EV). These vehicles were designated to drive on specific roads, which were chosen to serve the needs of the experiment. This allowed the study of the effect of different types of vehicles on pedestrian behaviour.

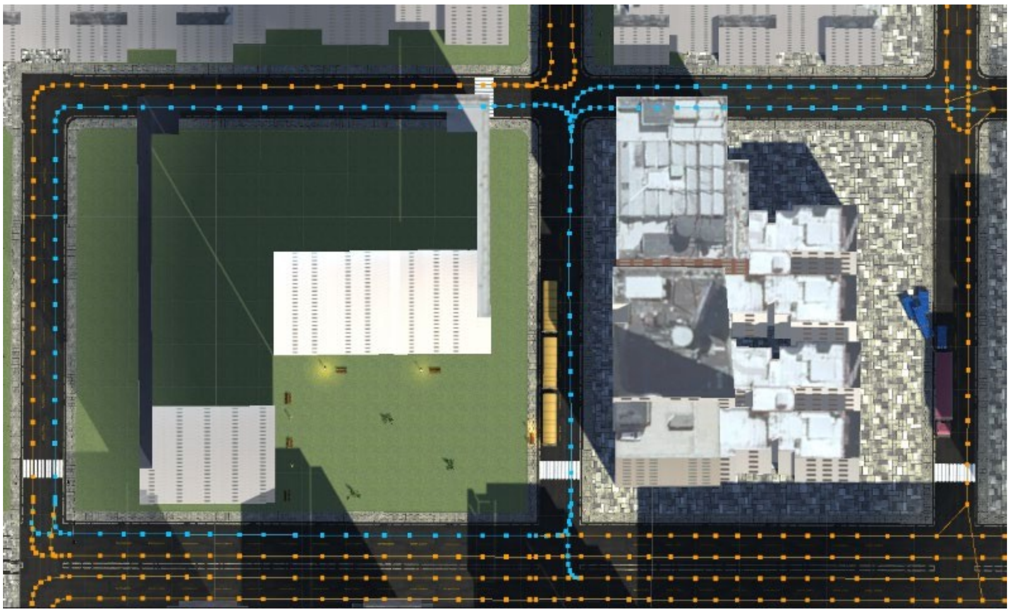


Figure 4.5: On the blue routes only conventional vehicles can move, while on the orange routes either a single EV or both types of vehicles can move

- **Speed Lanes:** different traffic speeds were set on selected roads, in order to increase the frequency of vehicle crossings on them. This arrangement allows for the creation of areas with higher traffic flow, facilitating the observation of pedestrian reactions under conditions of increased traffic.

Figure 4.6: In the white ones the speed is 90km/h, in the green ones 50km/h, in the yellow ones 110km/h.

- **Grid Layout**: a virtual grid of 100x100 units around the player was defined. Vehicles can spawn within this grid, and vehicles exiting from it can be destroyed. This setting helps to optimise system performance by limiting the number of active vehicles and reducing the load on the processor.

Figure 4.7: Cars can be created in the 8 peripheral boxes, while anything outside this grid is destroyed

- **Traffic Flow (Traffic):** set the maximum number of vehicles that can be visible at any time. Based on the defined grid, the ideal number of vehicles was set to 25. This value was chosen after tests that took into account the need for realism in traffic without affecting the performance of the system.

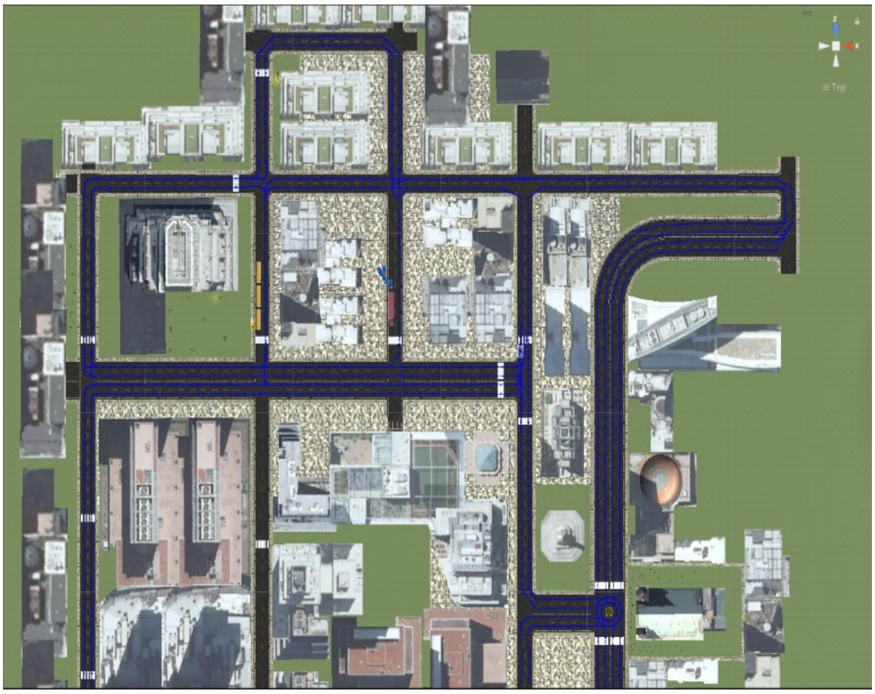


Figure 4.8: The network on which vehicles can move

- **Crossings Priority**: Designed intersections without traffic lights traffic lights indicating the priority of roads. At these intersections, greater priority was given to the busiest roads through adjustments to the traffic system. This ensured smooth traffic flow and avoided collisions between vehicles, simulating realistic traffic conditions.

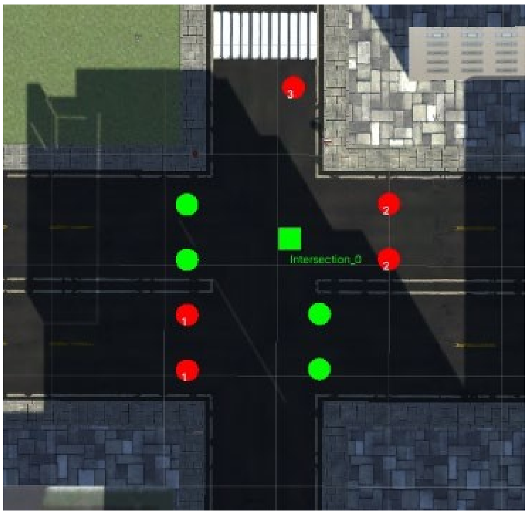


Figure 4.9: The exits at the junction are marked with a green circle and the entrances are marked in red

- **Traffic Light Timings:** the activation times of traffic lights were adjusted to reduce congestion and provide sufficient time for pedestrians to cross the road. After testing, the following timings were established: 14 seconds for the red/green light and 3 seconds for the orange light. These settings allow a balanced traffic flow to be maintained while facilitating safe pedestrian crossing.

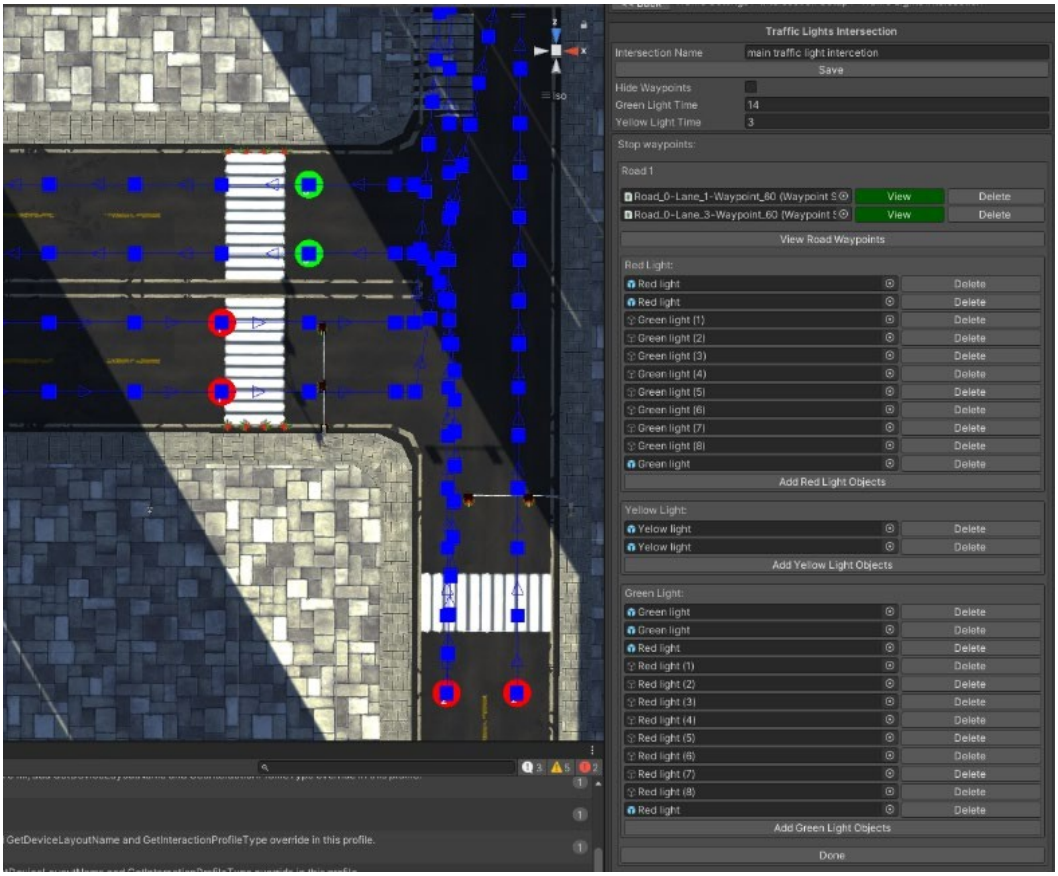


Figure 4.10: Right in Inspector has all the prefabs for the lanterns. On the left are the routes and the entrances/exits of the intersection

With the above configurations, the Gley Traffic System was effectively adapted to the requirements of the experiment, allowing the creation of a realistic and functional urban environment. The flexibility of the system made it possible to fine-tune the traffic parameters, contributing to the reliable conduct of the study and drawing valid conclusions about pedestrian behaviour in different traffic conditions.

4.3 Implementation System Traffic Pedestrian Traffic System (Pedestrian Traffic System)

To further increase the realism in our experiment, a pedestrian traffic system was implemented using Non-Playable Characters (NPCs). This addition helps to enhance the liveliness of the virtual city and provides additional stimuli to the user, increasing the level of cognitive load. This system consists of several subsystems, which work together to achieve a realistic simulation of pedestrian traffic.
The main components of the system are:

- **Waypoint Editor**: It is the UI that allows the creation and management of NPCs' waypoints (NPCWaypoints). Through the Waypoint Editor, the developer can define the routes and how to connect between waypoints, making it easier to design complex routes.
- **NPCWaypoints**: this is the class that implements the NPCs' waypoints. This class contains the attributes and properties of the waypoints, such as location, orientation and connections to other waypoints.

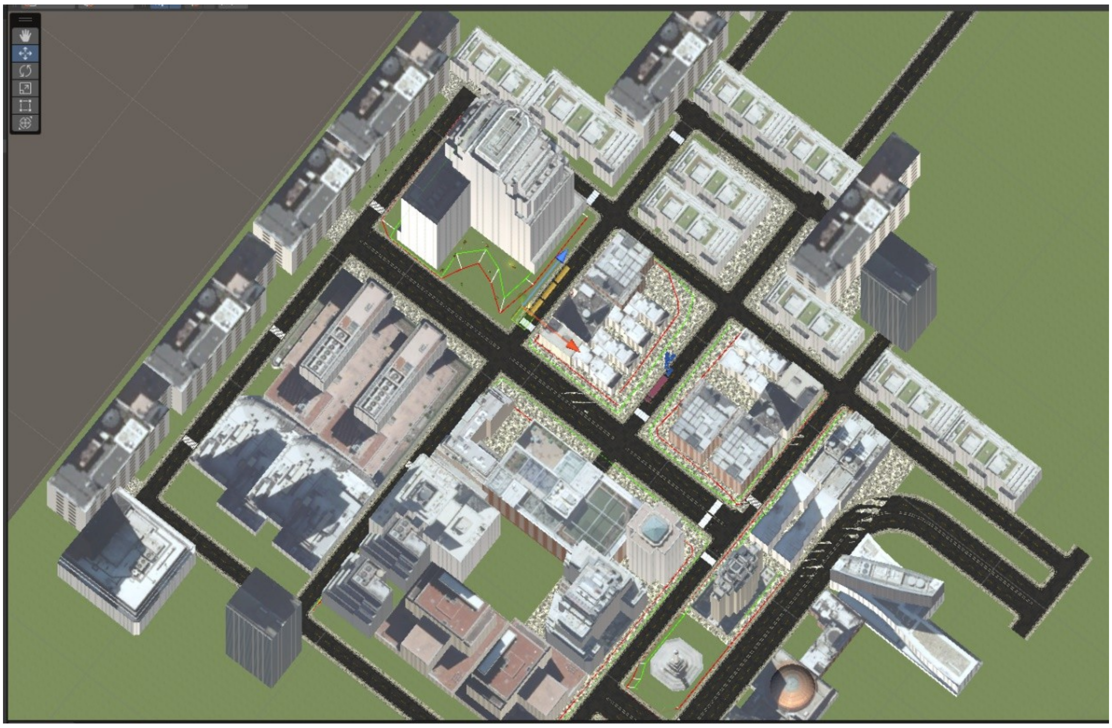


Figure 4.11: Red and green lines mark the NPC movement areas.

- **Waypoint Navigator**: this is the code section that implements the component that is attached to the NPC. The role of the Waypoint Navigator is to places the NPC at an initial waypoint and guides him along the specified route.

- **Eric**: "Eric" is the template (prefab) used for NPCs and is the main character provided by Unity in the Starter Assets/Third Person Controller. Eric has a built-in animator for walking movement, allowing for realistic movement without the need for additional animation development.
- **Character Navigation Controller**: This is the script that controls the movement of the NPC, including speed, rotation speed and checking if the NPC has reached its destination. This script works with the Waypoint Navigator to move the NPC from one waypoint to the next.
- **Pedestrian Spawner**: this subsystem is responsible for spawning replicas of Eric on the implemented paths in a random manner. The Pedestrian Spawner allows the number and frequency of NPCs to be determined, helping to control the density of pedestrian traffic in the virtual environment.

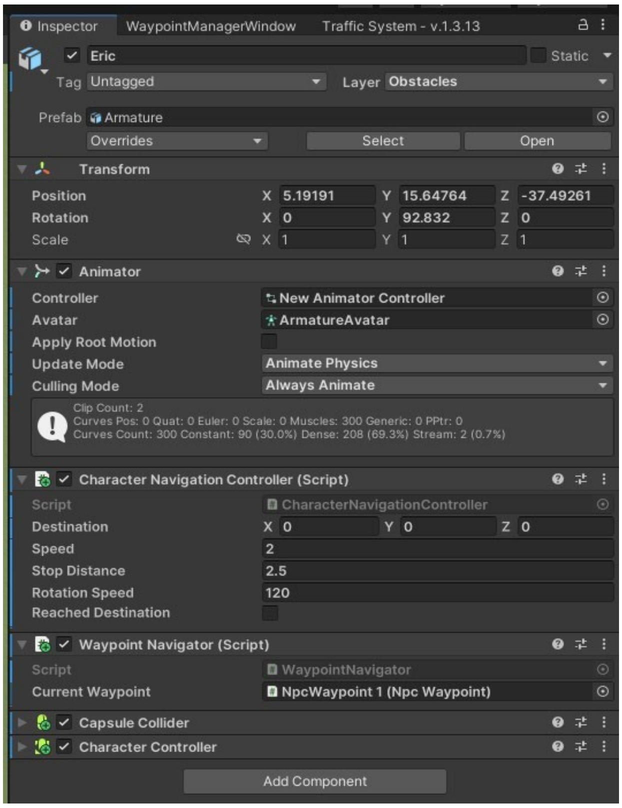


Figure 4.12: Components of Eric for proper operation of the Pedestrian Traffic System

Note that no interaction between the NPCs and the player was implemented, nor do the NPCs have the ability to cross the road. This decision was made in order to simplify the implementation, allowing the focus to be on the main study of user behaviour without additional variables that could complicate the results.

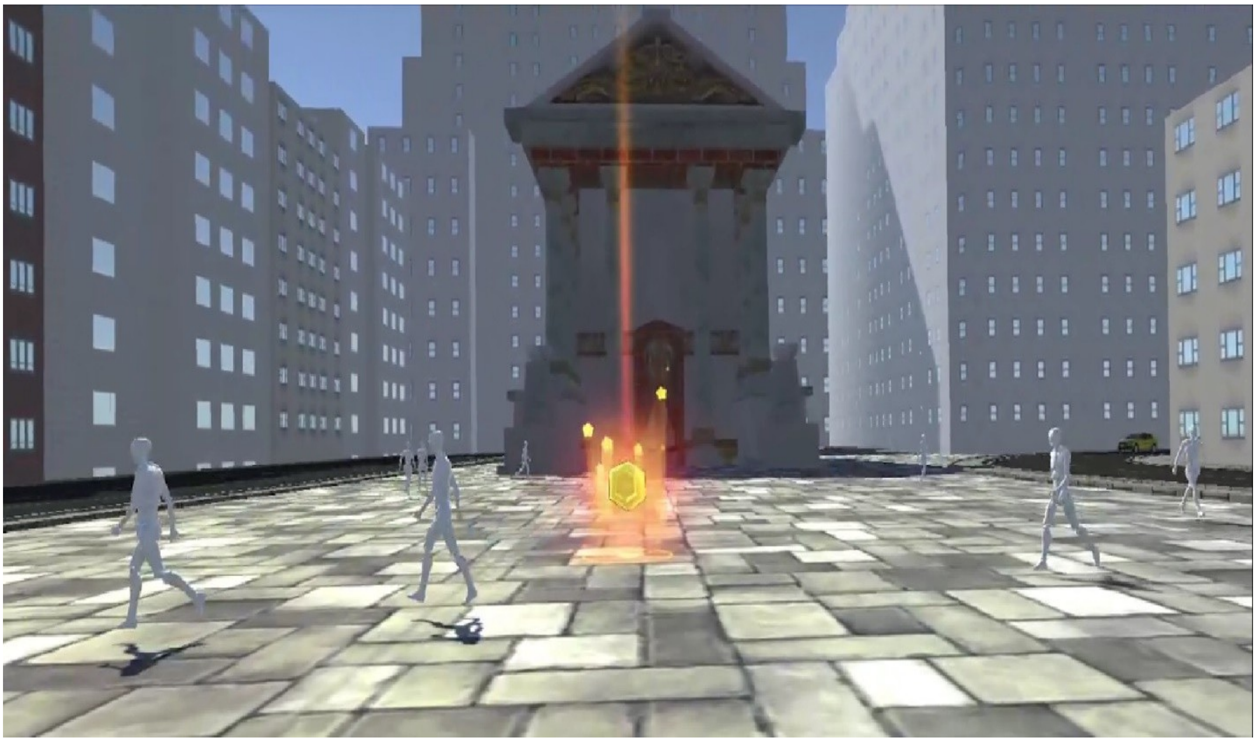


Figure 4.13: Gameplay snapshot of the NPC movement on foot, here you can see the last checkpoint.

4.4 Implementation System Guidance (Checkpoint System)

To guide the player within the virtual world, a system of **checkpoints** was implemented. The purpose of this system was to guide the player towards the various test scenarios in a way that avoids disorientation while maintaining a sense of freedom of movement.

After testing at various points in the virtual world, it was decided to use eight (8) checkpoints to achieve the optimal balance between guidance and freedom. These checkpoints were placed strategically, taking into account the distance between scenarios, the complexity of the environment and the need to avoid monotony (See Figures 4.1- 4.4, orange dots). To achieve the functionality of the system, a component(Checkpoint Manager) was developed to control the player's contact with checkpoints. In particular, this component detects if the player has made contact with the active checkpoint. If this condition is met, it deactivates the existing checkpoint and displays the next one in the queue.

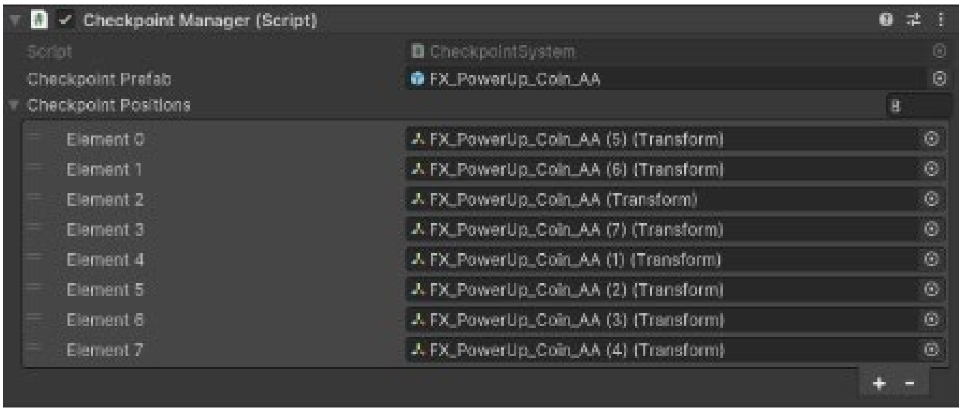


Figure 4.14: Checkpoint Manager

4.5 Player Implementation and VR Equipment Setup

After creating the virtual environment with the roads, intersections, traffic speed and the route the user will take, we proceeded to create the player.

4.5.1 Equipment (Hardware) AND Applications (Software)

For the research, we used the HTC Vive Pro Eye, one of the first virtual reality (VR) systems to incorporate eye tracking capabilities. Announced by HTC in 2019, it offers high-definition VR experiences. It consists of two controllers, two room sensors and the HMD with eye tracking system [36].

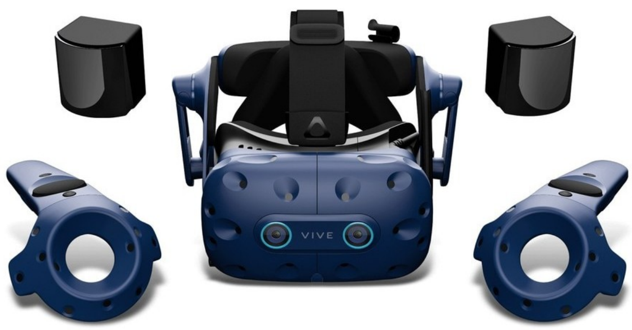


Figure 4.15: The VR equipment consisting of the HMD, 2 space sensors and 2 handheld cotrollers.

To use the equipment through the Unity Editor, the following 3rd party software was required:

4.5.1.1 Steam VR

It is used to support the VR system and communication with the hardware. SteamVR is a virtual reality platform developed by Valve Corporation. It acts as an integrated environment for developing, distributing, and operating virtual reality content. SteamVR provides a standard set of interfaces and a runtime environment that allows VR applications to interact with a variety of hardware devices, promoting hardware-agnostic software development.

The platform supports a wide range of VR headsets, including HTC Vive, Oculus Rift, Valve Index, and Windows Mixed Reality devices. Through SteamVR, users can access a variety of VR apps and games, as well as customize their virtual space through SteamVR Home, which offers an interactive and personalized environment [37].

On the development side, SteamVR provides the OpenVR SDK, a development software that offers application programming interfaces (APIs) for graphics rendering, traffic tracking, and input management. This allows developers to create VR applications that are compatible with various VR systems without having to develop separate code for each device [38].

4.5.1.2 SRAnipal SDK

The Vive SRanipal SDK is a Software Development Kit provided by HTC and designed to facilitate the integration of eye tracking and facial tracking functionality into virtual reality (VR) applications. This framework is specifically tailored for use with HTC's VR headsets that feature eye tracking technology, such as the HTC Vive Pro Eye [39].

Key features of the Vive SRanipal Framework:

- **Integration of MESH Monitoring:** The framework allows developers to access real-time data on the user's gaze direction, eye opening, pupil position and eye movements. This enables the creation of more immersive and interactive VR experiences, where apps can dynamically respond to where the user is looking.
- **Face Expression Monitoring:** In addition to eye tracking, SRanipal SDK supports facial expression tracking capabilities. It captures data on various facial expressions and movements, allowing for the creation of more expressive avatars and improving facial expressions.

social interactions in virtual reality through the reflection of users' emotions.

- **Foveated Rendering SUPPORT:** using eye-tracking data, the frame supports the foveated rendering technique, where the part of the image on which the user focuses is rendered at a higher resolution, while the image quality is reduced at the periphery of the field of view. This optimizes the GPU workload and improves performance without affecting visual quality where it is most important [41].
- **Full Access to APIs:** the SRanipal SDK provides a set of application programming interfaces (APIs) that are compatible with popular game engines such as Unity and Unreal Engine. This simplifies the development process for integrating eye and face tracking functionality [40].
- **Calibration AND Management User Management:** Includes Includes tools Tools for .
  calibration of eye tracking and supports multiple user profiles, ensuring accuracy and personalisation for different users.

4.5.2 First-person controller initialization in Unity

First we needed the XR Plugin Management through which we select the OpernXR template that allows compatibility with various VR hardware.

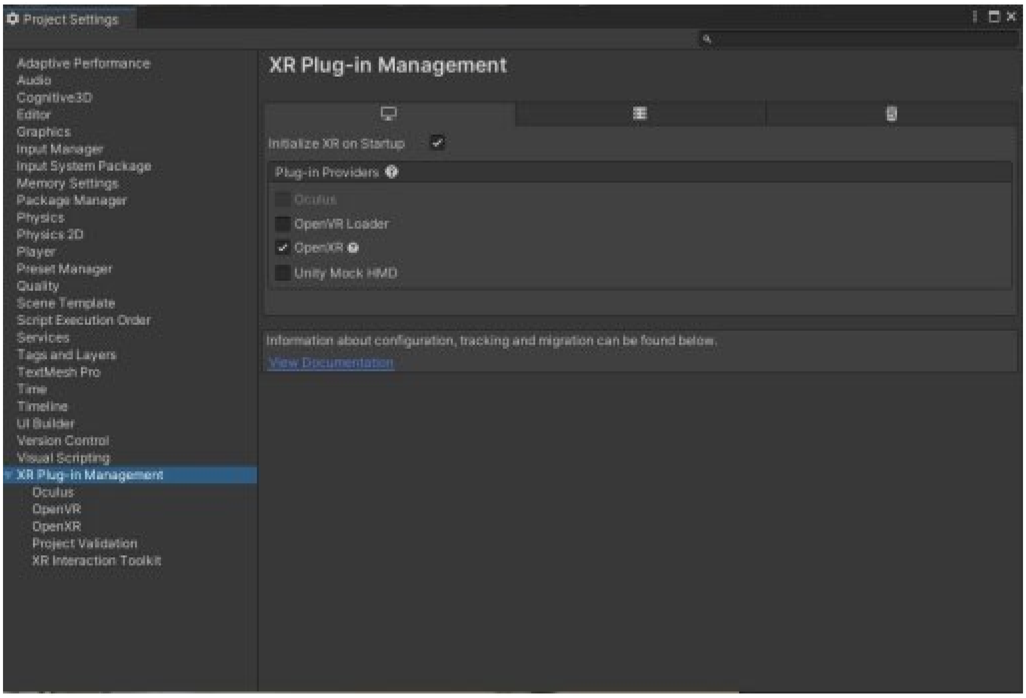


Figure 4.16: XR plugin management menu

Next, we installed the XR Interaction Toolkit via Unity's Package Manager. The XR Interaction Toolkit is necessary for managing user interactions and input in the VR environment. After setting all of the toolkit's actions as the default (default), we proceeded to create the XR Origin (XR Rig) in our Scene. The XR Origin is the key element (asset) for creating a first-person controller, which represents the player in the virtual environment.

Figure 4.17: The Actions

XR Origin includes the Interaction Manager, which we have defined as the Input Action Manager (see Figure 4.19). In addition, it includes the main camera, which represents the user's perspective, as well as the left and right controllers).

Figure 4.18: The XR Origin prefab

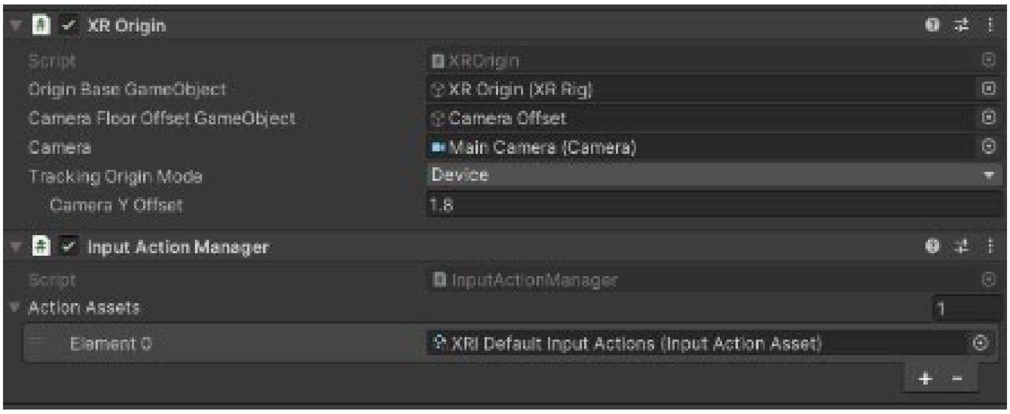


Figure 4.19: The two main script components of XR Origin.

For the eye-tracking data we got the prefab SRanipal Framework from the SDK that we had previously downloaded and added it to our Scene.

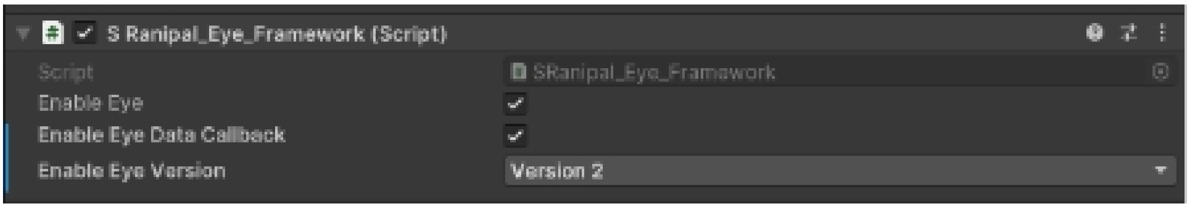


Figure 4.20: The Sranipal Framework component

4.5.3 Player Movement AND Rotation

In the next stage of development, we moved on to setting the player character to move in continuous movement, enhancing the realism of the virtual reality experience. To achieve this goal, we added the Locomotion System component to XR Origin, as well as the Continuous Move Provider (Action-based). To balance between realistic walking speed and stability, the character's speed was set to 5 units.

Figure 4.21: Locomotion System Component

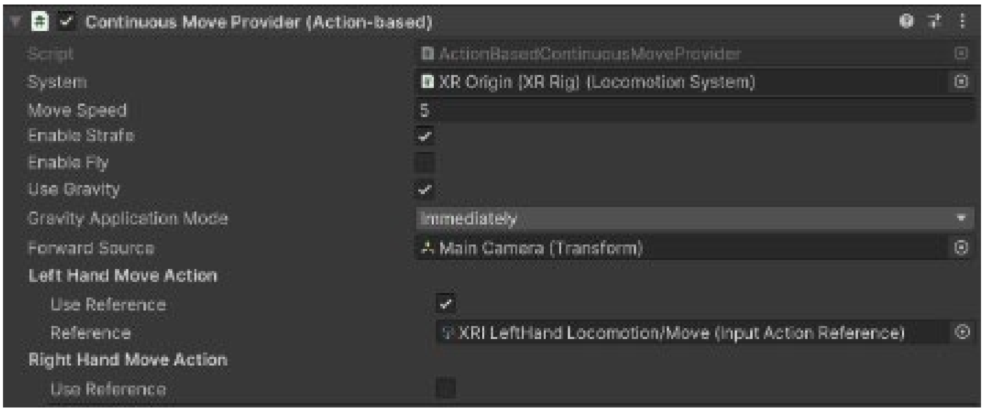


Figure 4.22: Continuous Move Provider Component. The mapping of the player's movement has been done on the left controller

In addition, we specified how the character will rotate. We chose Continuous Turn instead of Snap Turn, in order to provide a smoother and more realistic motion experience for the user. Therefore, we added the Continuous Turn Provider (Action-based) component to XR Origin as well.

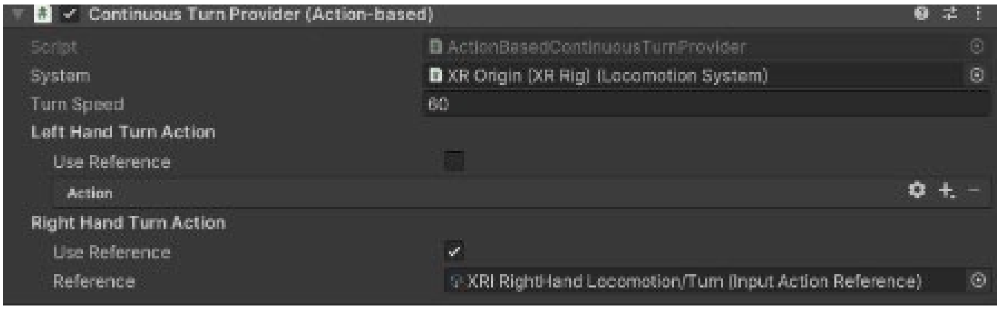


Figure 4.23: Continuous Turn Provider Component. The mapping of the player's turn has been done on the right controller.

With these settings, we ensured a more natural and immersive experience for the user, allowing them to move and rotate in the virtual environment in a way that simulates real movement.

4.6 Data collection

For the collection and analysis of the eye-tracking data, **Cognitive3D**, a platform that allows the collection, visualization and analysis of data from VR/AR applications, was used. To integrate it into the project, the Cognitive3D SDK was installed via Unity's **Package Manager**, and the prefab **Cognitive3D Manager** was added to the scene.

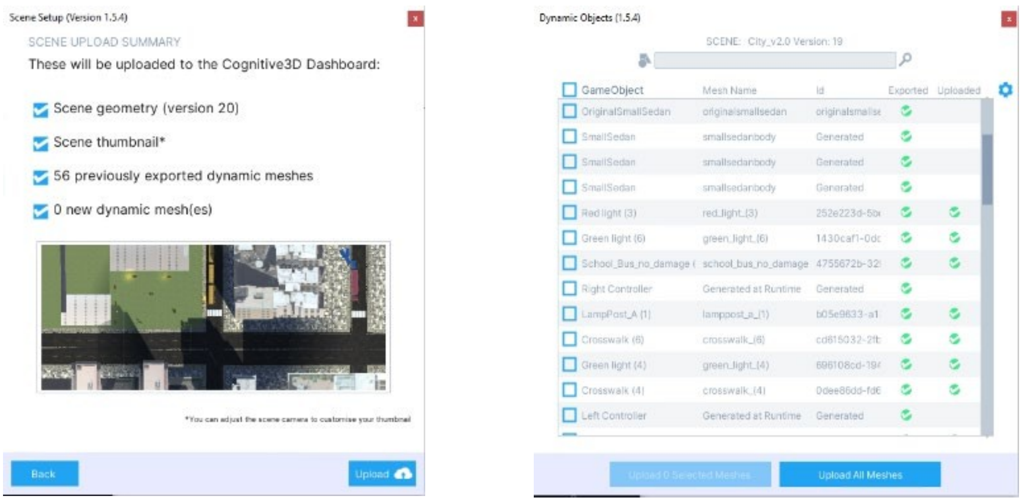


Figure 4.24: Cognitive3D's Scene Setup parameters that upload the project to the application.

It is important to note that we used Cognitive3D's built-in component, **Dynamic Object**, on the 3D objects (**meshes**) for which we wished to collect data. This allowed us to track the user's interactions with specific objects and record the focus of their attention.

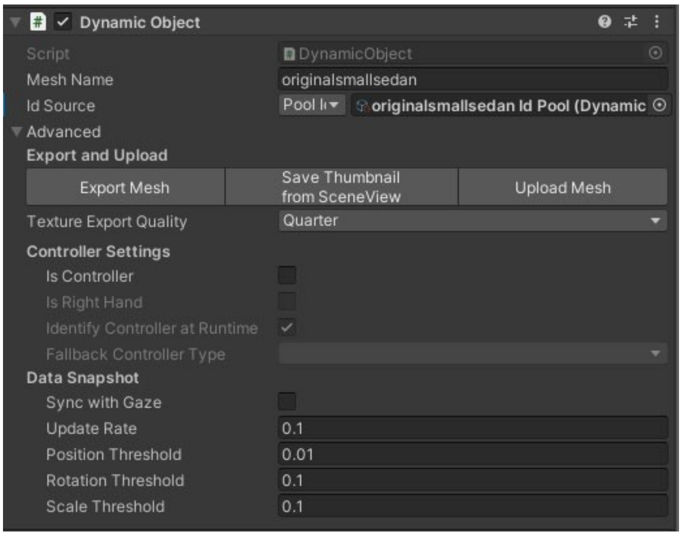


Figure 4.25: The DynamicObject component we put on the vehicles so we can see them in the Cognitive3D replay.

5

Conduct & Experiment Results

5.1 Experiment protocol

The experiment consisted of four stages:

1. **Completion of the Preliminary Phase Questionnaire**
At the initial stage, the participant was asked to fill in an interview form and a general questionnaire. This questionnaire collected basic information necessary to analyse the data and understand the participant's profile.

2. **Equipment Setup AND Calibration**
In the second stage, the virtual reality equipment was adapted to the participant. Specifically:
    - **Headset fitting**: the HMD was placed on the participant's head, with adjustment of the clamping, height and inter-eye distance to ensure comfort and optimal performance.

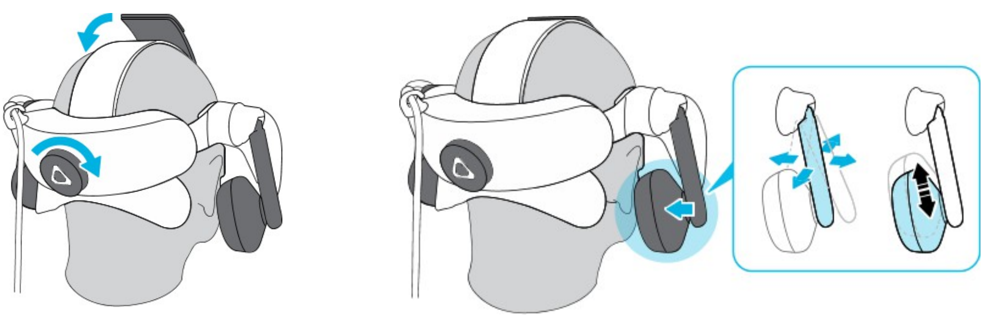


Figure 5.1: HMD correct application instructions

- **Explanation of Controls**: detailed instructions were given on how to use the controls and the various functions of the system.
- **Eye-Tracking Calibration**: the eye-tracking calibration procedure was performed to ensure accurate measurements during the experiment.

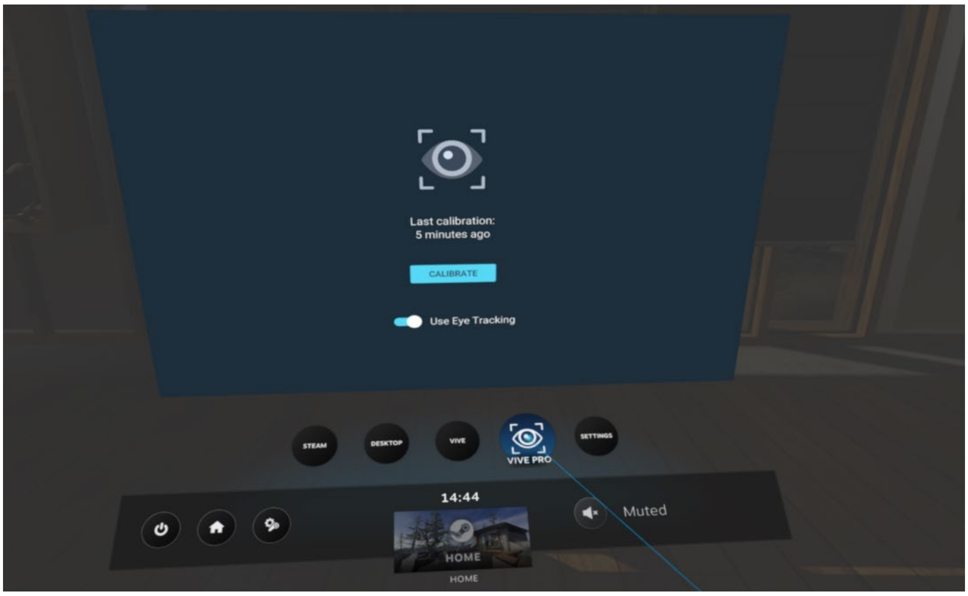


Figure 5.2: Snapshot of the eye-tracker calibration menu.

3. Running the Experiment in a Virtual Environment

In the third stage, the participant was introduced to the virtual environment of the experiment. The following instructions were provided:

- Goal: To follow the predetermined checkpoints that appeared in front of him.
- **Final Destination**: to reach an ancient Greek temple, which was the final destination of the route.
- **Guidelines**: No further details were provided t o observe the participant's physical behavior.

During the experiment, there was no communication with the participant unless a deviation from the predefined purpose of the experiment was observed.

4. Post-Experimental Interview AND Assessment

After completing the experiment, the participant participated in an interview. The purpose of the interview was:

- **Experience Assessment**: Record the participant's impressions and feelings about the virtual experience.
- **Feedback**: Identify any problems or difficulties encountered by the participant.

- **Suggestions for improvement**: to collect ideas and suggestions for improving the system and the overall user experience.

The information collected was used for qualitative analysis of the results and to enhance the reliability of the survey.

Note: All data collected during the experiment were treated with absolute confidentiality and used exclusively for the purposes of this research, in accordance with the principles of ethical research and the protection of personal data.

Various specialized tools and applications were used to collect the necessary data. In particular, Google Forms was used to conduct the questionnaire and interview, facilitating the efficient collection and organization of the participants' responses. The Cognitive3D platform was used to collect eye-tracking data. Due to the fact that Cognitive3D is at an early stage of development and presented some bugs during its use, an alternative design was adopted: a recording of the user's game-view was performed using the OBS application. This approach ensured that the necessary data was recorded in cases where Cognitive3D's replay system was experiencing problems, thus ensuring the integrity and completeness of the collected data.

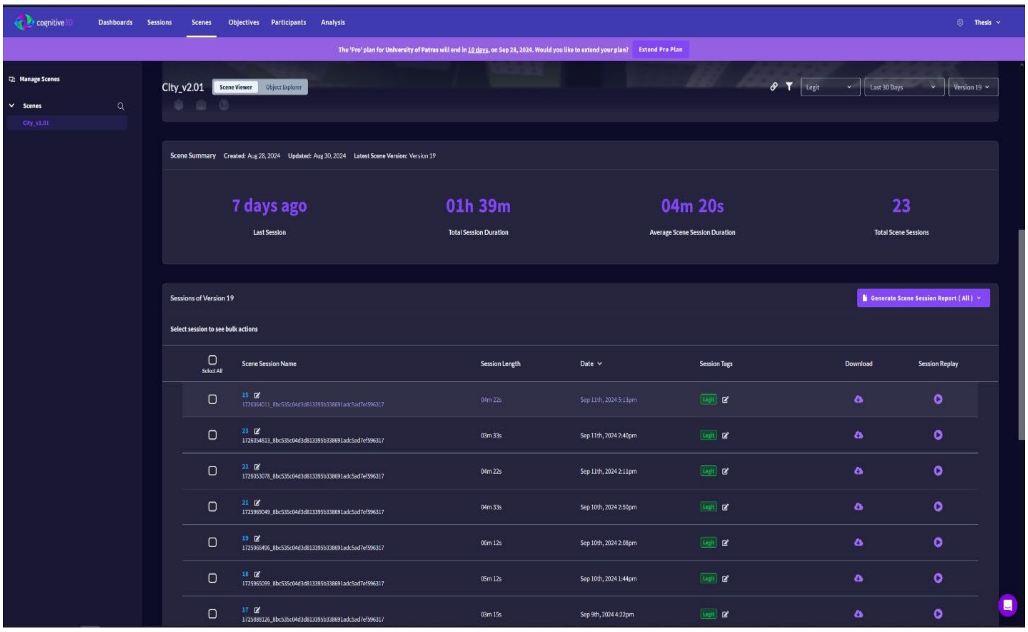


Figure 5.3: The Scene Tab of Cognitive3D where we see the Sessions and some general metrics

5.2 Execution of the experiment

Conducting the experiment was a crucial stage in the development of our research. Initially, the experiment was conducted exclusively at the Quality Assurance and Human-Computer Interaction Laboratory of the University of Patras, as the specialized equipment of the laboratory was necessary for the implementation of the study.

Prior to the start of the main tests, pilot tests were carried out to estimate the time required for a user to complete the process. This estimate was important for determining the overall expected duration and for the efficient organisation of the experiment. We arrived at an average duration of 25 minutes per participant, distributed as follows:

- 2 minutes to complete the questionnaire.
- 5 minutes to set up and calibrate the equipment.
- 3 to 10 minutes for participation in the virtual environment (gameplay).
- 10 minutes for the post-experimental interview.

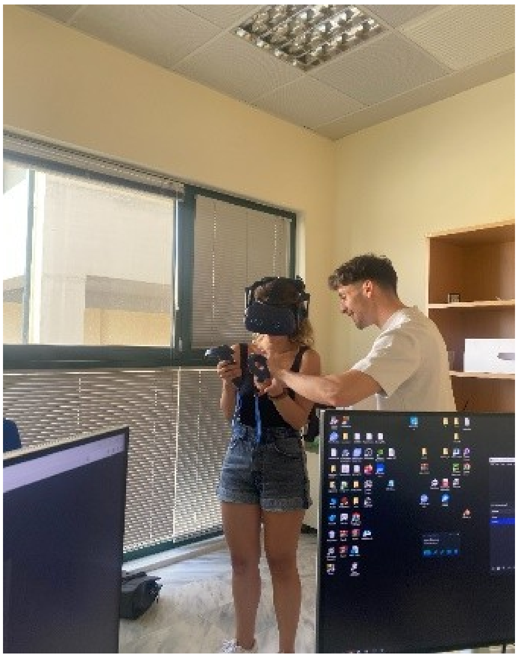


Figure 6.1: Photo of the experiment

5.3 Questionnaire data

In total, **23 people** participated in the experiment. The selection of participants and the conduct of the experiment were carried out in accordance with the ethical and moral standards in

research, ensuring the anonymity and protection of participants' personal data.
The demographic consists 100% of students aged 20-26.

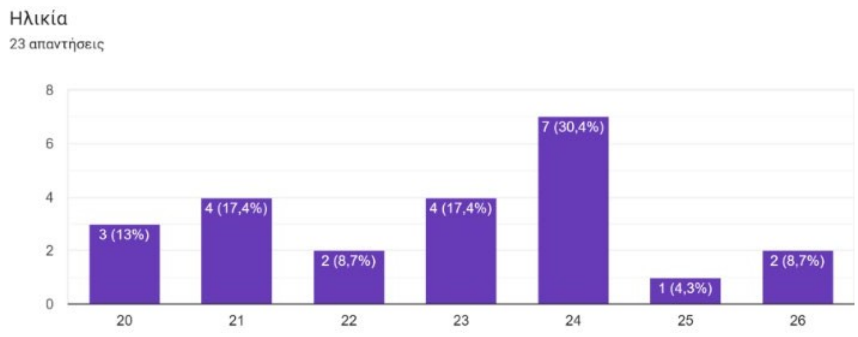


Figure 6.1: Ages

Users were asked whether they had taken a traffic education course and whether they had a driving licence.

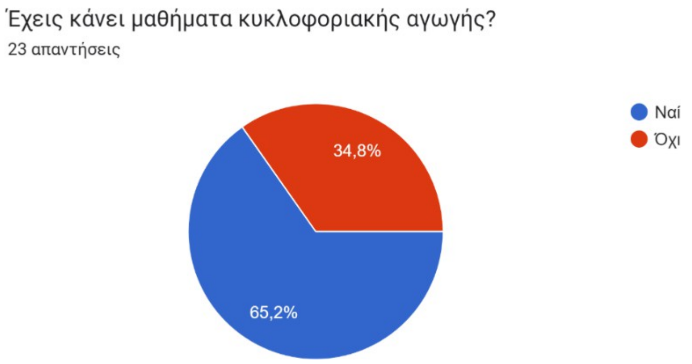


Figure 6.2: Traffic education lessons

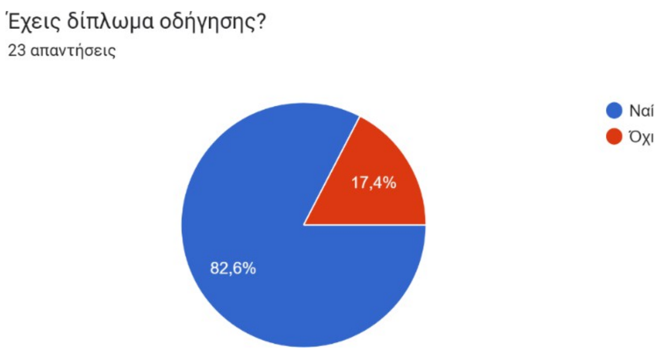


Figure 6.3: Driving Diploma

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They were then asked about what they use to get around town and how often they use their feet.

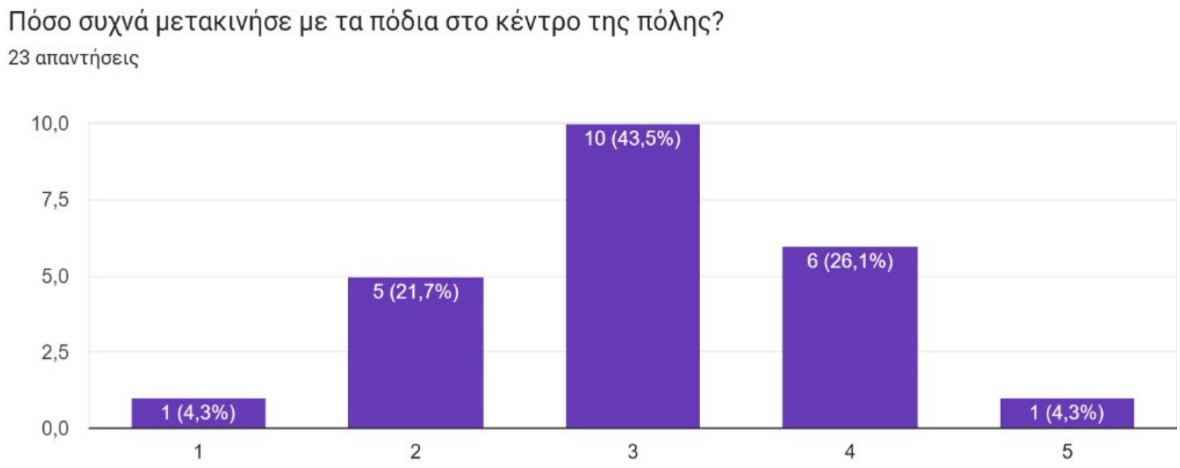

Figure 6.4: Frequency of walking (1: Not at all - 5: Daily)

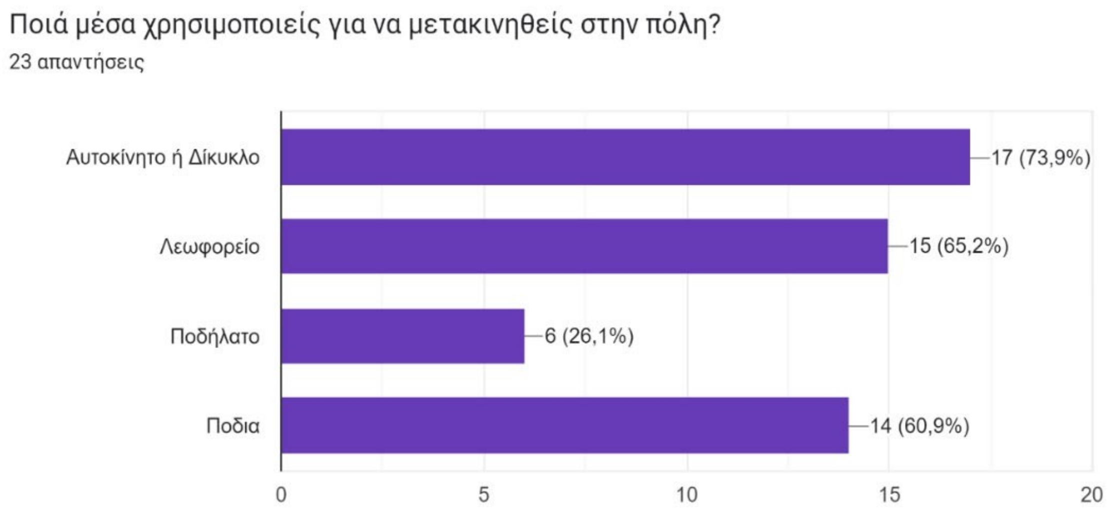

Figure 6.5:Means of transport

Finally, they were asked about their relationship with video games and more specifically VR.

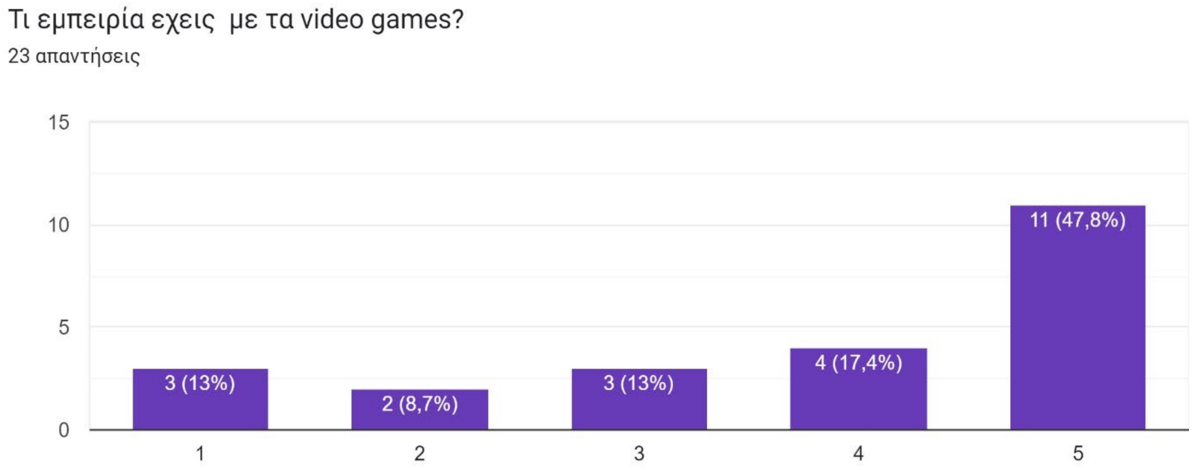

Figure 6.6: Experience with video games (1: None - 5: I play daily)

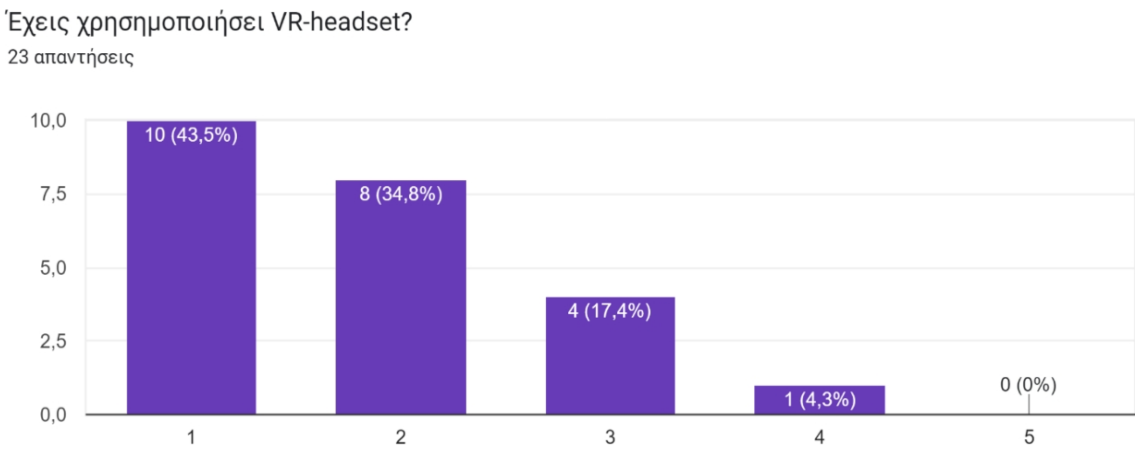

Figure 6.7: Experience with VR (1: No - 5: Everyday)

5.4 Gameplay results

This subsection presents the results of the different pedestrian crossing scenarios applied in the experiment.

5.4.1 NON-VISUAL SCENARIO, with Auditory Stimulus

In this scenario, the user's view is covered by a bus, and there is the possibility of hearing passing vehicles. It was observed that 10 out of 23 users (43.5%) crossed the road without checking for any passing vehicle, with 6 of them being hit by a vehicle. In contrast, 13 out of 23 users (56.5%) showed more caution and checked for passing vehicles before crossing. The post-experimental interview showed that most participants relied more on their visual perception than their auditory ability when crossing.

Figure 6.2: Snapshot in 3rd person view from the Cognitive3D Replay that detects the eye fixations and the user's gaze in scenario 5.4.1

5.4.1.1 Index

The results of this scenario show that the absence of visual contact with the road environment significantly affects pedestrian behaviour. Despite the presence of auditory stimuli, almost half of the participants did not check for passing vehicles, indicating that pedestrians rely mainly on their visual perception to assess risks. The high frequency of accidents (6 of the 10 who did not check were hit) highlights the need for increased caution when visibility is limited and the enhancement of auditory awareness as a means of detecting risks.

5.4.2 SCENARIO Non VISUAL, Non Auditory Stimulus

In this scenario, the user's line of sight is covered by a truck, while the passing vehicles are electric and do not produce sound. It was observed that 16 out of 23 users (69.5%) checked for passing vehicles before crossing the road. From the post-experimental interview it was found that some participants only checked because of the noise of the truck and not because of the perception of danger from possible passing vehicles.

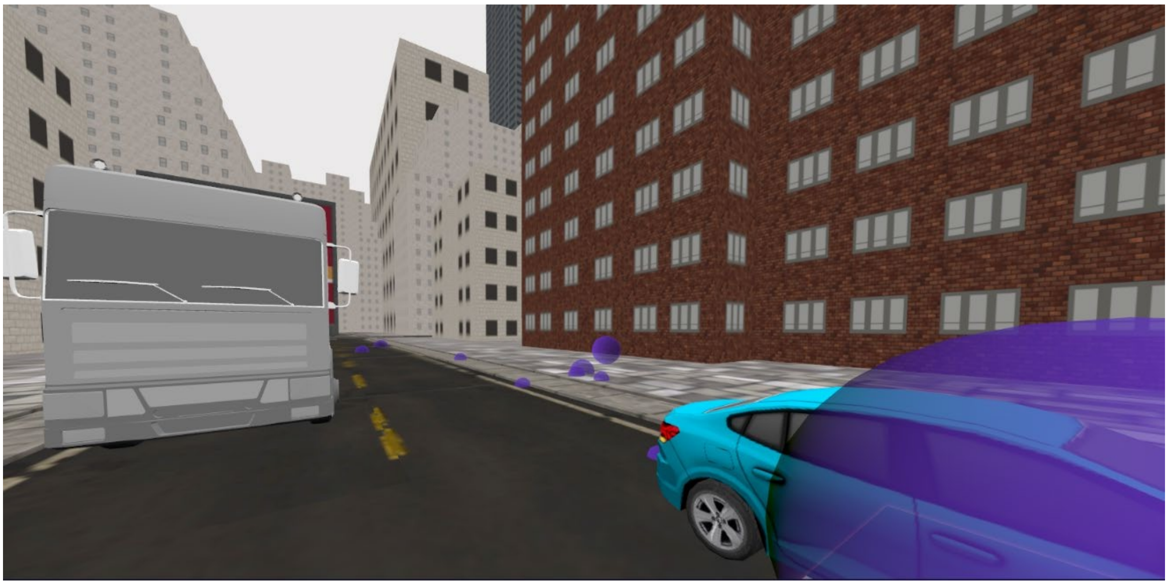

Figure 6.3: Snapshot in 1st person view from the Cognitive3D Replay that detects the eye fixations and the user's gaze in scenario 5.4.2

5.4.2.1 Index

This scenario demonstrates that when both visual and auditory perception is limited, pedestrians tend to be more cautious, as shown by the increased rate of checking for passing vehicles. However, the reliance of some participants on truck noise suggests that pedestrians may not fully perceive the hazards of quiet vehicles, such as electric vehicles. This highlights the need for increased awareness of these new modes of transport and the adaptation of pedestrian behaviour to them.

5.4.3 SCRIPT with VISUAL, Non-Audible Stimulus

In this scenario, 56.5% of the participants (13/23) crossed the crossing, while the remaining 43.5% (10/23) chose to cross the road diagonally, as this was the fastest route to the next checkpoint.

5.4.3.1 Index

The results of this scenario have to be interpreted considering that it was the first scenario of the experiment and many participants were still disoriented, trying to get used to the virtual reality (VR) environment and the way of moving in the game. The initial adaptation difficulty may have affected their ability to locate the crossing or follow the intended path.

Nevertheless, the fact that a significant proportion of participants (43.5%) chose the shortest route, ignoring the crossing, suggests that convenience and speed may override safety in pedestrian decision making, especially when there are no immediate visual or auditory cues of danger.

Therefore, the results probably reflect a combination of factors: pedestrians' preference for the most direct and quickest route, as well as initial adaptation to the VR environment. This highlights the importance of providing participants with sufficient familiarisation time before the critical scenarios begin to ensure that the results reflect their natural behaviour rather than the effect of the technology.

5.4.4 SCRIPT with Visual AND Auditory Stimulus

This scenario had the highest crossing success rate, as 21 of the 23 participants (91.3%) crossed the road using the crossing. Only
2 participants (8.7%) crossed diagonally, as they had not followed the crossing in the previous scenario either (5.4.3).

5.4.4.1 Index

The presence of both visual and auditory stimuli seems to encourage pedestrians to use the designated crossings. The high compliance rate underlines the importance of combined sensory stimuli in promoting safe behaviour. The two participants who did not follow the crosswalk likely have established habits that are not influenced by the stimuli.

5.4.5 SCENARIO with Illuminated Signage Along the Crossing

In this scenario, with the incorporation of traffic lights along the crossing, it was observed that 17 out of 23 participants (73.9%) noticed the traffic lights. Notably, 7 of these 17 participants (41.2%) spotted the traffic signal before the traditional traffic signal. Of these, 13 (56.5%) said they liked the idea, while the remaining 4 participants (17.3%) either did not understand its function or found it uninteresting. There were also 6 participants (26.1%) who did not notice the signage at all. Finally, 5 participants (21.7%) crossed the road from a point without a crossing.

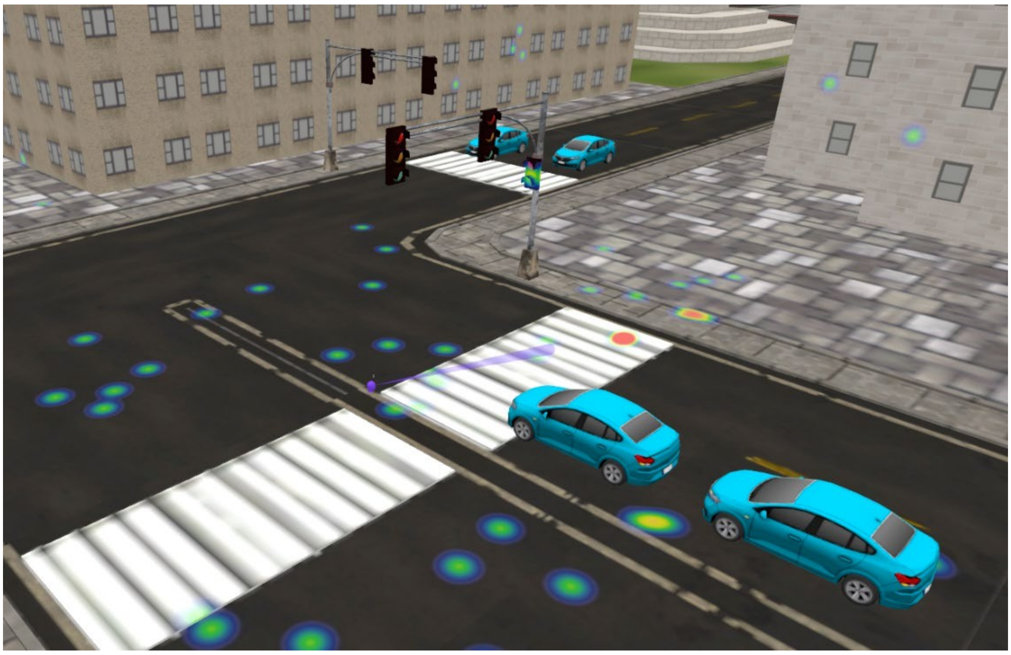

Figure 6.4: Snapshot in 3rd person view from the Cognitive3D Replay that captures the eye gaze of the user focusing on the traffic light along the crosswalk.

5.4.5.1 Index

The introduction of traffic lights seems to improve pedestrian awareness, with the majority noticing and expressing a positive opinion. The fact that some people identified the traffic lights before the traditional traffic signal suggests that such innovations can enhance pedestrian perception. However, the existence of participants who did not notice the signage or crossed at an impermissible location highlights the need for further improvement in the design and promotion of such technologies.

5.4.6 Scenario with Visual Contact Only in the Lantern of Vehicles

In this scenario, 16 of the 23 participants (69.5%) crossed the crosswalk, of which 12 looked at the traffic light before proceeding. The remaining 7 participants (30.5%) chose the shortest route to the next checkpoint.

5.4.6.1 Index

The absence of a pedestrian traffic light and the presence of only a vehicle traffic light seem to influence pedestrian behaviour, with many relying on the observation of the vehicle traffic light to decide when to cross the road. The choice of the shortest route by a significant proportion of participants suggests that convenience remains an important factor in pedestrian decision making, even when there is a hazard.

5.4.7 Barrier Scenario (LED Stripe) on the Shortest Path

In this scenario, only 3 of the 23 participants (13%) did not notice the obstacle (LED stripe), of which 2 immediately found the correct route, while one crossed the road without realizing that he should not have done so. Of the remaining 20 participants (87%), 14 (60%) did not cross the shortest route and found the correct one. It was noted that the participants who crossed incorrectly also realized their mistake when the alarm sound was activated upon contact with the obstacle even though it did not prevent them from crossing.

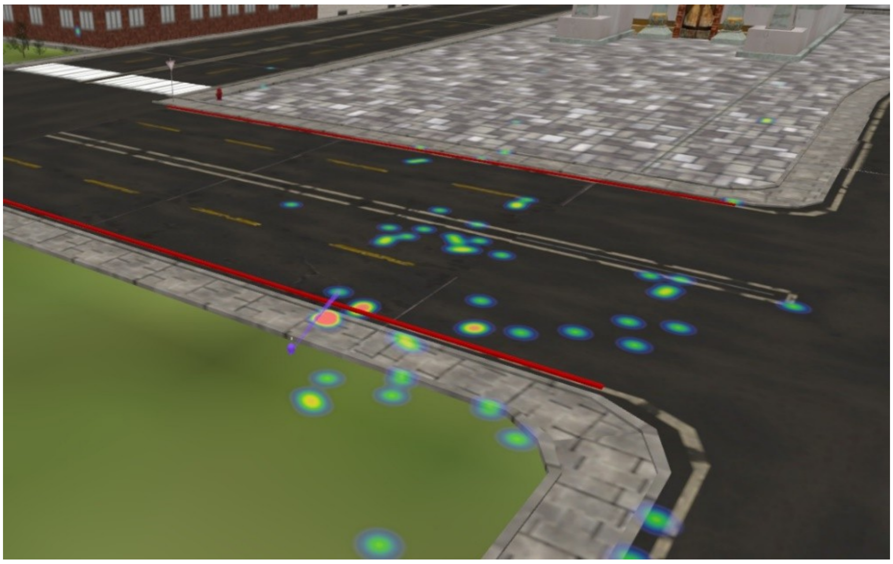

Figure 6.5: Snapshot in 3rd person view from Cognitive3D's Replay that captures the user's eye gaze focusing on the LED stripe.

5.4.7.1 Index

LED barrier placement appears to be effective in preventing pedestrians from using unauthorized routes. The high percentage of compliant participants suggests that such physical barriers, combined with visual and audible signals, can direct pedestrian behavior toward safer options. However, the failure of some participants to observe the barrier suggests that the visibility and design of the barrier may need improvement to be more effective.

5.4.8 General Experiment Results

For scenarios 5.4.5 and 5.4.6, where there was a crossing indication (e.g. pedestrian or vehicle traffic light), 16 out of 23 participants (69.5%) respected the priority of the indications. In terms of total crossing crossings, 9 of the 23 participants (39.1%) crossed at all crossings, 8 (34.7%) crossed at three, 3 (13%) crossed at two, 2 (8.6%) crossed at one, and 1 participant (4.3%) did not cross at any crossing.

In relation to pedestrian safety, 11 of the 23 participants (47.8%) were not hit by a vehicle, while the remaining 12 were hit at least once. Note that 6 of the 12 participants who were hit were injured in scenario 5.4.1 (non-visual, with auditory stimulus). There were also 2 participants who were hit twice during the experiment. In addition, hits were recorded in scenario 5.4.2 (2 subjects), 5.4.3 (3 subjects), 5.4.4 (1 subject) and 5.4.5 (2 subjects) who did not follow the crossing in this scenario.

The post-experimental interview revealed that 21 out of 23 participants (91.3%) had a positive view of smart city implementations, while the remaining 2 participants did not find them particularly useful. When asked which crossing they found safest, 12 out of 23 (52.2%) mentioned the crossing with a traffic light along the crossing (scenario 5.4.5), while the rest mentioned several of the crossings in scenarios 5.4.3, 5.4.4 and 5.4.5, mainly because they were one-way, making it necessary to look only from one side.

When asked if they would suggest any other form of crossing or ways to enhance pedestrian safety, 5 participants suggested the construction of pedestrian bridges or underpasses, while other ideas were mentioned such as illuminating the crossing itself with the appropriate colour, folding bollards that prevent pedestrians from crossing if there is a red light and overlapping signs for people with visual and/or hearing impairments.

Finally, when asked if the experiment would make them more careful in the future, 14 out of 23 participants (60.8%) said they would not change their behaviour or said they were already careful enough in real life. The remaining 9 participants (39.1%) answered in the affirmative, with a particular emphasis on those who were hit by a car during the experiment, which made them realise the importance of paying attention at pedestrian crossings.

5.4.8.1 Index

The overall results of the experiment suggest that, despite the majority of participants having a positive view of smart city technologies, this does not always translate into safe behaviour during the experiment. It is important to note that many participants treated the experiment as a game and did not feel the risk that would have been present in reality. This perception may have influenced their behaviour, leading to an increased number of accidents and traffic violations.

The lack of a sense of real risk may explain why almost half of the participants were hit by a vehicle at least once. This highlights the limitations of virtual reality in representing real risk and the need for more realistic simulations that enhance the user's experience and sense of risk.

In addition, participants' suggestions for improving safety show an awareness of potential risks and a desire for infrastructure that promotes safety and accessibility. The use of virtual reality as a tool for education and awareness raising can have a positive impact, but should take into account the tendency of users to perceive the environment as unreal.

Finally, the influence of the experiment on the future behaviour of some participants suggests that, although many did not feel at risk during the experiment, the experience nevertheless provoked thought about road safety. This suggests that such approaches can increase awareness, but further research is needed to enhance the sense of actual risk in virtual environments.

6

Conclusions AND Perspectives

6.1 Conclusions

This chapter presents the conclusions drawn from the results of the experiment discussed in Chapter 6. Through the analysis of the different pedestrian crossing scenarios, important findings on pedestrian behaviour, the effectiveness of different safety measures, and the potential for improving safety at pedestrian crossings in an urban environment are extracted.

6.1.1 Effect of Visual AND Auditory Stimuli

The results showed that pedestrians rely heavily on their visual perception to assess risks. In scenario 5.4.1, where eye contact was limited, almost half of the participants did not check for passing vehicles, leading to a high accident rate. The presence of auditory stimuli was not enough to compensate for the lack of visual information.

Similarly, in scenario 5.4.2, the absence of both visual and auditory stimuli led pedestrians to be more cautious, with the majority checking for passing vehicles. This suggests that perceived uncertainty may encourage cautious behaviour.

6.1.2 Influence OF Technological Interventions

The introduction of smart city technologies, such as traffic lights along the crossing (scenario 5.4.5) and LED barriers (scenario 5.4.7), had a positive effect on pedestrian behaviour. Most participants noticed and responded positively to these new infrastructure, suggesting that such interventions can improve pedestrian safety and perception.

6.1.3 Pedestrian Behaviour AND Habits

The results showed that convenience and speed often override safety in pedestrian decisions. In several scenarios, a significant number of participants chose the shortest route, ignoring crossings. This underlines the need to design infrastructure that combines safety with practicality.

In addition, the treatment of the experiment as a "game" by some participants influenced their behaviour, reducing their sense of risk. This suggests that virtual reality, while a powerful research tool, should be designed to simulate reality as closely as possible.

6.1.4 Familiarity with Technology AND the Environment

The initial confusion and disorientation in the VR environment, particularly in the first scenario (5.4.3), affected the participants' performance. This highlights the importance of providing sufficient familiarisation time with the technology before starting the experiments in order for the results to be reliable.

6.2 Perspectives and Future Research

Participants rated the crossing with traffic lights along its length (scenario 5.4.5) as the safest, indicating the effectiveness of such interventions in enhancing the sense of safety. Participants' suggestions for pedestrian bridges, underpasses, illuminated crossings and systems for people with visual or hearing impairments underline the need for multidimensional solutions addressing different needs.

6.2.1 Perspectives AND Future Research

Enhancing the sense of presence and risk in the VR environment can improve the reliability of the results. The use of more advanced technologies such as haptic feedback and more realistic visualisation could contribute to this.

6.2.2 Extension of the Sample

Conducting the survey with a larger and more diverse sample will allow generalisation of the findings and a better understanding of the differences between different population groups.

6.2.3 Education AND Awareness through VR

Virtual reality can be used as an educational tool to promote safer pedestrian behaviour. Developing educational programmes representing realistic risk situations, pedestrians can learn to react correctly to different scenarios.

6.2.4 Development AND EVALUATION OF new TECHNOLOGICAL interventions

Continued research into the introduction and evaluation of new technological solutions, such as smart crossings with adaptive signalling or pedestrian warning systems, will contribute to improving safety in the urban environment.

6.3 Final Thoughts

This research has shown the potential of using virtual reality and eye-tracking to study pedestrian behaviour. Despite the limitations, the findings provide valuable insights into understanding the factors affecting pedestrian safety and suggest directions for future interventions.

Promoting pedestrian safety is a critical issue in modern cities. The integration of smart city technologies and user education can make a significant contribution to achieving this goal. Continued research in this area is essential to create safer and more sustainable urban environments.

Annex A:

Consent form

Δήλωση συναίνεσης και αποδοχής καταγραφής

Συμφωνώ να συμμετάσχω στη μελέτη που διεξάγεται στο πλαίσιο διπλωματικής εργασίας του τμήματος Μηχανικών Η/Υ και Πληροφορικής του Πανεπιστημίου Πατρών.

Κατανοώ και επιτρέπω τη χρήση της εγγραφής της αλληλεπίδρασής μου κατά τη διάρκεια της μελέτης. Καταλαβαίνω ότι οι πληροφορίες και η εγγραφή είναι μόνο για ερευνητικούς σκοπούς και ότι το όνομά μου θα καταγραφεί μόνο ως βεβαίωση συναίνεσης και δεν θα χρησιμοποιηθεί για κανέναν άλλο σκοπό χωρίς άλλη άδεια. Μπορώ επίσης να αρνηθώ να απαντήσω σε οποιεσδήποτε ερωτήσεις δεν επιθυμώ να απαντήσω και να παραμείνω στην έρευνα όπως επίσης και να αποχωρήσω οποιαδήποτε στιγμή χωρίς καμία συνέπεια. Ο ερευνητής μπορεί να μου ζητήσει να αποσυρθώ από την έρευνα, αν ανακύψουν περιστάσεις που το απαιτούν.

Κατανοώ ότι η συμμετοχή μου σε αυτή τη μελέτη είναι εθελοντική και συμφωνώ να ενημερώσω άμεσα τον υπεύθυνο της μελέτης για οποιαδήποτε απορία, δυσφορία ή επιφύλαξη έχω κατά τη διάρκεια της μελέτης.

ΟΝΟΜΑΤΕΠΩΝΥΜΟ: ____

Υπογραφή: ____

Σας ευχαριστούμε, η συμμετοχή σας στη μελέτη είναι πολύ σημαντική για την έρευνά μας

Google Drive link to install the project

https://drive.google.com/file/d/1EPErI4fQNeq6EPLqn2yIubrSHz9qQjlf/view?usp=sharing

Pre-Gameplay QUESTIONNAIRE

https://docs.google.com/forms/d/e/1FAIpQLSeQme4rW7Vfn6pYQPeWXq7e3R7iLv2EUIr7U9rMOsFk301vfQ/viewform?usp=sf_link

Post-Gameplay interview

https://docs.google.com/forms/d/e/1FAIpQLScxOiXwj891r-f-jWPxST2bHUrw3NMOuS85BWPlBgjU3MMEtQ/viewform?usp=sf_link

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